Debris/Ice/TPS Assessment and Integrated Photographic Analysis of Shuttle Mission STS-95

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DEBRIS/ICE/TPS ASSESSMENT
AND
INTEGRATED PHOTOGRAPHIC ANALYSIS
OF
SHUTTLE MISSION STS-95

29 October 1998

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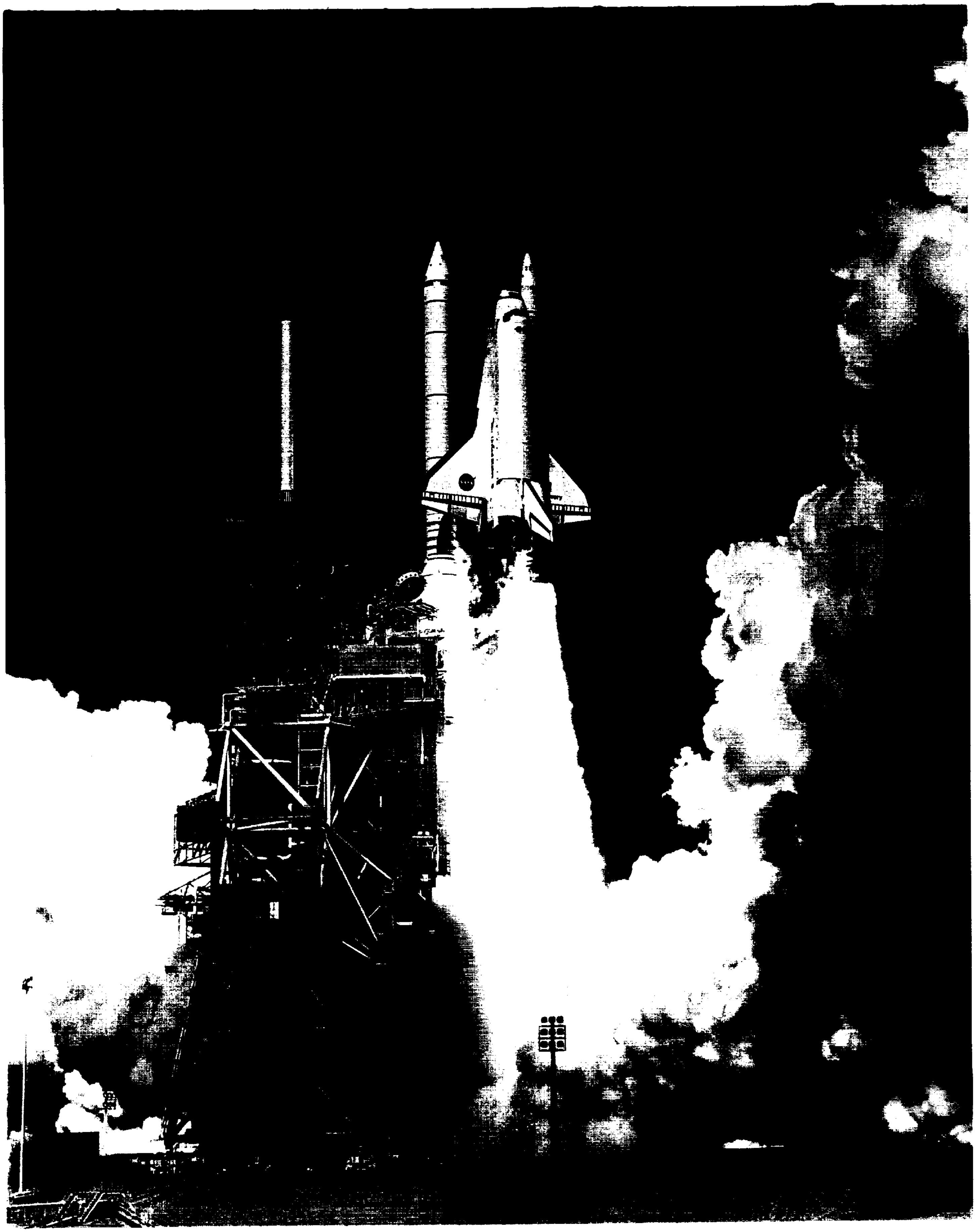

Photo 1: Launch of Shuttle Mission STS-95

1.0 SUMMARY OF SIGNIFICANT EVENTS

STS-95 consisted of OV-103 (25th flight), ET-98 and BI-096 SRB's on MLP-2 and Pad 39B. Discovery was launched at 98:302:19:19:33.984 UTC (2:19 p.m. local) on 29 October 1998. Landing was at 12:04 p.m. local/eastern time on 7 November 1998.

Drag Chute Door

An IFA concerning loss of the drag chute door at liftoff was generated as a result of real-time surveillance by the Ice Team.

The drag chute door detached from the drag chute compartment (shear pin side) at 19:19:30.648 UTC. The door swung downward pivoting about the hinge at 19:19:30.998, then dropped vertically from the hinge until impacting the SSME #1 aft manifold at 19:19:31.301 UTC. The impact caused the door to be deflected in the +Z direction and continue to fall aft into the SSME flame trench. No damage to the SSME #1 nozzle was visible. After an IFA was taken, an Anomaly Investigation Board was formed to investigate the premature release of the door.

Long range tracking films showed no indications that components of the drag chute or debris objects originating from the drag chute compartment fell aft during ascent.

Post launch analysis of high speed films showed the drag chute was intact and properly restrained by nylon straps inside the drag chute compartment. There were no visual indications that any of the pyrotechnic devices had fired (the sabot cover adjacent to the drag chute was intact). Measurements of the door's motion revealed the door had not been propelled open from the chute compartment, but just fell away due to gravity only.

After Orbiter landing, the drag chute and associated hardware inside the drag chute compartment appeared to be in excellent condition with very few visible heat effects. The deployment system was assessed and determined to be safe for towing to the OPF without firing the pyrotechnic devices on the runway. In addition, SSME #1 appeared to be undamaged by the drag chute door impact. A white scuff mark was visible on the aft manifold at the nozzle exit plane directly aft of the door hinge location. The metal was not bent or deformed.

Signs for early shear pin failure or door separation from the door frame were checked in the launch photography. Initially in the investigation, the apparent gap between the door and the chute compartment was thought to be significant but was later determined to be an expected interface line between adjacent TPS-covered carrier panels. The actual door structure would not be visible.

Laboratory analysis, conducted on door pieces recovered on the pad, showed no anomalies. The shear pin fragments exhibited the proper material properties and hardness. Review of the as-built paper, OMI documentation, and interviews with technicians uncovered no installation problems or workmanship discrepancies.

Subsequent attempts to duplicate the door failure in the laboratory were not entirely successful leaving the Investigation Board to conclude an unexplained anomaly possibly associated with the environment - an acoustic vibration or overpressure wave that exceeded the design parameters of the door. The pad and MLP for the next few launches will be instrumented to gather data on the SSME startup environment. In addition, the drag chute door design is being modified and will incorporate greater material margins. Until that effort is complete, the drag chute door will be bolted to the Orbiter structure and landings will be made without using the chute.

2.0 PRE-LAUNCH BRIEFING

The Debris/Ice/TPS and Photographic Analysis Team briefing for tanking test activities was conducted on 28 October 1998 at 1400 hours. The following personnel participated in various team activities, assisted in the collection and evaluation of data, and contributed to reports contained in this document.

P. Weber	NASA - KSC	Chief, ET/SRB Mechanical Systems Branch
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J. Rivera	NASA - KSC	ET Mechanisms/Structures
R. Page	NASA - KSC	SSP Integration
K. Revay	USA - SPC	Supervisor, ET/SRB Mechanical Systems
J. Blue	USA - SPC	ET Mechanical Systems
W. Richards	USA - SPC	ET Mechanical Systems
M. Wollam	USA - SPC	ET Mechanical Systems
G. Fales	USA - SPC	ET Mechanical Systems
T. Ford	USA - SPC	ET Mechanical Systems
C. Hill	BNA - LSS	Systems Integration
J. Cook	THIO - LSS	SRM Processing
S. Otto	LMSO - LSS	ET Processing
J. Ramirez	LMSO - LSS	ET Processing

Two cracks were detected in the +Y+Z quadrant of the intertank. One crack 6-8 inches in length was located in the second stringer valley in the +Y direction from the PAL ramp; the second crack was 10-12 inches in length and located in the fourth stringer valley in the +Z direction from the PAL ramp. The cracks appeared to originate from the as-sprayed foam at the aft end of the stringers extending forward from the LH2 tank splice. A third crack 6-8 inches long was located in the -Y-Z quadrant in the second stringer valley from the thrust panel. All cracks were no greater than 1/16 inch wide with no visible offset or ice/frost formation and were acceptable for flight per the NSTS-08303 criteria and IPR rationale from the flight of the first Super Light Weight Tank (STS-91).

The Final Inspection Team observed very light condensate, but no ice or frost accumulations, on the LH2 tank acreage. TPS surface temperatures ranged from upper 50's to low 60's (degrees F) depending more on sunlit versus shadowed area readings than the "thick/thin" TPS configuration.

Less than usual amounts of ice/frost had accumulated in the LO2 feedline bellows and support brackets.

A 4-inch long by 1/4-inch wide stress relief crack had formed, as expected, on the -Y vertical strut forward facing TPS. There was no ice/frost present and no offset. The condition was acceptable for launch per the NSTS-08303 criteria.

There were no TPS anomalies on the LO2 ET/ORB umbilical. Ice/frost accumulations were limited to small patches on the aft and inboard sides. Ice/frost fingers on the separation bolt pyrotechnic canister purge vents were typical.

Ice and frost in the LH2 recirculation line bellows and on both burst disks was typical. The LH2 feedline bellows were wet with condensate.

Less than usual amounts of ice/frost had accumulated on the LH2 ET/ORB umbilical purge barrier top and outboard sides. Typical ice/frost fingers were present on the pyro canister and plate gap purge vents. No unusual vapors or cryogenic drips had appeared during tanking, stable replenish, and launch.

3.2.4 FACILITY

All SRB sound suppression water troughs were filled and properly configured for launch.

No leaks were observed on the GUCP or the LO2 and LH2 Orbiter T-0 umbilicals.

3.3 T-3 HOURS TO LAUNCH

After completion of the Final Inspection on the pad, surveillance continued from the Launch Control Center. Twenty-two remote controlled television cameras and two infrared radiometers were utilized to perform scans of the vehicle. No ice or frost on the acreage TPS was detected. Protuberance icing did not increase noticeably. At T-2:30, the GOX vent seals were deflated and the GOX vent hood lifted. Although frost covered some of the ET nose cone louvers - an expected condition - no ice was detected. When the heated purge was removed by retraction of the GOX vent hood, frost continued to form on the louvers and area of the composite nose cone surrounding the louvers until liftoff.

Photo 2: STS-95 Ready for Launch

OV-103 Discovery (25th flight), ET-98, and BI-096 SRB's on Pad 39B and MLP-2. The Final Inspection Team observed very light condensate, but no ice or frost accumulations, on the LH2 tank acreage. TPS surface temperatures ranged from upper 50's to low 60's degrees F.

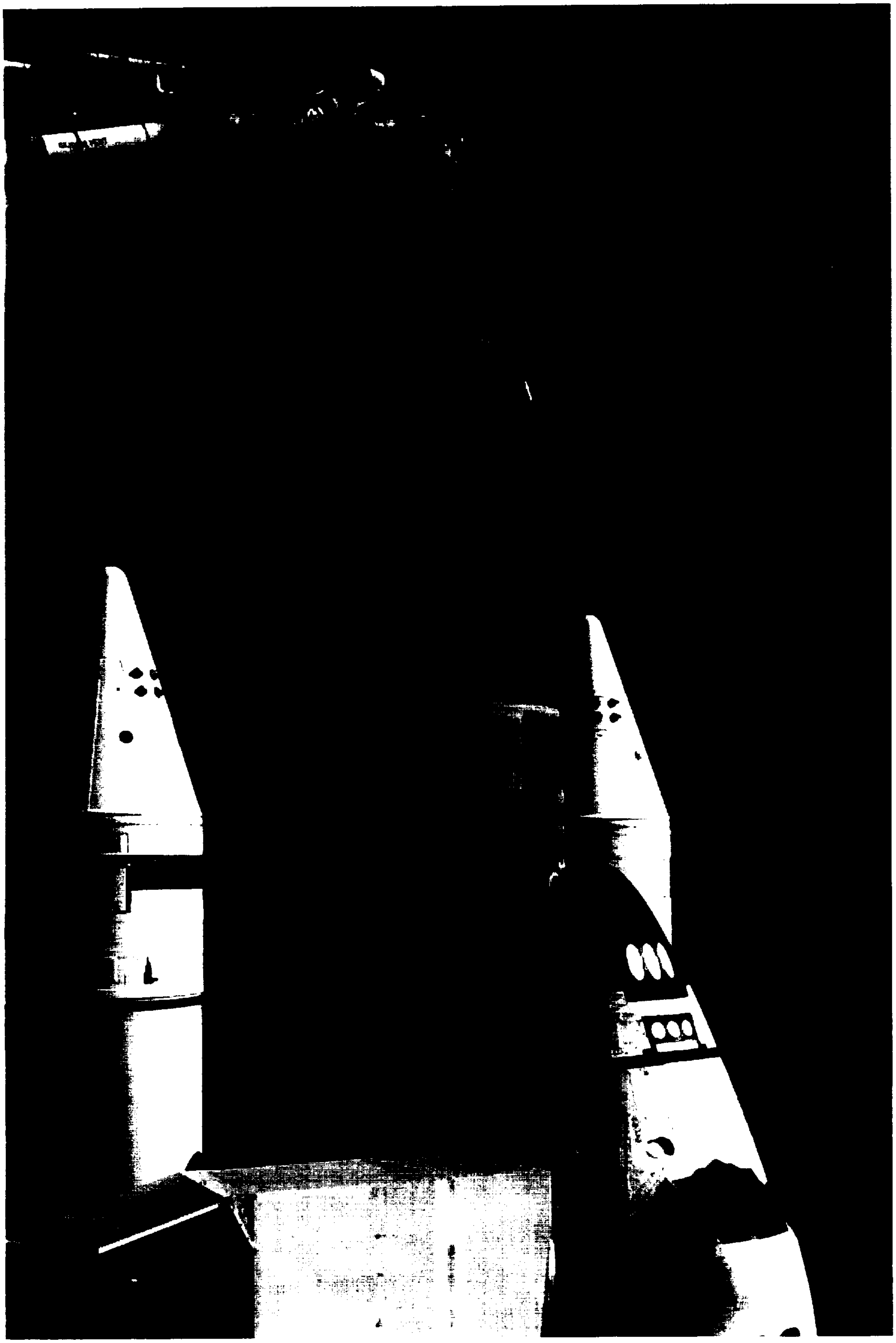


Photo 3: LO2 Tank After Cryoload

The Final Inspection Team observed very light condensate, but no ice or frost accumulations, on the LO2 tank acreage. TPS surface temperatures ranged from high 70's to low 80's degrees F.

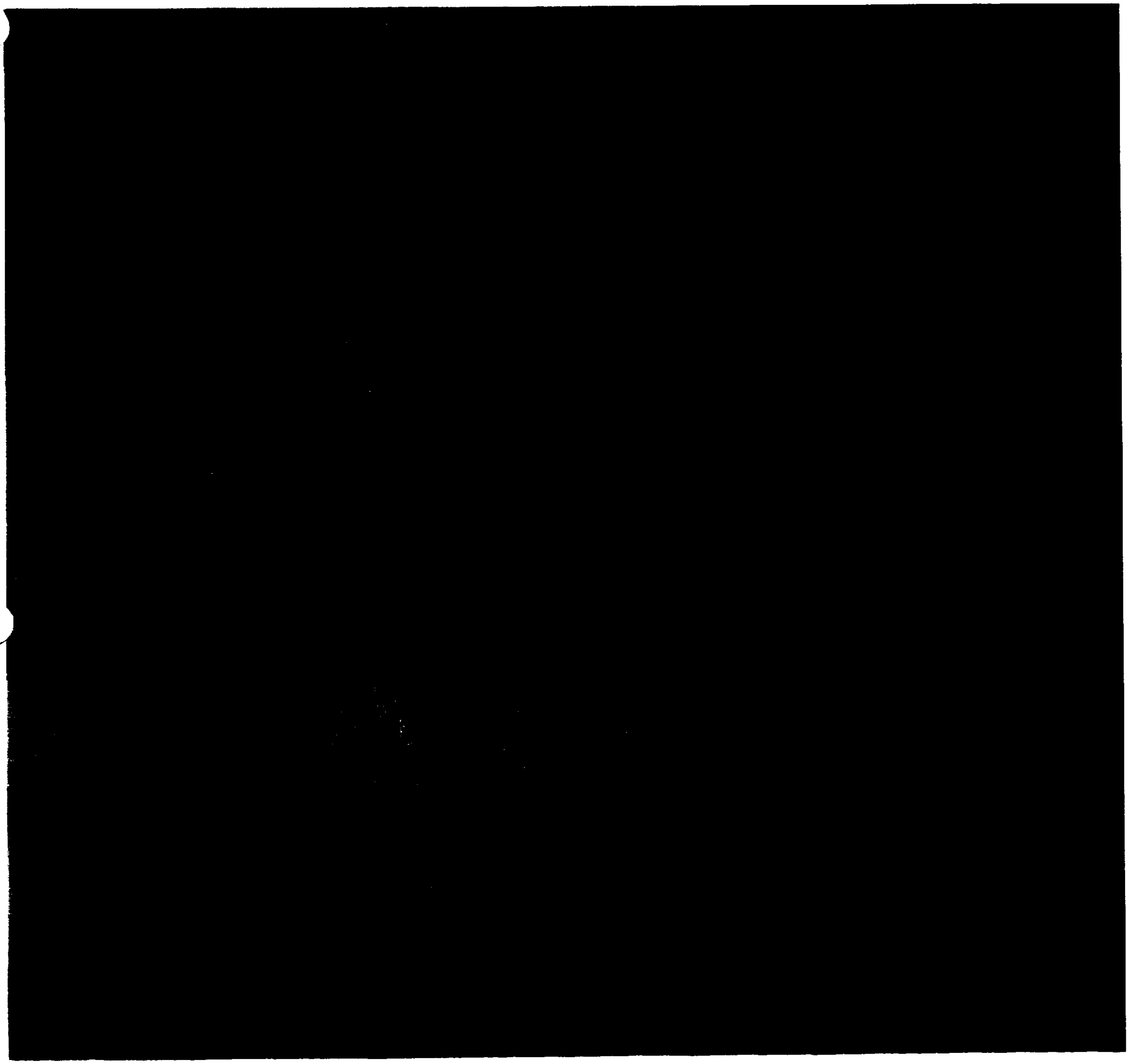


Photo 4: Cracks in Intertank Foam

Two cracks were detected in the +Y+Z quadrant of the intertank. One crack was 6-8 inches in length while the second crack was 10-12 inches in length. A third crack (shown here) 6-8 inches long was located in the -Y-Z quadrant in the second stringer valley from the thrust panel. The cracks appeared to originate from the as-sprayed foam at the aft end of the stringers extending forward from the LH2 tank splice.

Photo 5: LH2 ET/ORB Umbilical

Less than usual ice accumulated on the top and outboard sides of the LH2 ET/ORB umbilical. Ice/frost fingers on the pyrotechnic canister and plate gap purge vents were typical. Note the two places of trimmed foam on the -Y vertical strut aft surface.

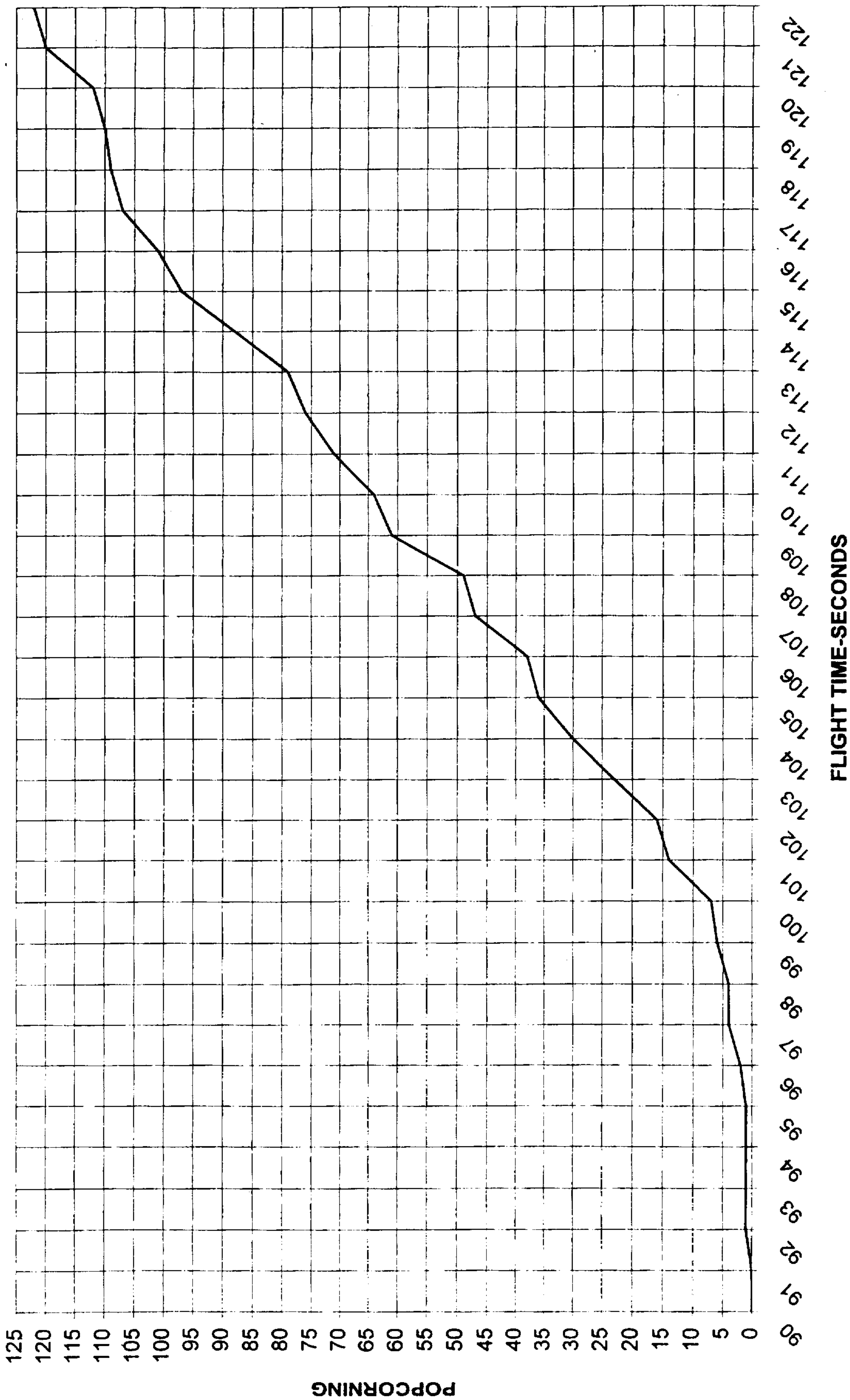


Figure 1: Number of Divots vs. Flight Time

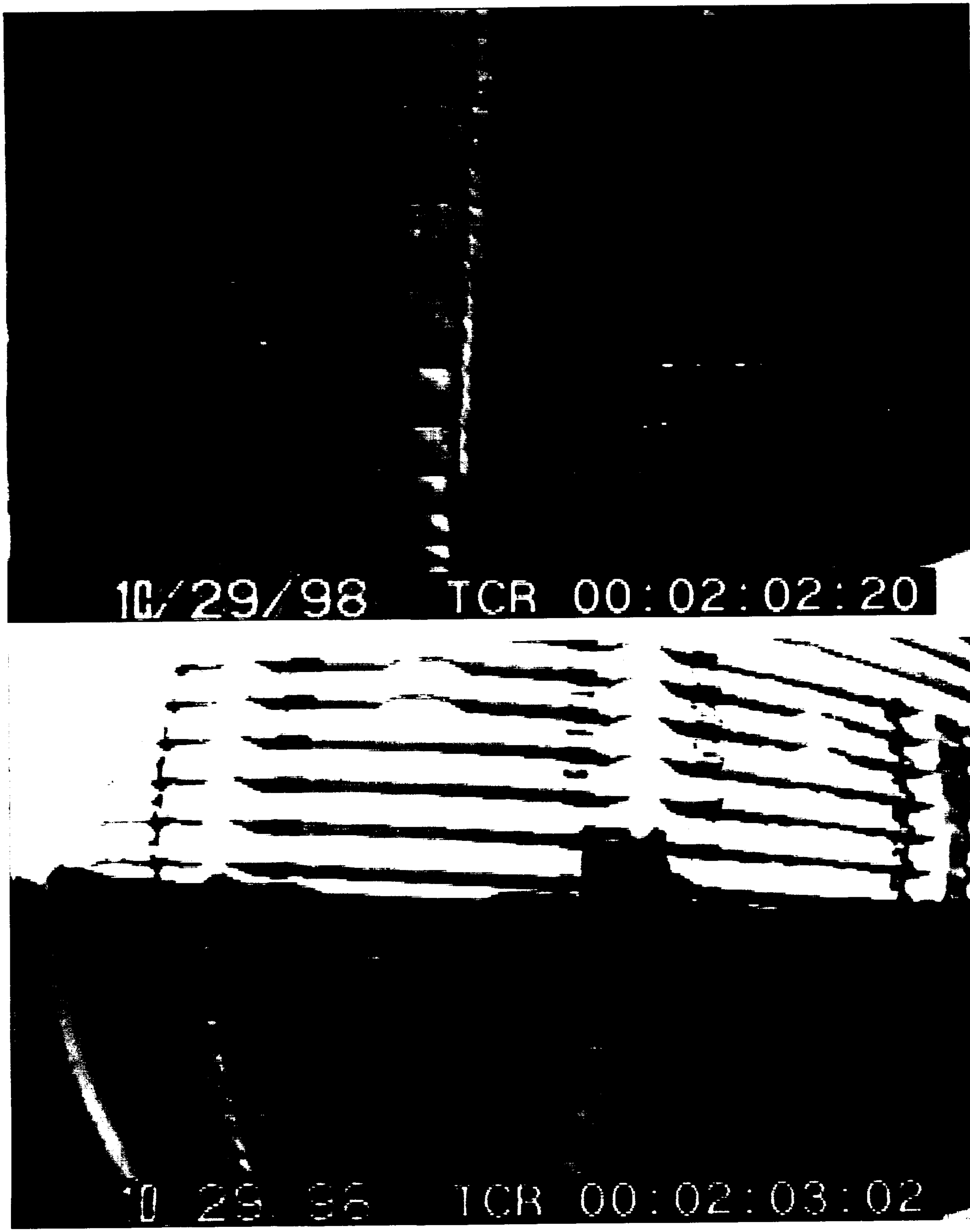
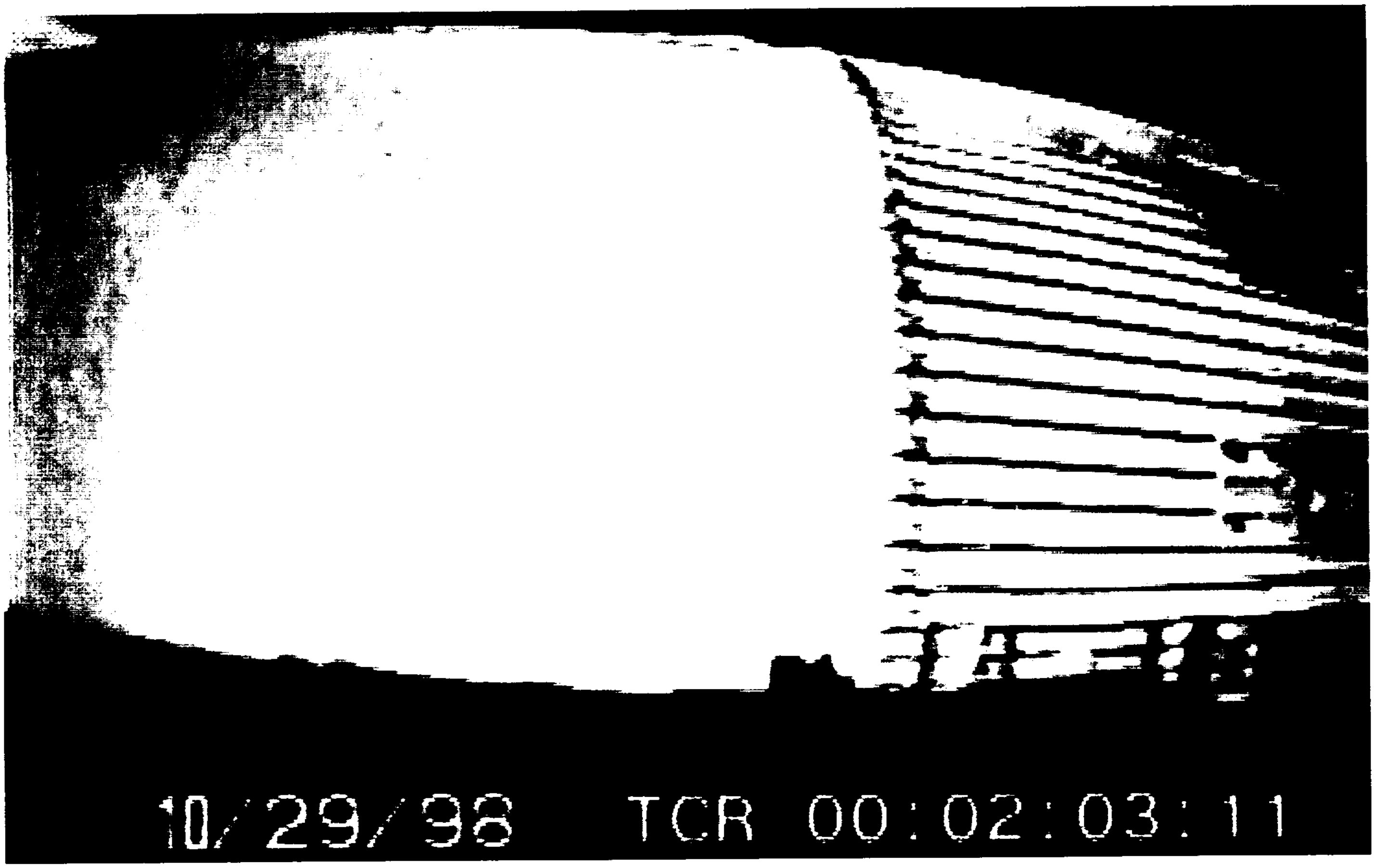


Photo 17: ET Thrust Panel at SRB Separation

Note absence of divots on the aft section of ET thrust panel (aft of the EB fitting)



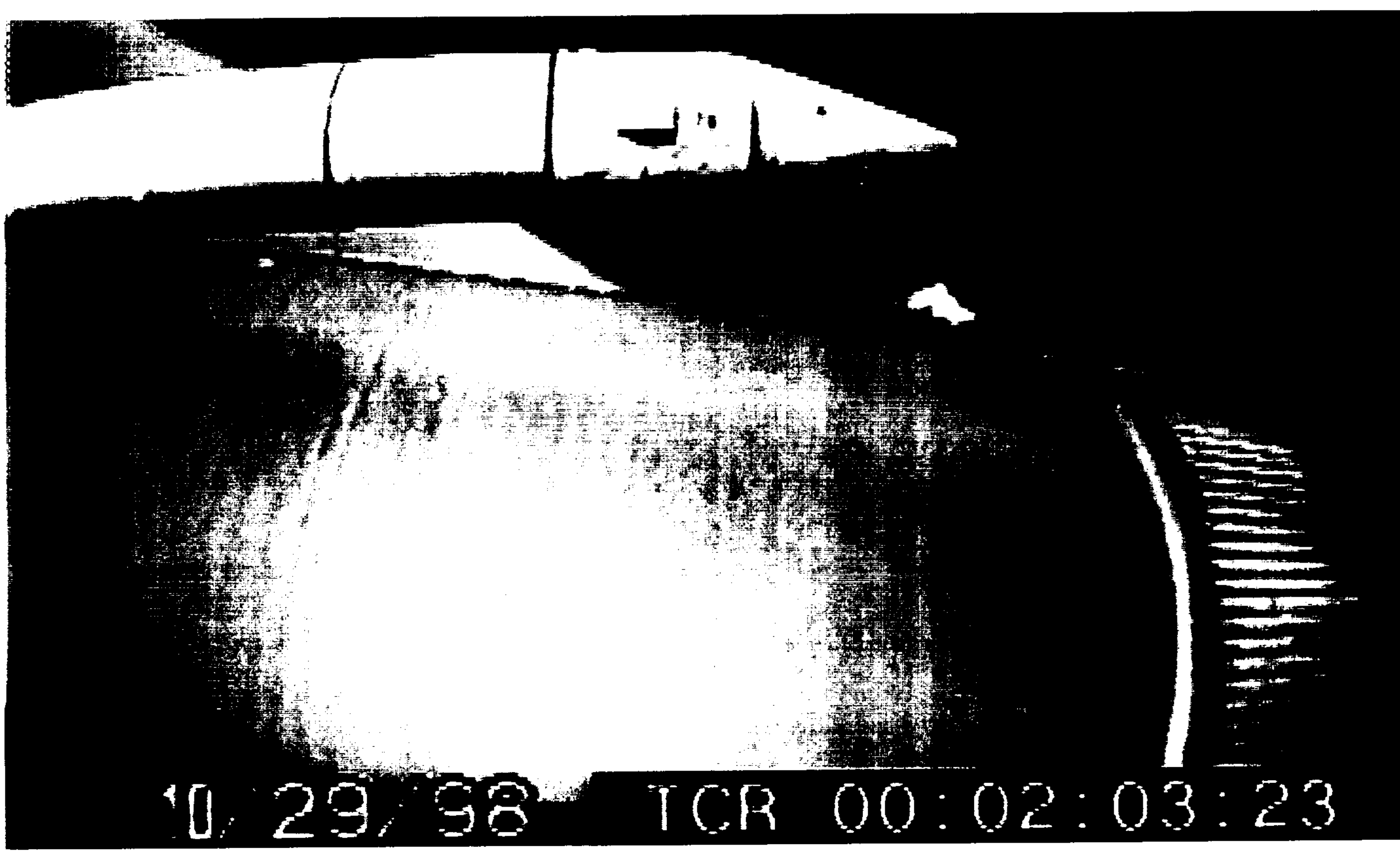
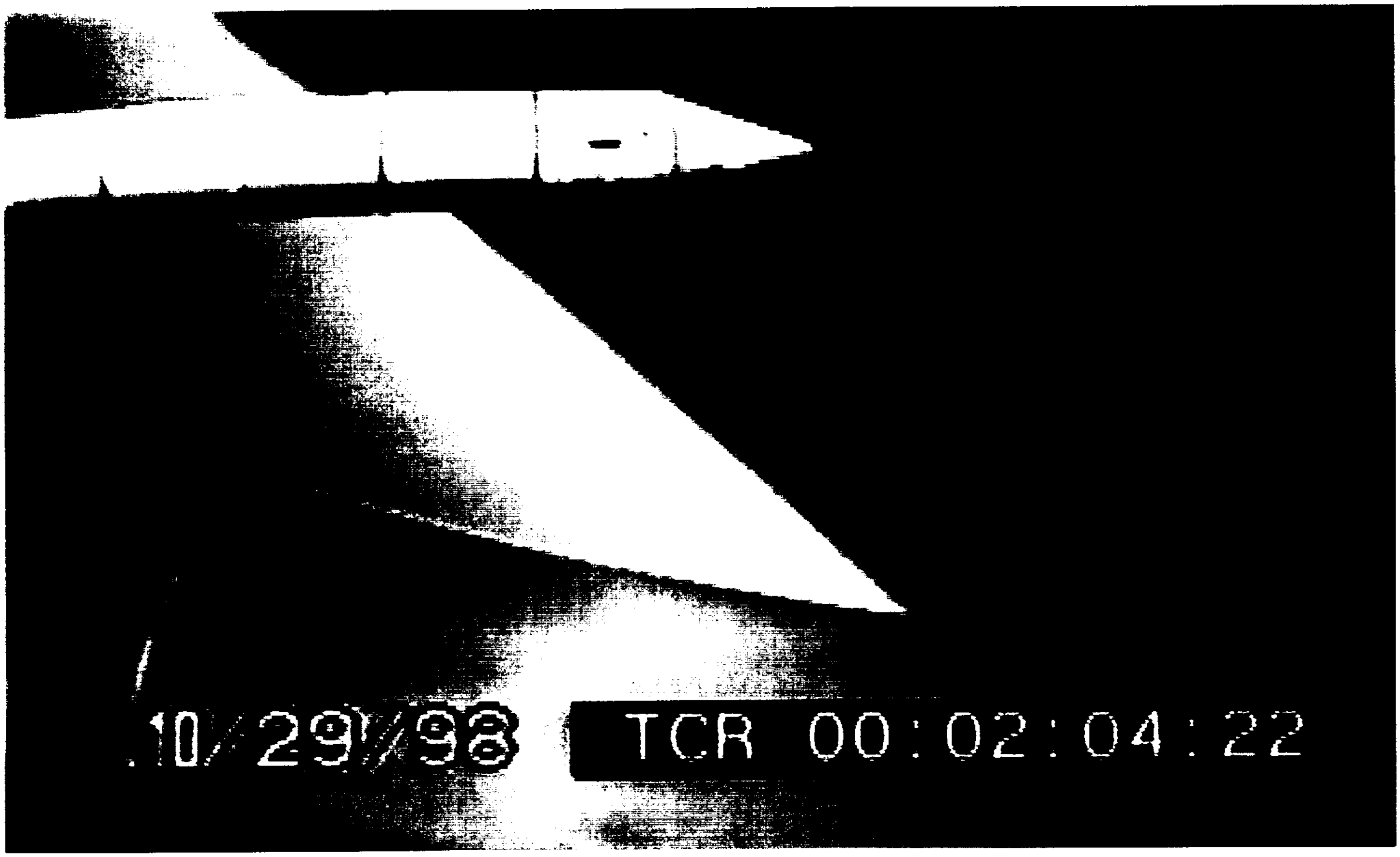


Photo 18: ET -Z Side

TPS on ET -Z side is in excellent condition. No divots are visible in the LH2 tank flange. Likewise, MSA insulation on SRB forward skirt is in excellent condition just after separation.



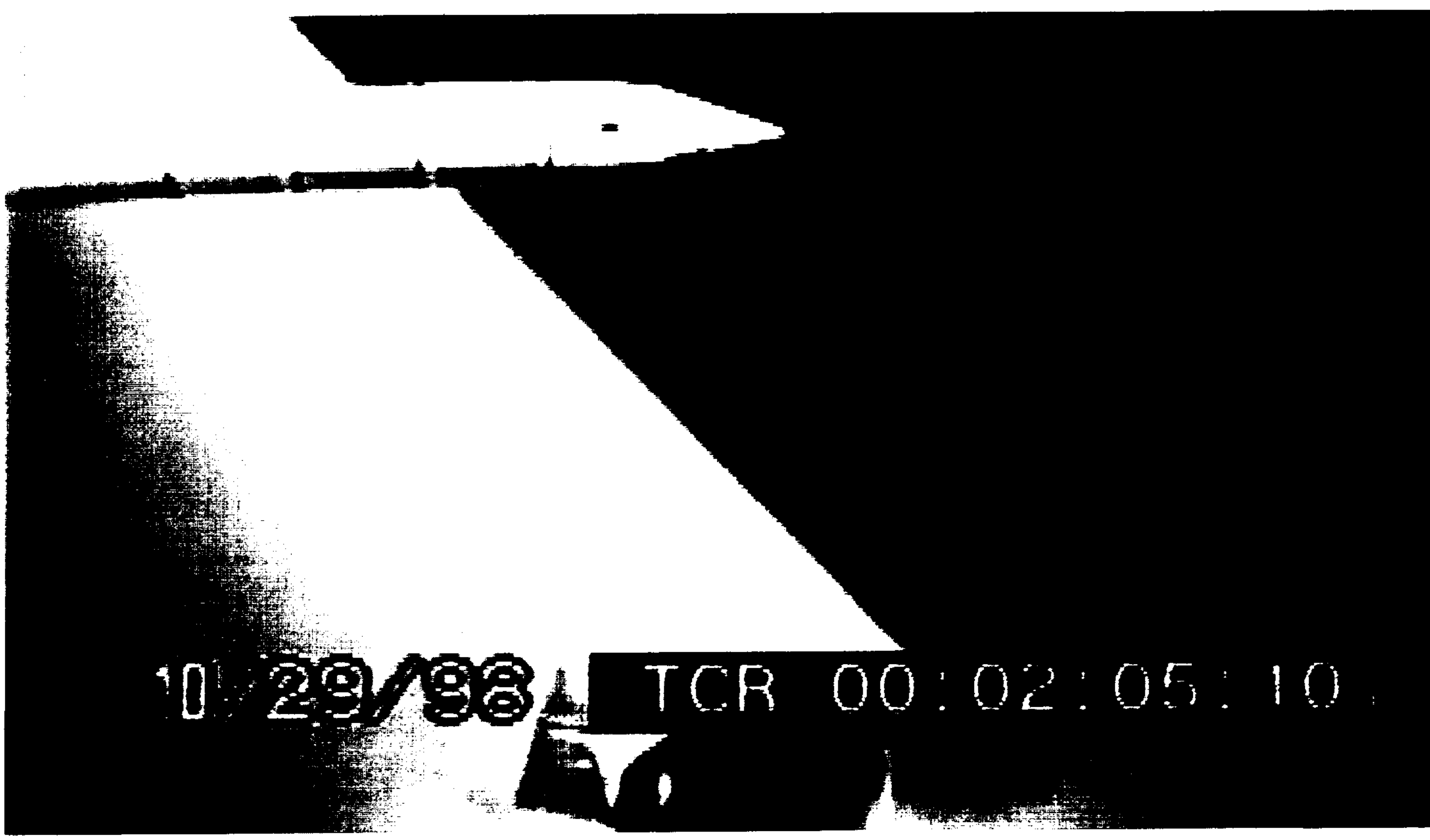


Photo 19: SRB Separation from External Tank

TPS on ET third hard point and aft dome is in good condition.
Orbiter elevons and a portion of the body flap are visible to the left of the ET aft dome.

Photo 20: -Y Vertical Strut

Pre-Launch view of trimmed foam on -Y vertical strut aft surface

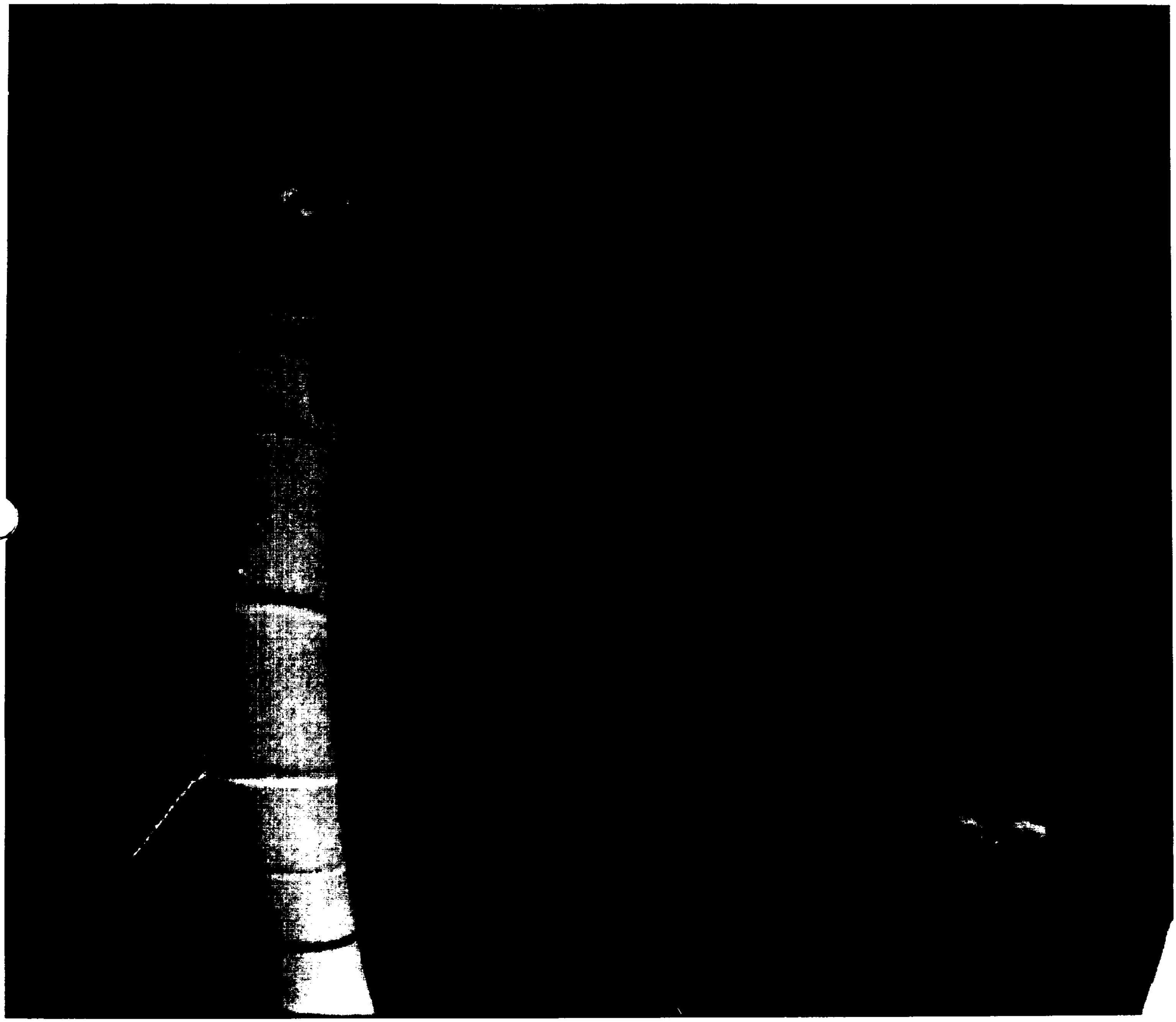


Photo 21: SRB Separation from ET

SRB separation from ET was nominal. Note condition of trimmed foam areas on ET -Y vertical strut (arrows) two minutes into flight. Also note typical erosion of foam from aft surface of the LO2 ET/ORB umbilical cable tray.

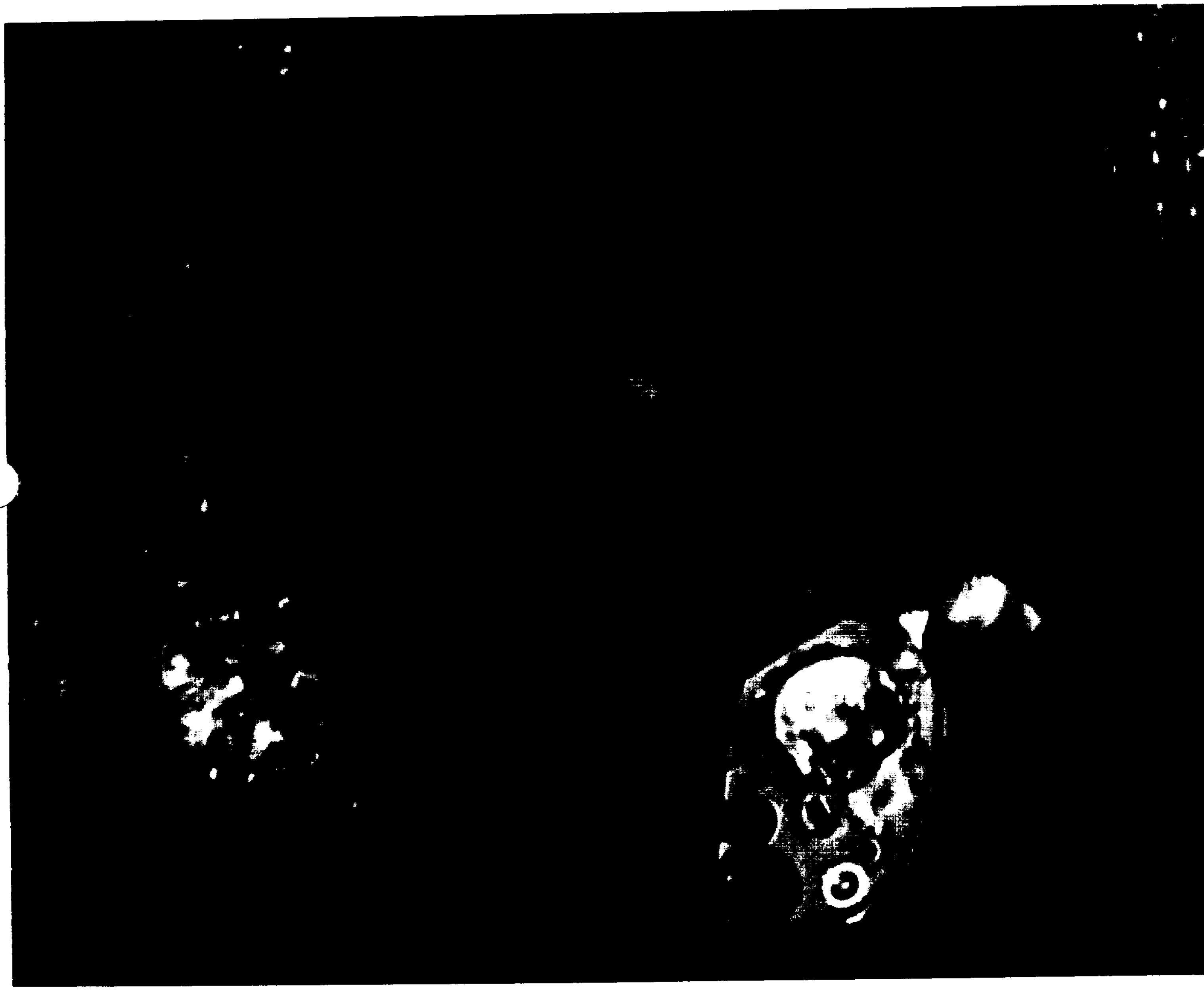


Photo 22: ET LH2 ET/ORB Umbilical

View from ET LH2 ET/ORB umbilical 16mm camera shows no damage to the LH2 umbilical after separation. Note frozen hydrogen in the 17-inch flapper valve. Also note accumulation of ice at XT-2058 adjacent to the transportation fitting closeout (arrow).

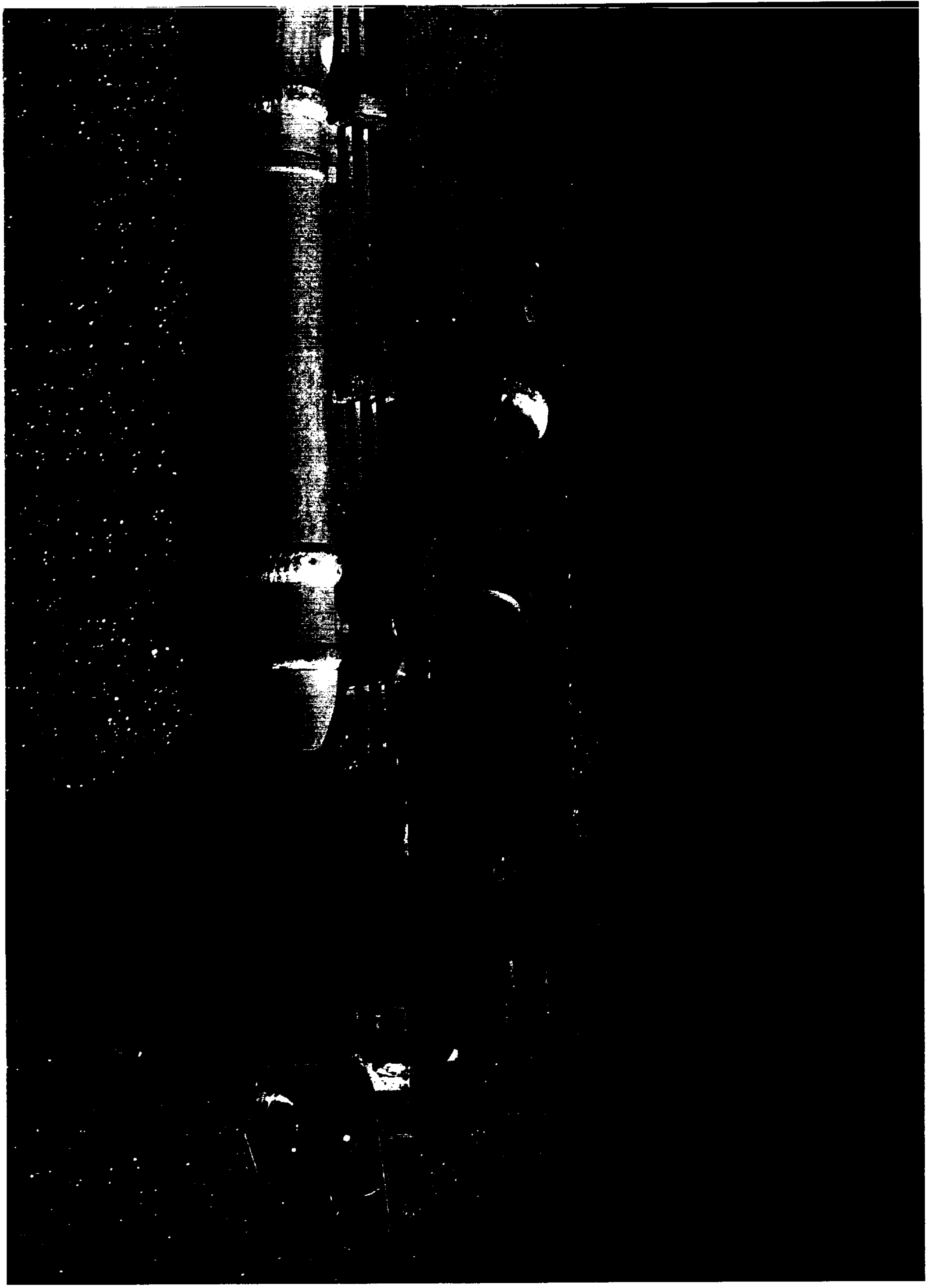


Photo 23: ET LO2 ET/ORB Umbilical

A 6x4 inch shallow divot at XT-1851 was located at the leading edge of the pressurization line ramp. Erosion of the LO2 feedline flange closeouts was typical. Ascent erosion and debris impact sites were visible on the +Y thrust strut in the SLA, the TPS covering, and the flange closeout. The LO2 ET/ORB umbilical cable tray exhibited typical erosion and divoting.

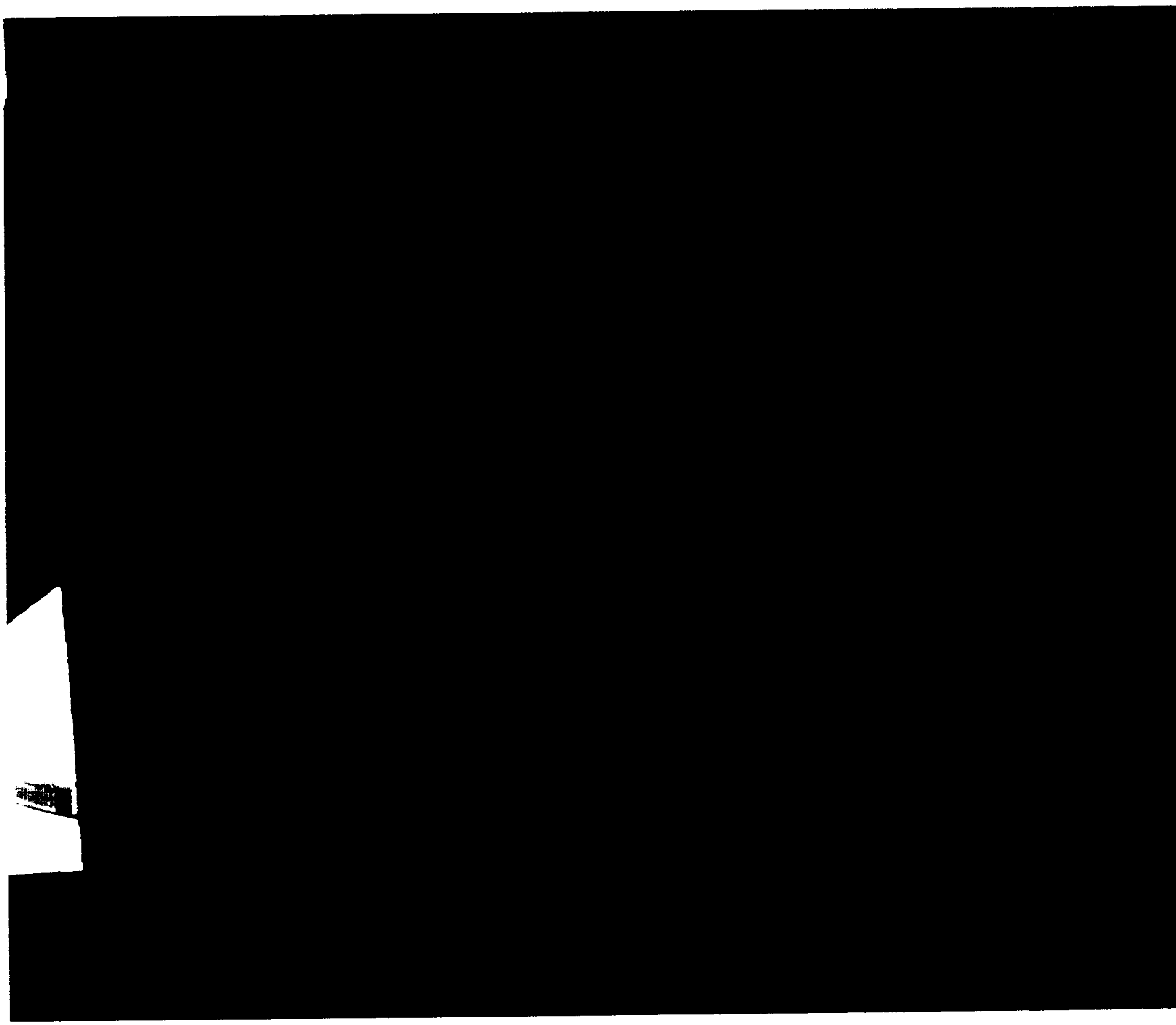


Photo 24: Bipods Pre-Launch View

Pre-Launch view of ET bipods, bipod jack pad stand off closeouts, and LH2 tank-to-intertank flange closeout

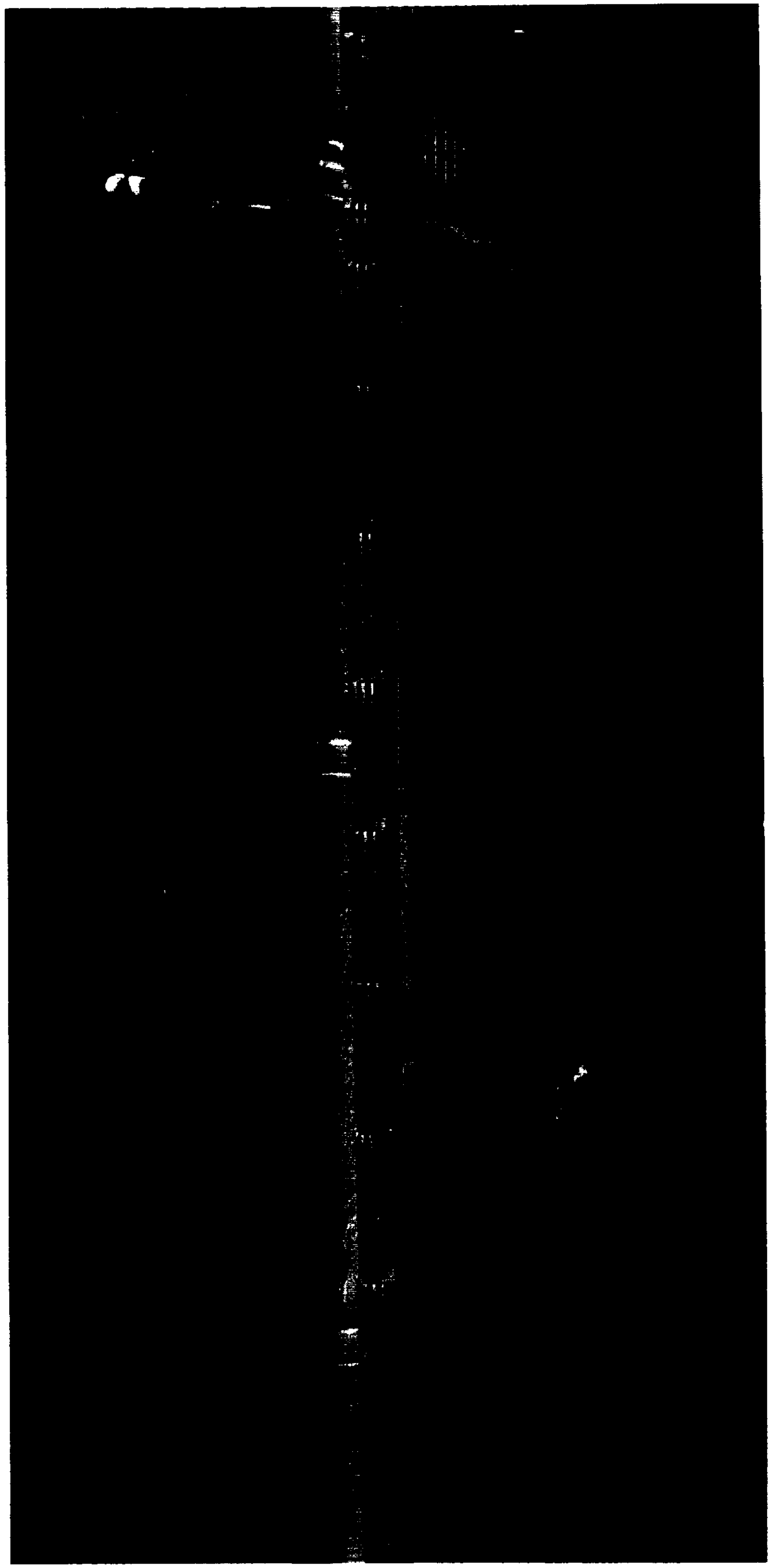


Photo 25: Divots in LH2 Tank Flange Closeout

Both bipod jack pad standoff closeouts were intact. Two 10-12 inch diameter divots occurred in the LH2 tank-to-intertank flange closeout between the ET centerline and the -Y jack pad standoff closeout (which did not appear to be affected by the proximity of the divot). LH2 tank acreage TPS was in excellent condition.

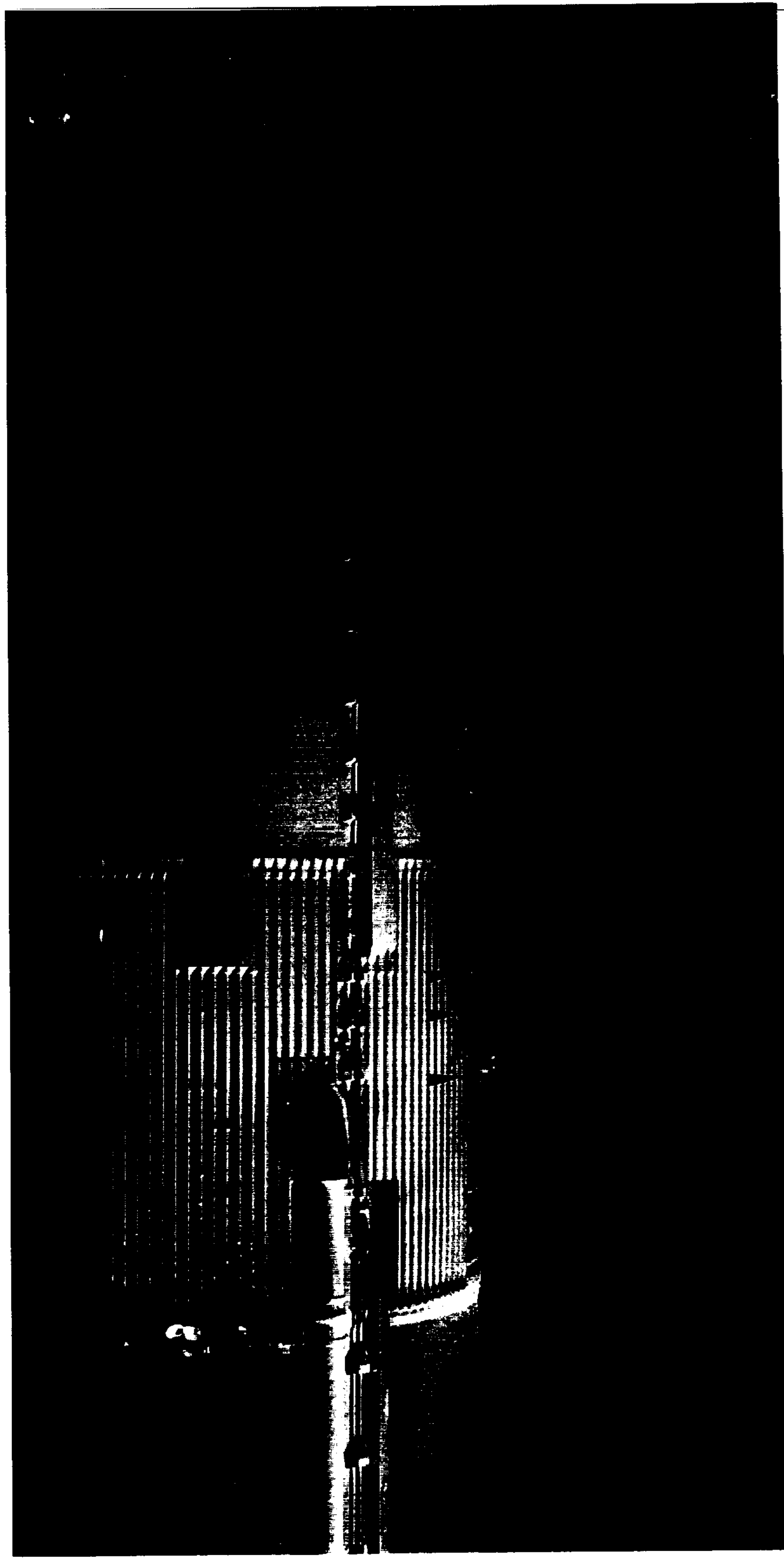


Photo 26: ET-98 SLWT LO2 Tank

Sixteen small divots occurred in the area inboard of the EB fitting between the circumferential ribs. In the next section separated by circumferential ribs forward of the EB fitting, 6 very small divots could be discerned, though a bright spot on a ramp was thought to be a divot 3-inches in diameter. Only two divots could be seen in the next section forward. A 7-inch long divot was present on an intertank stringer head in the -Y direction from the +Z aero vent. No primer or substrate was detected in the divot.

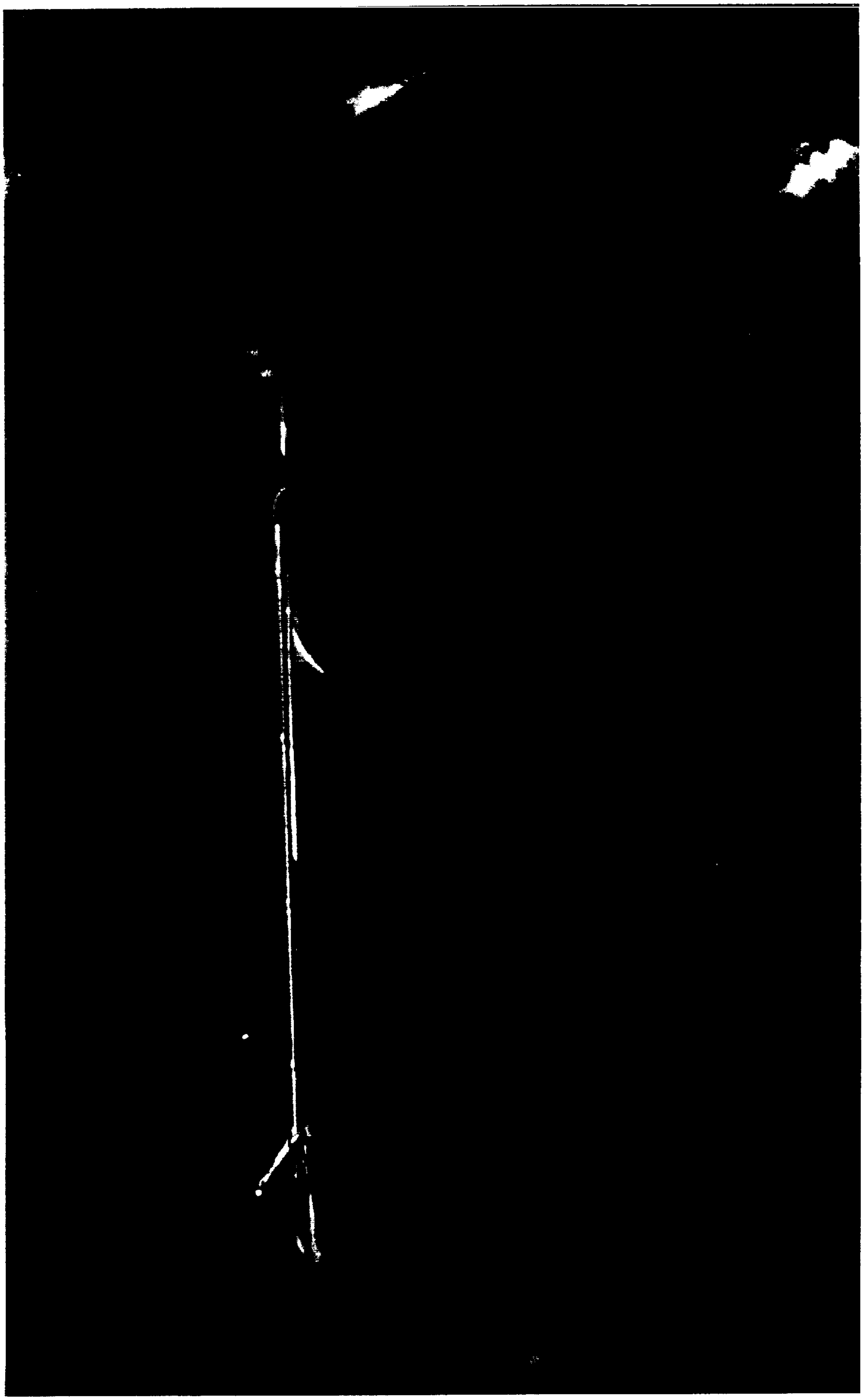


Photo 27: ET +Y Side

Crew hand held view of External Tank showing no nose cone or +Y side anomalies

Photo 6: Overall View of SSME #3

First flight of Dow-Corning 93-104 silicone ablative material to insulate SSME nozzle aft manifolds during re-entry. The red-colored "insulator panels" were applied to 135 degrees of SSME #2 and #3 aft manifold -Z sides to preclude "bluing" (due to heating at 1200-1400 degrees Fahrenheit) detected on previous flights.

4.0 POST LAUNCH PAD DEBRIS INSPECTION

The post launch inspection of MLP 2, Pad B FSS, RSS, and pad apron was conducted on 29-30 October 1998 from Launch + 2 hours to dusk, and 1.5 hours on the 30th.

Eighteen pieces of the Orbiter drag chute door were recovered on the south side of the pad from the SSME flame trench to the perimeter fence. The door separated from the Orbiter 2 seconds after SSME ignition. No other flight hardware was found.

No stud hang-ups occurred on this launch. Boeing-Downey reported an Orbiter liftoff lateral acceleration of 0.13 g's, which is below the threshold (0.14 g's) for stud hang-ups. SRB south holddown post erosion was less than usual. North holddown post blast covers and T-0 umbilicals exhibited typical exhaust plume damage. The SRB aft skirt GN2 purge lines had remained upright after liftoff. However, both purge flex lines exhibited structural damage and melting of the exterior wire braid.

The Tail Service Masts (TSM's) appeared undamaged and the bonnets were closed properly. There was no unusual erosion at the bases of the TSMs where excess grout had been removed. Likewise, the Orbiter Access Arm (OAA) was undamaged.

The GH2 vent line was latched in the fifth of eight teeth of the latching mechanism. The GUCP 7-inch QD surface exhibited no apparent damage. All observations indicated a nominal retraction and latchback, though the GH2 vent line exhibited heat effects/damage from the SRB exhaust plume. The aluminized thermal blanket was torn and scorched by the plume.

The GOX vent arm showed no indications of plume damage.

Debris findings on the FSS included loose cable tray covers at the 175 and 195 foot levels, an approximate 2 foot section of 1-½ inch angle iron at the 245 foot level stairs, and the elevator door was 'blown-in' at the 255 foot level.

No unusual debris was noted in the flame trench, in the north SRB plume blast area, or in the acreage. Overall, damage to the pad appeared to be minimal.

Condensation collars formed on the vehicle during ascent - an expected occurrence due to the ambient weather conditions (TV-4, TV-21).

Four debris induced streaks occurred in the SSME exhaust plumes during ascent (E-213, -222, -223).

SRB tailoff and separation appeared normal. Slag falling out of the exhaust plume before, during, and after SRB separation was typical (TV-13).

5.1.1 DRAG CHUTE DOOR INVESTIGATION

The drag chute door detached from the drag chute compartment (shear pin side) at 19:19:30.648 UTC. The door swung downward pivoting about the hinge at 19:19:30.998, then dropped vertically from the hinge until impacting the SSME #1 aft manifold at 19:19:31.301 UTC. The impact caused the door to be deflected in the +Z direction and continue to fall aft into the SSME flame trench. No damage to the SSME #1 nozzle was visible. Two small, dark debris objects were detected in the hinge area when the door detached but a possible relationship with cause or effect could not be determined (OTV 170, 151; E-2, -3, -19, -20, -76, -77). Later, an IFA was taken and an Anomaly Investigation Board formed to investigate the premature release of the door.

Long range tracking films showed no indications that components of the drag chute or debris objects originating from the drag chute compartment fell aft during ascent.

Post launch analysis of high speed films showed the drag chute was intact and properly restrained by nylon straps inside the drag chute compartment. There were no visual indications that any of the pyrotechnic devices had fired (the sabot cover adjacent to the drag chute was intact). Measurements of the door's motion revealed the door had not been propelled open from the chute compartment, but just fell away due to gravity only.

Signs for early shear pin failure or door separation from the door frame were checked. Initially in the investigation, the apparent gap between the door and the chute compartment was thought to be significant but was later determined to be an expected interface line between adjacent TPS-covered carrier panels. The actual door structure would not be visible.

Laboratory analysis of the recovered door pieces showed no anomalies. The shear pin fragments exhibited the proper material properties and hardness. Review of the as-built paper, OMI documentation, and interviews with technicians uncovered no installation problems or workmanship discrepancies.

Subsequent attempts to duplicate the door failure in the laboratory were not entirely successful leaving the Investigation Board to conclude an unexplained anomaly possibly associated with the environment - an acoustic vibration or overpressure wave that exceeded the design parameters of the door. The pad and MLP for the next few launches will be instrumented to gather data on the SSME startup environment. In addition, the drag chute door design is being modified and will incorporate greater material margins. Until that effort is complete, the drag chute door will be bolted to the Orbiter structure and landings will be made without using the chute.

Photo 7: Drag Chute Door Closeout

Pre-Launch view of the drag chute door closeout showing -Y (shear pin) and +Y (hinge) sides. Initially in the investigation, the apparent gap between the door and the chute compartment was thought to be significant, but was later determined to be an expected interface line between adjacent TPS-covered carrier panels. The actual door structure would not be visible.

Photo 8: Drag Chute Door (E-19)

Two frames from high speed 16mm film camera E-19 running at 400 frames per second show the drag chute door before release and subsequent impact with the SSME #1 aft manifold. No damage to the engine nozzle was visible after the impact.

Photo 9: Drag Chute Door (E-20)

Two frames from high speed 16mm film camera E-20 running at 400 frames per second show the drag chute door before release and after separation from the hinge on the +Y side of the chute compartment. Note clear detail is visible on the intact drag chute and restraining nylon straps along with the adjacent sabot cover inside the chute compartment.

Photo 10: Drag Chute Door -Y Side

Two frames from high speed 16mm film camera E-20 running at 400 frames per second show the drag chute door just before and at the time of impact with the SSME #1 aft manifold. Note clear detail on the inside webbing of the door and shear pin flanges.

Photo 11: Drag Chute Door (E-2)

Two frames from high speed 16mm film camera E-2 running at 400 frames per second show the drag chute door just before release and at the time of impact with the SSME #1 aft manifold. The -Y-Z corner of the door contacted the engine nozzle causing the door to deflect in the +Z direction without contacting any other flight hardware.

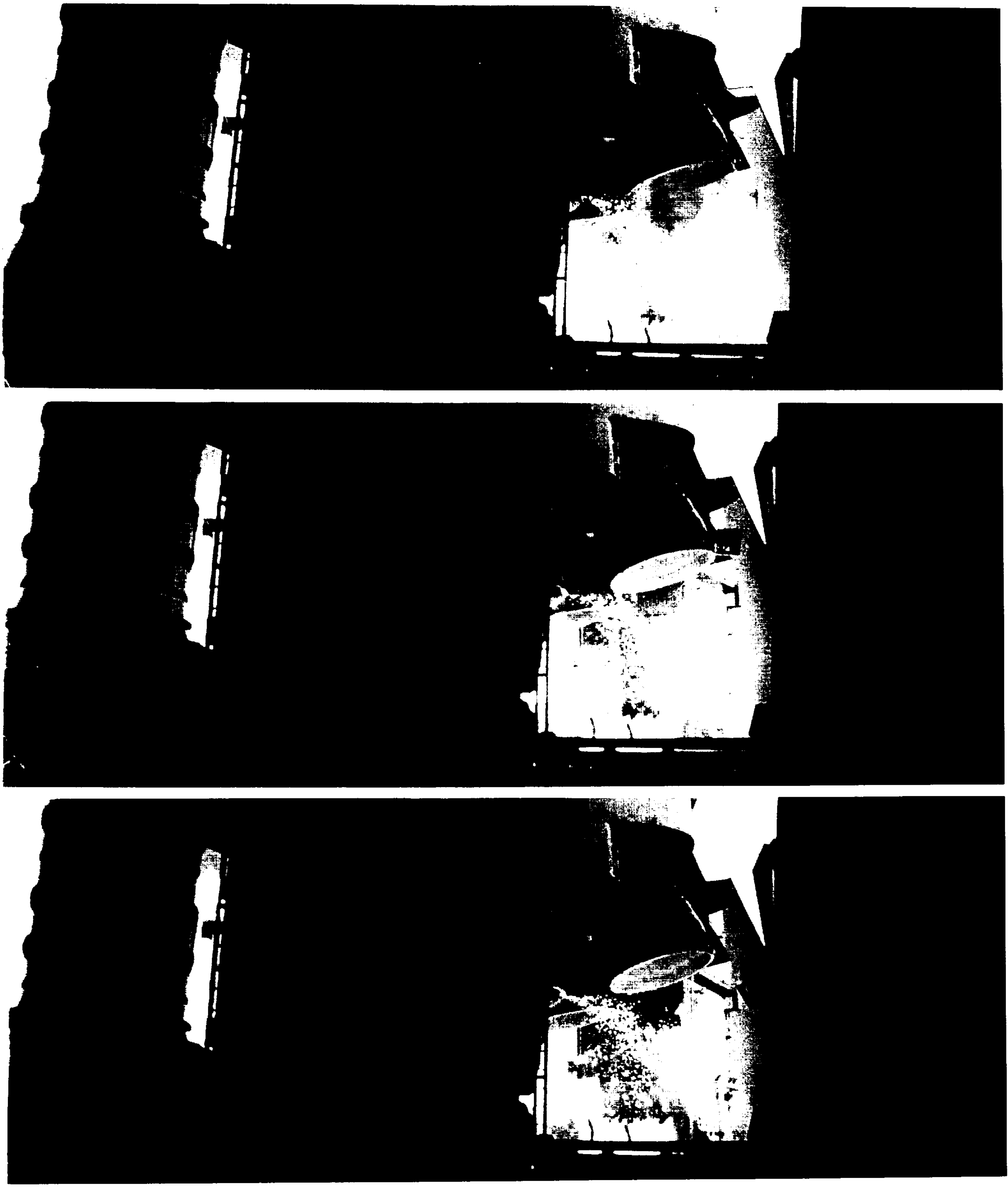


Photo 12: Drag Chute Door (E-3)

Three frames from high speed 16mm film camera E-3 running at 400 frames per second show the drag chute door just before release, impact with the SSME #1 aft manifold, and deflection in the +Z direction.

5.2 ON-ORBIT FILM AND VIDEO SUMMARY

OV-103 was equipped to carry umbilical cameras: 16mm motion picture with 5 mm lens; 16mm motion picture with 10mm lens; 35mm still views. The flight crew provided hand held still images. The +X translation was performed.

5.2.1 SRB 8mm Video Camera

An 8mm video camera, which had previously been used to view SRB chute deployment, was installed in the left SRB forward skirt to view a portion of the -Y thrust panel on the +Z side of the thrust fitting. A lens with a very wide field of view was used to maximize the visible section of thrust panel but in turn resulted in some image distortion. A grid of one-inch black squares and asterisks spaced 5.5 inches apart were placed on the stringer head TPS to aid in divot size measurement. Post flight review of the film revealed the field of view, exposure, focus, lighting, and visible detail were all good.

General observations included SRB separation from the ET at 122.403 seconds MET. The majority of divots in the ET thrust panel occurred on the rib heads/top edges. The divots were shallow with no substrate exposed. Most of the divots were concentrated near the EB fitting, though some divots could be seen as far outboard as the second stringer beyond the thrust panel. Most divots were located in the NCFI. After separation, the widening field of view caused by the booster falling away showed the entire thrust panel aft of the EB fitting and the intertank stringer sections to the flight door area. Virtually no divots were observed in this region. The LH2 tank -Z side acreage, aft dome, and third hard point also appeared to be in nominal condition.

Timed observations showed the appearance of the first divot at 92 seconds MET.

90 - 100 seconds:	7 divots in the field of view with none larger than 1-inch
100 - 110 seconds:	64 divots with 10-15 larger than 1-inch
110 - 120 seconds:	112 divots with approximately 30 larger than 1-inch. The largest divot was estimated to be 2.5-inches long
120 - Separation:	122 divots total

Figure 1 shows the increasing number of divots from 92 seconds MET through SRB separation.

5.2.2 ET/ORB Umbilical 16mm Films

In the 16mm films, lighting of the ET after separation was good though the far -Y side of the ET was in deep shadow. Focus and field of view were good.

SRB separation from the External Tank appeared nominal. The wide angle ET/ORB LH2 umbilical camera provided a view of both SRB forward skirts/frustums/nose caps during separation. The nose caps, which are not recovered for post flight inspection, were intact and appeared to be in good condition.

ET-98 separation from the Orbiter was normal. No divots were detected in the LO2 tank acreage. No anomalies were detected on the composite nose. The trimmed/sanded area on the LO2 tank at XT-536 was darkened somewhat due to ascent aeroheating, but no divoting or loss of foam occurred.

The +Z side of the intertank generally was in good condition though some very small "popcorn" type divots could be seen in the high heating area forward of the bipods. A divot 7 inches long was visible on the head of a stringer in the -Y direction from the +Z aero vent. The thrust panels were not visible in these views.

5.2.4 Crew Hand Held Still Images

The flight crew obtained 37 images of the External Tank after separation. All of the views showed the +Y+Z quadrant of the ET. Most of the Tank was in shadow with the exception of the LO2 feedline and the +Z axis.

From time to time, the +Y thrust panel inboard of the EB fitting was visible. No large divots in the TPS were detected. Divots less than 3-inches in size, which were expected based on the LH SRB camera data, could not be discerned due to the subject distance and image resolution. The outboard side of the +Y thrust panel was in shadow and too dark to view any kind of detail.

Live downlink from the RMS elbow camera later in the day revealed a section of AFRSI protruding from the left OMS pod outboard side.

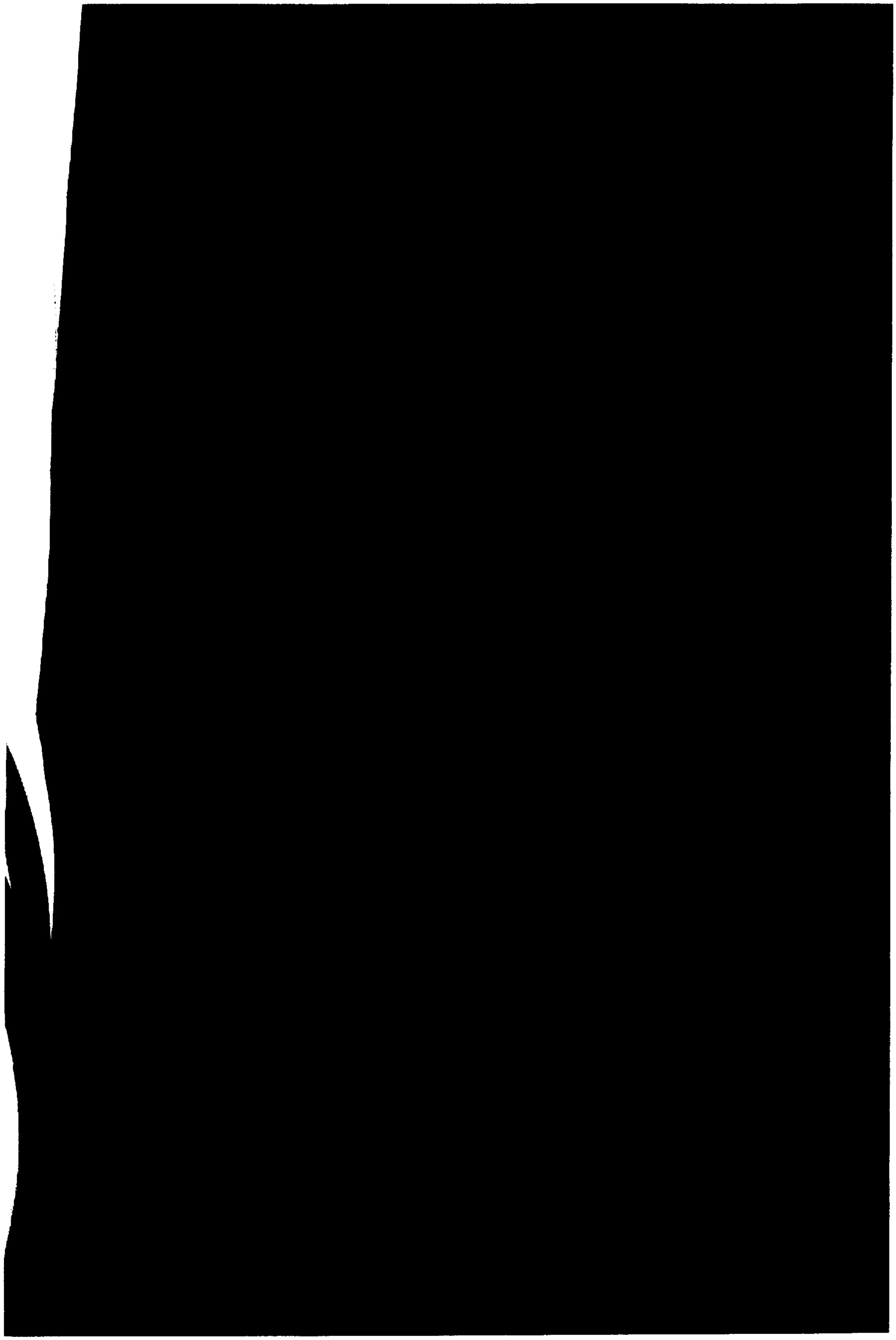


Photo 13: ET -Y Thrust Panel Markings

Pre-Launch view of the ET -Y thrust panel on the +Z side of the EB fitting. A grid of one-inch black squares and asterisks spaced 5.5 inches apart were placed on the stringer head TPS to aid in size measurement of divots occurring in flight.

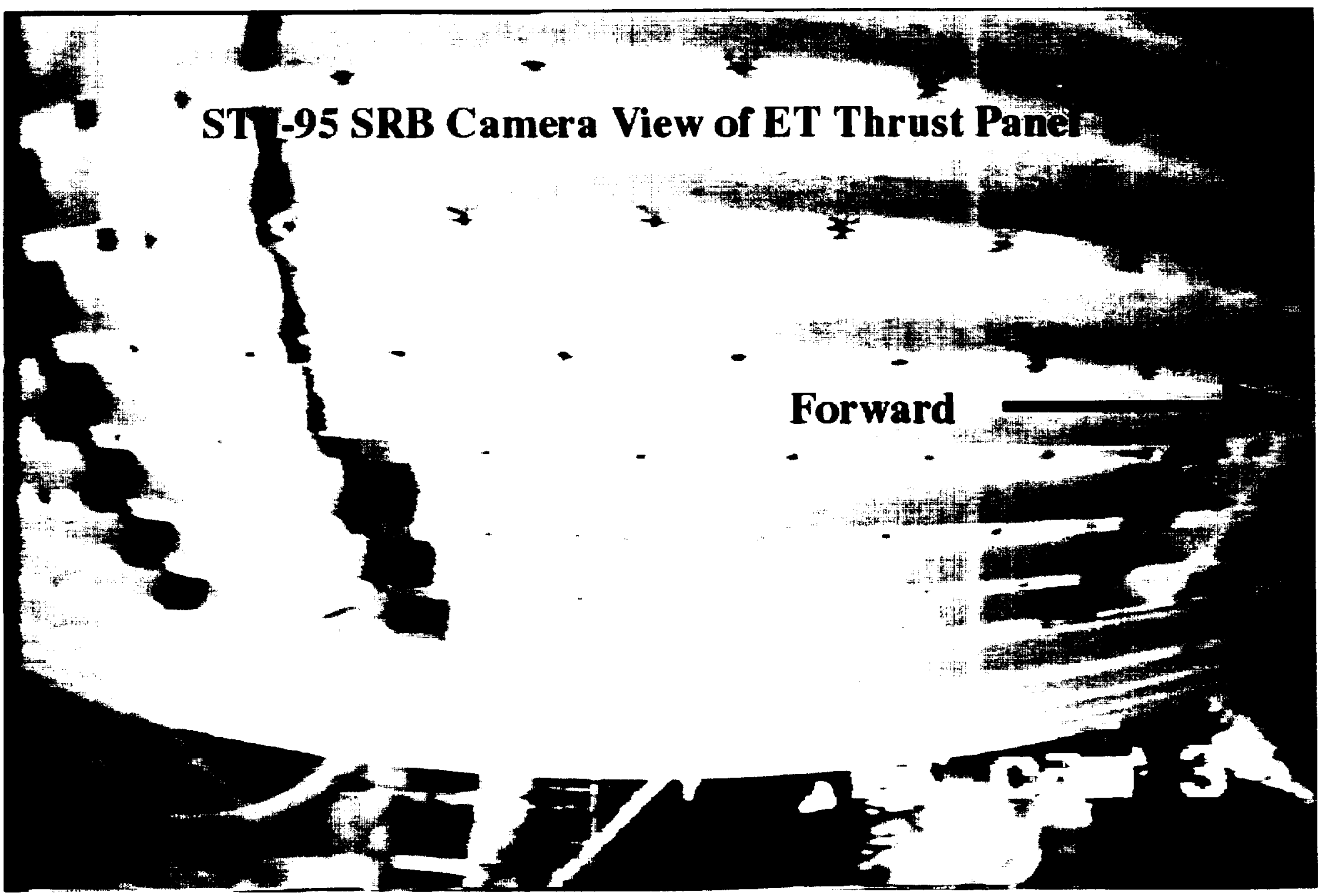
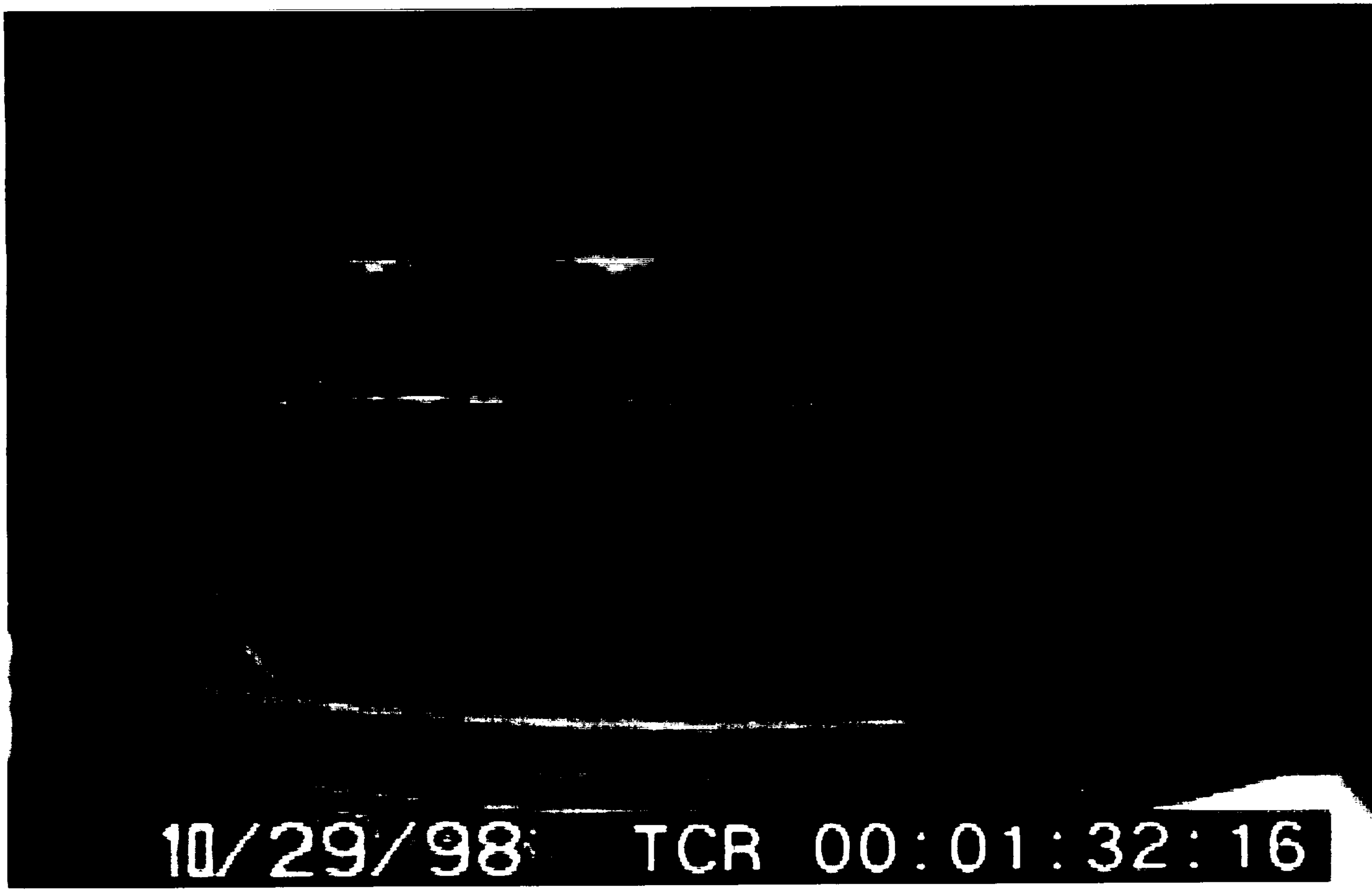


Photo 14: ET -Y Thrust Panel Camera View

Pre-Launch view of the ET -Y thrust panel as seen by the SRB video camera. A lens with a very wide field of view was used to maximize the visible section of thrust panel but in turn resulted in some image distortion.



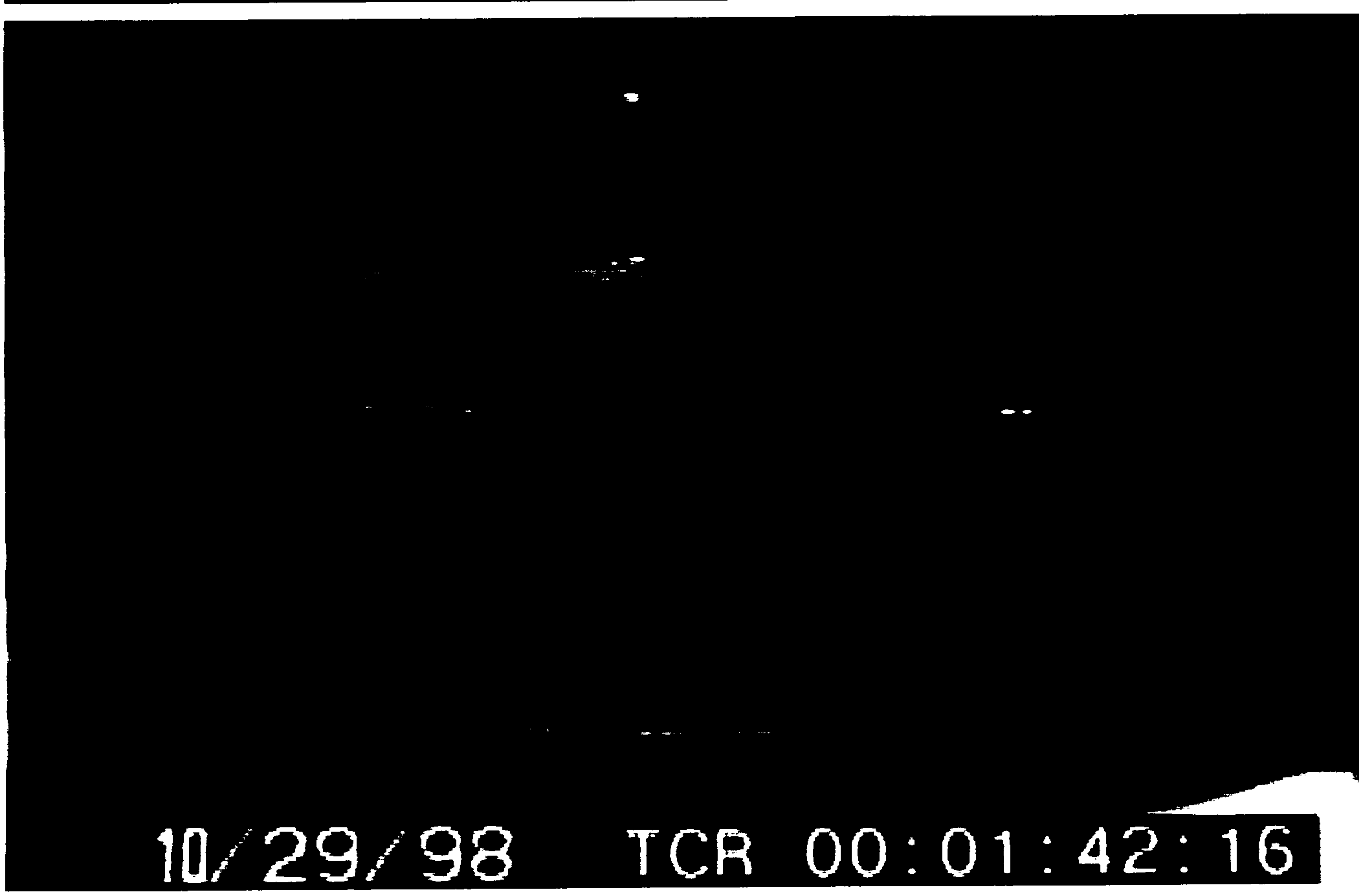


Photo 15: Thrust Panel, 92 - 102 Seconds MET

The first divot appeared at 92 seconds mission elapsed time (top photo).
The bottom photo shows the number of divots appearing in the next 10 second interval.

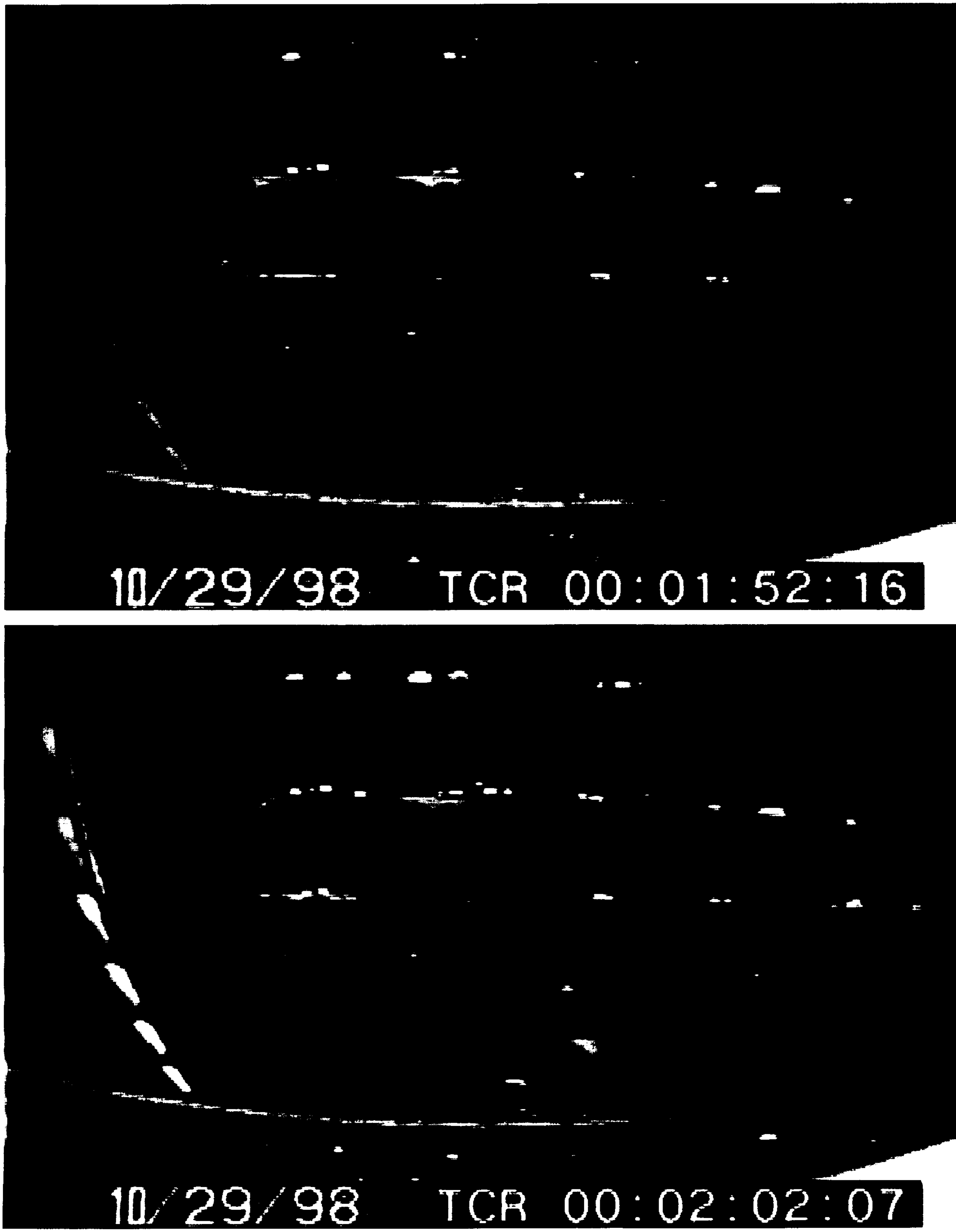


Photo 16: Thrust Panel, 112 - 122 Seconds MET

5.3 LANDING FILM AND VIDEO SUMMARY

A total of 21 films and videos, which included nine 35mm large format films, one 16mm film, and eleven videos, were reviewed.

The landing gear extended properly. The infrared scanners showed no debris falling from the Orbiter during final approach.

Due to the loss of the protective drag chute door at liftoff and suspect condition of the chute itself, the Orbiter drag chute was not deployed for this landing. Rollout and wheel stop were uneventful.

TPS damage on the lower surface of both right and left glove areas was visible in some of the films.

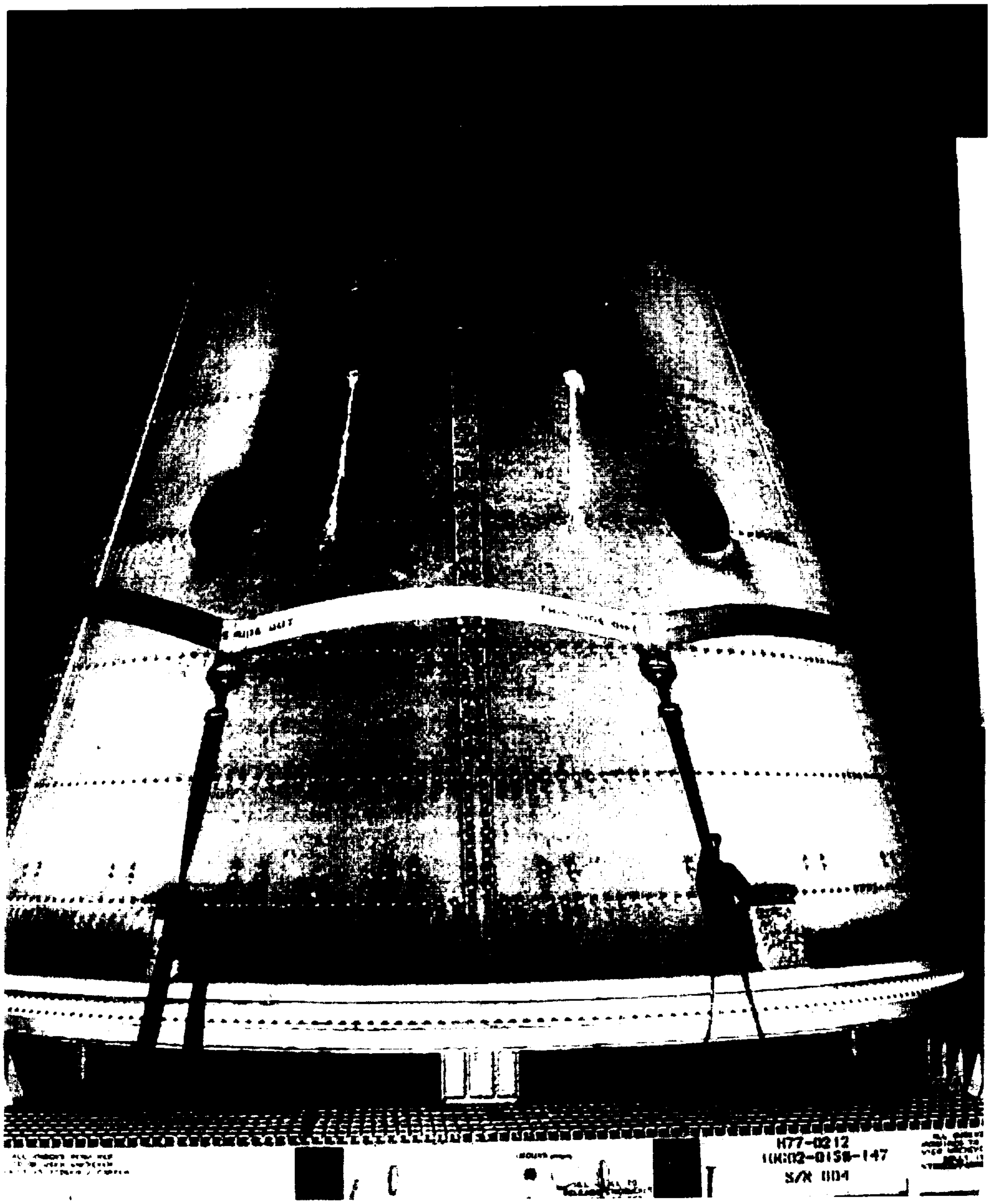


Photo 28: Frustum Post Flight Condition

Both frustums were in excellent condition. No TPS was missing and no debonds/unbonds were detected over fasteners or acreage. Virtually none of the Hypalon paint had blistered or peeled. All eight BSM aero heat shield covers had locked in the fully opened position though the attach rings on the two outboard covers on the left frustum had been bent by parachute riser entanglement.

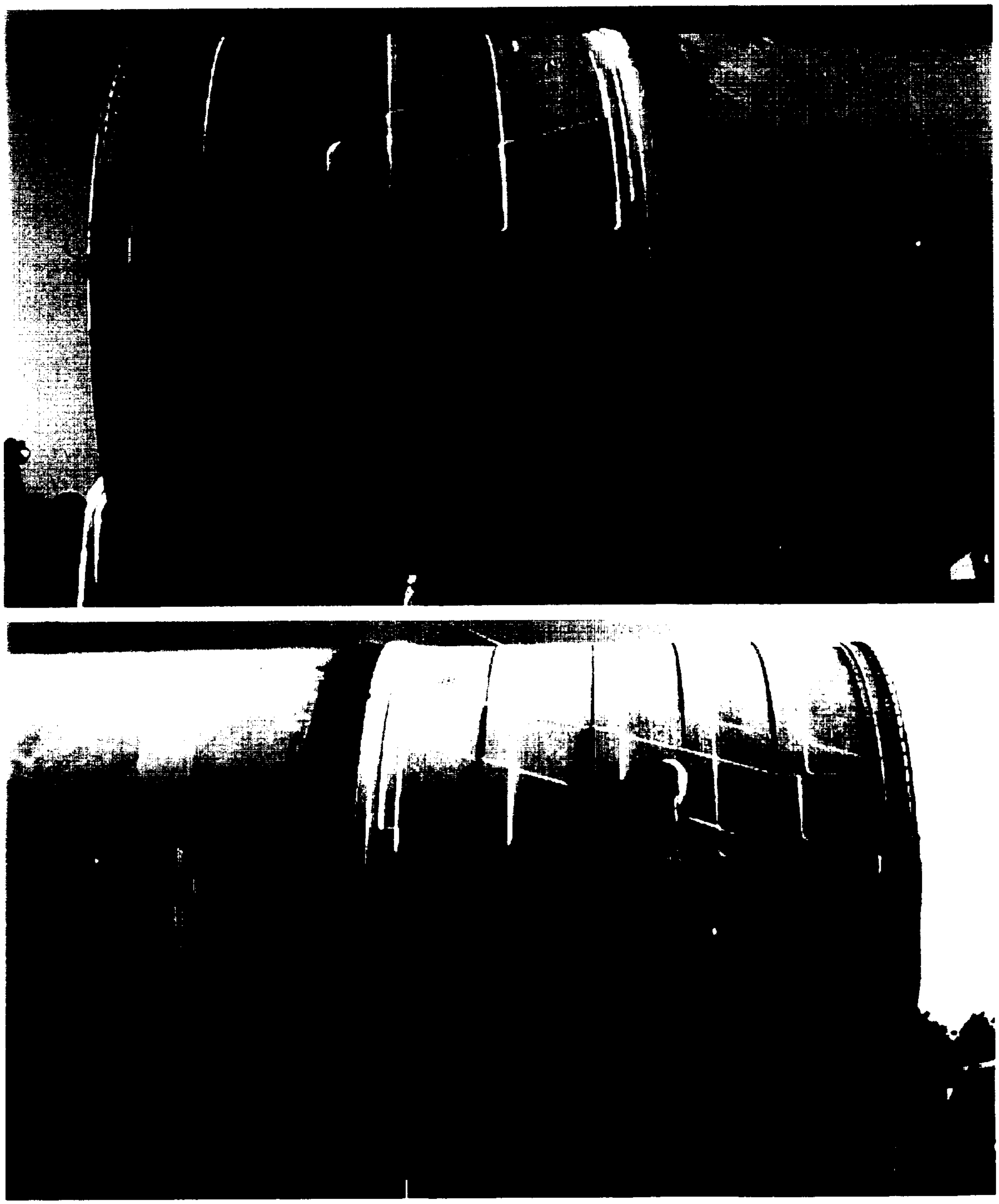


Photo 29: Forward Skirt Post Flight Condition

The forward skirts exhibited no debonds or missing TPS. RSS antennae covers/phenolic base plates were intact. Hypalon paint was blistered/missing over the areas where BTA closeouts had been applied. All primary frustum severance ring pins and retainer clips were intact though the left skirt lost two back-up ring bolts and one nut at water impact.

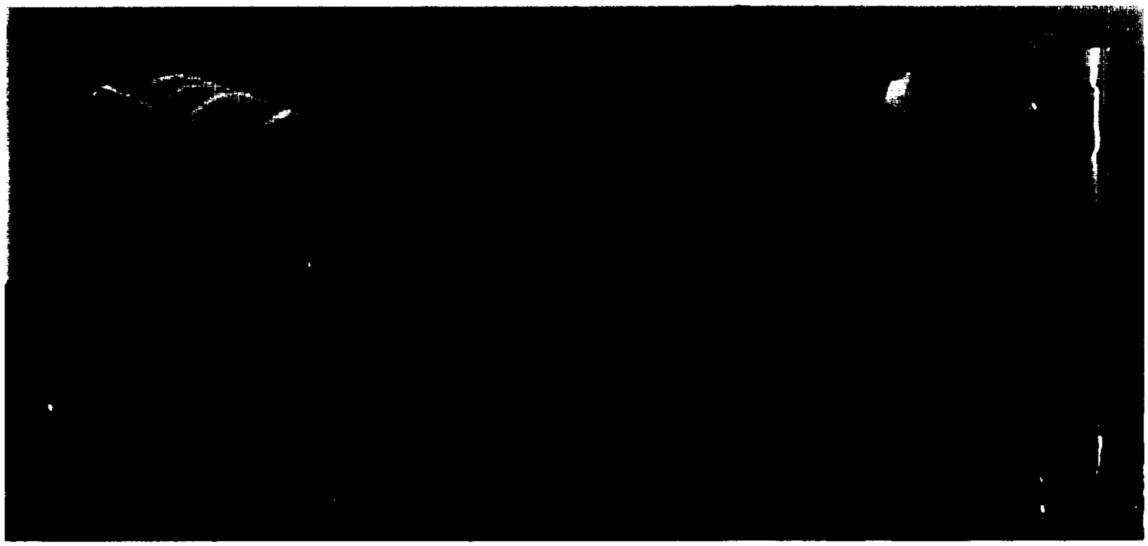


Photo 30: Aft Booster/Aft Skirt Post Flight Condition

Separation of the aft ET/SRB struts appeared normal. Damage to the fairings was attributed to water impact. TPS on the external surface of both aft skirts was intact and in good condition. The holddown post Debris Containment Systems (DCS) appeared to have functioned normally. However, the HDP #1 and #7 DCS plungers were obstructed by frangible nut halves that most likely was the result of water impact. There was no evidence of a stud hang-up on this launch.

7.0 ORBITER POST LANDING DEBRIS ASSESSMENT

After the 12:04 p.m. local/eastern time landing on 7 November 1998, a post landing inspection of OV-103 Discovery was conducted at the Kennedy Space Center on SLF runway 33 and in the Orbiter Processing Facility bay #1. This inspection was performed to identify debris impact damage and, if possible, debris sources.

The Orbiter TPS sustained a total of 187 hits, of which 45 had a major dimension of 1-inch or larger. This total does not include the numerous hits on the base heat shield attributed to SSME vibration/acoustics and exhaust plume recirculation. A comparison of these numbers to statistics from 71 previous missions of similar configuration (excluding missions STS-23, 24, 25, 26, 26R, 27R, 30, 42, 86, 87, 89, 90, and 91, which all had damage from known debris sources), indicates both the total number of hits and the number of hits 1-inch or larger was greater than the cumulative mission average (Reference Figures 2-4. Note: since no debris impacts were recorded on the right side of the Orbiter, the corresponding Figure was omitted).

The following table breaks down the STS-95 Orbiter debris damage by area:

	HITS > 1"	TOTAL HITS
Lower surface	42	139
Upper surface	1	6
Window Area	2	33
Right side	0	0
Left side	0	4
Right OMS Pod	0	1
Left OMS Pod	0	4
TOTALS	45	187

The Orbiter lower surface sustained 139 total hits, of which 42 had a major dimension of 1-inch or larger. Most of this damage was concentrated aft of the nose gear doors to the main landing gear wheel wells on both left and right chines. (Virtually no damage occurred on the Orbiter centerline. Seven small damage sites just aft of the nose gear doors were attributed to small pieces of rubber from the nose gear tires during touchdown spinup). The outboard damage sites on the chines followed the same location/damage pattern documented on STS-86, STS-87, STS-89, STS-90, and STS-91. It should also be noted that this was the second flight of the new Super Light Weight Tank. The overall size and quantity of damage sites were very similar to that sustained from the first flight of the SLWT.

	STS-86	STS-87	STS-89	STS-90	STS-91	STS-95
Lower surface total hits	100	244	95	76	145	139
Lower surface hits > 1-inch	27	109	38	11	45	42
Longest damage site	7 in.	15 in.	2.8 in.	3.0 in.	3.0 in.	4.0 in.
Deepest damage site	0.4 in.	1.5 in.	0.2 in.	0.25 in.	0.5 in.	0.4 in.

Hazing and streaking of forward-facing Orbiter windows was moderate to heavy. Damage sites on the window perimeter tiles was less than usual in quantity and size. Some of the damage sites were attributed to old repair material falling out and were not included in this assessment.

The post landing walkdown of Runway 33 was performed immediately after landing. No debris concerns were identified.

In summary, both the total number of Orbiter TPS debris hits and the number of hits 1-inch or larger was greater than the cumulative fleet average when compared to previous missions (Figure 5). Since the damage pattern and number of hits was related to the loss of TPS from the ET thrust panels (and therefore an identified debris source), these data were not incorporated into the cumulative statistics of hits and averages.

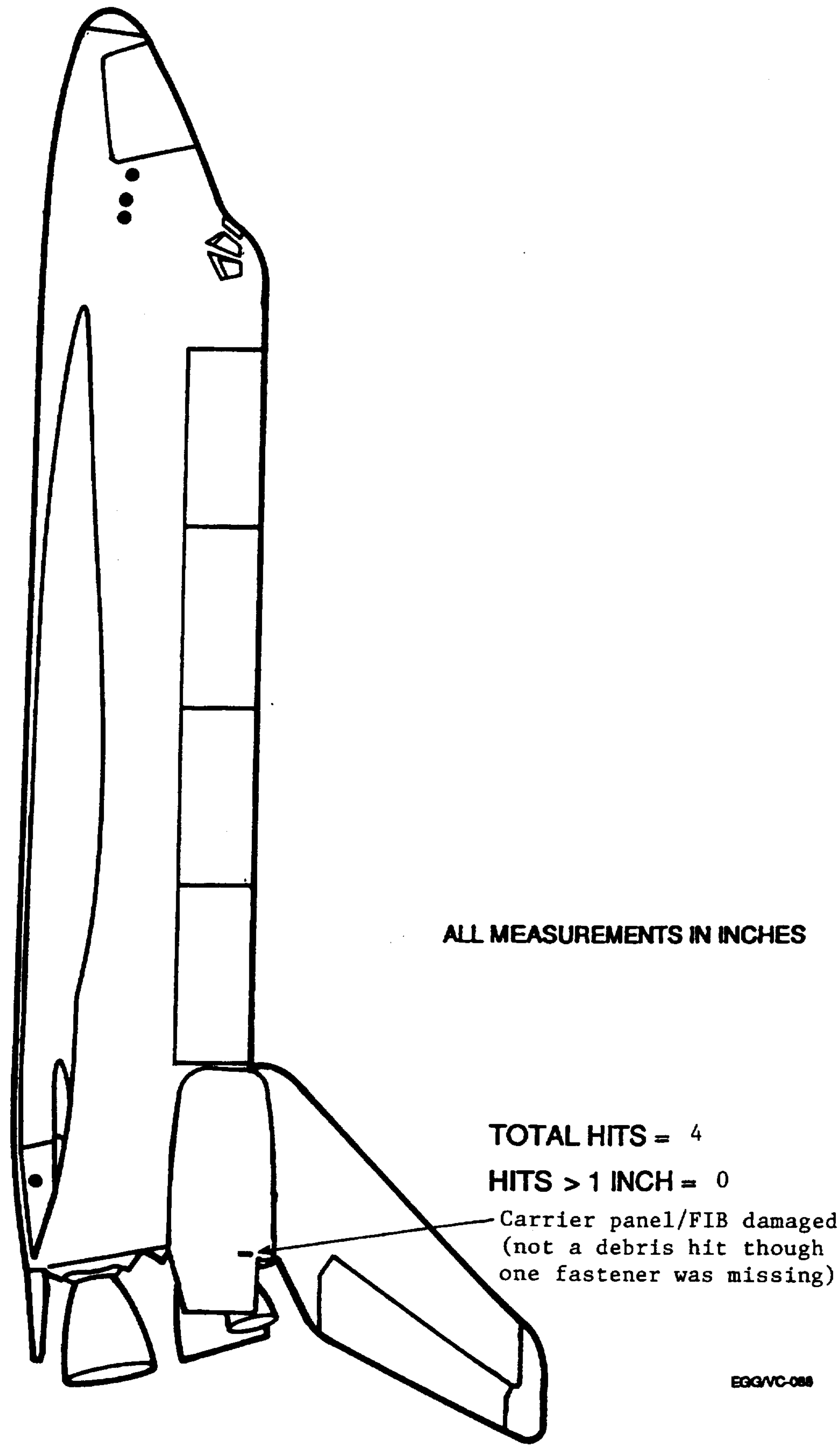


Figure 3: Orbiter Left Side Debris Damage Map

	LOWER SURFACE		ENTIRE SURFACE	
	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS
STS-6	21	89	36	120
STS-8	3	29	7	56
STS-9 (41-A)	9	49	14	58
STS-11 (41-B)	11	19	34	63
STS-13 (41-C)	5	27	8	36
STS-14 (41-D)	10	44	30	111
STS-17 (41-G)	25	69	36	154
STS-19 (51-A)	14	66	20	87
STS-20 (51-C)	24	67	28	81
STS-27 (51-I)	21	96	33	141
STS-28 (51-J)	7	66	17	111
STS-30 (61-A)	24	129	34	183
STS-31 (61-B)	37	177	55	257
STS-32 (61-C)	20	134	39	193
STS-29	18	100	23	132
STS-28R	13	60	20	76
STS-34	17	51	18	53
STS-33R	21	107	21	118
STS-32R	13	111	15	120
STS-36	17	61	19	81
STS-31R	13	47	14	63
STS-41	13	64	16	76
STS-38	7	70	8	81
STS-35	15	132	17	147
STS-37	7	91	10	113
STS-39	14	217	16	238
STS-40	23	153	25	197
STS-43	24	122	25	131
STS-48	14	100	25	182
STS-44	6	74	9	101
STS-45	18	122	22	172
STS-49	6	55	11	114
STS-50	28	141	45	184
STS-46	11	186	22	236
STS-47	3	48	11	108
STS-52	6	152	16	290
STS-53	11	145	23	240
STS-54	14	80	14	131
STS-56	18	94	36	156

	LOWER SURFACE		ENTIRE SURFACE	
	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS
STS-55	10	128	13	143
STS-57	10	75	12	106
STS-51	8	100	18	154
STS-58	23	78	26	155
STS-61	7	59	13	120
STS-60	4	48	15	106
STS-62	7	36	16	97
STS-59	10	47	19	77
STS-65	17	123	21	151
STS-64	18	116	19	150
STS-68	9	59	15	110
STS-66	22	111	28	148
STS-63	7	84	14	125
STS-67	11	47	13	76
STS-71	24	149	25	164
STS-70	5	81	9	127
STS-69	22	175	27	198
STS-73	17	102	26	147
STS-74	17	78	21	116
STS-72	3	23	6	55
STS-75	11	55	17	96
STS-76	5	32	15	69
STS-77	15	48	17	81
STS-78	5	35	12	85
STS-79	8	65	11	103
STS-80	4	34	8	93
STS-81	14	48	15	100
STS-82	14	53	18	103
STS-83	7	38	13	81
STS-84	10	67	13	103
STS-94	11	34	12	90
STS-85	6	37	13	102
AVERAGE	13.3	83.2	19.6	124.3
SIGMA	7.1	43.9	9.5	51.9
STS-95	42	139	45	187

MISSIONS STS-23,24,25,26,26R,27R,30R,42,86,87,89, 90, AND 91 ARE NOT INCLUDED IN THIS ANALYSIS SINCE THESE MISSIONS HAD SIGNIFICANT DAMAGE CAUSED BY KNOWN DEBRIS SOURCES

Figure 5: Orbiter Post Flight Debris Damage Summary

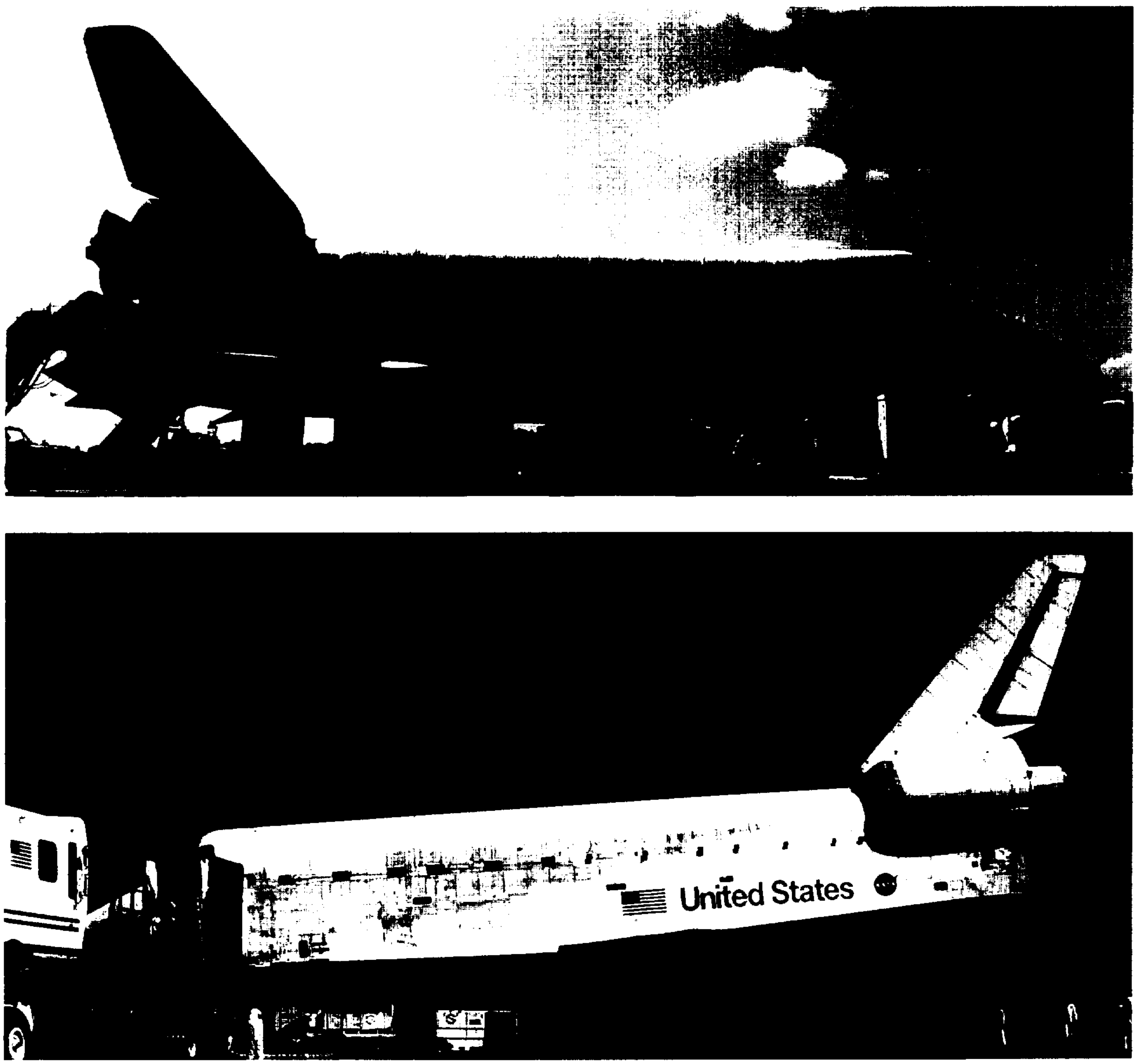


Photo 31: Overall View of Orbiter Sides

Photo 32: OMS Pod TPS Damage

A partially detached carrier panel and associated FIB on the LH OMS pod near the aft RCS thrusters was severely damaged by reentry heating. (This was the protruding panel observed on orbit by the flight crew). The carrier panel/blanket just aft of this location was also damaged by repeated contact with the discrepant panel flaying in the airstream.

Photo 33: Lower Surface Tile Damage

The Orbiter lower surface sustained 139 total hits, of which 42 had a major dimension of 1-inch or larger. Most of this damage was concentrated aft of the nose gear doors to the main landing gear wheel wells on both left and right chines. The overall size and quantity of damage sites is consistent with damage sustained by impacts from ET thrust panel insulation.

Photo 34: Windows

Hazing and streaking of forward-facing Orbiter windows was moderate to heavy. Damage sites on the window perimeter tiles was less than usual in quantity and size. Some of the damage sites were attributed to old repair material falling out and were not included in this assessment.

Photo 35: Base Heat Shield

Less than usual amounts of tile damage occurred on the base heat shield. All SSME Dome Mounted Heat Shield (DMHS) closeout blankets were in excellent condition though there was some fraying on the SSME #1 blanket at the 5-6 o'clock position. Note intact drag chute, which was not used for this landing due to concerns about possible damage during ascent after losing the drag chute door at liftoff.

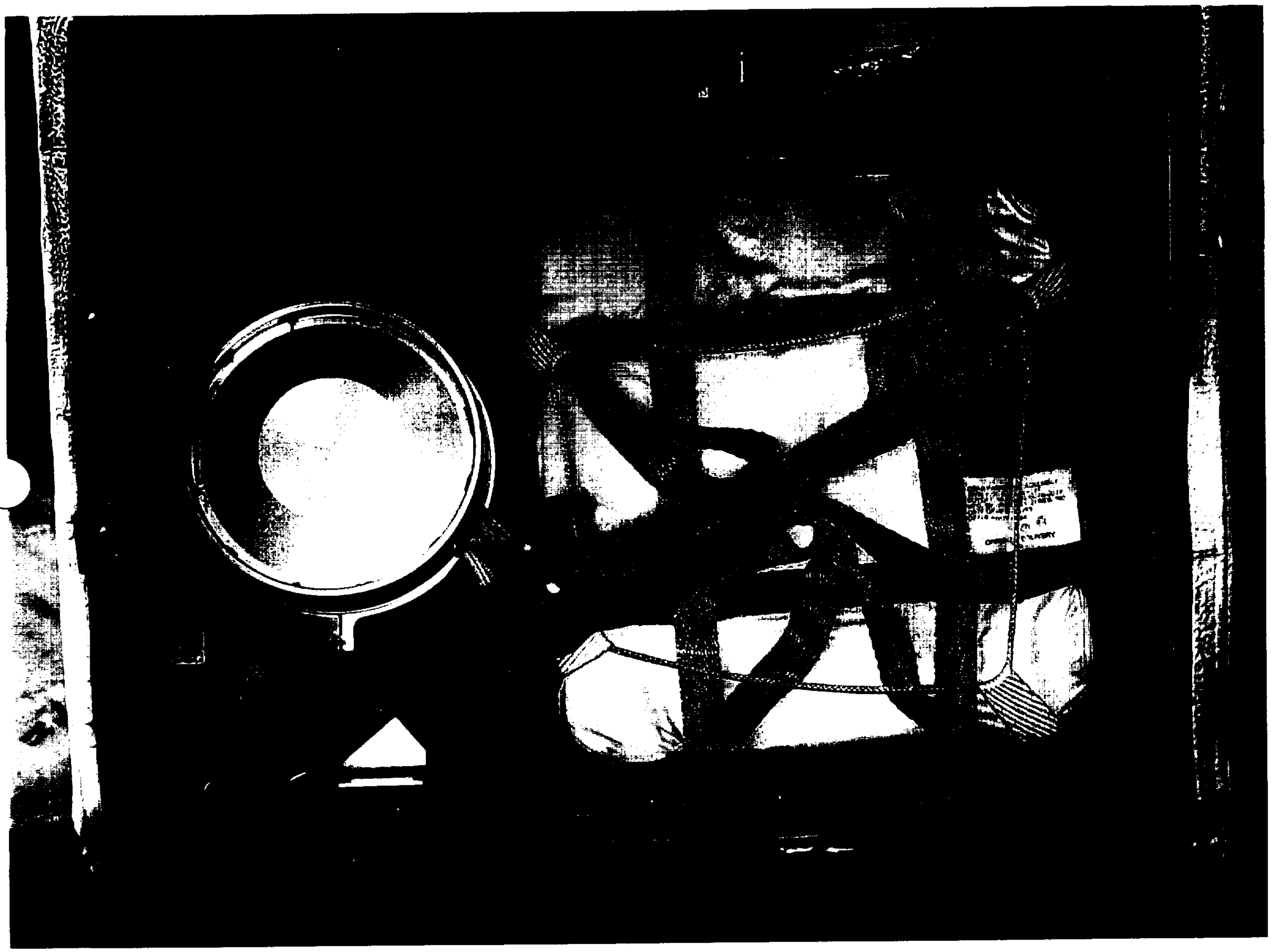


Photo 36: Drag Chute Compartment

After losing the drag chute door at liftoff, the drag chute was exposed to ascent, on-orbit, and re-entry environments. Close examination after landing determined the drag chute was intact and the nylon restraining straps barely discolored. There was no damage to the pyrotechnic devices or firing lines. Also note no apparent damage to the drag chute door hinges or shear pin flanges.

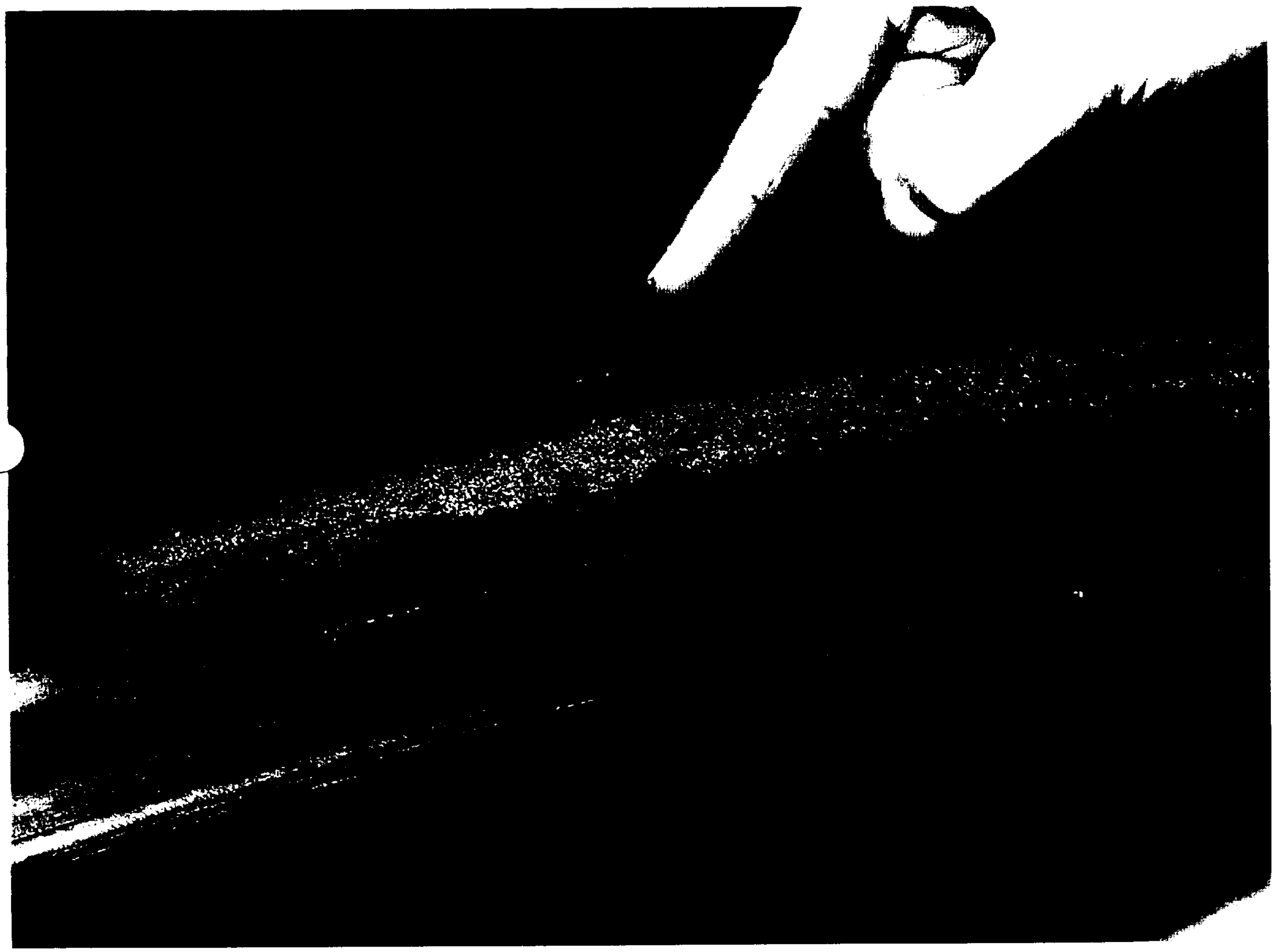
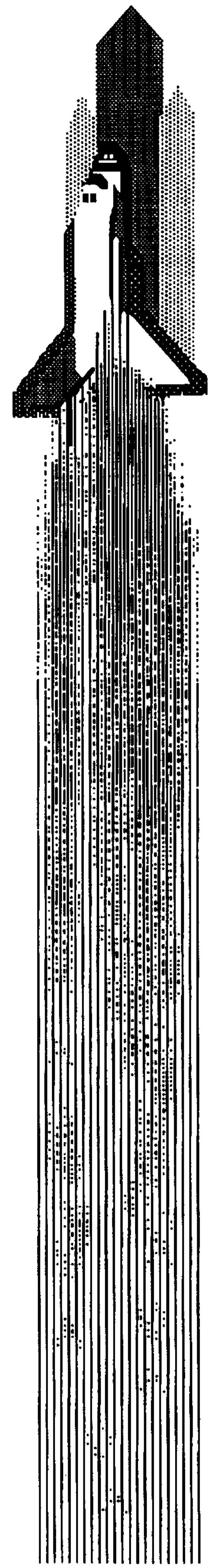


Photo 37: SSME #1 Aft Manifold

Point of impact by the drag chute door at liftoff. The impact occurred on the aft manifold and did not damage the engine nozzle or any of the high pressure hydrogen tubes.

APPENDIX A. JSC PHOTOGRAPHIC ANALYSIS SUMMARY

<u>Space Science Branch</u>
Image Science and Analysis Group



STS-95 Summary of Significant Events

January 29, 1999

Table of Contents

1. STS-95 (OV-103): FILM/VIDEO SCREENING AND TIMING SUMMARY

1.1 SCREENING ACTIVITIES

1.1.1 Launch

The STS-95 launch of Discovery (OV-103) from Pad B occurred on Thursday, October 29, 1998 at approximately 302:19:19:33.994 UTC as seen on camera E8. SRB separation occurred at approximately 19:21:36.343 UTC as seen on camera ET207.

On launch day, 22 of the 24 expected videos were received and screened. Camera videos KTV11 and ET213 were not received.

The drag chute door was observed to detach from the Orbiter at 302:19:19:31.060 UTC and was seen impacting the rim of SSME bell #1 at 302:19:19:31.291 UTC. The port side of the door was noted to detach first, swinging aft in a hinge like movement, followed by the detaching of the starboard side of the door and the complete detachment of the drag chute door from the Orbiter. The door struck the rim of the SSME #1 bell. No damage to the engine was noted. Image analysis support was provided to the Space Shuttle Program for the assessment of the vehicle condition for a safe return and landing and also on the root cause of the incident. A summary of the image analysis support provided to the drag chute door release investigation is included in section 2.3.

Twenty launch films were screened on November 1, 1998. Twenty-two additional films were received for contingency support and anomaly resolution.

Umbilical well cameras flew for the second time on OV-103 on STS-95. Photography of the left SRB and the LSRB/ET aft attach and the external tank aft dome was acquired using umbilical well camera films during SRB separation. Photography of the external tank was acquired during ET separation. Handheld video and still photography of the ET was acquired following separation. For the first time, video of the external tank -Y thrust panel was acquired from a camera mounted on the LSRB.

1.1.2 On-Orbit

Enhancements were made from on-orbit video views of a dislodged blanket on the left OMS pod. Enhancements of this video was provided to Space Shuttle program engineers for assessment of the damage. See Section 2.7.

1.1.3 Landing

Discovery landed on runway 33 at the KSC Shuttle Landing Facility on November 7, 1998 at 12:03 p.m. EST. Eleven videos and ten films were received.

The landing touchdown appeared normal. A sink rate analysis of the main landing gear was performed for the main gear touchdown (see Section 2.8). The

2. SUMMARY OF SIGNIFICANT EVENTS

2.1 DEBRIS FROM SSME IGNITION THROUGH LIFTOFF

As on previous missions, numerous light-colored pieces of debris were seen aft of the launch vehicle before, during, and after the roll maneuver (umbilical ice debris, RCS paper, SRB flame duct debris, and water baffle debris). Multiple pieces of ice debris were seen falling from the ET/Orbiter umbilicals and along the body flap during SSME ignition. (Cameras OTV009, OTV149, OTV154, E31, E34).

An unidentified light-colored piece of debris (possible RCS paper) was seen aft of the trailing edge of the vertical stabilizer speed brake during SSME ignition (19:19:29.589 UTC). A second similar event was seen near the speed brake trailing edge at the mid point level at 19:19:34.895 UTC. These debris did not appear to be related to the drag chute door release event. (Camera E76).

A light-colored piece of debris was seen between the RSRB and the LO2 TSM during SSME ignition (19:19:29.0 UTC). (Camera E2).

A single piece of probable flame duct debris was seen traveling near the RSRB toward the Orbiter and then fell aft of the vehicle during liftoff (19:19:34.9 UTC). (Camera E5). A single piece of probable flame duct debris was seen near the LSRB traveling near the LH2 TSM at liftoff (19:19:35.5 UTC). (Camera E4).

2.2 DEBRIS DURING ASCENT

See Section 2.3.1.1, Drag Chute Door Event Timeline.

2.3 MOBILE LAUNCH PLATFORM (MLP) EVENTS

2.3.1 Drag Chute Door Release

The drag chute door was seen to separate from the Orbiter along the port edge, pivot downward on the starboard hinge, detach, fall aft, and strike the rim of SSME #1. The door then fell aft and was lost from view below the MLP deck.

All views of the drag chute door detaching and striking the rim of SSME #1 were analyzed (cameras E2, E3, E19, E20, E52, E62, E63, E76, E77, OTV151, OTV170). Available close-up perimeter tracking camera videos and films were screened for evidence of debris emanating from the drag chute compartment during early ascent (E52, E54, E57). Long range tracking camera videos and films were screened for evidence of debris emanating from the drag chute compartment during ascent through SRB separation and beyond (E205, E207, E208, E213, E224, ET204, ET207, ET208, ET212, KTV2, KTV4B, KTV5, KTV7B, KTV21B).

The launch camera films including the tracking cameras were viewed by image analysts at the three NASA centers (KSC, MSFC, and JSC). Based on the individual NASA center imagery screening assessments, no debris was seen near the drag chute door compartment. Because of the excellent quality cloud-free photography, it was concluded that material of significant size, particularly the drag chute exiting from the drag chute compartment, would have been detected if it had occurred prior to SRB separation and possibly would have been detected for up to forty-five seconds after SRB separation.

The following includes examples of the more prominent events seen during ascent:

19:19:43.477, 19:19:51.971, 19:20:01.924 19:20:04.351, 19:20:09.266 UTC (Cameras, E207, E220, E224, ET207, ET212, KTV4B) - Light-colored flares were seen in the SSME exhaust plume during ascent. Similar flares have been typically seen on previous missions and are probably induced by RCS paper debris.

19:19:52.140 UTC (Camera E52) - A single, large light-colored piece of unidentified debris was seen falling aft near the LSRB and the ET aft dome. Due to its position, it did not appear that it could have originated from the vicinity of the drag chute compartment.

19:19:52.752 UTC (Camera E213) - A large piece of light-colored debris was seen beneath the body flap (-Z side) and fell along the LSRB. This debris appeared to be a piece of umbilical purge barrier (baggy) material.

19:19:57.875 UTC (Camera E213) - A large light-colored piece of debris was seen near the RSRB aft skirt which was probably a piece of instafoam.

19:19:59.451 UTC (Camera E213) - A light-colored piece of debris, first seen above (+Z) the right inboard elevon, fell aft along the SSME exhaust plume. This debris appeared to be to the right of the Oribiter center line (+X axis). Similar debris in this position has been seen on previous missions and is believed to be forward RCS paper.

19:20:01.572 UTC (Camera E224) - A large, significant appearing, debris object was seen aft of the right wing trailing edge near the RSRB aft skirt. Because of its position, this debris did not appear to have come from the drag chute compartment.

19:20.01.734 UTC (Camera E213) - Forward RCS paper debris was seen falling across the leading edge of the right wing, passing over the right wing, and falling aft near the vertical stabilizer.

19:20:09.7 through 19:20:21.37 (Camera E224) - On three occasions, light colored objects were seen moving in the -Y direction from the mid-level of the RSRB and again in the +Y direction from the forward tip of the LSRB. These objects may have been birds close to the camera.

19:20:12.132 UTC (Camera E220) - A spray of multiple pieces of light-colored debris were seen near the base of the vertical stabilizer and falling along the port OMS pod. This debris was first seen forward of the drag chute compartment and is believed to be RCS paper.

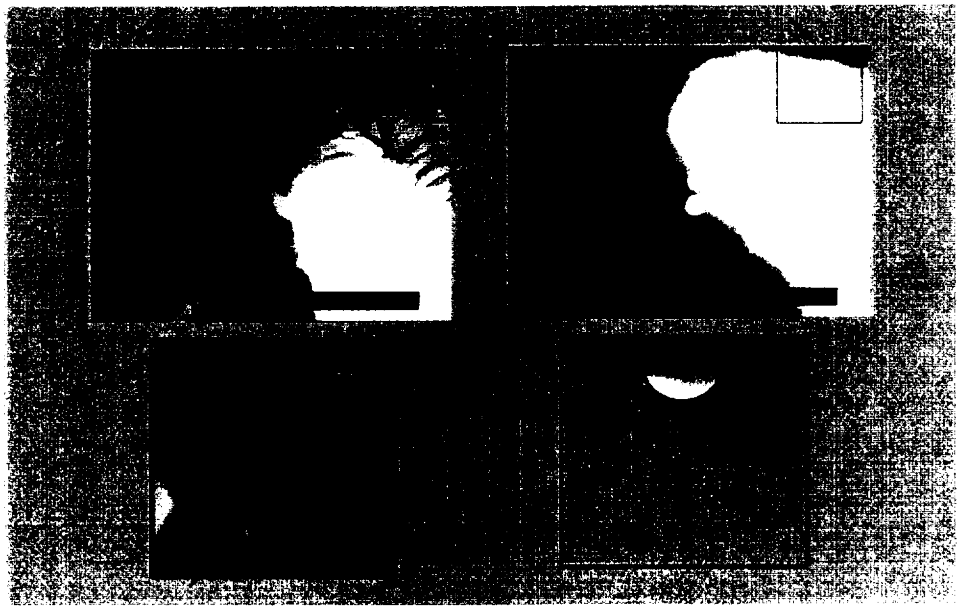


Figure 2.3.1.1 (A) Debris During Ascent

19:20:12.192 UTC (Camera ET207) - Two light-colored pieces of debris (probably forward RCS paper) were seen near the aft end of the vertical stabilizer.

19:20:40.367 UTC (Camera ET208) - An unidentified debris-like object or objects were seen falling aft along the SRB exhaust plume.

19:20:49.095 UTC (Camera ET207) - A single light-colored piece of debris was seen falling along the SRB exhaust plume.

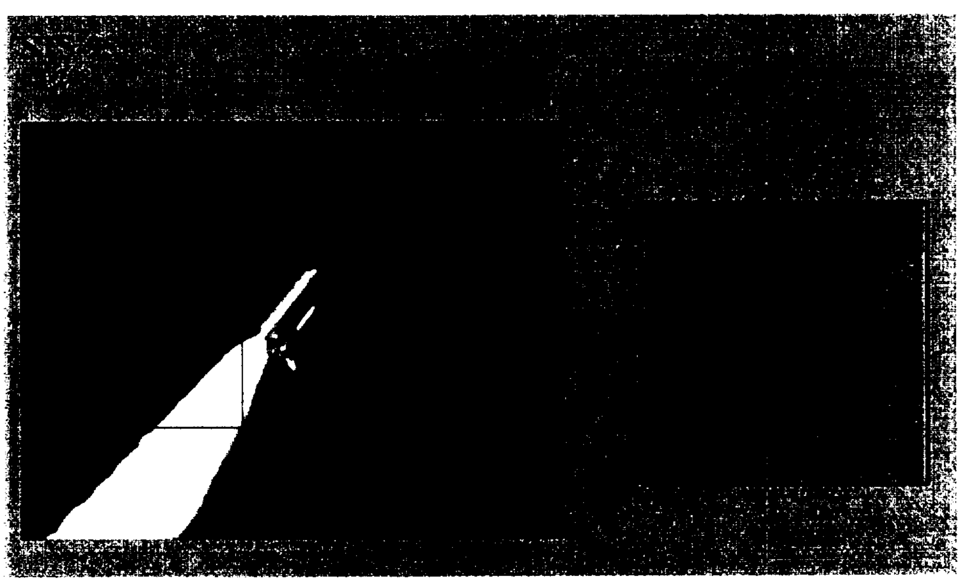


Figure 2.3.1.1 (B) Debris Cloud seen near SRB plume

19:21:02 UTC (approximate) (Camera E205) - An unidentified piece of debris was seen near the right SRB exhaust plume approximately 1/3 of the vehicle length aft of the vehicle. The source of this debris was not confirmed because of the view angle. Although inconclusive, there is a remote possibility this debris could have originated from the drag chute door compartment. Similarly positioned unidentified debris has been seen on previous missions.

19:21:05.3 - 19:21:22.4 UTC - Recirculation or the expansion of hot burning gasses was visible at the aft end of the Orbiter. Recirculation is a normal event and was typically seen on previous missions.

19:21:36.343 UTC (Camera ET207) SRB separation.

2.3.1.2 Drag Chute Door Release Analysis Tasks

Door Velocity after Impact

The velocity of the door after detachment from the Orbiter was measured from camera OTV170. The velocity of the door at the time of impact was calculated to be 12 ± 1 ft/sec. This velocity is consistent with the door falling solely due to gravity.

Orientation of the Door at Impact

The angle at which the door struck the SSME bell with respect to the Orbiter's xz plane was determined. Figure 2.3.1.2 (A) shows a representation of the door impact angle in Shuttle Structural Coordinates. The angle of impact is designated Alpha (α). Alpha was determined to be approximately $19^{\circ} \pm 5^{\circ}$ with respect to the Orbiter's Xo-Zo plane.

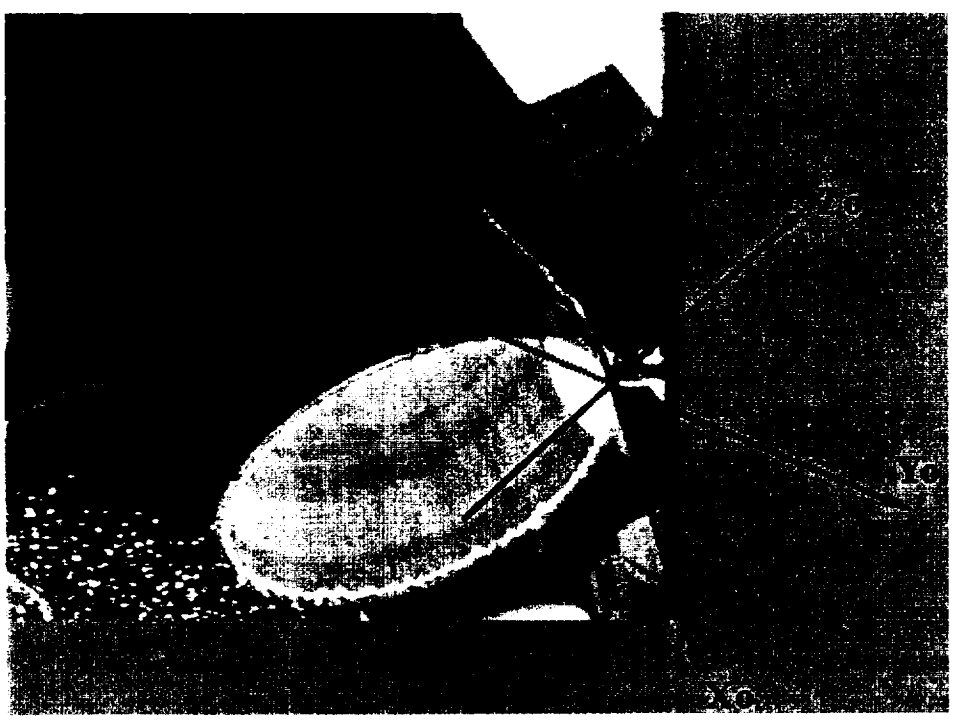


Figure 2.3.1.2 (A) Drag Chute Door Impact Angle Alpha (α)

STS-95 Drag Chute Angular Velocity Analysis

Figure 2.3.1.2 (B) Sample Frame used for Angular Velocity Calculation (Camera E20)

The angular velocity of the drag chute door was calculated immediately prior to detachment of the door from the Orbiter. The angular velocity at the time of door release was calculated to be 200 ± 20 degrees/sec. Comparison to a gravity induced door rotation showed that the door did not swing out with an angular velocity greater than would be expected due solely to gravity. This implies that no extra force or pressure, other than gravity, was exerted on the door.

Drag Chute Door Motion Prior to Detachment

On STS-95 a line that appeared to be a "gap" or "crack" was noted along the shear pin side (-Y) side of the drag chute door just prior to launch. The effect was most noticeable on the high speed (400 frame per second) MLP camera E20. Figure 3.2.1.2 (C) shows the reference coordinate system for the drag chute door and Figure 3.2.1.2 (D) shows an enhancement that highlights the apparent gap seen on one of the frames in which the gap was most evident. The gap appeared to vary in size, having an almost on/off appearance, and was most evident on the +Z side of the shear pin side of the door. In fact, in very few frames was the gap seen across more than half the -Y side and in no frame, prior to door opening, was the gap seen to extend along the entire -Y side of the door. The change in the size of the gap was most noticeable when viewing the film very slowly at approximately one frame per second. This effect implies that if the gap were a real effect it would have a very high frequency (in the hundreds of Hz range) since it appeared and disappeared every few frames. If the gap is real it is also not clear whether we are seeing a movement of the blanket material covering the door and the door frame caused by the movement of the door or whether the blanket material is simply vibrating (flapping) due to the overall vibrations caused by SSME startup.

There was also uncertainty as to whether the gap represents a real motion or vibration of the door or whether it is due only to some type of lighting or camera focus problem. Review of the STS-95 film revealed a great deal of image blurring, camera vibration, and lighting changes especially during SSME ignition. As with the appearance of the gap, the blurring effect was also most noticeable when viewing at one frame per second. Distinguishing between the appearance of a true gap and the appearance of a false gap caused by film distortion was the driver for this analysis. There were two parts to the analysis. The first was a characterization of the frames surrounding a frame that shows an apparent gap in the door. This analysis investigated the role that image focus played in the appearance and disappearance of the gap. Secondly, films showing the drag chute door from STS-80, STS-83, STS-87, and STS-90, which launched at approximately the same time of day as STS-95, were reviewed in order to characterize the appearance of the gap area on other missions. It was hoped that comparison with past missions could provide a baseline for how the drag chute door normally appears. Also review of past missions might reveal the same effect of an apparent gap and film distortion.

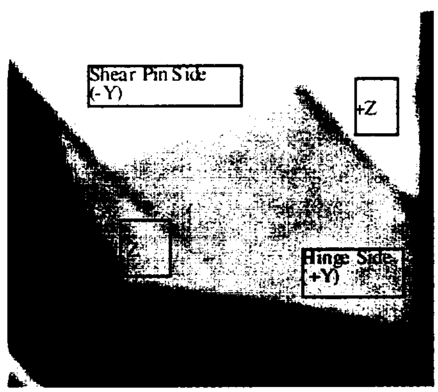


Figure 2.3.1.2 (C) Drag Chute Door on STS-95 Reference Coordinate System (Camera E20)

Figure 2.3.1.2 (D) Enhanced View of Gap in Drag Chute Door
(Gap area is highlighted)

A comparison was made between frames where the gap was seen and adjacent frames in which the gap was not seen. This comparison demonstrated that the gap disappeared due to a change in focus. This effect suggests that the appearance and disappearance of the gap was due only to change in camera focus. The camera focus changed at a high frequency (i.e. every few frames) which is probably due to slight movement of the film in the camera (there-by moving the film relative to the focal plane) due to the excessive vibration caused by the startup of the SSMEs.

Films from camera E20 from previous missions that launched at a similar time of day were chosen for review. However, the door looked very different for each mission and there was really no standard or baseline for how the gap area on the door should appear.

The review of previous missions showed that the appearance of the area surrounding the drag chute door is very sensitive to lighting and camera focus. The area on the door where the apparent gap was noted on STS-95 looked different for each mission, even when the time of launch was similar (note that seasonal differences influencing sun angle and sky cloud cover conditions were not accounted for.).

Although the appearance of the gap was probably caused by changes in camera focus, the possibility of a real gap between the door and the frame or between the blanket material and the frame cannot be totally ruled out. There is insufficient information to provide a conclusive answer. Also, no conclusive evidence can be ascertained from previous missions as to whether the gap along the drag chute door on STS-95 was real or due to camera focus and/or lighting effects.

SSME #1 Nozzle Motion

During the investigation of the loss of the drag chute door during the launch of STS-95, a significant amount of translation in the SSME #1 nozzle location was noticed. Further inspection of the E20 launch film revealed that this translation began within 1/400th of a second of the initial visual indication of drag chute door separation from the vehicle. Visual inspection of STS-91 and STS-89 launch video from the same camera perspective indicated that the magnitude of the SSME translation was significantly larger during STS-95.

An 80 frame segment of film (0.2 seconds of elapsed time) was selected from the E20 camera position during STS-95, STS-91 and STS-89. Each specific segment was selected to capture maximum SSME #1 nozzle translation, as determined by visual inspection of the launch film. Photographic analysis techniques were employed to quantify the magnitude of the relative nozzle translation in inches based on the known radius of the SSME bell at the nozzle. Table 2.3.1.2 lists the specific time sequence analyzed for each mission, the maximum translation seen in each axes and uncertainty in the positional estimates.

Mission Number	Time Sequence (in GMT)	Range of Movement in Y Axis (in inches)	Range of Movement in Z Axis (in inches)	Maximum Estimated Uncertainty of any Point Location (in inches)
STS-95	19:19:30.673 to 19:19:30.868	-6.2" to 1.3"	-6.0" to 3.2"	0.5"
STS-91	22:06:20.828 to 22:06:21.023	-1.6" to 0.8"	-3.0" to 1.6"	0.5"
STS-89	02:48:11.688 to 02:48:11.886	-3.2" to 3.6"	-1.4" to 2.0"	0.7"

Table 2.3.1.2 SSME #1 Nozzle Motion on STS-95, STS-91, and STS-89

Plots displaying the relative movement an observer would see in the center of the engine nozzle if they were positioned behind the vehicle looking forward at the SSMEs are shown in Figure 2.3.1.2 (E). The axes of the plots are oriented within +/- 5 degrees of the Y and Z axes of the Shuttle Coordinate System. The relative movement shown on each plot begins at the 0,0 coordinate location. The plots compare the magnitude of relative movement for each mission, but does not infer any absolute positional relationship between the SSME center locations during the three missions.

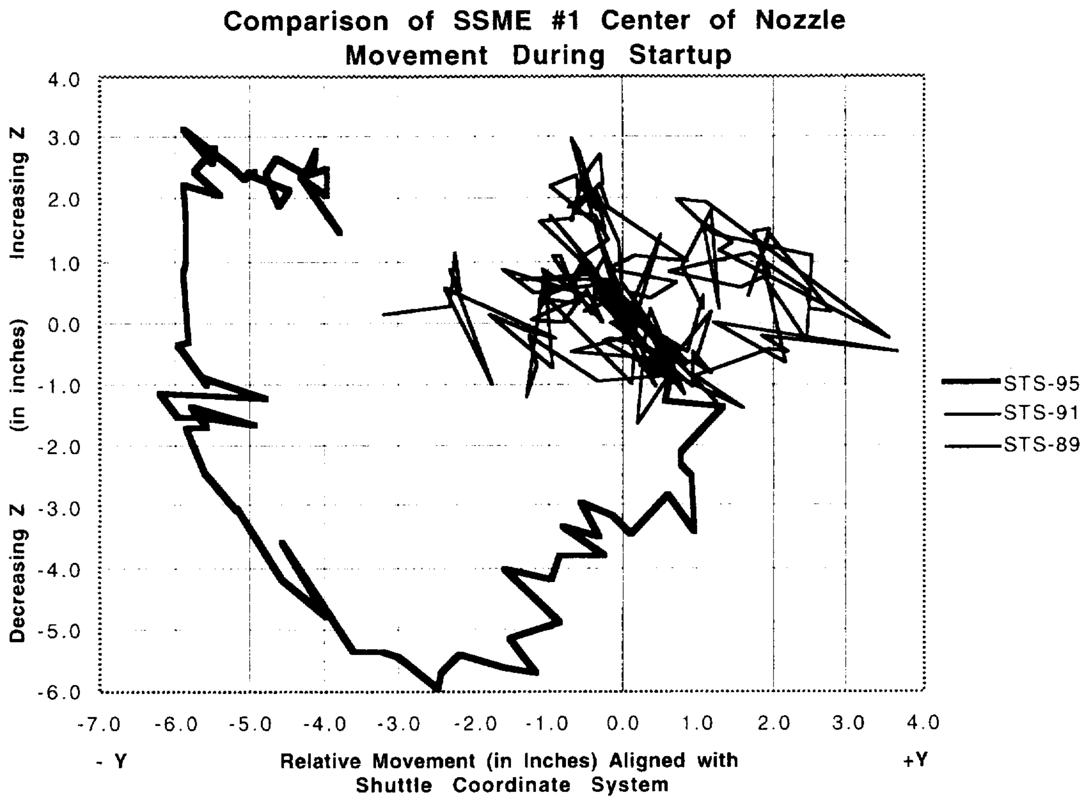


Figure 2.3.1.2 (E) SSME #1 Relative Motion Plots for STS-95, STS-91, and STS-89

Flash in SSME #1 Plume

An orange-yellow-colored flash was seen in the SSME #1 exhaust plume during engine start-up on the camera E2 film. Previous mission films and videos of SSME ignitions were reviewed. A flash in the SSME #1 exhaust plume during the engine start-up was seen on the STS-91 camera E2 film. This flash appeared very similar to the one observed on STS-95 during the SSME #1 start-up. Based on the STS-91 observation and the presence of flashes seen on other previous missions, it was concluded that the flash observed on STS-95 was not an anomalous event.

Imagery Products

Example images of the drag chute door release were provided to the Drag Chute Door Release Investigation Team. Included were the "best effort" image enlargements/enhancements of the apparent gap just prior to door release, the inside of the door after door release, the port edge of the door showing the area of the shear pins, the starboard door edge showing the area of the hinges, the drag chute and mortar inside the compartment, and the debris seen at the time of the door detachment from the Orbiter. Film-to-video conversions of four representative tracking camera views of the launch vehicle from lift-off through ascent to SRB separation and beyond were also provided to the investigation team.

2.3.2 Other Mobile Launch Platform Events

Orange vapor, probably free burning hydrogen, was seen forward of the SSME rims during SSME ignition (E19, E20, E76). Orange vapors drifting forward from the aft end of the vehicle have been observed on previous missions.

During SSME ignition, the SSME Mach diamonds did not form in the expected sequence based on the analysis of the high-speed engineering films. The times for the Mach diamond formation recorded in Table 2.3.2 below are from camera film E19.

SSME	TIME (UTC)
SSME #2	19:19:30.760
SSME #1	19:19:30.877
SSME #3	19:19:30.937

Table 2.3.2 SSME Mach Diamond Formation

2.4 ASCENT EVENTS

Body flap motion was visible during ascent (ET207, E207, E212). JSC-EP engineers compared the body flap position data to their experience data base. From the positional data, the body flap motion was assessed to be within the range of that noted on previous missions. No follow-up action was requested.

See Section 2.3.1.1, Drag Chute Door Event Timeline, for additional events seen during ascent.

2.5 ONBOARD PHOTOGRAPHY OF THE EXTERNAL TANK

2.5.1 Analysis of the Umbilical Well Camera Films

Umbilical well cameras flew for the second time on OV-103 on STS-95. Two rolls of the STS-95 16mm umbilical well film, one roll of 35mm umbilical well film, and one roll of 35mm handheld film were received. The +X translation maneuver was performed on STS-95 to facilitate the imaging of the ET with the umbilical well cameras. The film quality is very good.

<u>35mm Umbilical Well Camera Film</u>

The LH2 tank and the LO2 tank/Ojive TPS appear to be in excellent condition on the close-up 35mm umbilical well camera film. The sanded area on the LO2 nose cone appears undamaged. Similar to STS-90, STS-91, and other previous missions, a gray-colored band of pock marked or possible missing TPS is visible on the +Z ET nose just aft of the ET nose cone fairing. Discoloration in this area is probably due to aero friction and heating. The RSRB separation motor burn scar appeared typical of previous missions with only a small area of possible very shallow divoting visible.

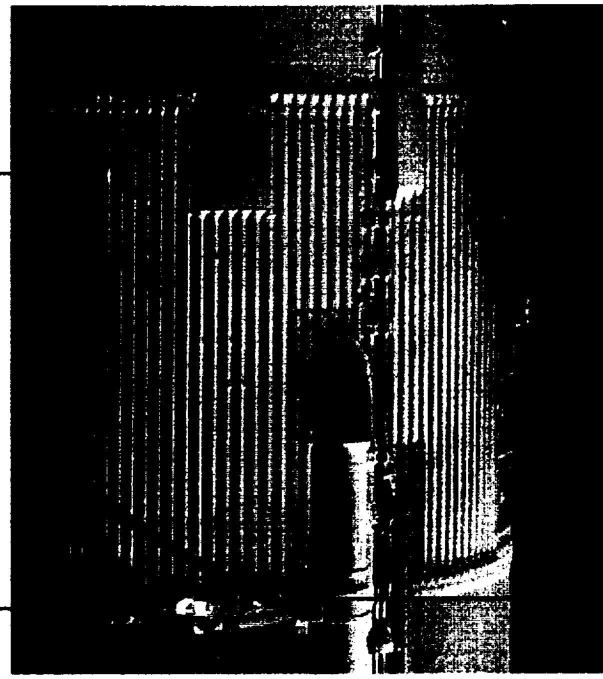


Figure 2.5.1 (A) 35 mm Umbilical Well Camera View of the ET Intertank

Two large divots (approximately 7 inches in size) are visible on the LH2 tank-to-intertank close out flange between the legs of the forward ET/Orbiter attach bipod (annotation 1). The divots have sufficient depth to show shadow but probably not primed substrate. A smaller third divot is visible on the same flange near the right (+Y) foot of the forward bipod (annotation 2). The bipod jack pad close-outs appeared intaçt. An intertank stringer head divot approximately seven inches in length is visible in the -Y direction from the +Z intertank aero vent (annotation 3). Approximately ten very small, randomly located, divots were counted on the intertank stringer heads.

The visible portion (+Z/+Y) of the right SRB thrust panel is in direct sun light on the 35mm umbilical well film. A bright divot estimated to be seven inches in size is visible on the +Y thrust panel forward of the RSRB forward attach (annotation 4). Approximately ten shallow divots estimated to be approximately three inches in size appear to be present near the same attach. The left (-Y) SRB thrust panel is not imaged on the 35mm umbilical well film.

Minor TPS chipping and very small divots (typical of previous missions) were seen on the LO2 feedline, feedline flanges, and on the forward end of the +Y ET/Orbiter thrust strut. Ablation and divoting of the TPS on the vertical section of the +Y electric cable tray adjacent to the LO2 umbilical is visible. A divot approximately six inches in size is visible between the LO2 feedline and the electric cable tray on the LH2 tank TPS just forward of the forward end of the +Y thrust strut. Two shallow divots estimated to be approximately three inches in size are visible on the LH2 tank TPS forward of the cross beam. Multiple, but insignificant appearing, shallow "pop corn" divots are visible on the aft LH2 tank TPS. "Pop corn" divots in this location were typically seen on previous mission films. The shallow "pop corn" divots visible on the ET aft dome appear to be less than typically seen on previous mission films.

The face of the LO2 umbilical carrier plate appeared to be in excellent condition (the lightning contact strips appeared to be in place).

16mm Umbilical Well Camera Film

Two rolls of the STS-95 16mm umbilical well film were received. The film quality is very good on the two 16mm umbilical well camera films. However, the -Y side of the ET is in shadow and is too dark for analysis. OV-103 provided timing data to the 16mm umbilical well cameras.

The LSRB separation appeared normal on the 16mm umbilical well camera films. Numerous light-colored pieces of debris (insulation), and dark debris (charred insulation) were seen throughout the SRB separation film sequence. Typical ablation and charring of the ET/Orbiter LH2 umbilical electric cable tray and the aft surface of the -Y upper strut fairing prior to SRB separation were seen. Numerous irregularly-shaped pieces of debris (charred insulation) were noted near the base of the LSRB electric cable tray prior to SRB separation. Pieces of TPS were seen to detach from the aft surface of the horizontal section of the -Y ET vertical strut. Normal blistering of the fire barrier material on the outboard side of the LH2 umbilical was seen. Ablation of the TPS on the aft dome was less than usual. Both the left and right SRB nose caps were visible during SRB separation.

The ET separation from the Orbiter appeared normal. Typical vapor and multiple light colored pieces of debris were seen after the umbilical separation.

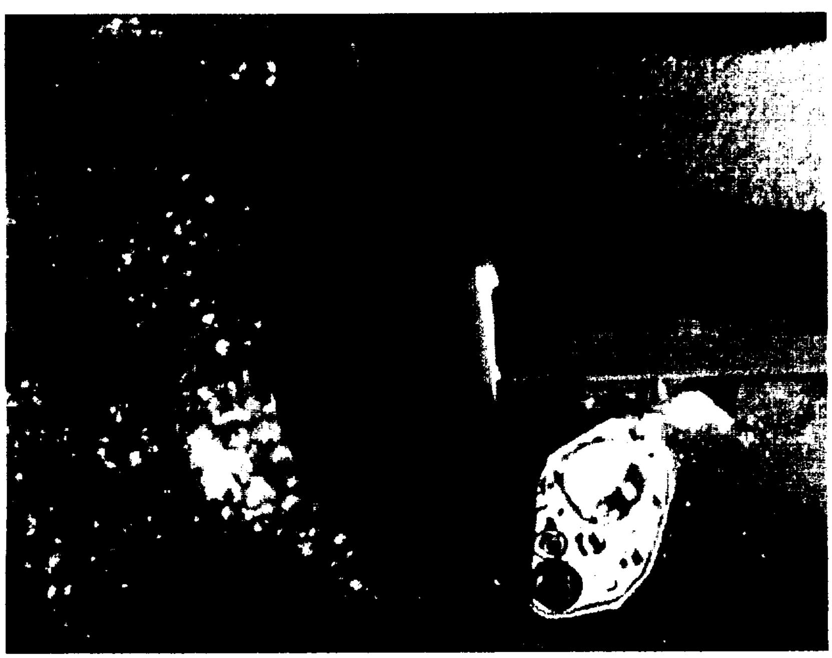


Figure 2.5.1 (B) 16 mm Umbilical Well Camera View of the ET LH2 Umbilical

No anomalies were noted on the face of the LH2 umbilical after ET separation. As typically seen on previous missions, frozen hydrogen was visible on the orifice of the LH2 17 inch connect. Typical small erosion marks are visible on both the +Y and -Y thrust struts. No anomalous conditions on the +Z of the ET other than those seen at better resolution on the 35mm umbilical well film were noted.

Dark-colored linear-shaped marks, possibly from shock waves off the right EB fitting, were visible extending diagonally across the +Y/+Z intertank stringer heads toward the bipod.

2.5.2 Analysis of the Handheld Photography of the ET

The STS-95 handheld film of the External Tank (ET-98) is good quality with both good focus and, except for shadowed areas, good exposure. Timing data is present on the handheld film. The first picture was taken at 13:40 (minutes:seconds) MET.

The astronauts performed a manual pitch maneuver from the heads-up position to bring the ET into view in the Orbiter overhead windows for the handheld photography. (STS-95 was the fifth flight using the roll-to-heads-up maneuver).

Figure 2.5.2 (A) 35 mm Handheld Camera View of the +Y/-Z sides of the ET

Screening Summary

Sixty-five images of the ET were acquired using the handheld 35mm Nikon camera with a 400mm lens (rolls 393 and 394).

The images of the ET are silhouetted by the late afternoon sun which resulted in large areas of shadow on the ET that hindered analysis. Views of the +Y side of the ET and the ET nose were acquired including the +Y thrust panel. No views of the -Y thrust panel or the -Y axis of the ET were obtained. Enhancements were made to bring out detail in the shadowed areas including the +Y thrust panel in the -Y direction from the EO fitting. If present, divots greater than three inches in size should have been detectable on the sun lit portion of the +Y thrust panel and may have been detectable in the enhanced shadow area. However none were confirmed. On the enhanced image of the shadow area, several light-colored marks (possible, but not confirmed divots) are visible on the +Y/-Z LH2 tank-to-intertank close out flange. The normal SRB separation burn scars and aero-heating marks were noted on the +Y intertank and nose TPS of the ET.

The distance of the ET from the Orbiter was calculated to be approximately 1.1 km on the first photographic frame acquired. The separation rate from the Orbiter was calculated from the first 18 frames of photography (prior to venting) to be 5.5 m/sec.

Venting from what appeared to be the -Y intertank hydrogen vent is visible on four frames (see Table 2.5.2(A). The venting occurred approximately four minutes later on STS-95 than was seen on the previous mission (STS-91) film.

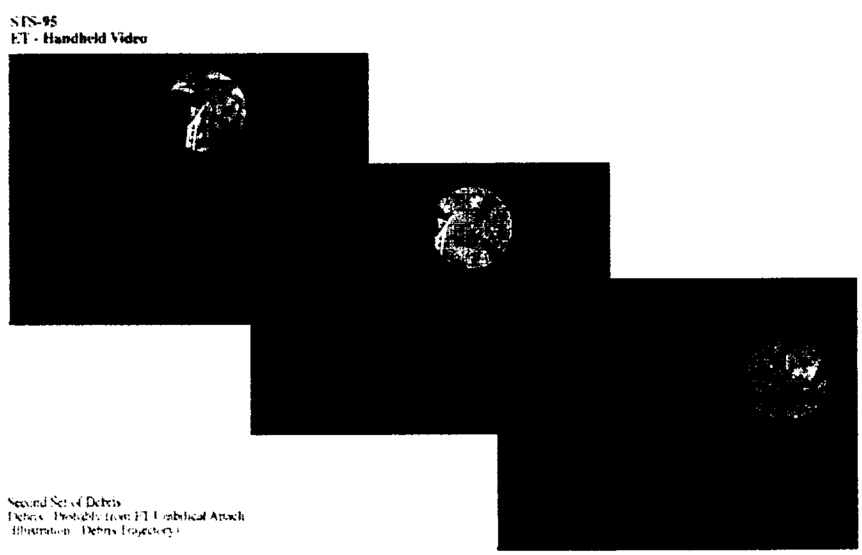


Figure 2.5.2 (B) Handheld Video Camera View of the ET and Debris

Extensive venting from the -Y intertank hydrogen vent is also visible on the handheld video of the ET. Venting and white-colored debris (frozen hydrogen) are visible originating from the vicinity of the LH2 umbilical. See Figure 2.5.2 (B). These events occurred when the ET was an estimated distance of two to three kilometers from the Orbiter.

FRAME	GMT TIME (Hr:Min:Sec)	MET (Min:Sec)
STS-95-394-014	19:40:32	20:58
STS-95-394-015	19:40:33	20:59
STS-95-394-016	19:40:33	20:59
STS-95-394-017	19:40:34	21:00

Table 2.5.2 (A) ET Venting Times from Handheld Film Camera

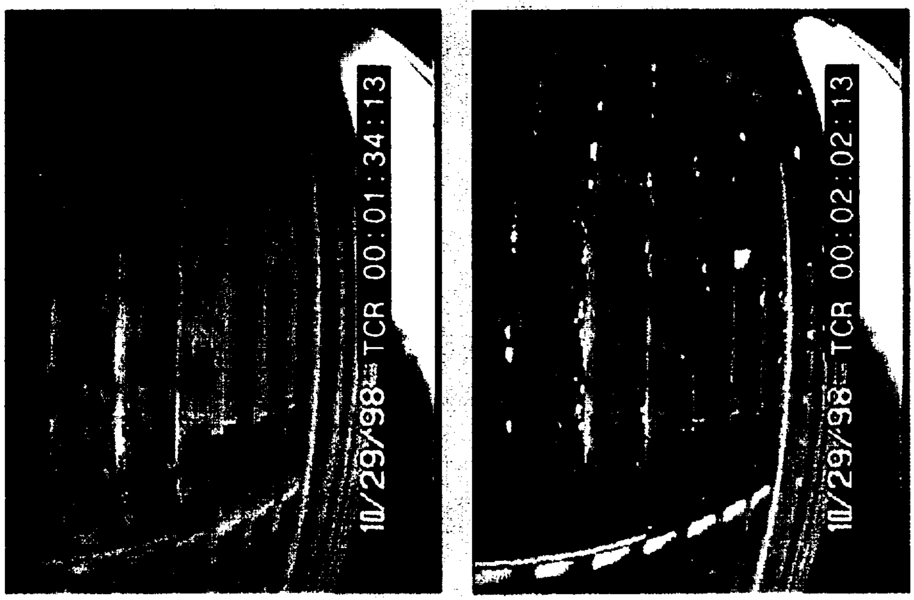
The ET rate of tumble, i.e., the end-to-end rotation of the ET about its center of mass and the rate of roll about the ET X axis was very slow (less than one degree/sec) prior to the ET venting (seen at approximately 21 minutes MET). Table 2.5.2(B) contains a comparison of the averaged tumble rate measurements for the previous four Space Shuttle missions. Venting was seen on all five missions.

MISSION	TUMBLE RATE (Degrees/Second)	MET (Min:Sec)
STS-87	11	17:23 - 18:08
STS-89	12	31:42 - 35:27
STS-90	3	14:30*
STS-91	11	16:29 - 18:46
STS-95	<1	13:40 - 20:50

* Only the first four frames had timing. Relative time from video was used to determine the STS-90 tumble rate.

Table 2.5.2 (B) ET Tumble Rates

2.6 SRB CAMERA VIEW OF ET THRUST PANEL



BEFORE
Prior to 94 sec MET

AFTER
~ 122 sec MET

Figure 2.6 (A) ET Thrust Panel Video - Before and After Ablation

Excellent quality video of the ET thrust panel was acquired from the left SRB camera. Multiple small divots, most less than one inch in size, were seen to form on the STS-95 -Y ET Thrust Panel video between 92 and 120 seconds MET. See the "before and after" views shown on Figure 2.6 (A). The majority of the divots occurred on the top surface of the rib heads. The divots were shallow and no exposed substrate was detected. Also, a darkening of the TPS along with a more coarse appearing texture of the TPS caused by the ablation of the TPS surface material is apparent on the "after" view. For scale reference, the visible star (*) patterns painted on the thrust panel rib heads are one inch in size and are spaced at 5.5 inch intervals along the rib heads in the X axis direction.

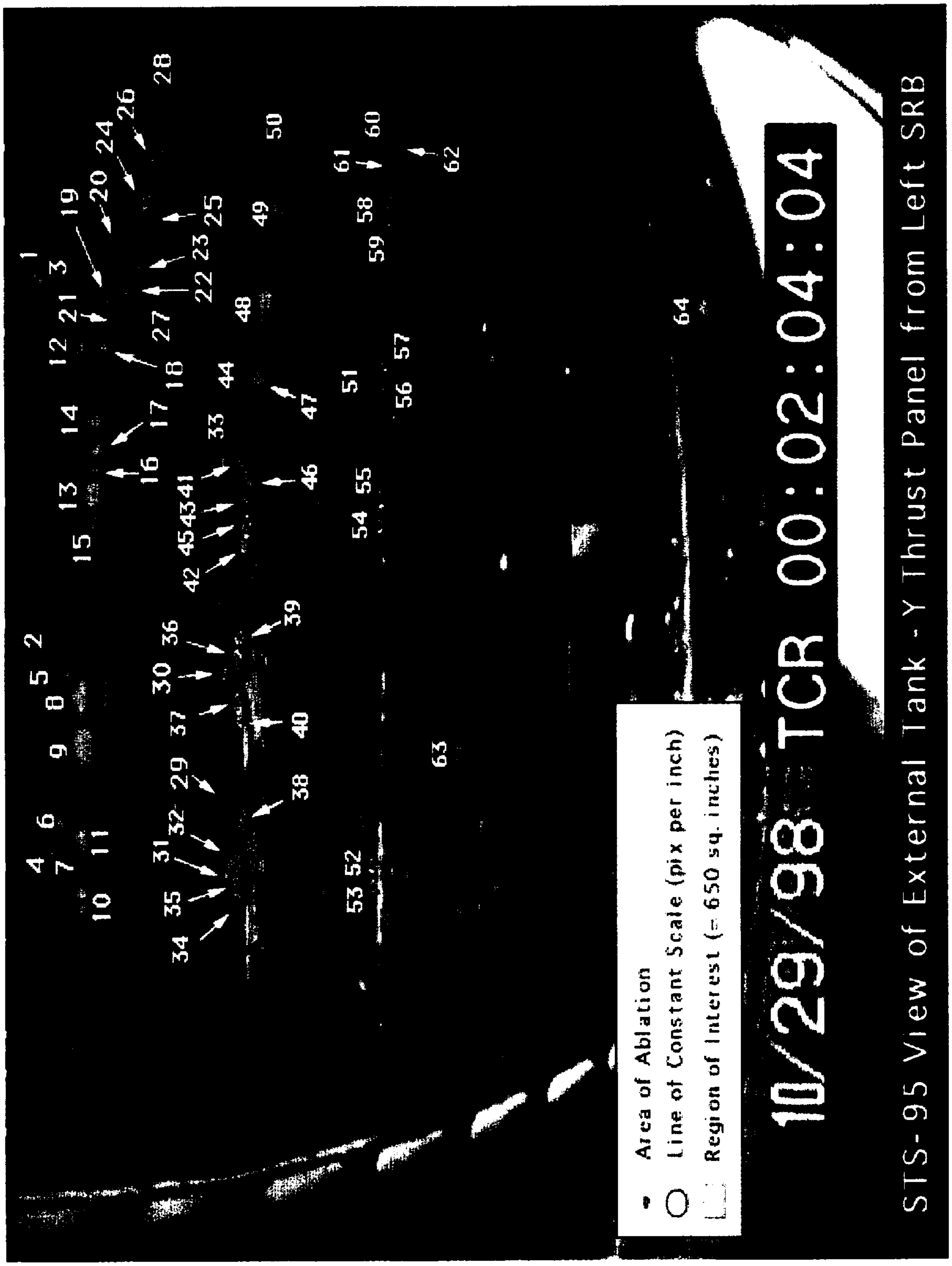


Figure 2.6 (B) -Y Thrust Panel Measurement Area

Sixty-four areas of ablation larger than 0.1 inches in diameter were identified on the surface of the External Tank -Y Thrust Panel video view. This ablation began 30 seconds prior to SRB separation. Using a variable image scale derived from a pattern of one-inch wide star-shaped markings placed on the panel prior to launch, a maximum diameter and a mean diameter was measured for each ablation area within a predefined region of interest covering 650 +/-50 square inches.

Each ablation area is expected to have created a similarly sized particle, with a few exceptions. Five ablation areas were observed to have been created in successive incremental steps, rather than at once, and the smaller sizes of the resulting particles have been noted.

The resultant particle sizes were determined in two ways, one using the maximum diameter of the ellipse best fit to each ablation area, and another using twice the mean radius measured from the center of each area.

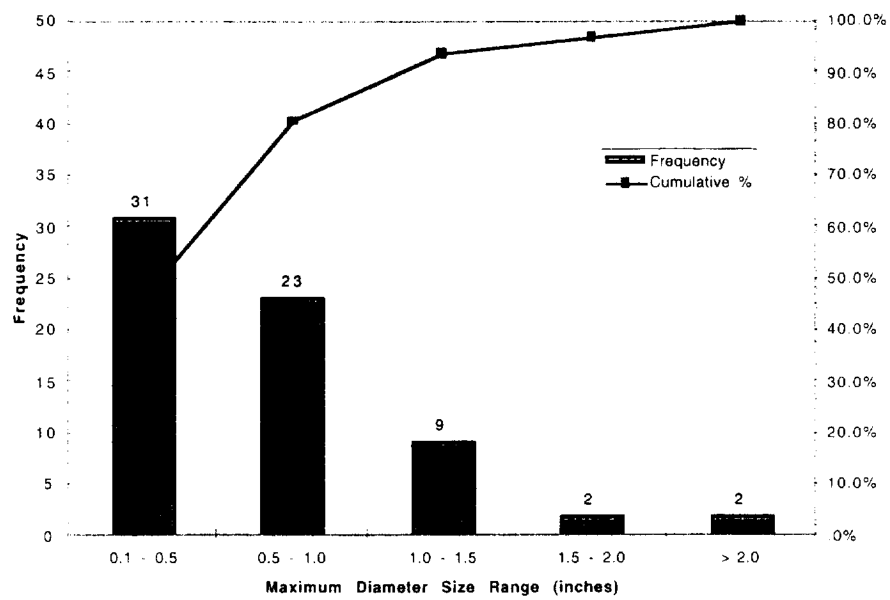


Figure 2.6 (C) Size Distribution for Maximum Diameter of Particles Originating from STS-95 External Tank -Y Thrust Panel Ablation.

The histogram shown in Figure 2.6(C) gives the frequency of particles having maximum diameters that fall within the specified ranges. Three ablation features (IDs 1, 3, 64) were outside the predefined region of interest and were not included in the histogram. A complete list of the maximum and mean diameter measurements for each particle is provided in Table 2.6.

By taking the maximum diameter, 13 particles would have been larger than one inch, and two of these would have been larger than 2 inches. One of the three ablation areas outside the region of interest (ID 64) was estimated to be larger than 1.7 inches, and may have been larger than 2.0 inches, but an accurate image scale could not be determined for this area.

It should be noted that the count for particles smaller than 0.5 inches is not a complete count for features within this size range. Also, the selected area of interest includes surface areas that are hidden from view. These areas constitute the sides of the rib-like stringers oriented horizontally in the image. While these areas may have contributed to the total amount of debris, they did not contribute to this analysis and were not considered in the calculation of the area of interest.

Table 2.6 Measurements of Ablation Areas Identified in Figure 2.6 (B)

Ablation Area ID	Number of Pixels	Major Axis of Area (pixels)	Mean Radius of Area (pixels)	Percent of Whole (if piece-wise)	Local Image Scale (inches/pix)	Maximum Diameter of Resultant Debris (inches)	Mean Diameter of Resultant Debris (inches)
1	37	7.6	3.0		0.111	0.85	0.66
2	14	4.6	1.7		0.059	0.27	0.20
3	16	4.8	1.8		0.111	0.53	0.41
4	12	4.9	1.5		0.059	0.29	0.18
5	14	5.0	1.7		0.056	0.28	0.19
6	18	5.6	2.0		0.056	0.31	0.22
7	13	5.2	1.7		0.056	0.29	0.18
8	111	18.5	5.9		0.056	--	--
8a	--	--	--	40%	0.056	0.41	0.26
8b	--	--	--	20%	0.056	0.21	0.13
8c	--	--	--	40%	0.056	0.41	0.26
9	158	19.6	6.8		0.056	1.09	0.75
10	81	15.1	4.7		0.059	--	--
10a	--	--	--	30%	0.059	0.27	0.17
10b	--	--	--	70%	0.059	0.62	0.39
11	60	12.0	4.0		0.056	0.67	0.44
12	19	6.6	2.2		0.091	0.60	0.39
13	72	12.9	4.4		0.067	0.86	0.58
14	32	8.0	2.9		0.083	0.67	0.49
15	22	6.7	2.3		0.067	0.45	0.30
16	24	6.5	2.4		0.071	0.47	0.34
17	17	5.1	1.9		0.077	0.39	0.30
18	10	4.0	1.4		0.091	0.36	0.25
19	9	3.7	1.3		0.100	0.37	0.26
20	12	4.0	1.6		0.111	0.44	0.35
21	12	4.8	1.5		0.091	0.43	0.28
22	31	8.5	2.7		0.100	0.85	0.54
23	24	8.3	2.4		0.111	0.93	0.54
24	66	13.0	4.3		0.125	1.62	1.06
25	14	4.4	1.7		0.111	0.49	0.37
26	104	15.1	5.4		0.143	--	--
26a	--	--	--	60%	0.143	1.29	0.92
26b	--	--	--	40%	0.143	0.86	0.62
27	11	4.3	1.5		0.091	0.39	0.26
28	33	7.3	2.8		0.167	1.22	0.94
29	15	4.9	1.8		0.059	0.29	0.21
30	22	6.1	2.3		0.059	0.36	0.27
31	4	2.1	0.7		0.063	0.13	0.09
32	49	10.2	3.5		0.063	0.64	0.44
33	8	4.6	1.2		0.083	0.38	0.20
34	34	8.8	2.9		0.067	0.59	0.38
35	6	3.2	1.1		0.063	0.20	0.13
36	33	8.2	2.8		0.059	0.48	0.33
37	28	8.8	2.6		0.059	0.52	0.31
38	34	10.3	3.0		0.059	0.60	0.35
39	13	4.9	1.6		0.063	0.31	0.20
40	10	5.8	1.4		0.059	0.34	0.17
41	21	6.3	2.1		0.077	0.48	0.33
42	22	6.9	2.2		0.067	--	--
42a	--	--	--	20%	0.067	0.09	0.06
42b	--	--	--	80%	0.067	0.37	0.24
43	32	7.8	2.8		0.071	0.55	0.40
44	6	3.4	0.9		0.083	0.28	0.16
45	25	10.0	2.7		0.071	0.71	0.38
46	45	11.1	3.5		0.071	0.79	0.51
47	54	11.4	3.8		0.083	0.95	0.63
48	155	23.1	7.1		0.100	--	--
48a	155	23.1	7.1	50%	0.100	1.15	0.71
48b	155	23.1	7.1	50%	0.100	1.15	0.71
49	79	13.4	4.6		0.125	1.68	1.16
50	24	6.0	2.4		0.167	1.01	0.79
51	23	6.2	2.3		0.091	0.56	0.41
52	22	6.8	2.3		0.077	0.52	0.35
53	25	7.9	2.4		0.083	0.66	0.41
54	37	13.5	3.5		0.083	1.12	0.58
55	6	3.2	1.1		0.083	0.27	0.18
56	28	9.2	2.8		0.100	0.92	0.55
57	15	6.0	1.8		0.111	0.67	0.40
58	81	14.6	4.7		0.167	2.43	1.58
59	24	7.3	2.4		0.143	1.04	0.67
60	68	12.0	4.2		0.200	2.40	1.69
61	21	6.2	2.1		0.167	1.04	0.71
62	6	3.4	0.9		0.200	0.68	0.38
63	16	6.3	1.9		0.083	0.53	0.32
64	--	--	--		--	--	>1.70*

* An accurate scale measurement could not be made. The size constraint is based on a visual comparison with ID #60.

After ET separation, no divots were observed on the views showing the ET thrust panel aft of the EB fitting, the ET intertank region extending to the access door, the LH2 tank -Z TPS, or the ET aft dome.

2.7 ON-ORBIT SUPPORT

Figure 2.7 Dislodged OMS Blanket

Video images of a dislodged port OMS pod blanket were down linked by the crew. Image enhancements of this dislodged blanket were provided to the MER Manager prior to landing.

2.8 LANDING EVENTS

2.8.1 Landing Sink Rate Analysis

Image data from video camera SLF South was used to determine the landing sink rate of the main gear. In the analysis, data from approximately one second of imagery immediately prior to touchdown was considered. Data points defining the main gear struts were collected on every frame (30 frames of the data during the last second prior to touch down). An assumption was made that the line of sight of the camera was perpendicular to the Orbiter's y-axis. The distance between the main gear struts was used as a scaling factor. The main gear height above the runway was calculated by the vertical difference between the main gear struts and the reference point. These heights were then regressed with respect to time and the trendline was determined. Sink rate equals the slope of this regression line.

The left main gear sink rate for STS-95 landing at one second, at half a second, and at a one quarter of a second are provided in Table 2.8.1. A plot describing these sink rate is provided in Figure 2.8.1.

Time Prior to Touchdown	1.00 Sec.	0.50 Sec.	0.25 Sec.
Left Main Gear Sink Rate	1.7 ft/sec	1.7 ft/sec	1.9 ft/sec
Estimated Error (1σ)	± 0.2 ft/sec	± 0.2 ft/sec	± 0.1 ft/sec

Left Main Gear Touchdown = 311:17:03:29.900 (UTC)

Table 2.8.1 Main Gear Landing Sink Rate

The maximum allowable main gear sink rate values are 9.6 ft/sec for a 212,000 lb vehicle and 6.0 ft/sec for a 240,000 lb vehicle. The landing weight of the STS-95 vehicle was estimated to be 228,639 lbs.

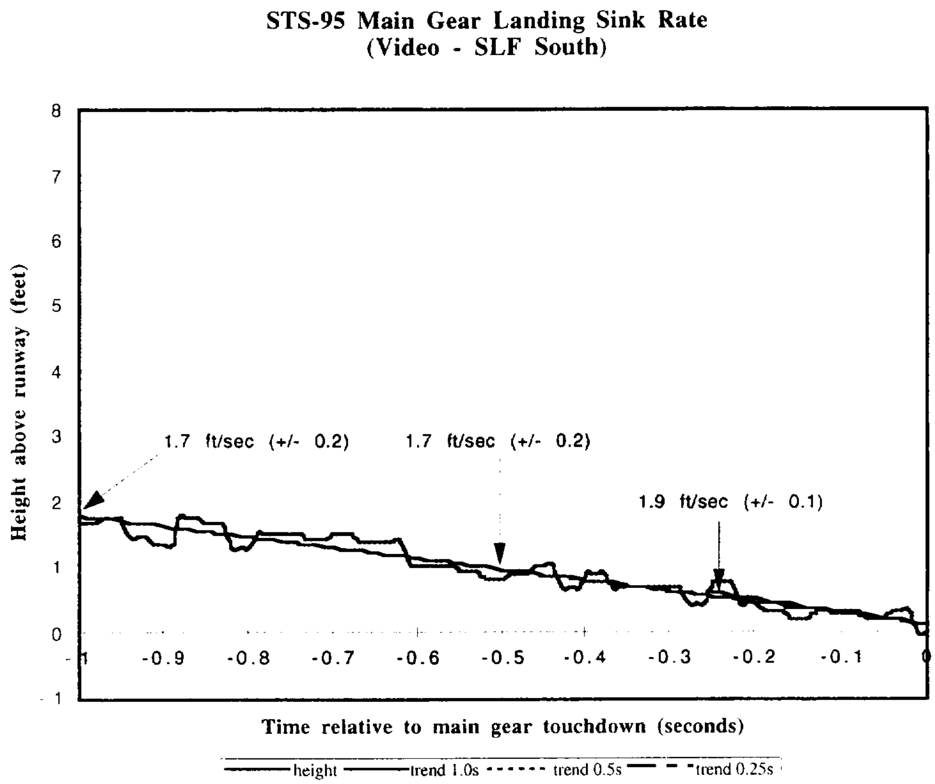


Figure 2.8.1 Main Gear Landing Sink Rate

2.9 OTHER

2.9.1 Normal Events

Normal events observed included elevon and body flap motion prior to liftoff, RCS paper debris from SSME ignition through liftoff, ET twang, ice and vapor from the LO2 and LH2 TSM T-0 umbilicals prior to and after disconnect, multiple pieces of ET/Orbiter umbilical ice debris falling along the body flap during liftoff, acoustic waves in the exhaust cloud during liftoff, debris in the exhaust cloud after liftoff, expansion waves after liftoff, vapor off the SRB stiffener rings, charring of the ET aft dome, ET aft dome outgassing, condensation around the launch vehicle during ascent, linear optical effects, recirculation, SRB plume brightening, and slag debris during and after SRB separation.

2.9.2 Normal Pad Events

Normal pad events observed included the Hydrogen burn ignitor operation, the FSS deluge water activation, the MLP deluge water activation, GH2 vent arm retraction, TSM T-0 umbilical operations, and TSM door closure.

APPENDIX B. MSFC PHOTOGRAPHIC ANALYSIS SUMMARY

STS-95 Engineering Photographic Analysis Report

Table of Contents

Introduction

The launch of space shuttle mission STS-95, the twenty-fifth flight of the Orbiter Discovery occurred on October 29, 1998, at approximately 1:19 P.M. Central Daylight Time from launch complex 39B (LC-39B), Kennedy Space Center (KSC), Florida. Launch time to be reported as 98:302:19:19:33.984 Universal Coordinated Time (UTC) by the MSFC Flight Evaluation Team. Photographic and video coverage has been evaluated to determine proper operation of the flight hardware. Video and high-speed film cameras providing this coverage are located on the fixed service structure (FSS), mobile launch platform (MLP), LC-39B perimeter sites, Eastern Test Range tracking sites and onboard the vehicle.

Engineering Analysis Objectives

The planned engineering photographic and video analysis objectives for STS-95 include, but are not limited to the following:

- Verification of cameras, lighting and timing systems.
- Overall propulsion system coverage for anomaly detection and structural integrity.
- Determination of SRB PIC firing time and SRB separation time.
- Verification of SRB and ET Thermal Protection System (TPS) integrity.
- Correct operation of the following:
  - SSME ignition and mainstage
  - SRB debris containment system
  - LH2 and LO2 17-inch disconnects

- Ground umbilical carrier plate
- Free hydrogen ignitors
- Booster separation motors

Camera Coverage Assessment

The following table illustrates the camera coverage received at MSFC for STS-95.

	16mm	35mm	Video
MLP	16	0	4
FSS	5	0	3
Perimeter	0	7	5
Tracking	0	10	11
Onboard	2	2	2
Totals	23	19	25

Total number of film and videos received to date: 67

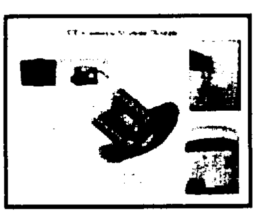
An individual motion picture camera assessment is provided as Appendix A. Appendix B contains detailed assessments of the video products received at MSFC.

Ground Camera Coverage

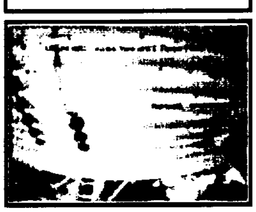
Ground based photographic coverage of the STS-95 was considered excellent. The clear sky and the afternoon sun provided excellent conditions for the long range tracking cameras. However, some cameras experienced problems. Camera E9 experienced film fog which rendered the data unusable. Camera E223 never acquired the vehicle. IRIG timing was not recorded on camera E205.

Onboard Camera Coverage

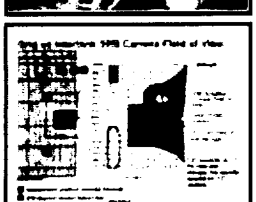
The 8mm video camera which was placed in the forward skirt of the left SRB to view the ET Thrust Panel provided excellent data on the condition of the Thrust Panel TPS during launch. This camera also provided an good view of SRB separation.



A standard speed 8mm video camera was flown on the Forward Segment of the Left SRB to view the condition of the TPS on the ET Thrust Panel during ascent of the vehicle. The camera was recovered with the SRB after the launch.



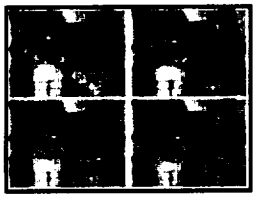
The video camera is supplied with a wide angle lens to view as much of the ET thrust panel as possible. The wide angle lens and the close proximity of the ET results in image distortion of the Thrust Panel.



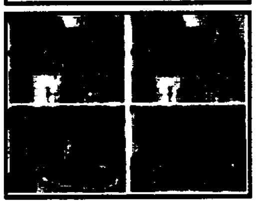
A grid of one inch black squares and "*" symbols have been placed on the Thrust Panel to aid Engineering Photo Analysis in determining size and location of TPS divots. The resulting camera field of view and grid are illustrated in this chart.

Also onboard were two 16mm film cameras located in the Orbiter's LH2 umbilical well. These cameras recorded SRB and ET separation and provided excellent results . A 35mm still camera was in a the LO2 umbilical well recording images of the ET after separation. This camera also provided excellent results

Anomalies



The Drag chute door detached from the Orbiter during SSME ignition, striking SSME #1 nozzle near the Aft Manifold. No damage to the engine was visible.



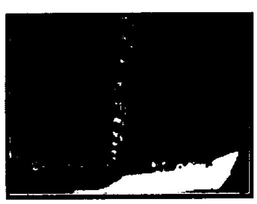
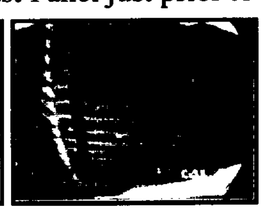
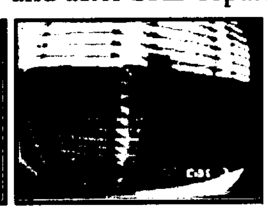
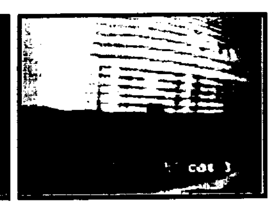
This sequence shows a close-up of the door striking the engine nozzle.

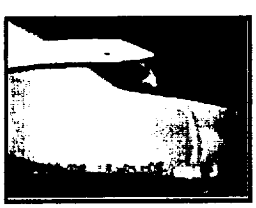
Observations

ET Thrust Panel

This is an image of the ET Thrust Panel early during powered flight.

The following images view the ET Thrust Panel just prior to and after SRB separation:



This image shows the right SRB after separation.

An engine streak from long-range video camera ET-207. This event was timed from film camera E-207 at 302:19:20:04.372 UTC.


A comparison of the startup motion of SSME #1 on STS-95, STS-91, and STS-89 (1.2 MB MPEG video).

T-Zero Times

T-Zero times are determined from cameras that view the SRB holddown posts numbers M-1, M-2, M-5, and M-6. These cameras record the explosive bolt combustion products.

Holddown Post	Camera Position	Time (UTC)
M-1	E9	Fogged film
M-2	E8	19:19:33.992
M-5	E12	19:19:33.993
M-6	E13	19:19:33.993

SRB Separation Time

SRB separation as recorded by observations of the BSM combustion products from the long-range film camera E-207 occurred at 302:19:21:36.38 UTC.

Appendix A - Individual film camera assessments

Appendix B - Individual video camera assessments

Appendix C - Definitions and acronyms

Individual film/video summary report

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