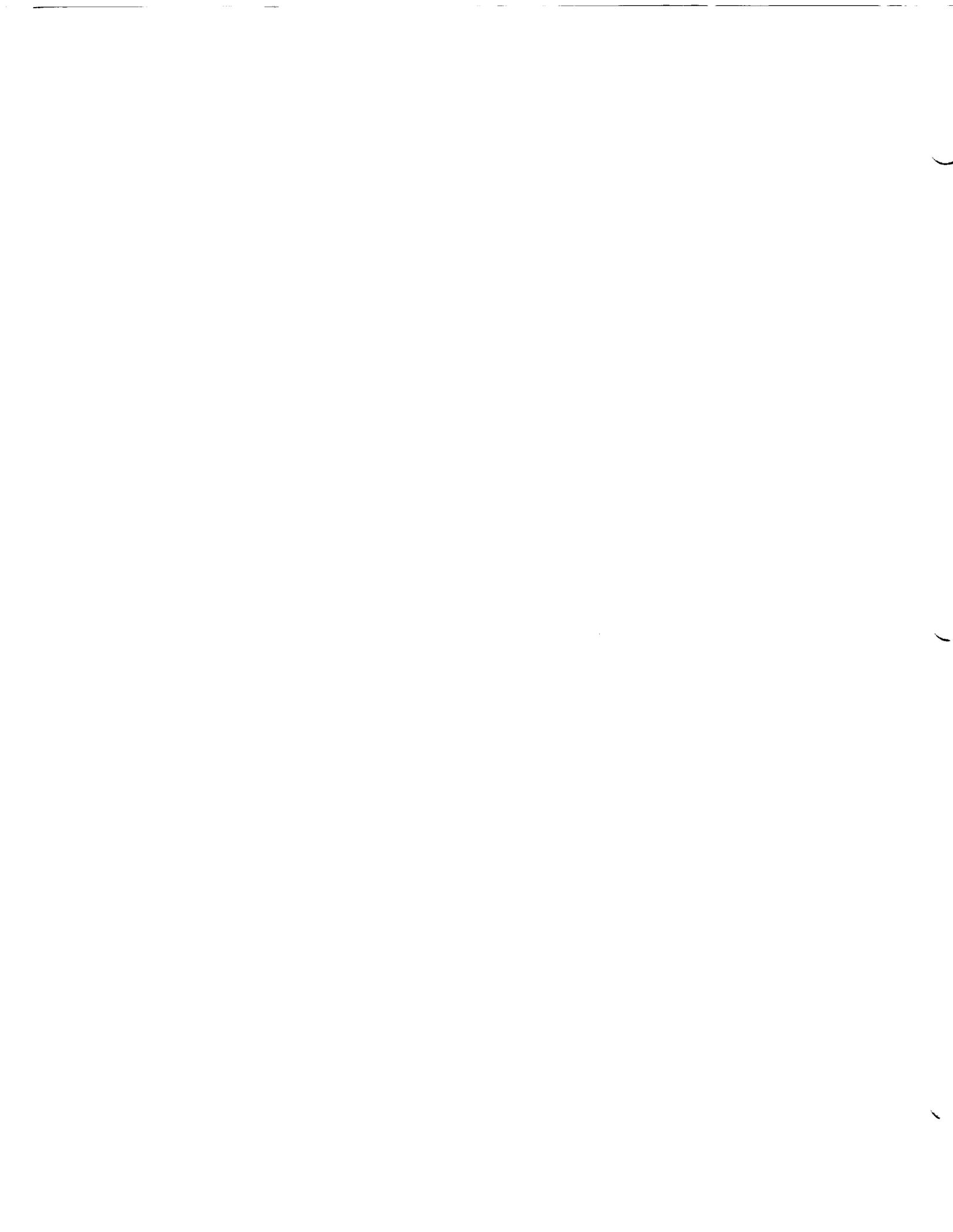




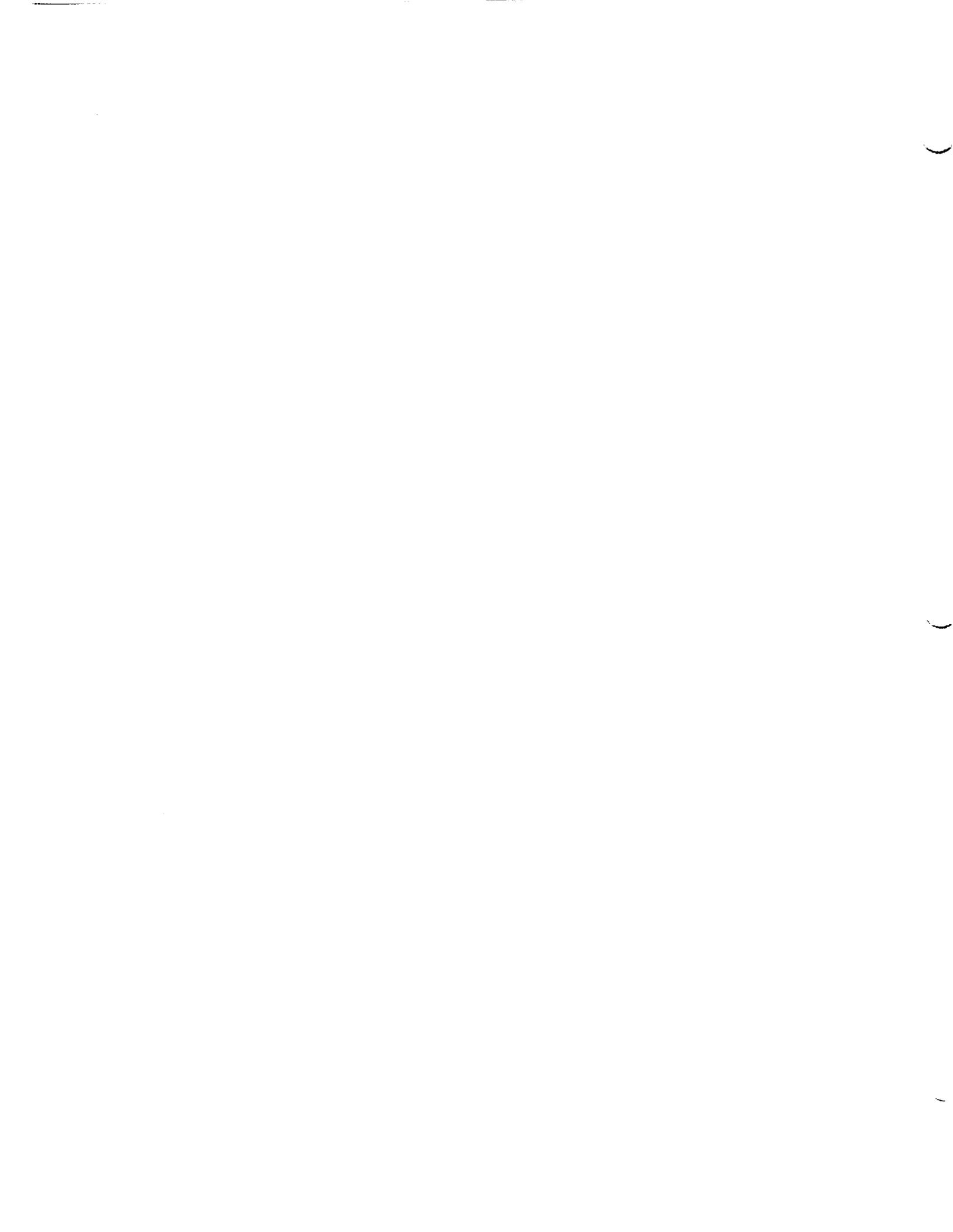
Debris/Ice/TPS Assessment and Integrated Photographic Analysis of Shuttle Mission STS-93

Gregory N. Katnik



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Kennedy Space Center, Florida*



**DEBRIS/ICE/TPS ASSESSMENT
AND
INTEGRATED PHOTOGRAPHIC ANALYSIS
OF
SHUTTLE MISSION STS-93**

23 July 1999

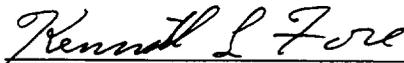
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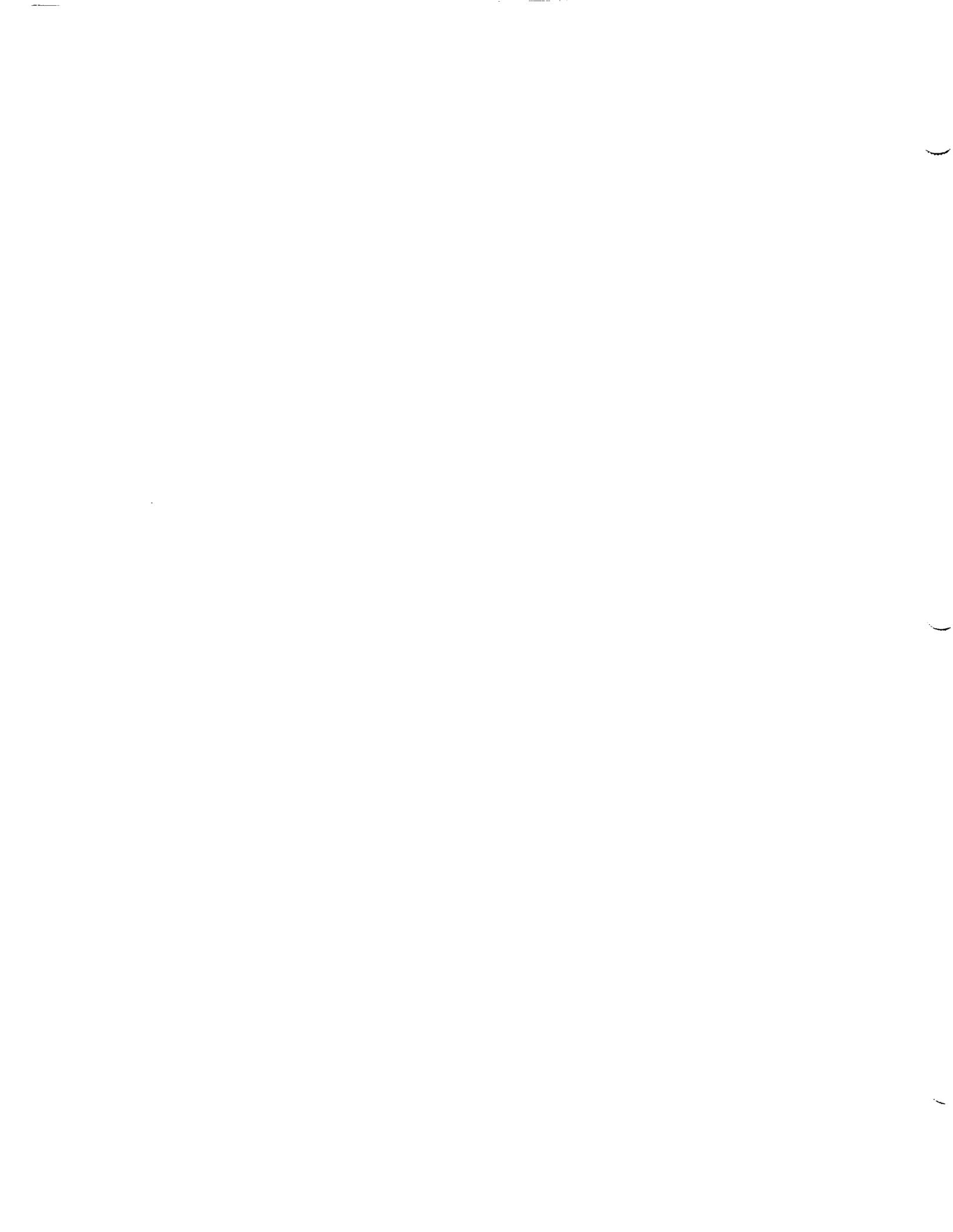


TABLE OF CONTENTS

TABLE OF CONTENTS	i
TABLE OF FIGURES	ii
TABLE OF PHOTOS	iii
FOREWORD	iv
1.0 SUMMARY OF SIGNIFICANT EVENTS	2
2.0 PRE-LAUNCH	3
2.1 PRE-LAUNCH SSV/PAD DEBRIS INSPECTION.....	3
3.0 SCRUBS	4
3.1 FINAL INSPECTION - SENSOR SCRUB	4
3.2 POST DRAIN INSPECTION	4
3.3 FINAL INSPECTION - WEATHER SCRUB	6
3.4 POST DRAIN INSPECTION	6
4.0 LAUNCH	8
4.2 FINAL INSPECTION	8
4.2.1 ORBITER.....	8
4.2.2 SOLID ROCKET BOOSTERS	8
4.2.3 EXTERNAL TANK.....	8
4.2.4 FACILITY	9
4.3 T-3 HOURS TO LAUNCH.....	9
5.0 POST LAUNCH PAD DEBRIS INSPECTION	16
6.0 FILM REVIEW	17
6.1.1 LAUNCH FILM AND VIDEO SUMMARY	17
6.1.2 SRB CAMERA VIDEO SUMMARY	26
6.2 ON-ORBIT FILM AND VIDEO SUMMARY	31
6.2.1 ET/ORB UMBILICAL FILMS	31
6.2.2 CREW HAND HELD STILL IMAGES/VIDEO.....	31
6.3 LANDING FILM AND VIDEO SUMMARY	33
7.0 SRB POST FLIGHT/RETRIEVAL DEBRIS ASSESSMENT	34
8.0 ORBITER POST LANDING DEBRIS ASSESSMENT	35
APPENDIX A. JSC PHOTOGRAPHIC ANALYSIS SUMMARY	A
APPENDIX B. MSFC PHOTOGRAPHIC ANALYSIS SUMMARY	B

TABLE OF FIGURES

Figure 1: Orbiter Lower Surface Debris Damage Map.....	37
Figure 2: Orbiter Left Side Debris Damage Map.....	38
Figure 3: Orbiter Right Side Debris Damage Map	39
Figure 4: Orbiter Upper Surface Debris Damage Map	40
Figure 5: Orbiter Post Flight Debris Damage Summary.....	41
Figure 6: Control Limits for Lower Surface Hits.....	42
Figure 7: Control Limits for Total Hits.....	43

TABLE OF PHOTOS

Photo 1: Launch of Shuttle Mission STS-93.....	1
Photo 2: Crack in Stringer Valley TPS	5
Photo 3: Thermal Short on Siphon Screen Cap.....	7
Photo 4: ET LO2 Tank and Intertank	10
Photo 5: LO2 Feedline Bellows	11
Photo 6: Crack in +Y Longeron TPS	12
Photo 7: LH2 Feedline and Recirculation Line.....	13
Photo 8: LH2 ET/ORB Umbilical.....	14
Photo 9: Overall View of SSME's	15
Photo 10: SSME #3 Hot-Wall Leak.....	19
Photo 11: SSME #3 Hot-Wall Leak at Liftoff	20
Photo 12: SSME #3 Hot-Wall Leak in Early Flight.....	21
Photo 13: SSME #3 Hot-Wall Leak	22
Photo 14: SSME #3 Hot-Wall Leak	23
Photo 15: Streaks in SSME Exhaust Plume	24
Photo 16: Debris Object Near OMS Pod	25
Photo 17: -Y Thrust Panel TPS	28
Photo 18: +Y Thrust Panel TPS	29
Photo 19: ET LH2 Tank -Z Flange Closeout.....	30
Photo 20: External Tank after Separation from Orbiter	32
Photo 21: Overall View of Orbiter Sides	44
Photo 22: Lower Surface Tile Damage	45
Photo 23: Lower Surface Tile Damage	46
Photo 24: Location of SSME #3 Hydrogen Leak.....	47
Photo 25: Cooling Tube Ruptures	48
Photo 26: LO2 Post Deactivating Pin	49
Photo 27: LO2 ET/ORB Umbilical	50
Photo 28: LH2 ET/ORB Umbilical.....	51
Photo 29: Windows	52

FOREWORD

The Debris Team has developed and implemented measures to control damage from debris in the Shuttle operational environment and to make the control measures a part of routine launch flows. These measures include engineering surveillance during vehicle processing and closeout operations, facility and flight hardware inspections before and after launch, and photographic analysis of mission events.

Photographic analyses of mission imagery from launch, on-orbit, and landing provide significant data in verifying proper operation of systems and evaluating anomalies. In addition to the Kennedy Space Center Photo/Video Analysis, reports from Johnson Space Center and Marshall Space Flight Center are also included in this document to provide an integrated assessment of the mission.

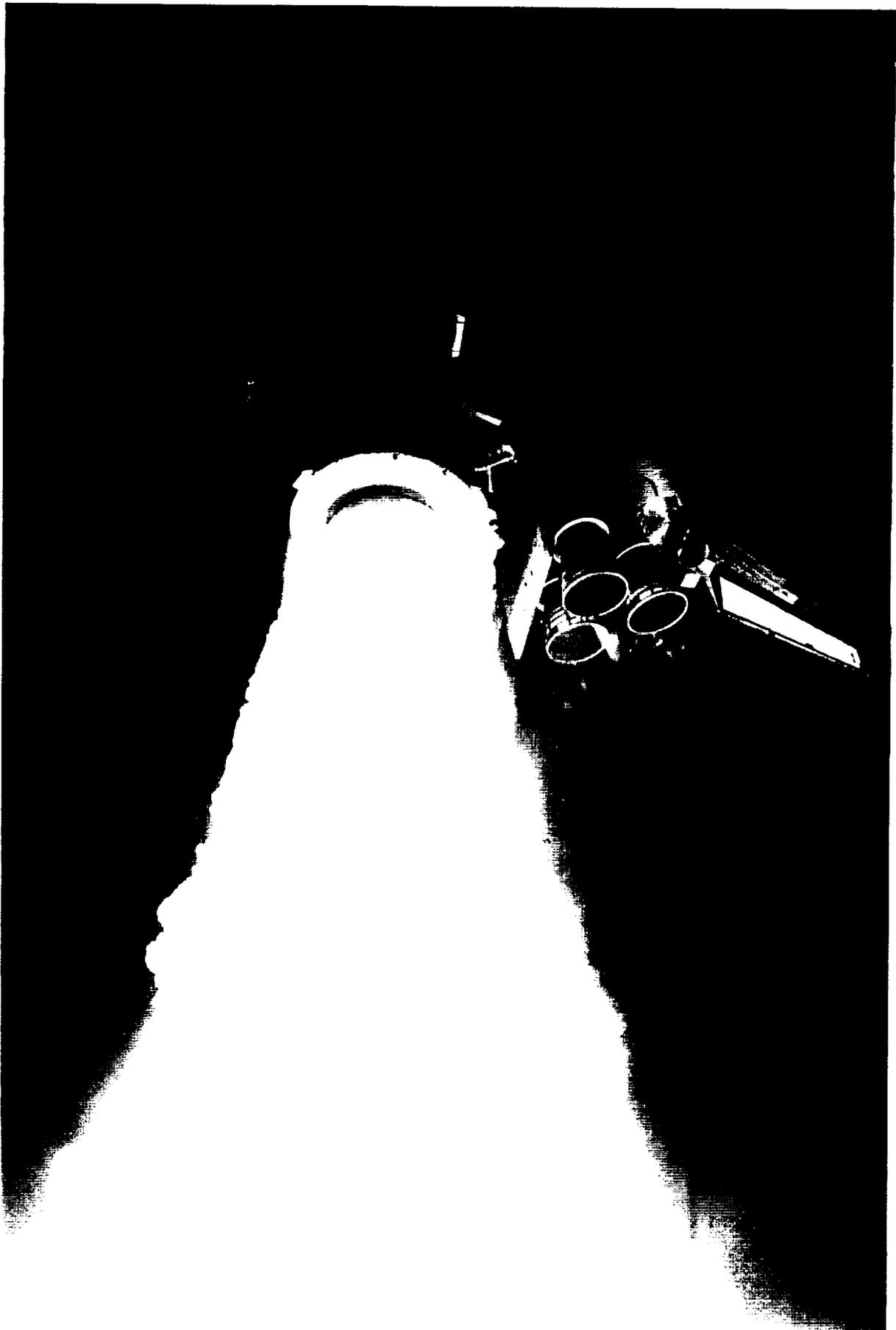
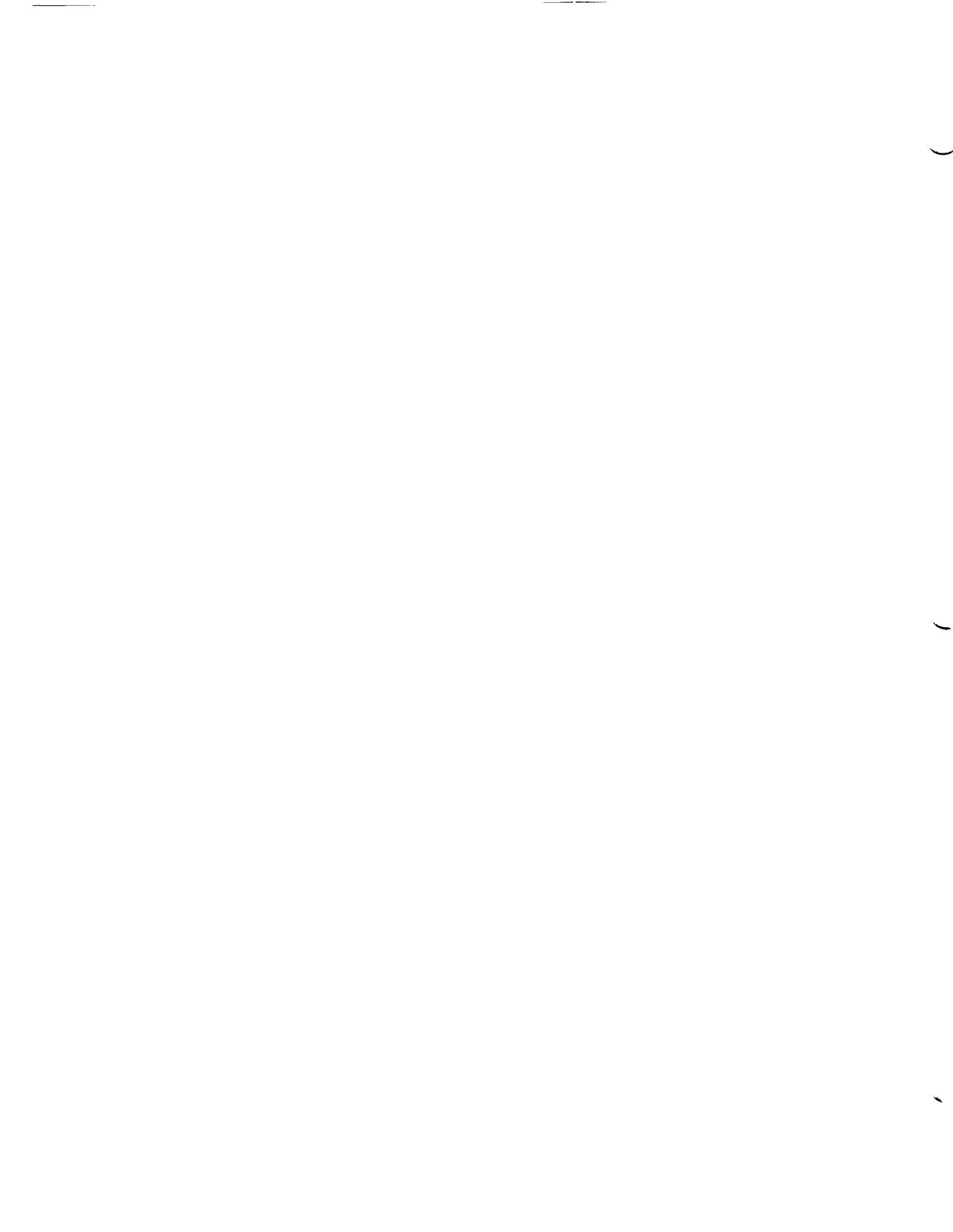


Photo 1: Launch of Shuttle Mission STS-93



1.0 SUMMARY OF SIGNIFICANT EVENTS

STS-93 consisted of OV-102 (26th flight), ET-99 and BI-097 SRB's on MLP-1 and Pad 39B. Columbia was launched at 204:04:30:59.984 UTC (12:31 a.m. local) on 23 July 1999. Landing was at 11:20 p.m. local/eastern time on 27 July 1999.

SSME #3 Nozzle Hot-Wall Leak

SSME ignition startup sequence was normal. However, a hot-wall propellant leak occurred in the SSME #3 nozzle -Y location at 04:30:58.515 UTC. This caused numerous flashes in the exhaust plume and a distortion of the Mach diamond. Flashes/streaks in the SSME plume occurred at 04:30:58.030, 04:30:58.153, and 04:30:58.515 UTC. During the Orbiter post landing inspection, the area inside the SSME #3 nozzle where the hot-wall leak had occurred prior to liftoff was readily visible by a rupture and surrounding discoloration in each of three adjacent cooling tubes. A LOX post deactivating pin was found to be missing in post flight SSME inspections and believed to be the debris object that impacted the tubes causing the rupture.

ET Thrust Panels

An 8mm video camera was flown in each SRB forward skirt for the purpose of documenting any TPS loss from the ET-99 thrust panels from launch through SRB separation. This flight incorporated thousands of pin-size vent holes with 0.3-inch spacing and 0.032-inch diameter holes to substrate in the intertank thrust panel machined foam.

In terms of general observations, there were significantly less divots in the vented areas compared to the non-vented areas. Divots in the vented areas were generally smaller than divots in the non-vented areas. Divots in both vented and non-vented areas were shallow with no primed substrate visible. Most divots occurred near the rib side walls and top edges. Valley divots were smaller in size than divots in the rib side walls/top edges. Divots were greater in number and larger in size in the high heating areas. A significant number of divots occurred outside the thrust panel in the stringer sections.

Post landing inspection revealed the Orbiter lower surface sustained 161 total hits, of which 42 had a major dimension of 1-inch or larger. Most of this damage was concentrated from the nose gear to the main landing gear wheel wells on both left and right chines. The outboard damage sites on the chines followed a similar location damage pattern documented on flights starting with STS-86.

With data from these flights showing out-of-family damage to Orbiter tiles, control limit analyses show a marked change starting with STS-86. Data from STS-72 through STS-85 consistently illustrate a relatively low average and reasonable upper control limit. These data represent an environment where the significant debris issues affecting the vehicle had been identified and corrected. However, a few earlier missions were also included to show the downward trend in debris damage representing corrective action still in progress. With the loss of TPS from the External Tank beginning on STS-86, the analysis clearly documents the increase in Orbiter tile damage as an out-of-family condition. Both the average and the upper control limit are significantly higher, and outside the 3-sigma value, for these flights.

The External Tank Project continues to work IFA STS-87-T-01 to prevent loss of foam from the External Tank and preclude further damage to Orbiter tiles.

2.0 PRE-LAUNCH

The Debris/Ice/TPS and Photographic Analysis Team briefing for launch activities was conducted on 18 July 1999. 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
W. Boyter	NASA - KSC	SRB Mechanical Systems
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
T. Ford	USA - SPC	ET Mechanical Systems
J. Stone	BNA - DNY	Shuttle Aerodynamics
R. Oyer	BNA - LSS	Systems Integration
C. Hill	BNA - LSS	Systems Integration
D. Leggett	BNA - LSS	Systems Integration
J. Stone	BNA - DNY	Shuttle Aerodynamics
J. Cook	THIO - LSS	SRM Processing
S. Otto	LMMSS	ET Processing
J. Ramirez	LMMSS	ET Processing

2.1 PRE-LAUNCH SSV/PAD DEBRIS INSPECTION

A pre-launch debris inspection of the launch pad and Shuttle vehicle was performed on 18 July 1999. The detailed walkdown of Pad 39B and MLP-1 included the primary flight elements OV-102 Columbia (26th flight), ET-99, and BI-097 SRB's.

A continuing problem with loose layered-paint chips and pieces of deck scale were highlighted on this flow as a significant debris issue. Consequently, MLP-1 was extensively reworked at the pad to remove this material from the deck surface and fixtures, such as the sound suppression water pipes. The completed work was inspected and approved by the Debris Team.

The pre-launch walkdown of the pad and SSV yielded two issues. Numerous rust particles, possibly as large as a square inch, were detected on the top of the LO2 TSM. A line item was entered in S0007, Appendix K accordingly.

An IPR was taken on abrasions and scratches probably caused by birds near the GOX vent seal areas. The condition was accepted for flight "as is" with MRB approval.

Although ET-99 intertank thrust panel foam was "pin hole" vented in +X+Z areas (in relation to the EB fittings), CR S071219M gave approval to vent the remaining unvented foam on the +Y thrust panel from XT-993.8 to XT-1035.5. Foam debris from within these zones was predicted to impact Orbiter lower surface tiles during flight.

3.0 SCRUBS

3.1 FINAL INSPECTION – SENSOR SCRUB

A Final Inspection of the cryoloaded vehicle was performed on 19 July 1999 from 1855 to 2040 hours during the two hour built-in-hold at T-3 hours in the countdown. There were no Launch Commit Criteria (LCC), OMRS, or NSTS-08303 criteria violations. No Ice, Debris, or TPS IPR's were taken. There were no acreage icing concerns. There were also no protuberance icing conditions outside of the established database. Two cracks were detected in ET intertank stringer valley TPS: one 16-18 inches long in the -Y+Z quadrant, and one 10-11 inches long in the -Y-Z quadrant. Neither crack exhibited ice, frost, nor offset. Therefore, the cracks were acceptable for flight per the NSTS-08303 criteria. No anomalies were detected on the facility, SRB's, and Orbiter. Although all RCS thruster paper covers were intact, F4R was tinted a light green.

Launch was scrubbed at T-8 seconds on 19 July 1999 due to an erroneous hydrogen leak detection sensor reading in the Orbiter aft compartment.

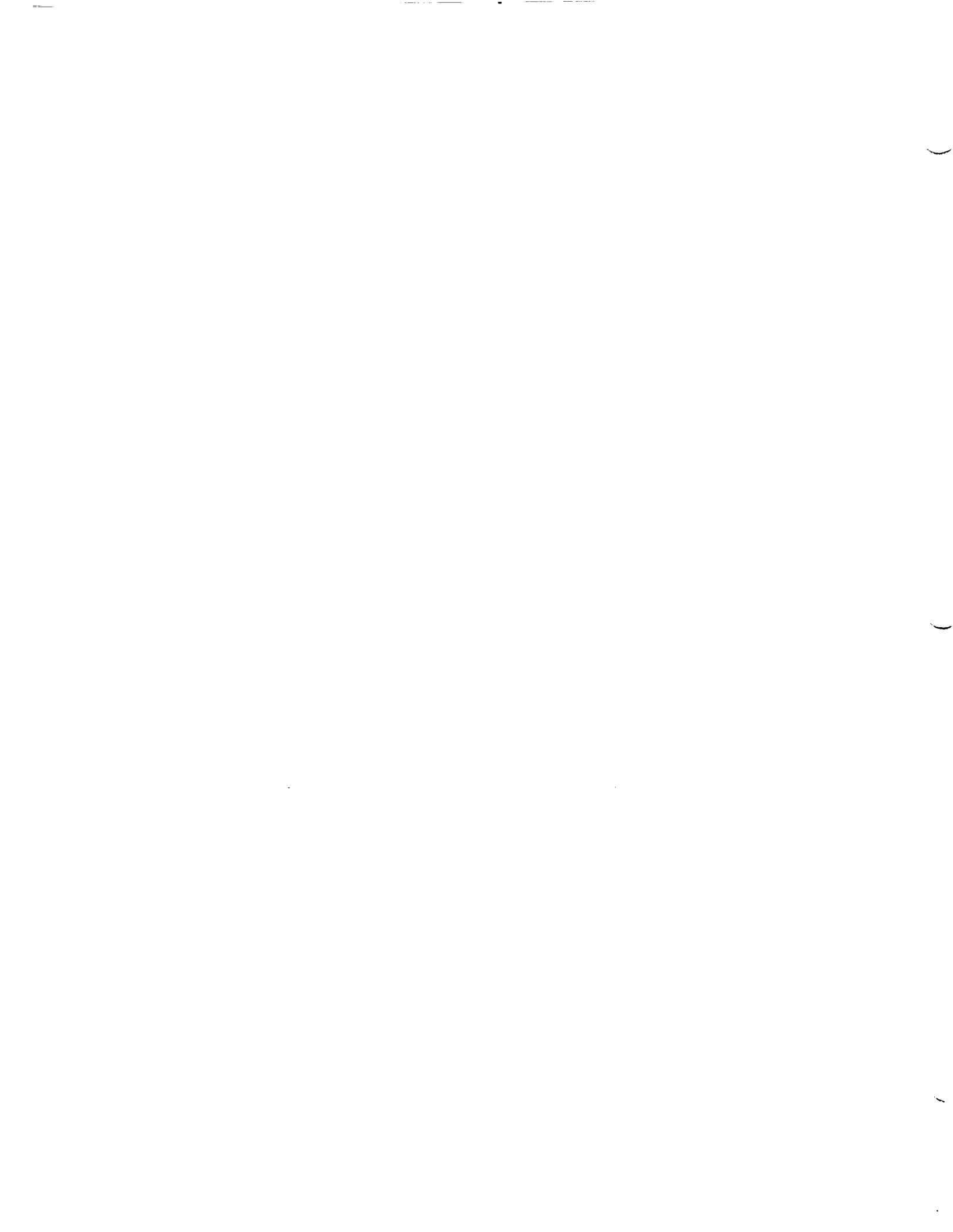
3.2 POST DRAIN INSPECTION

A scrub drain inspection was performed from 0600 to 0730 hours on 20 July 1999.

Due to the timing of the scrub with sound suppression water and hydrogen igniter activation, the Orbiter was closely inspected. No damage was detected on Orbiter tiles or SSME's. All RCS thruster paper covers were intact.

The ET showed no launch scrub damage from post cryoload thermal expansion. Typical ice/frost was still present on the ET/Orbiter LH2 umbilical purge curtain 'baggie', pyro canister closeouts, feedline and recirculation line bellows, and recirculation line burst disk. Ice/frost was also present at the ET/SRB cable tray to aft fairing interface +/- Y sides. The LO2 feedline clearance gap at the intertank fairing was nominal and no damage was visible. The LO2 feedline flange closeouts, attach points and brackets exhibited no crushed or loose foam. Ice/frost had formed on the XT-1871 tank base fitting. The LH2 aft dome manhole cover closeout ring had 'froth' present, but no visible insulation defects. The cracks detected by the Final Inspection Team adjacent to the -Y thrust panel had closed. Topcoat, but no foam, peeled at the -Y GOX vent seal land area in three places with 1.0-, 0.5-, and 0.25-inch diameters. This condition was documented on IPR 93V-0178, which was upgraded to PR ET-99-TS-0006 for MRB use "as-is".

No anomalies were noted on the SRB's, Pad B structure, or MLP deck.



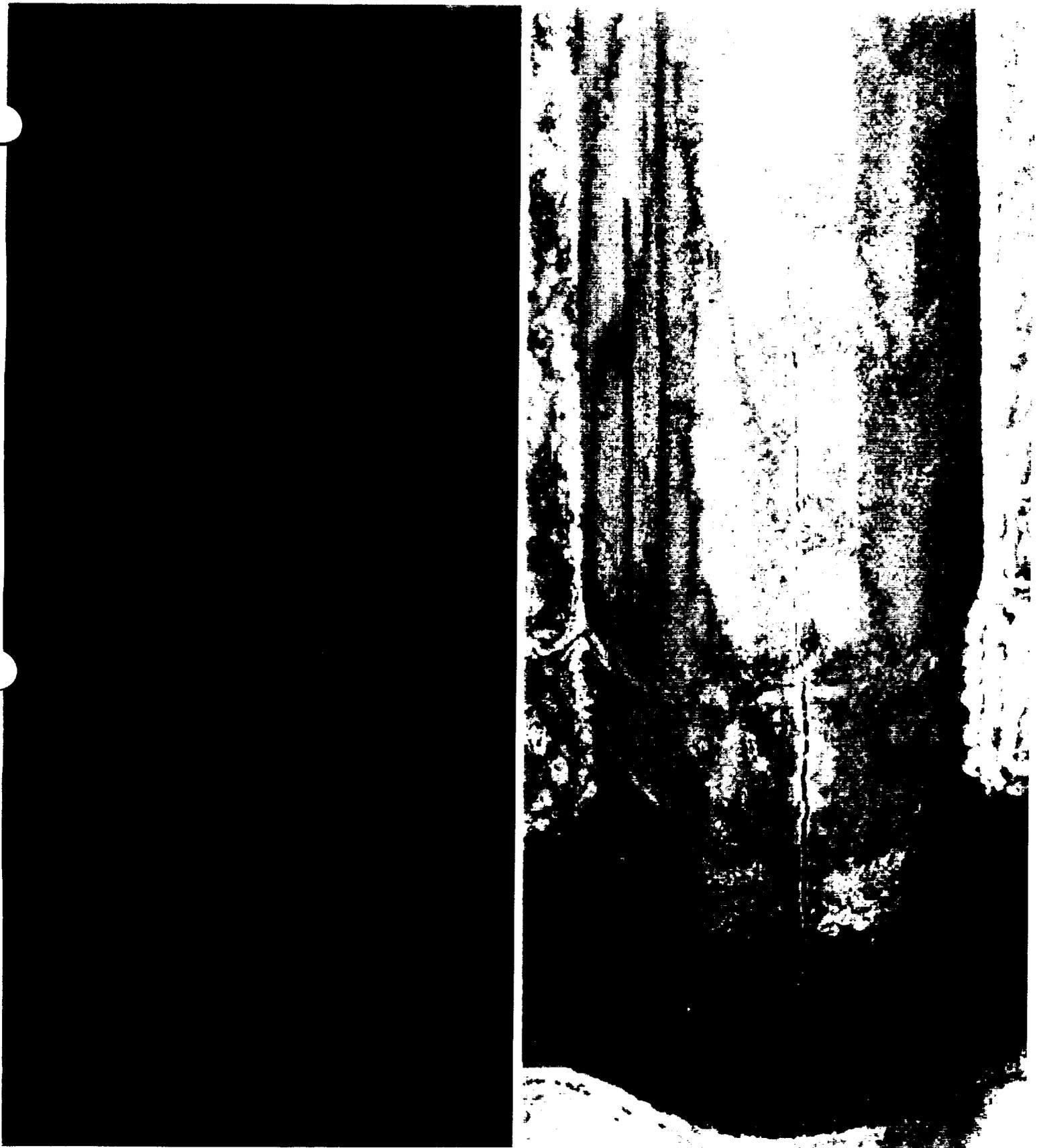
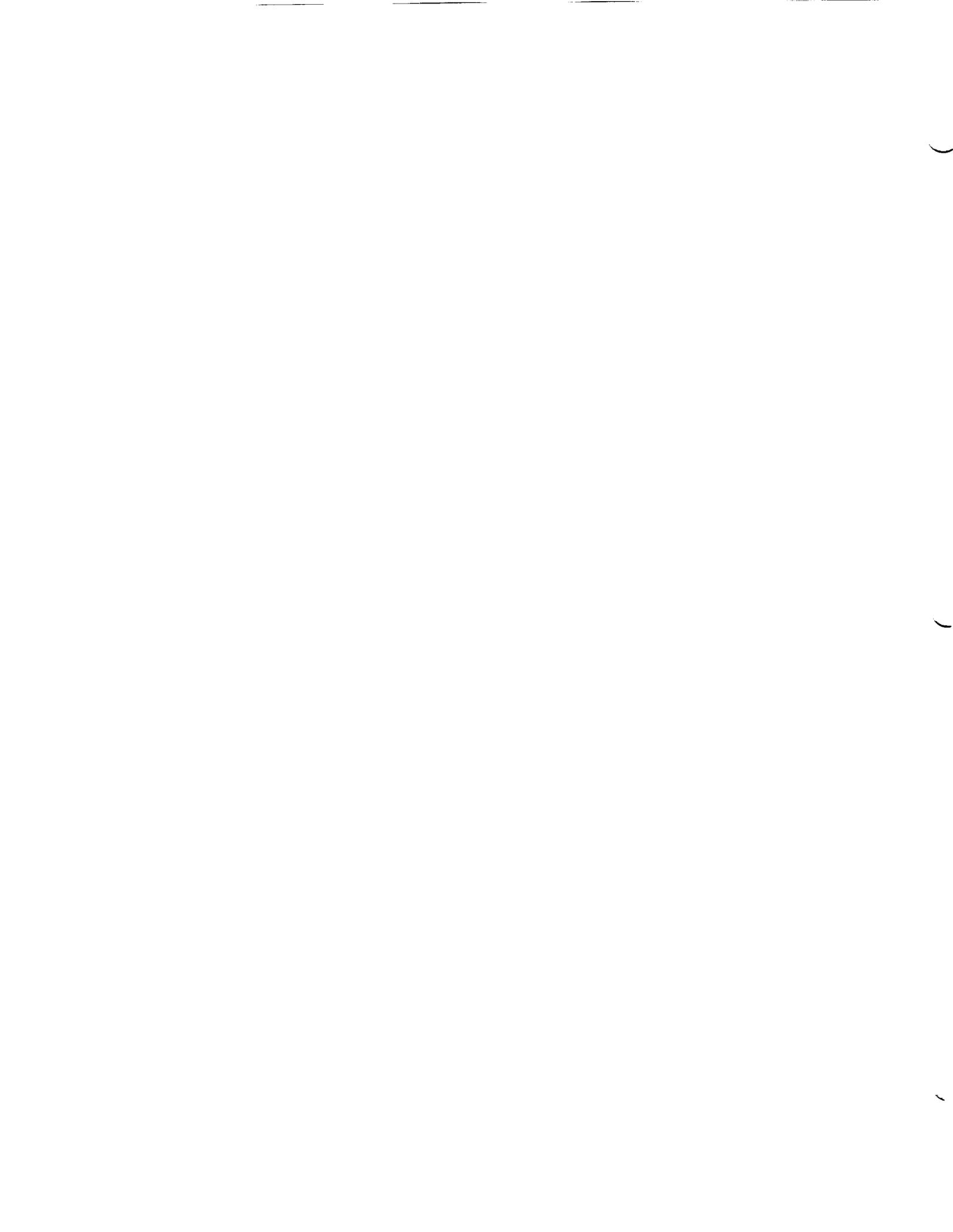


Photo 2: Crack in Stringer Valley TPS

One of two cracks (normal view and enhanced) detected in ET intertank stringer valley TPS: one 16-18 inches long in the $-Y+Z$ quadrant, and one 10-11 inches long in the $-Y-Z$ quadrant. Neither crack exhibited ice, frost, nor offset. Therefore, the cracks were acceptable for flight per the NSTS-08303 criteria.



3.3 FINAL INSPECTION - WEATHER SCRUB

A Final Inspection of the cryoloaded vehicle was performed on 21 July 1999 from 1850 to 2030 hours during the two hour built-in-hold at T-3 hours in the countdown. There were no Launch Commit Criteria (LCC), OMRS, or NSTS-08303 criteria violations. No Ice, Debris, or TPS IPR's were taken. There were no acreage icing concerns. There were also no protuberance icing conditions outside of the established database. Two cracks were again present in ET intertank stringer valley TPS: one 16-18 inches long in the -Y+Z quadrant, and one 10-11 inches long in the -Y-Z quadrant. Neither crack exhibited ice, frost, nor offset. Also, a 4-inch stress relief crack appeared in the -Y vertical strut TPS. All three cracks were acceptable for flight per the NSTS-08303 criteria. Three small frost spots had formed on the LH2 tank-to-intertank flange closeout.

No anomalies were detected on the facility, SRB's, and Orbiter. Although all RCS thruster paper covers were intact, F4R was tinted a light green.

Launch was scrubbed at T-5 minutes and holding as the window expired on 22 July 1999 due to weather LCC violations.

3.4 POST DRAIN INSPECTION

A scrub drain and T-20 hour inspection for a 24-hour turnaround was performed from 0620 to 0732 hours on 22 July 1999.

The ET showed no launch scrub damage from post cryoload thermal expansion. Typical ice/frost was still present on the ET/Orbiter LH2 umbilical purge curtain 'baggie', pyro canister closeouts, feedline and recirculation line bellows. Ice/frost was also present at the ET/SRB cable tray to aft fairing interface +/- Y sides. The LO2 feedline clearance gap at the intertank fairing was nominal and no damage was visible. The LO2 feedline flange closeouts, attach points and brackets exhibited no crushed or loose foam. The cracks detected by the Final Inspection Team adjacent to the -Y thrust panel had closed.

Additional topcoat peeled at the -Y GOX vent seal land area in one spot (3/8-inch diameter). This area was six inches in the +Z direction from the area previously documented on IPR 93V-0178. The new area was documented on an IPR, which addressed the cumulative effect of the missing topcoat.

Initial inspection revealed only condensate on the LH2 tank aft dome. Later, a venting thermal short occurred on the siphon screen cap bondline. The short was along a circumferential arc about 8 inches long in the -Y to -Z quadrant. The venting diminished in 10 minutes. Such thermal shorts are acceptable per the NSTS 08303 Ice/Debris Inspection Criteria.

No anomalies were noted on the Orbiter, SRB's, or Pad B structure. One finding on the MLP deck concerned a loose 6-inch diameter pipe cap east of the southeast corner of the stairway doghouse. The pad crew corrected this item.

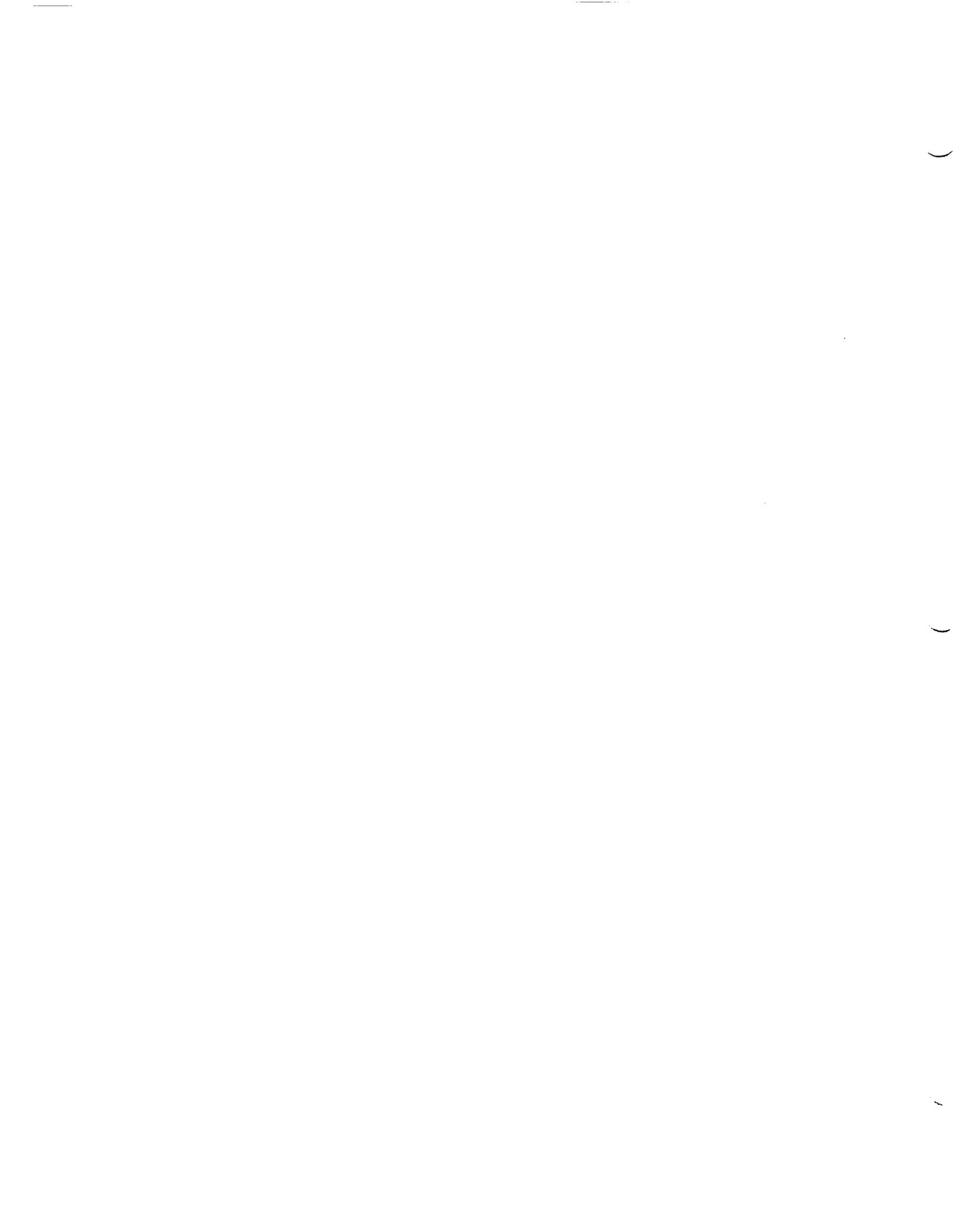
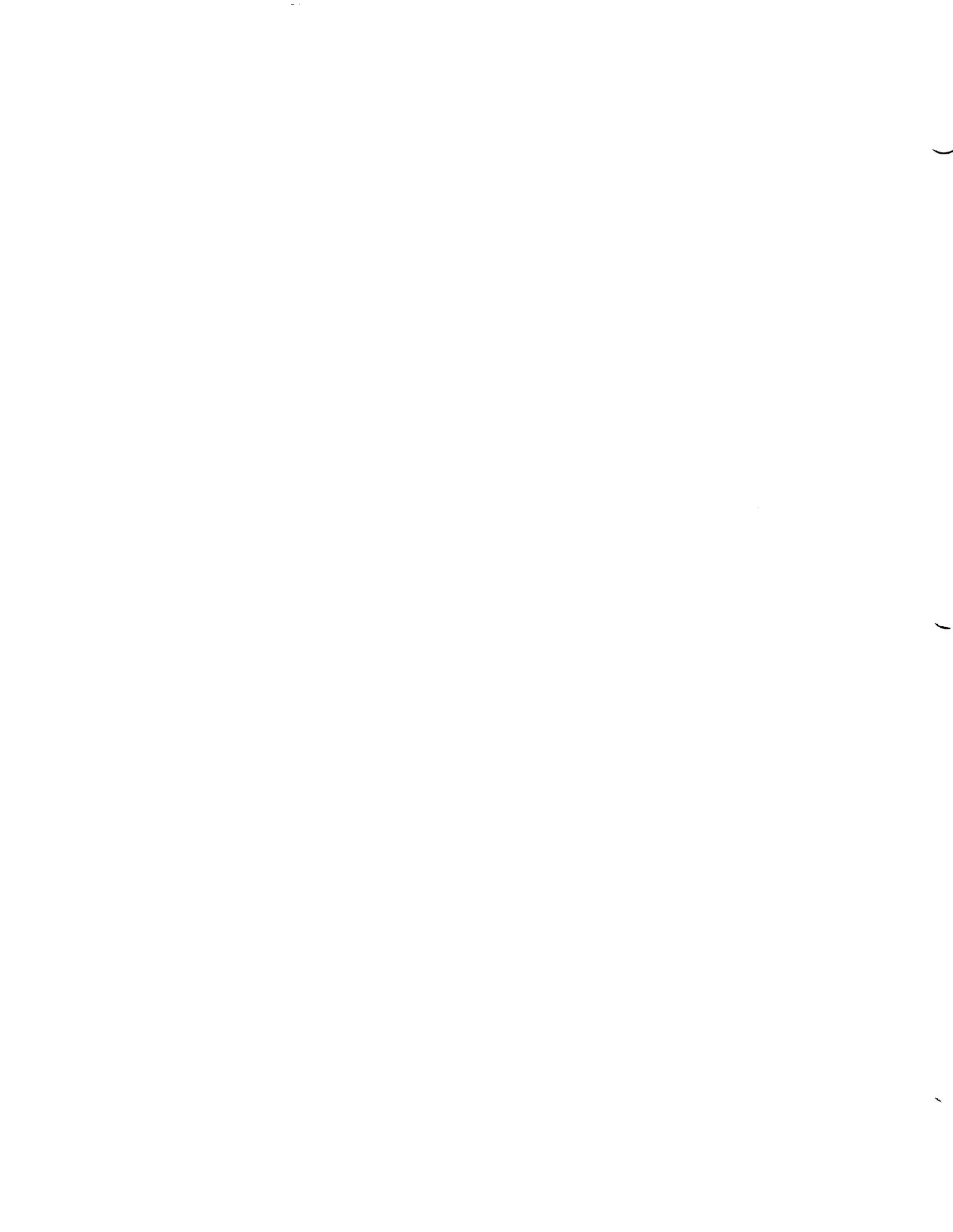




Photo 3: Thermal Short on Siphon Screen Cap

Initial inspection revealed only condensate on the LH2 tank aft dome. Later, a venting thermal short occurred on the siphon screen cap bondline. The short was along a circumferential arc about 8 inches long in the -Y to -Z quadrant. The venting diminished in 10 minutes. Such thermal shorts are acceptable per the NSTS 08303 Ice/Debris Inspection Criteria.



4.0 LAUNCH

4.2 FINAL INSPECTION

The Final Inspection of the cryoloaded vehicle was performed on 22 July 1999 from 1825 to 2010 hours during the two hour built-in-hold at T-3 hours in the countdown. There were no Launch Commit Criteria (LCC), OMRS, or NSTS-08303 criteria violations. One TPS IPR was taken for a 6-inch crack in the +Y longeron foam. There were no acreage icing concerns. There were also no protuberance icing conditions outside of the established database.

A portable Shuttle Thermal Imager (STI) infrared scanning radiometer was utilized to obtain vehicle surface temperature measurements for an overall thermal assessment of the vehicle, particularly those areas not visible from remote fixed scanners, and to scan for unusual temperature gradients.

4.2.1 ORBITER

No Orbiter tile or RCC panel anomalies were observed. All RCS thruster covers were dry and intact, though the F4R and R2U covers were tinted light green in color. Ice/frost had formed on SSME #1 and #2 heat shield-to-nozzle interfaces. The SSME #3 heat shield was wet with condensate. An infrared scan revealed no unusual temperature gradients on the base heat shield or engine mounted heat shields.

4.2.2 SOLID ROCKET BOOSTERS

SRB case temperatures measured by the STI radiometers were close to ambient temperatures. All measured temperatures were above the 34 degrees F minimum requirement. The predicted Propellant Mean Bulk Temperature supplied by THIO was 81 degrees F, which was within the required range of 44-86 degrees F.

4.2.3 EXTERNAL TANK

The ice/frost prediction computer program 'SURFICE' was run as a comparison to infrared scanner point measurements. The program predicted condensate, but no ice or frost, on the ET acreage TPS.

The Thermal Protection Systems performed nominally during cryoload. The Final Inspection Team observed wet TPS on the LO2 tank acreage due to light condensate, but no ice or frost accumulations. Surface temperatures averaged 71 degrees Fahrenheit.

No anomalies were detected in the intertank TPS though numerous small frost spots had formed on the intertank-to-LH2 tank and -LO2 tank flange closeouts and along the -Y bipod spindle ramp. Surface temperatures averaged 80 degrees F. Ice and frost accumulations on the GUCP were typical. The two stringer valley TPS cracks were again present, but had not changed in length or appearance.

The Final Inspection Team observed wet TPS on the LH2 tank acreage due to light condensate, but no ice or frost accumulations. Surface temperatures ranged from 58 to 71 degrees Fahrenheit. Small frost spots had formed on the PAL ramp bondline, on the press line/cable tray ramp-to-acreage interfaces, and near the +Y longeron knuckle,

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

IPR 093V-0196 was taken against a pear-shaped crack with visible offset on the ET +Y thrust strut longeron closeout at the -Z bondline (XT-2000). The crack was approximately 6 inches long by 2-3 inches wide with 3/8-inch offset. Frost was present only on the rind adjacent to the closeout. Nevertheless, the crack size exceeded the allowable database of NSTS-08303. MRB accepted the condition to fly "as is" based on design center aerodynamic, thermal, and structural analyses.

A 4-inch long by 1/8-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/frost had formed in the LH2 feedline bellows. Ice and frost in the LH2 recirculation line bellows and on both burst disks was typical. However, a more unusual finding was ice/frost on the bond line of the recirculation line-to-umbilical interface.

A typical amount of ice/frost had accumulated on the LH2 ET/ORB umbilical purge barrier outboard side and forward surface. 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.

4.2.4 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.

4.3 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 until liftoff. At the time of launch, there were no ice accumulations in the "no ice zone".

STS-93 was launched at 204:04:30:59.984 UTC (12:31 a.m. local) on 23 July 1999.

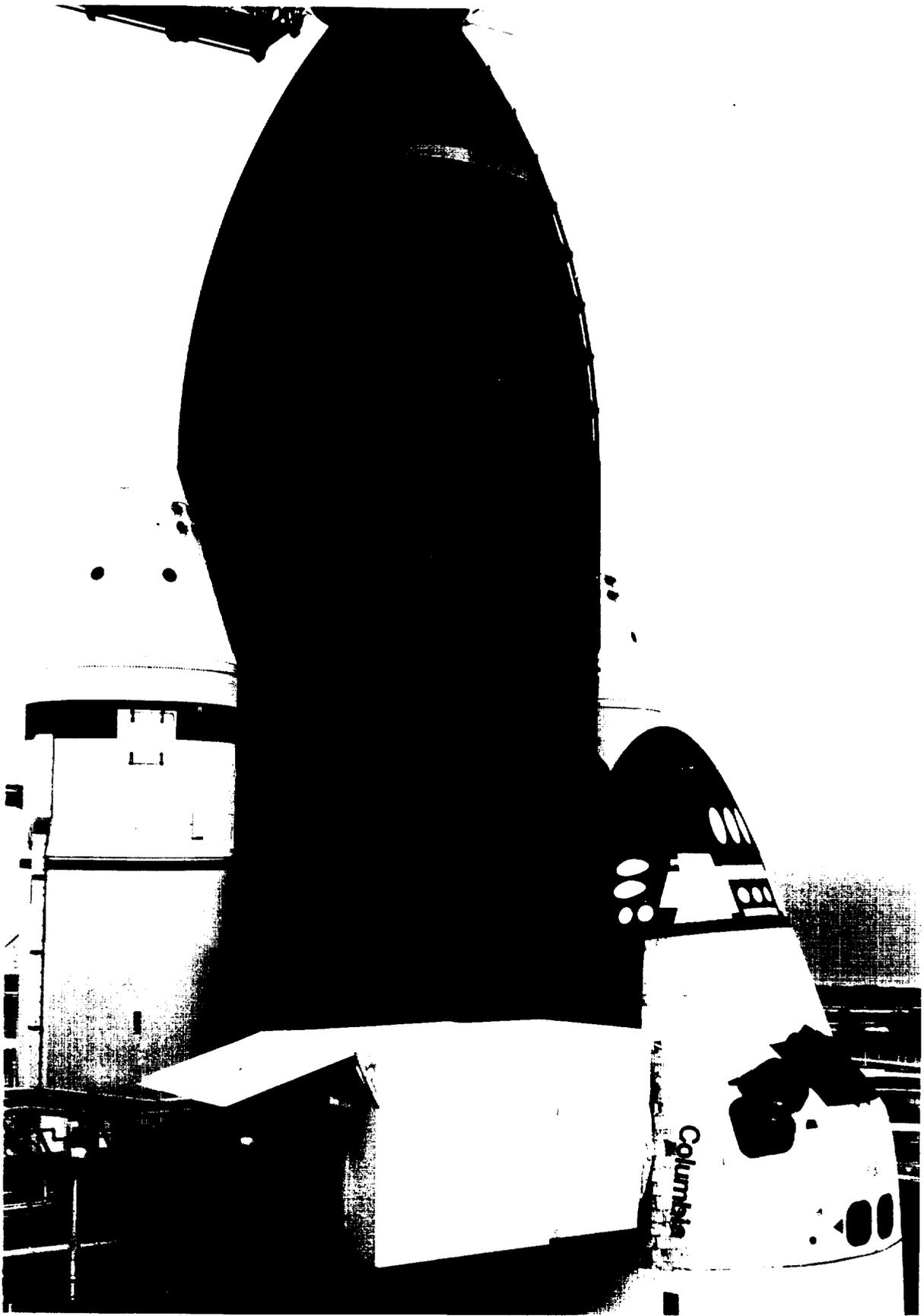


Photo 4: ET LO2 Tank and Intertank

The Thermal Protection Systems performed nominally during cryoload. LO2 tank acreage TPS was wet due to light condensate, but no ice or frost accumulations. No anomalies were detected in the intertank TPS though numerous small frost spots had formed on the intertank-to-LH2 tank and -LO2 tank flange closeouts.





Photo 5: LO2 Feedline Bellows

Typical amounts of ice/frost had accumulated in the LO2 feedline bellows and support brackets

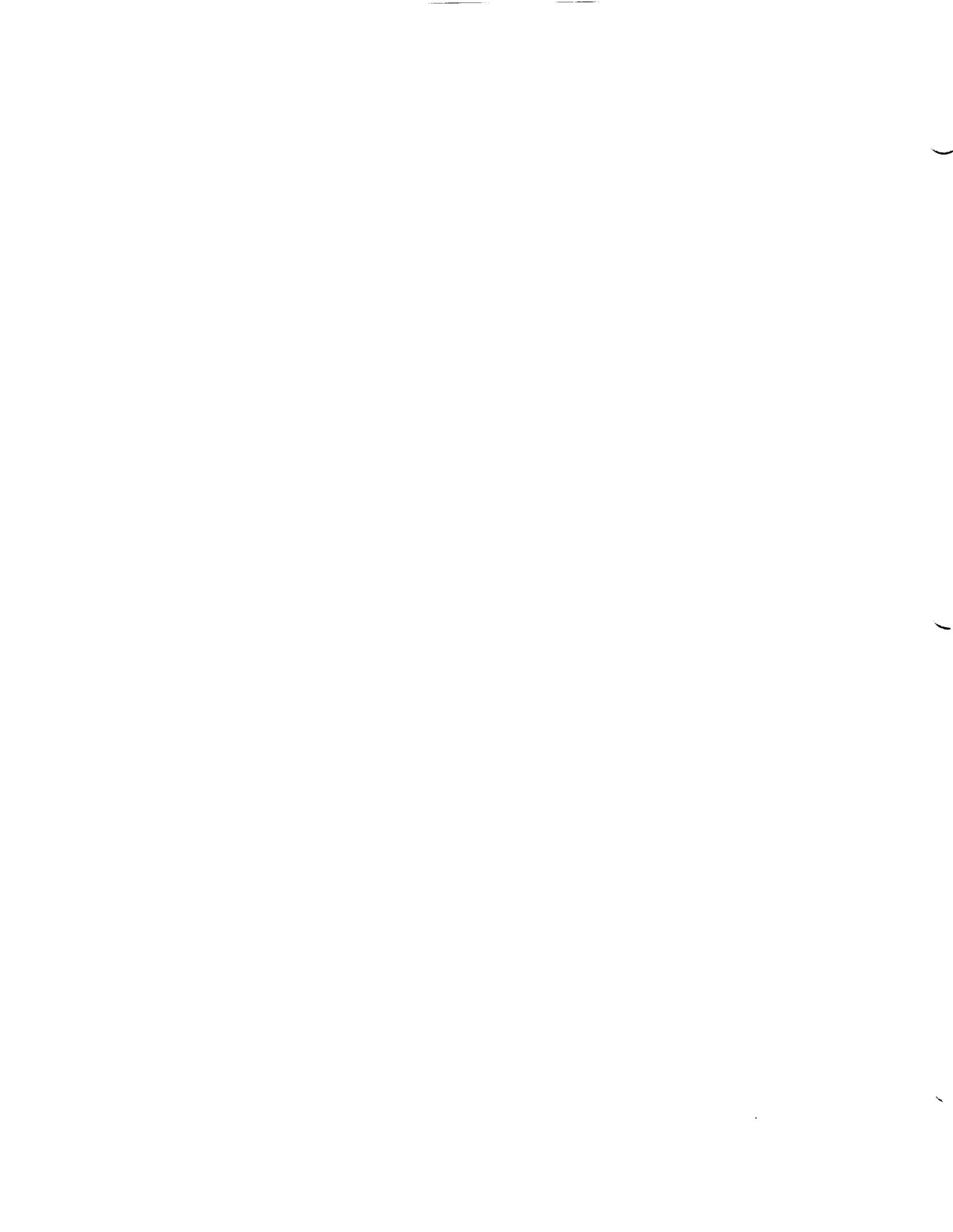
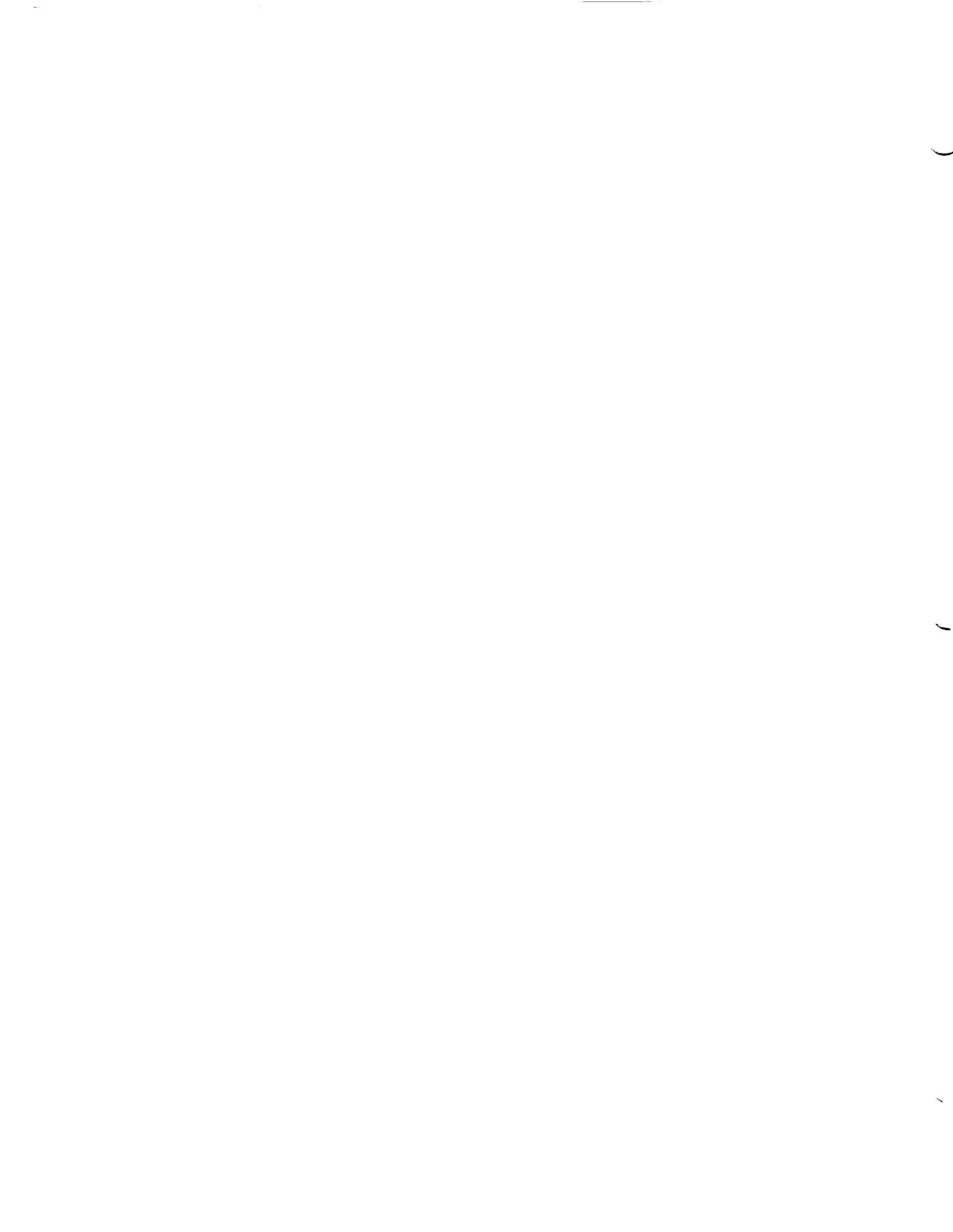




Photo 6: Crack in +Y Longeron TPS

IPR 093V-0196 was taken against a pear-shaped crack with visible offset on the ET +Y thrust strut longeron closeout at the -Z bondline (XT-2000). The crack was approximately 6 inches long by 2-3 inches wide with 3/8-inch offset. Frost was present only on the rind adjacent to the closeout. Nevertheless, the crack size exceeded the allowable database of NSTS-08303.



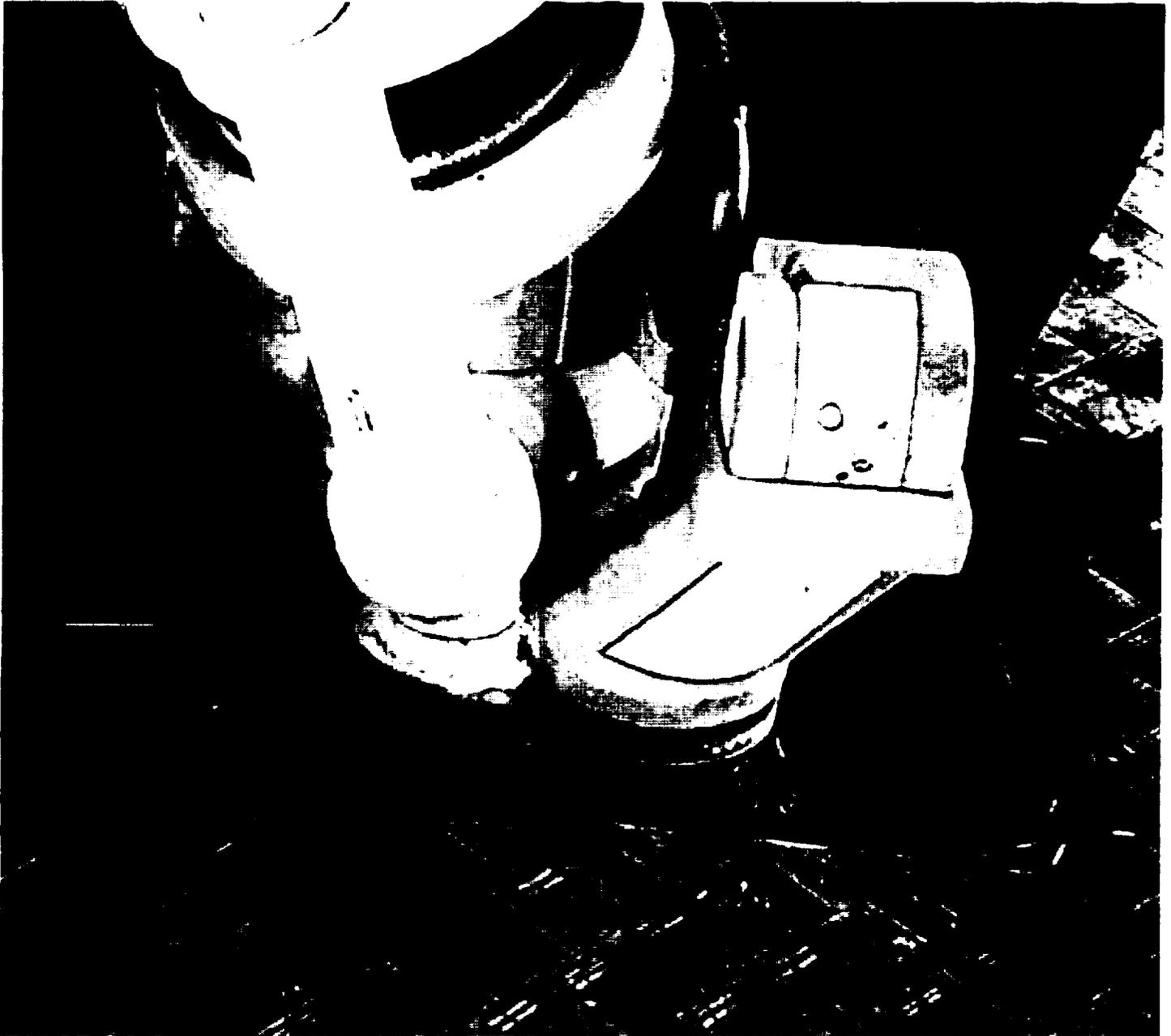


Photo 7: LH2 Feedline and Recirculation Line

Ice/frost had formed in the LH2 feedline bellows. Ice and frost in the LH2 recirculation line bellows and on both burst disks was typical. However, a more unusual finding was ice/frost on the bond line of the recirculation line-to-umbilical interface.

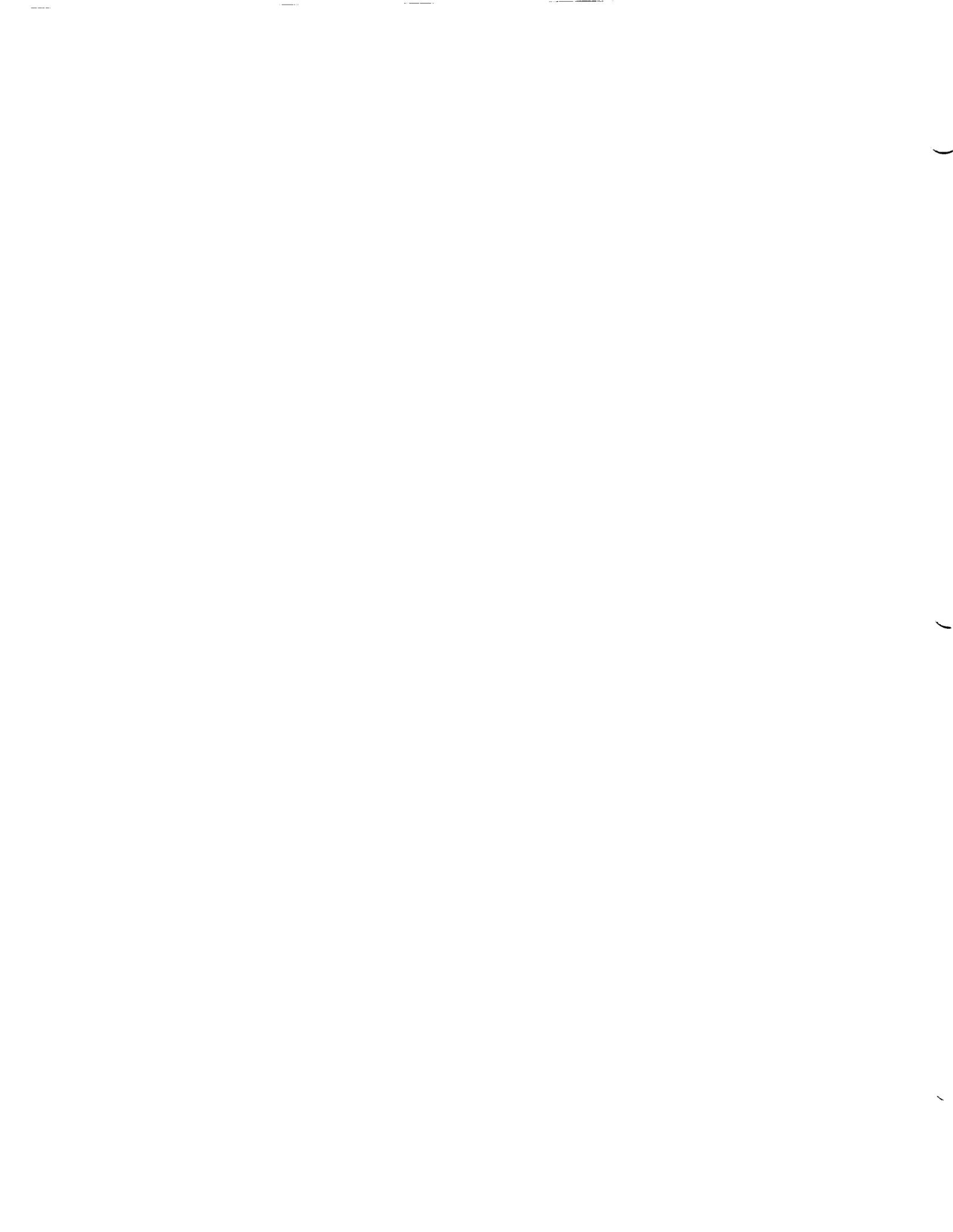
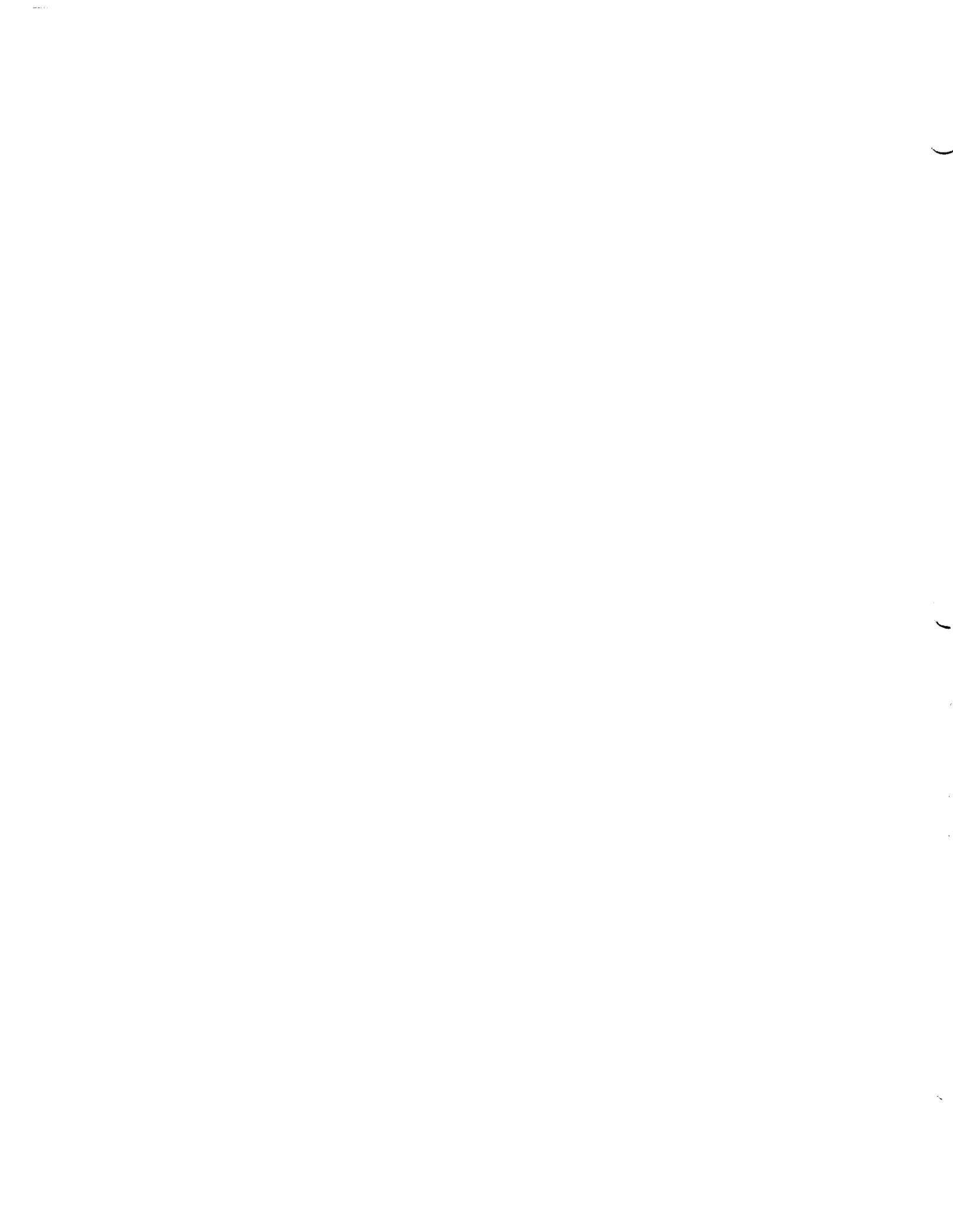




Photo 8: LH2 ET/ORB Umbilical

Ice/frost accumulations on the LH2 ET/ORB umbilical, plate gap purge vents, and pyrotechnic canister purge vents were typical



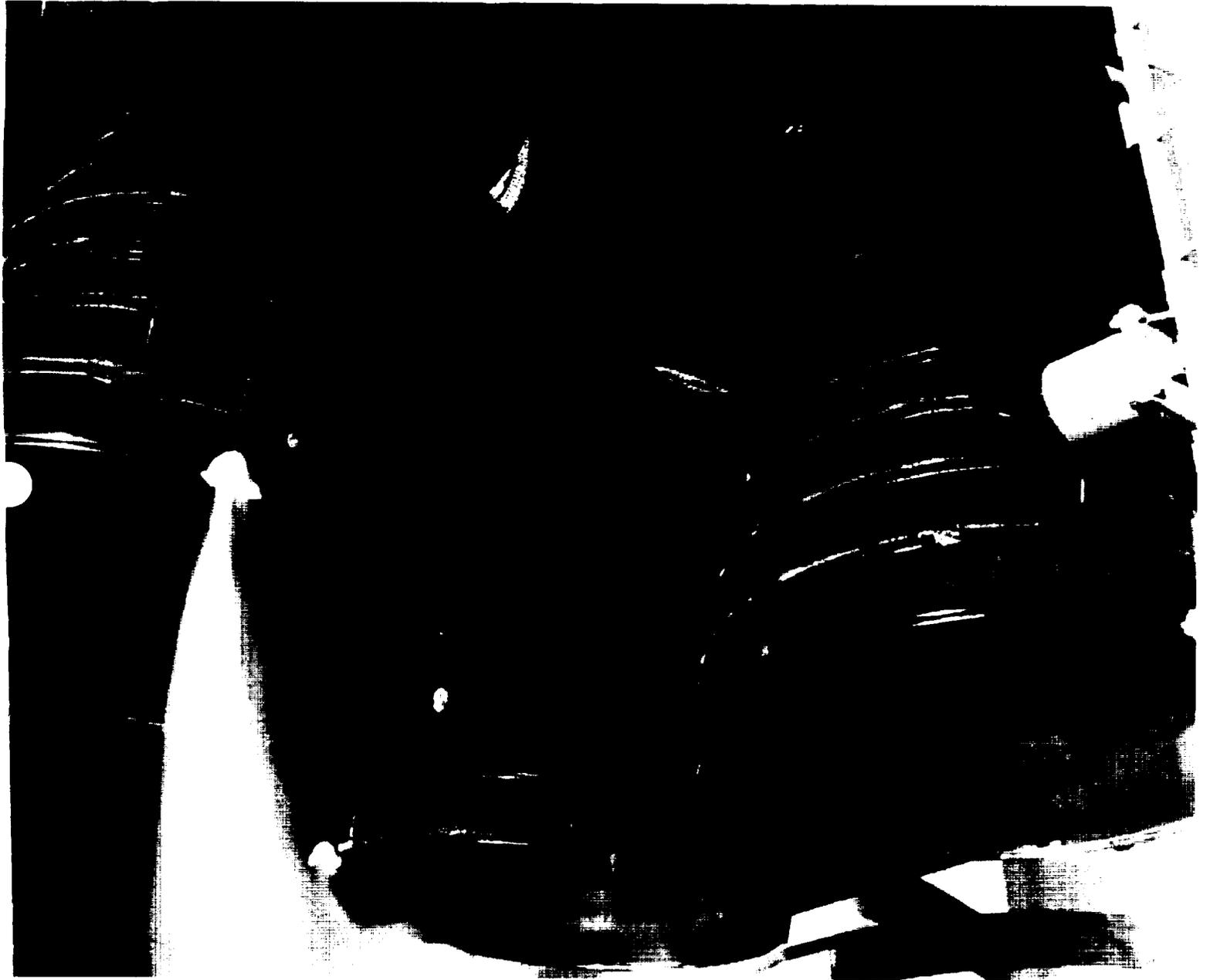


Photo 9: Overall View of SSME's



5.0 POST LAUNCH PAD DEBRIS INSPECTION

The post launch inspection of MLP-1, Pad 39B FSS and RSS was conducted on 23 July 1999 from Launch + 2 to 4 hours. No flight hardware was found.

No stud hang-up occurred on this launch. Boeing-Downey reported an Orbiter liftoff lateral acceleration of 0.08 g's, which was below the threshold (0.14g's) for stud hang-ups. SRB south holddown post erosion was typical. North holddown post blast covers and T-0 umbilical exhibited typical exhaust plume damage. Both SRB aft skirt GN2 purge lines were intact, though the protective tape was eroded away and the braided lines were damaged. The left GN2 purge flex line was bent.

The Tail Service Masts (TSM's) appeared undamaged and the bonnets were closed properly. Likewise, the Orbiter Access Arm (OAA) was not damaged.

The MLP deck was in good shape with no significant debris concerns. Many paint chips found scattered about were white on one side and gray on the other. These appeared to originate from the facility. There was evidence of a high-energy debris hit to the E-2 film camera lens cover.

The GH2 vent line latched in the fifth of eight teeth of the latching mechanism. The GUCP 7-inch QD sealing surface exhibited some minor roughness on the inner edge at two locations. All observations indicated a nominal retraction and latchback, though the SRB exhaust plume scorched the flex line aluminized blanket.

The GOX vent seals were in excellent shape with no indications of plume damage. A 1/8-inch diameter piece of topcoat adhered to the northeast seal.

Debris findings on the FSS included a variety of small signs/tags, pipe insulation and tie wraps. One 24" x 2" aluminum angle was found near the 215 foot level.

Overall, damage to the pad appeared to be minimal.

6.0 FILM REVIEW

Anomalies observed in the Film Review were presented to the Mission Management Team, Shuttle managers, and vehicle systems engineers. No IPR's or IFA's were generated as a result of the film review.

6.1.1 LAUNCH FILM AND VIDEO SUMMARY

A total of 92 films and videos, which included thirty-six 16mm films, seventeen 35mm films, and thirty-nine videos, were reviewed starting on launch day. Film review results contributed to the investigation of the hydrogen leak in the SSME #3 nozzle.

Frost formed on the ET louvers after GOX vent seal retraction. No ice was detected (OTV 161).

Ice fell from the LO2 feedline upper bellows at 04:31:03.3 UTC. One piece may have made a glancing contact with Orbiter lower surface tiles, but no damage was detected (OTV 161, E-34).

SSME ignition startup sequence was normal. However, a hot-wall propellant leak occurred in the SSME #3 nozzle -Y location at 04:30:58.515 UTC. This caused numerous flashes in the exhaust plume and a distortion of the Mach diamond. Flashes/streaks in the SSME plume occurred at 04:30:58.030, 04:30:58.153, and 04:30:58.515 UTC. The hydrogen leak was caused by the rupture of three adjacent cooling tubes, which most likely were impacted by an SSME LO2 post deactivating plug (later confirmed to be missing during post flight inspections). E-2, -3, -19, -20, -52, -54, -76, -77, -213; OTV 141, 151, 171, TV-4, ET-207, -208).

Free burning hydrogen drifted in the orbiter base heat shield area and past the vertical stabilizer during SSME ignition (OTV 170, 171, TV-7, TV-21).

SSME ignition caused numerous pieces of ice from the LH2 ET/ORB umbilical to fall aft. Some pieces impacted the umbilical cavity sill, but no damage was visible (OTV 109, 163).

Surface coating material was missing from two spots on the SSME #2 base mounted heat shield, one spot on the Orbiter base heat shield inboard of SSME #3, one outboard of SSME #2 and one near the center. (OTV 170; E-17, -18, -20, -76, -77).

There were no stud hang-ups. No debris fell from the HDP stud holes.

The GN2 purge lines separated cleanly from both SRB aft skirts at liftoff. The purge lines were visible for about two seconds after T-0 before being obscured from view by smoke. At that time, no anomalies were observed (E-8, -13).

The debris object that impacted the camera lens cover on the MLP deck southeast corner (E-2) could not be identified as the view was obscured prior to the impact. The time of impact was 04:31:05.378 (E-2).

The 6-inch crack in the +Y longeron TPS was visible at T-0 and liftoff, but no foam detached while in the view of view. The frost on the +Y thrust strut knuckle TPS fell aft during lift-off (OTV 154; E-52).

Water drained from the split rudder/speed brake as the vehicle cleared the tower (E-52,-213,-224)

Numerous light colored objects falling aft of the vehicle early in flight were identified as ice particles from the ET/ORB umbilicals and paper covers from the forward and aft RCS thrusters. A bird flew past the south side of the vehicle and exited from view toward the north. No contact with the vehicle was observed. (E-31, -34, -52, -54, -63, -76, -77, -207).

Numerous streaks occurred in the SSME plumes during ascent. The most significant was aft of SSME #2 from 04:31:23.206 to 04:31:23.787 UTC. These streaks were pale green in color and are usually indicative of some momentary impurity in the combustion process. Another streak aft of SSME #2 occurred at 04:31:24.077 UTC. SSME #1 exhaust plume exhibited a streak at 04:31:27.343 (E-52, -207, -212, -213, -220, -223)

A debris object appeared in the vicinity of the left OMS pod at 04:04:33:00.245 UTC, but identification and origin could not be determined (E-208 and TV13).

Orbiter body flap motion was easily visible in several films. Magnitude and frequency of the motion appeared to be similar to previous flights.

Local flow condensation on the vehicle occurred during ascent (TV-4, TV-13).

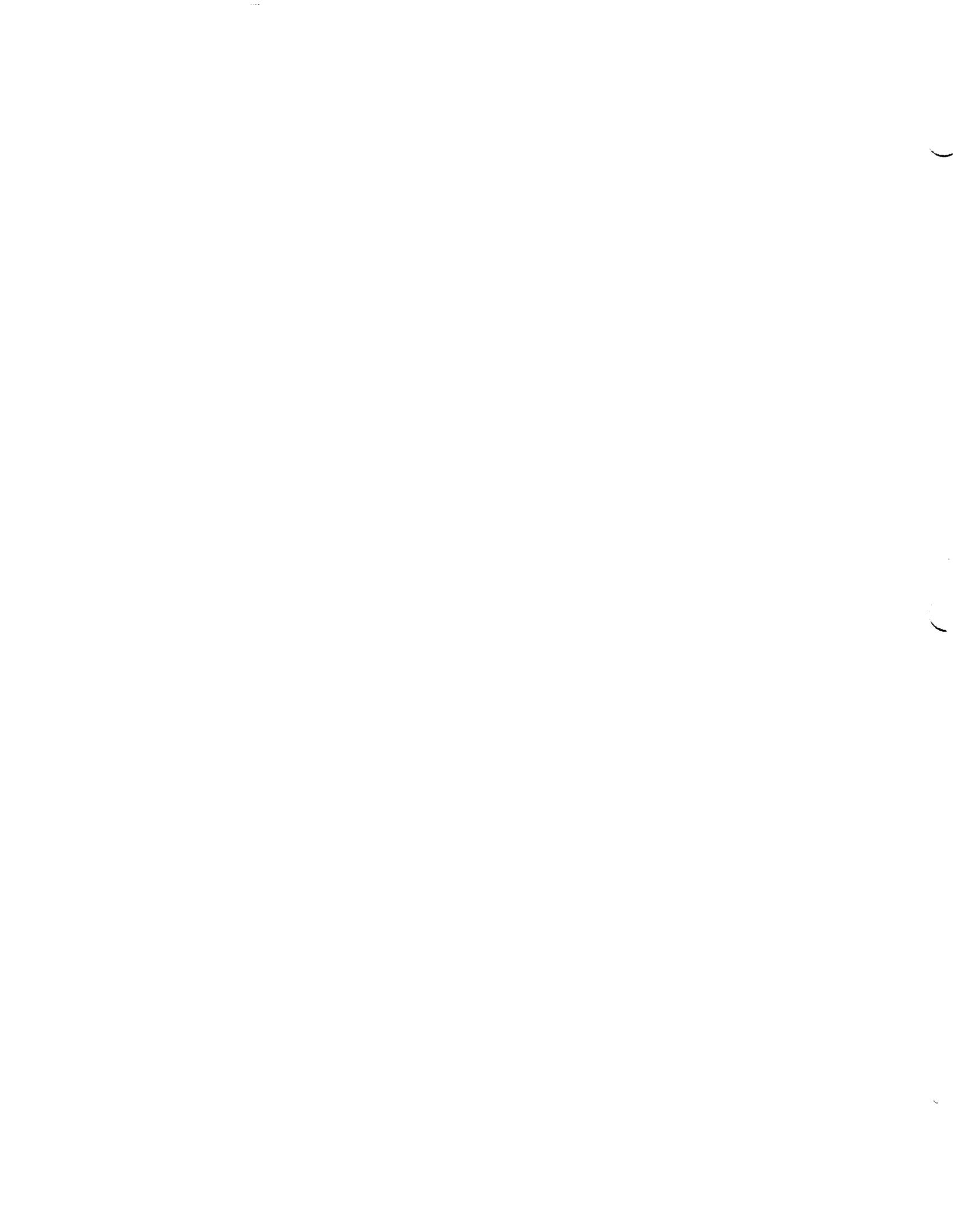
SRB separation appeared normal. Numerous pieces of slag were visible falling from the SRB exhaust plumes just before, during, and after separation. The large number of visible slag pieces was expected due to the dark conditions of a night launch (TV-4).





Photo 10: SSME #3 Hot-Wall Leak

A hot-wall propellant leak occurred in the SSME #3 nozzle at 04:30:58.517 UTC. The leak was caused by the rupture of three adjacent cooling tubes, which most likely were impacted by an SSME LO₂ post plug (later confirmed to be missing during post flight inspections). Several streaks, associated with the hot wall leak, were visible.



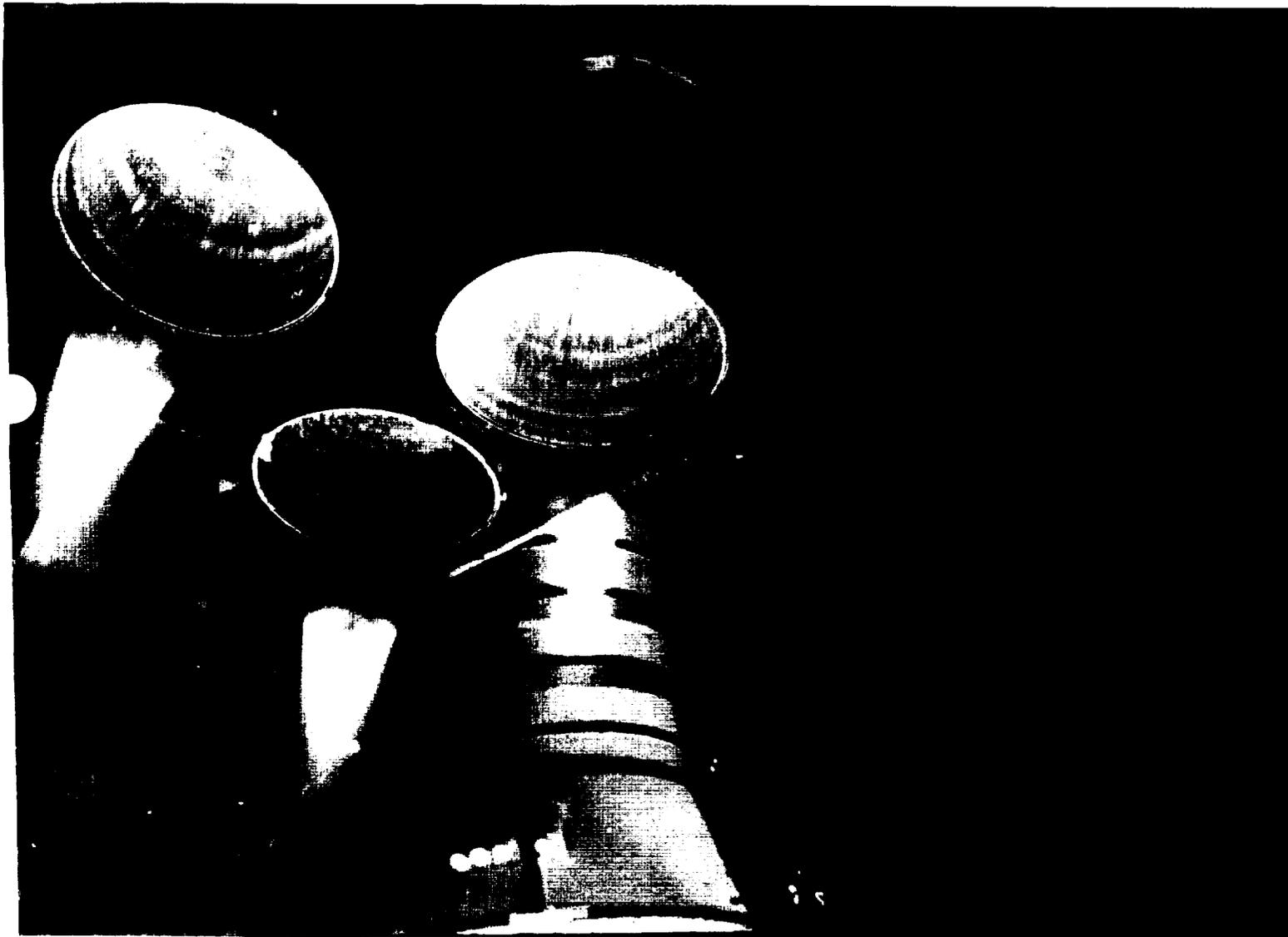


Photo 11: SSME #3 Hot-Wall Leak at Liftoff

MLP deck camera view (E-19) showing location and size of hot-wall leak in the SSME #3 nozzle just after liftoff

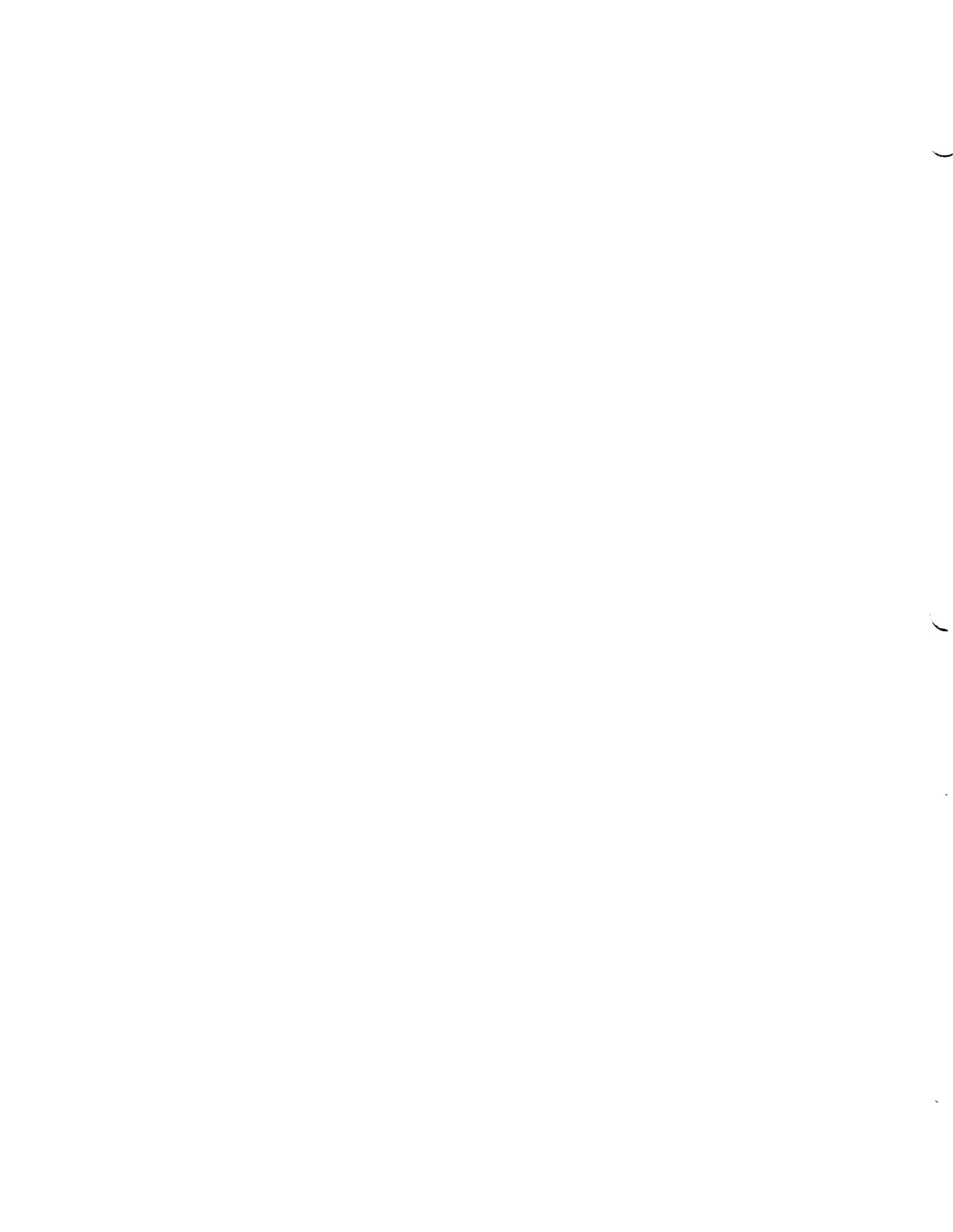




Photo 12: SSME #3 Hot-Wall Leak in Early Flight

Launch pad perimeter camera view (E-54) showing SSME #3 nozzle hot-wall leak after tower clear

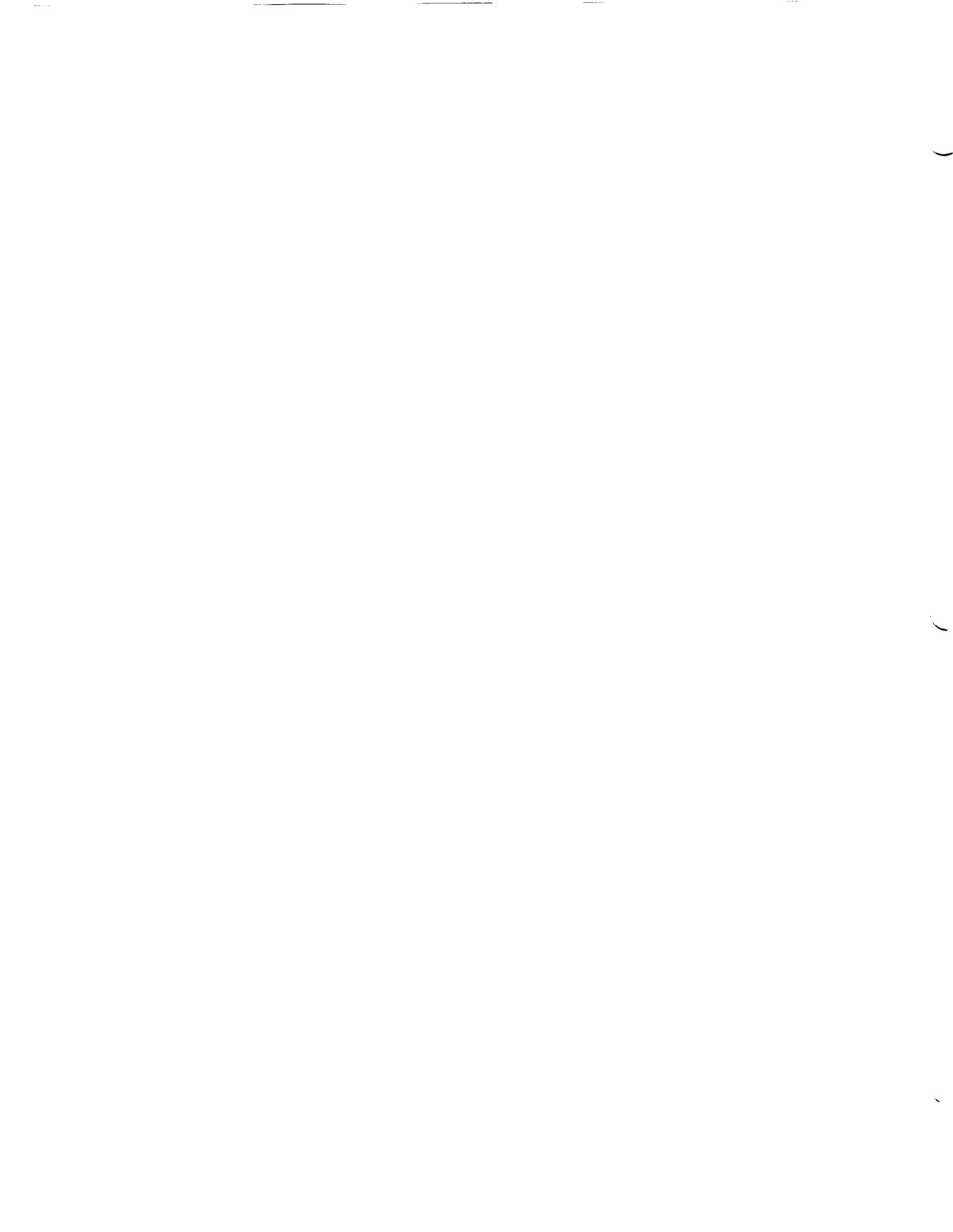




Photo 13: SSME #3 Hot-Wall Leak

Close-in view from long range tracker camera E-207 showing SSME #3 nozzle hot wall leak just after the roll maneuver.

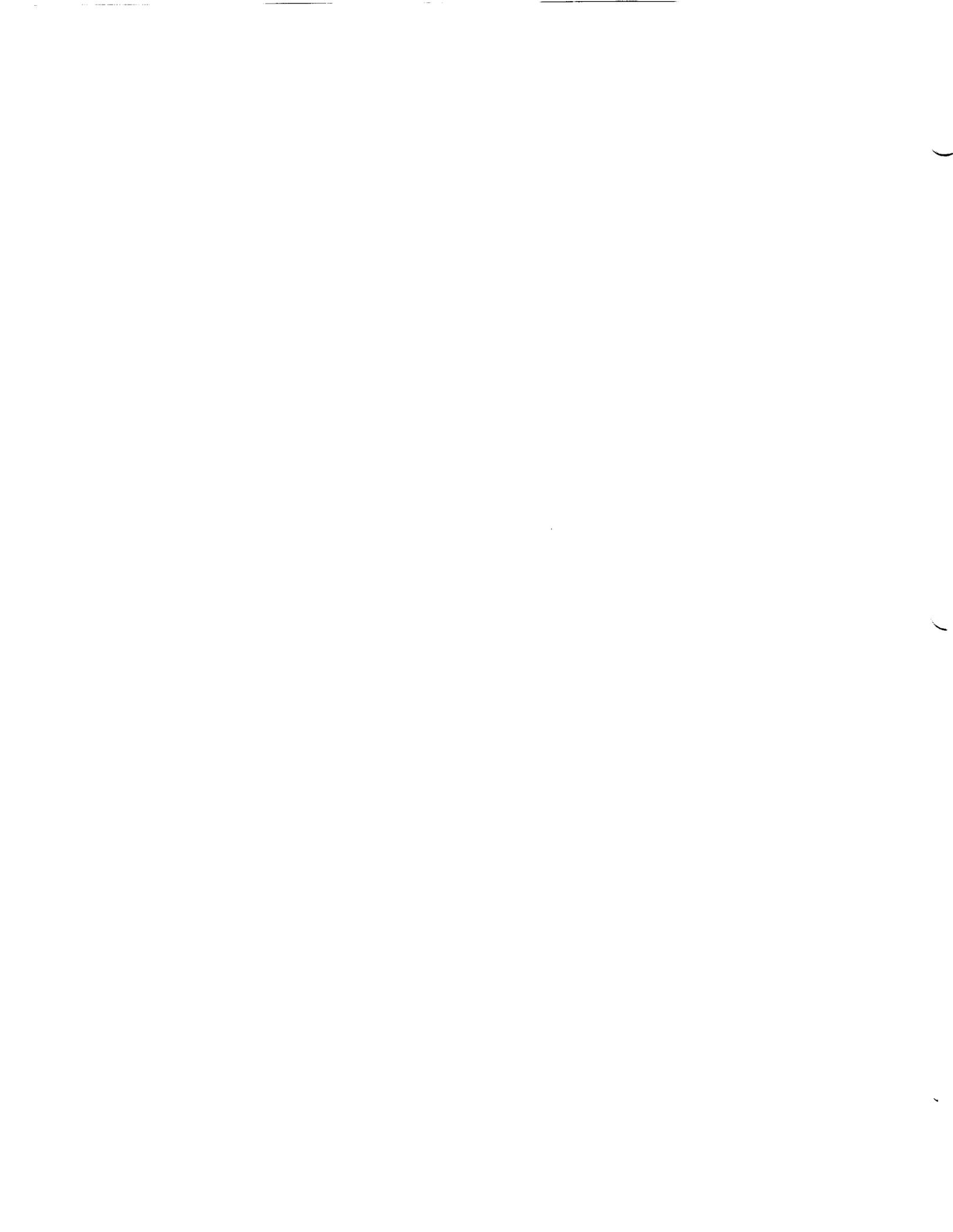




Photo 14: SSME #3 Hot-Wall Leak

Opposite view from long range tracker camera E-212 later in flight

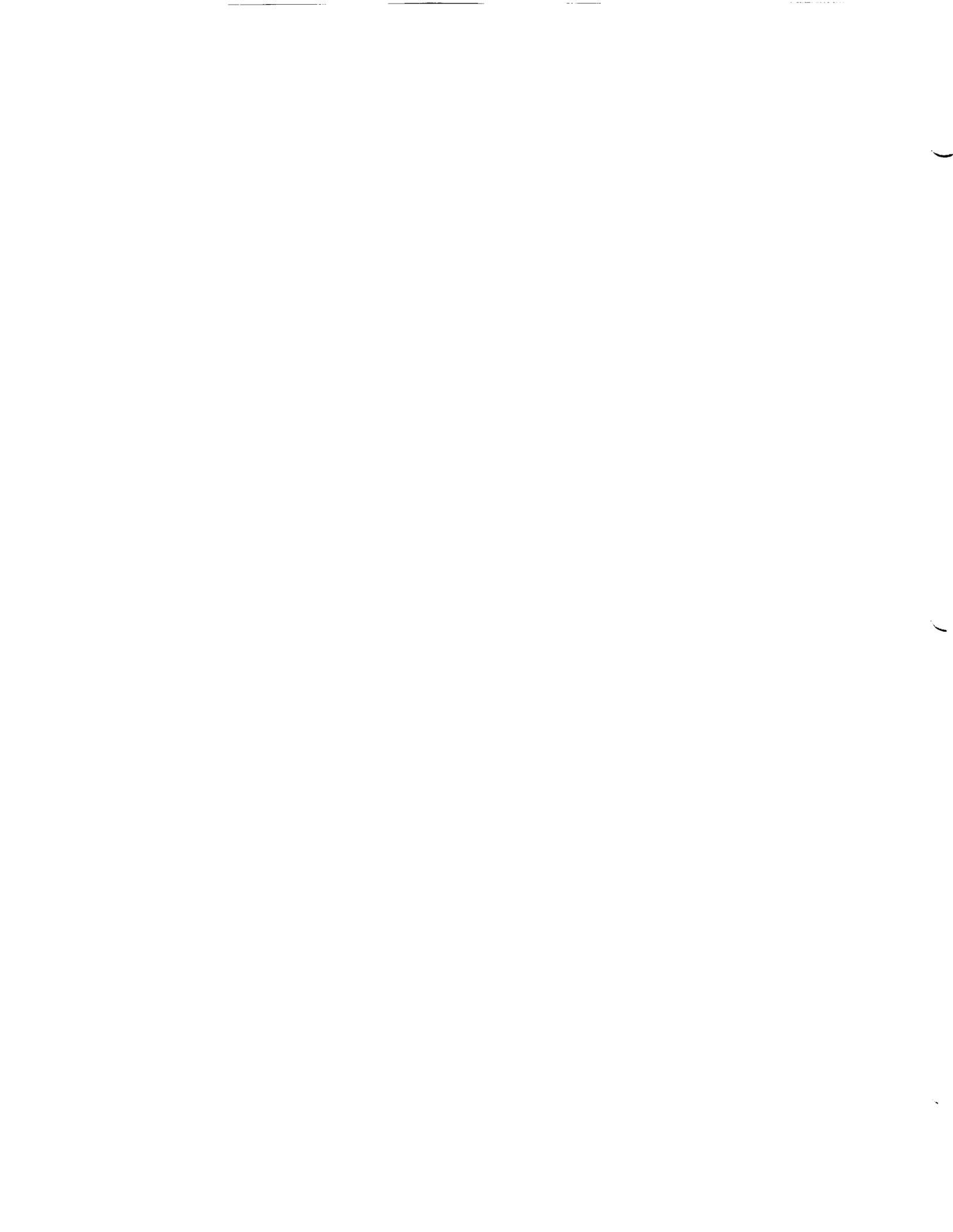
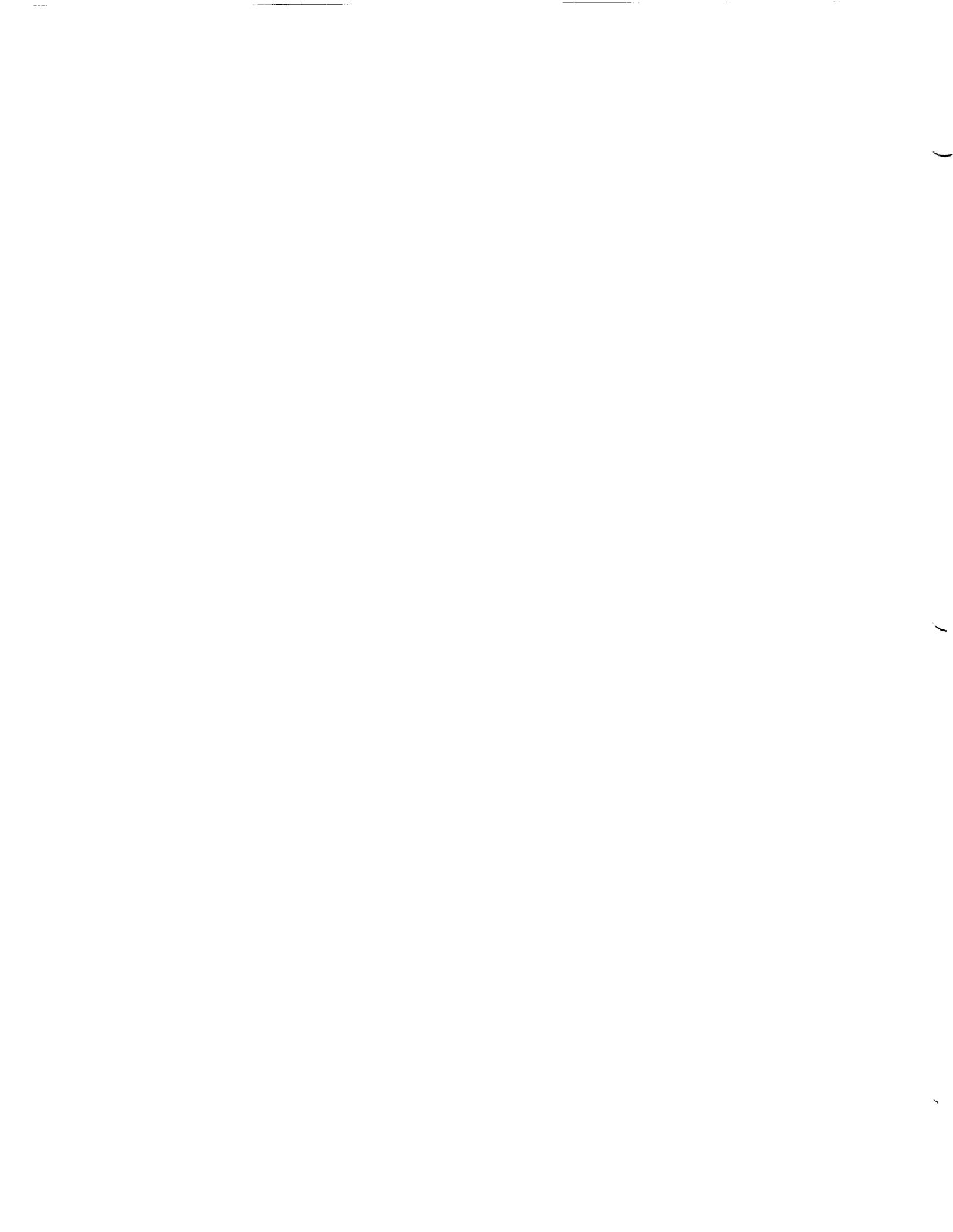




Photo 15: Streaks in SSME Exhaust Plume

Numerous streaks occurred in the SSME plumes during ascent. The most significant was aft of SSME #2 from 04:31:23.206 to 04:31:23.787 UTC. These streaks were pale green in color and are usually indicative of some momentary impurity in the combustion process.



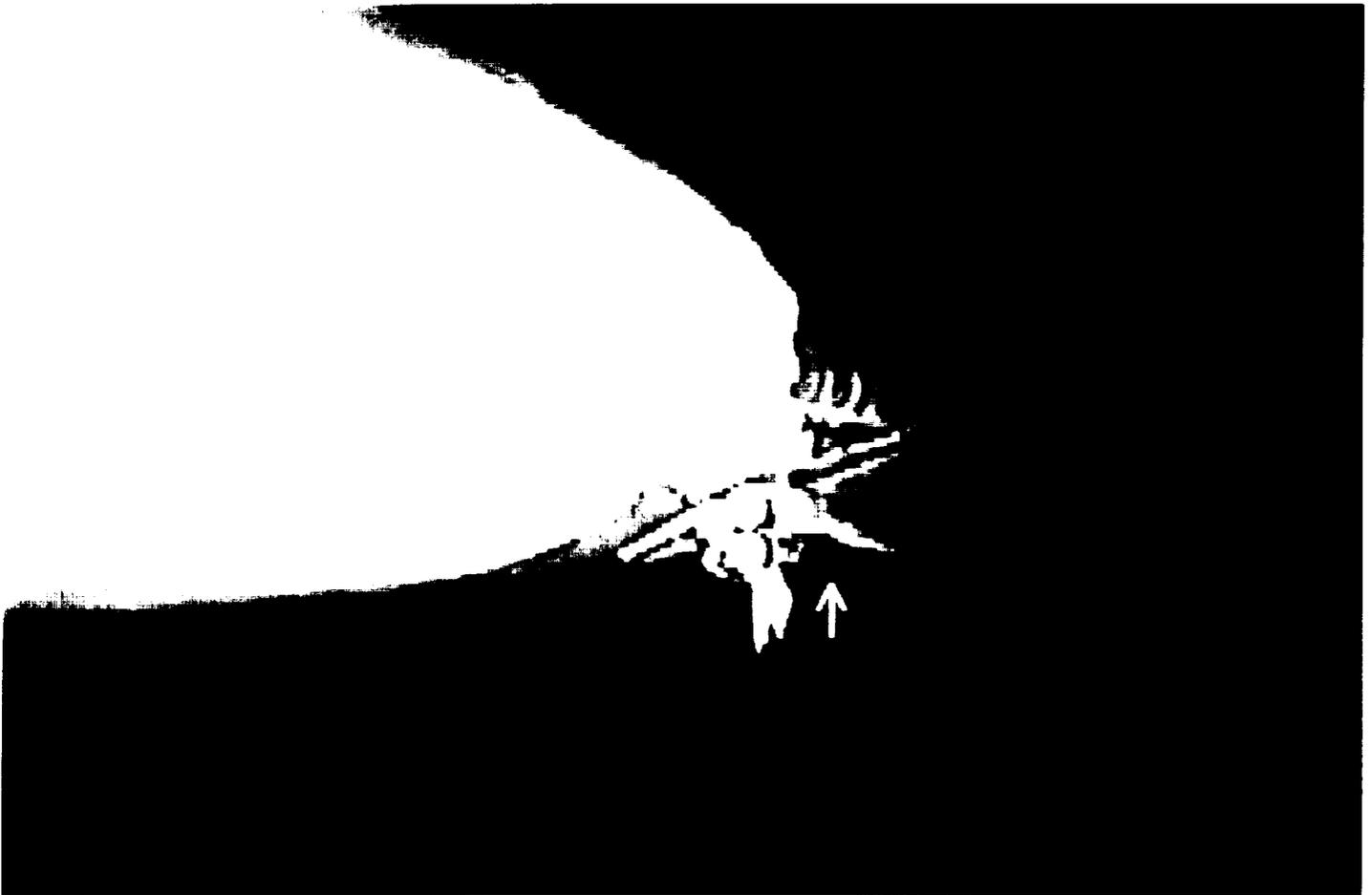
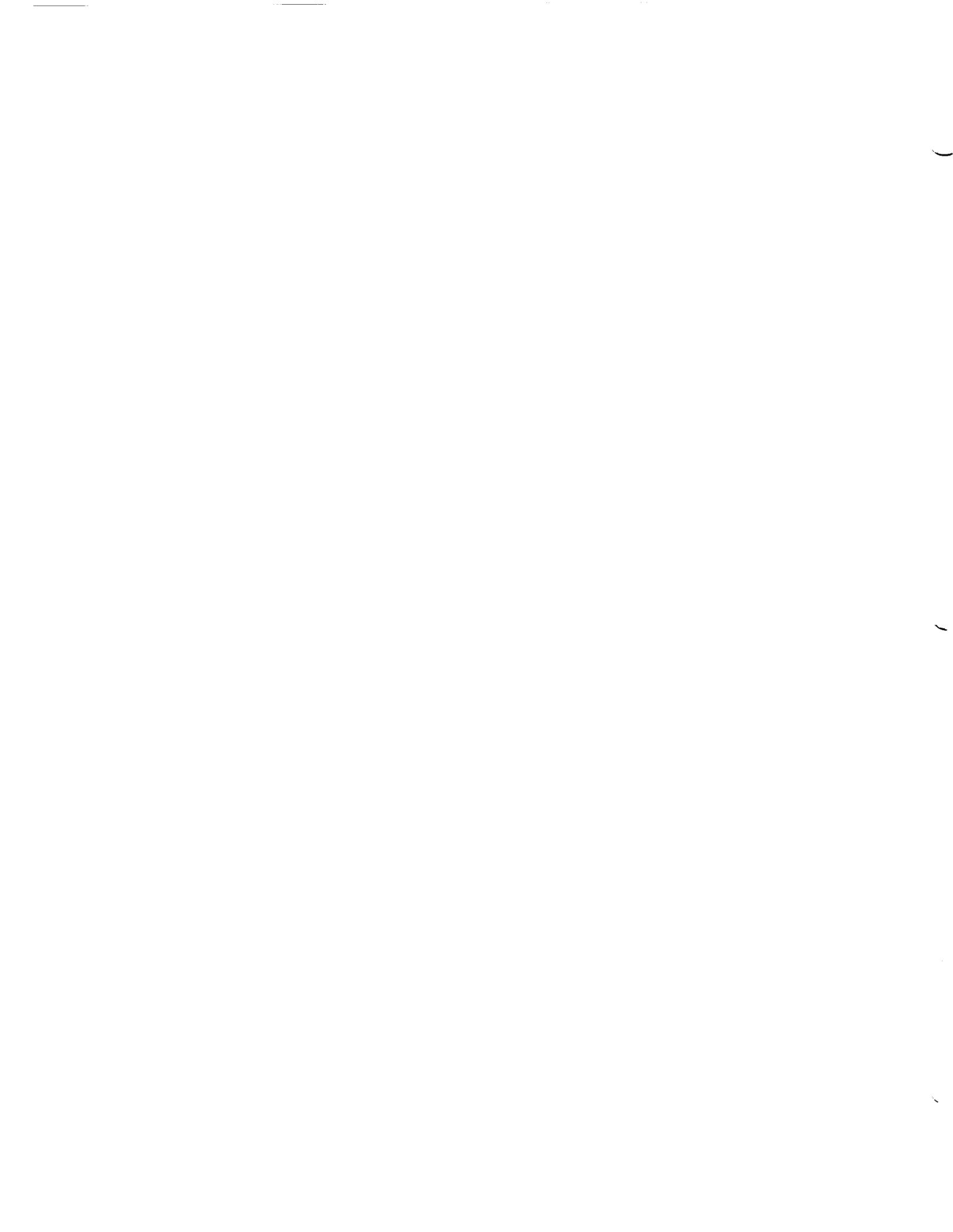


Photo 16: Debris Object Near OMS Pod

A debris object appeared in the vicinity of the left OMS pod at 204:04:33:00.245 UTC, but identification and origin could not be determined.



6.1.2 SRB CAMERA VIDEO SUMMARY

An 8mm video camera was flown in each SRB forward skirt for the purpose of documenting any TPS loss from the ET-99 thrust panels from launch through SRB separation.

-Y Side General Notes

Camera provided a good view with the available lighting. However, glare and shadows made precise divot identification difficult.

There were significantly fewer divots in the vented area compared to the non-vented area. Divots in the vented area were generally smaller than divots in the non-vented area.

Divots in both vented and non-vented areas appeared shallow. No primed substrate was visible.

Most divots occurred near the rib sidewalls and top edges. Very few divots occurred in the valleys and were smaller in size than divots in the rib sidewalls/top edges.

Numerous divots were noted outside the thrust panel in the stringer section.

Vapor vented from the outboard side of a rib at 101 seconds, but without detectable foam loss.

Divots in the circumferential ramps could not be confirmed.

-Y Side Divot Count

Mission Elapsed Time, MET	Event
96 seconds	first divot appeared
96-112 seconds	20 divots 15 stringer 5 non-vented, thrust panel 0 vented, thrust panel
112-123 seconds	150 divots 60 stringer 75 non-vented, thrust panel (10 divots, 1-2.5 inches) 15 vented, thrust panel
after SRB separation	less than 5 divots aft of Xt-1013

A second, more detailed, review of the -Y camera was initiated with the objective of obtaining a divot count for each one-second time interval. This visual review analyzed individual frames identifying and recording changes from frame to frame. This task was difficult due to the lighting conditions and the presence of as-sprayed rind on the corners of the longitudinal ribs. Sometimes the change in color of the rind gave the appearance of a divot.

The first divot appeared at 96 seconds and was located in the vented rib area. The largest divot occurred about 118 seconds, measured 4 inches in length, and was located in the non-vented rib area. No defects were observed in the circumferential ramp area and one divot was noted in the circumferential longitudinal rib area. The divot count numbers in the more detailed review have been revised when compared to the first preliminary review. An increase in stringer divots was confirmed and a decrease in divots in the rib area was recorded. This was caused by the rib edge defects being included in the preliminary report. Two large divots, one 18" x 9" with substrate exposed and a second divot 8-inches in diameter, were observed after SRB separation in the LH2 to intertank flange closeout extending into the LH2 tank NCFI.

+Y Side General Notes

Camera provided good view with the available lighting. However, glare and shadows made precise divot identification difficult.

There were significantly fewer divots in the vented thrust panel area compared to the non-vented stringer area.

Divots appeared shallow. No primed substrate was visible.

Most divots occurred near the rib sidewalls and top edges. Very few valley divots were observed and were smaller in size than divots in the rib sidewalls/top edges.

Numerous divots occurred outside the thrust panel in the stringer section.

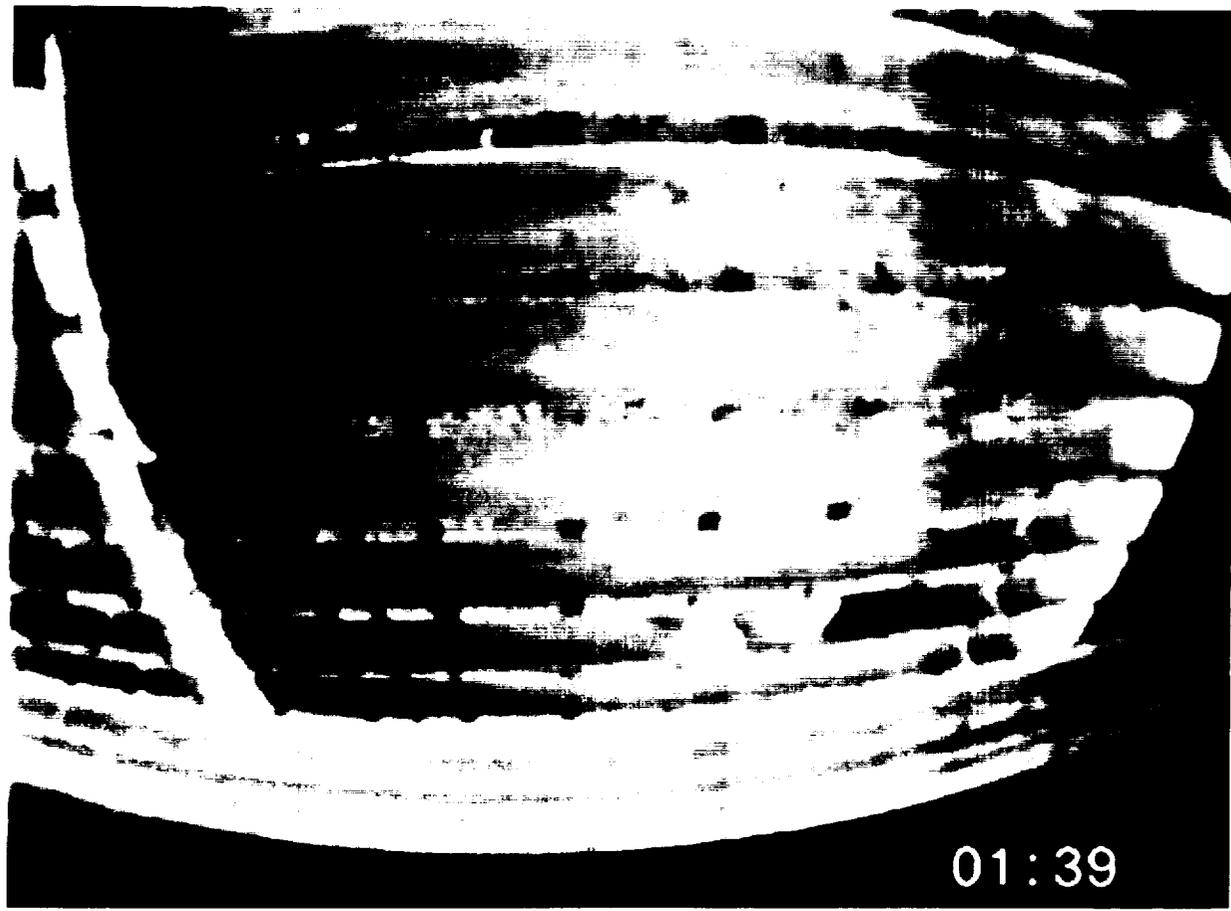
+Y Side Divot Count

Mission Elapsed Time, MET	Event
92 seconds	first divot appeared
92-102 seconds	8 divots 8 stringer 0 vented, thrust panel
102-112 seconds	32 divots 25 stringer 5 vented, thrust panel 2 circumferential ramp
112-123 seconds	117 divots 70 stringer 45 vented, thrust panel 2 circumferential ramp
after SRB separation	less than 8 divots aft of Xt-1013 numerous stringer divots observed on intertank -Z side

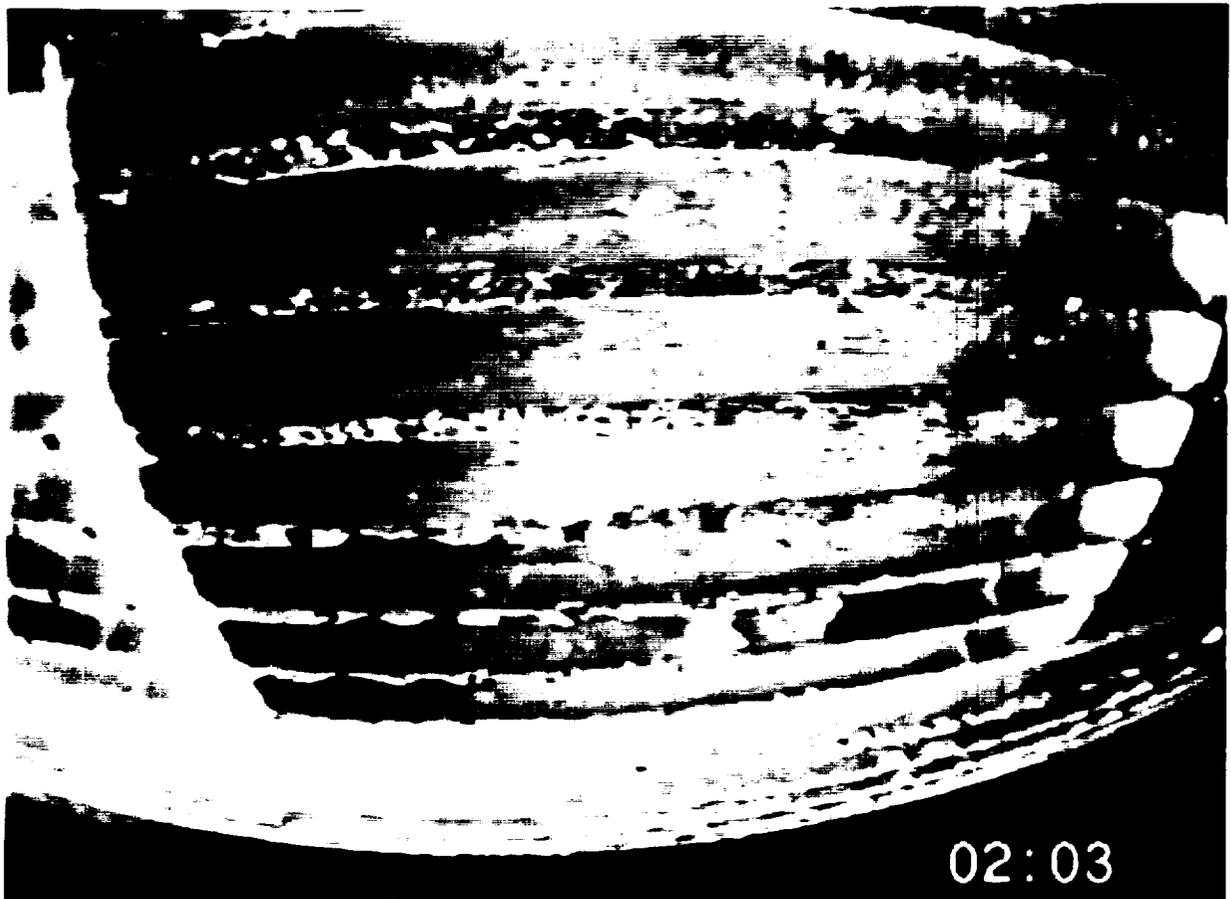
A second, more detailed, review of the -Y camera was initiated with the objective of obtaining a divot count for each one-second time interval. This visual review analyzed individual frames identifying and recording changes from frame to frame. This task was difficult due to the lighting conditions and the presence of as-sprayed rind on the corners of the longitudinal ribs. Sometimes the change in color of the rind gave the appearance of a divot.

The first divot appeared at 92 seconds and was located in the stringer area. The largest divot occurred in the stringer area and measured approximately 3 inches in length. The divots observed in the vented rib area were all very small (approximately 0.3 inches or less). The two circumferential ramp divots described in the preliminary report could not be confirmed. The number of stringer and rib divots in the more detailed review was revised downward when compared to the first preliminary review. Numerous divots were observed on the intertank -Z side after SRB separation.

Based on review of the STS-93 and STS-95 thrust panel divot count data, stringer venting should be certified as soon as possible. The circumferential vent test area did not show a performance difference when compared to the non-vented circumferential area. Neither of these areas showed a tendency to divot on STS-93. The circumferential ramps tend to behave similar to valleys based on the results of the STS-93 and STS-95 video reviews. Certification of the ramp areas should be a lower priority, or even deferred, until certification of the stringer sections is complete.



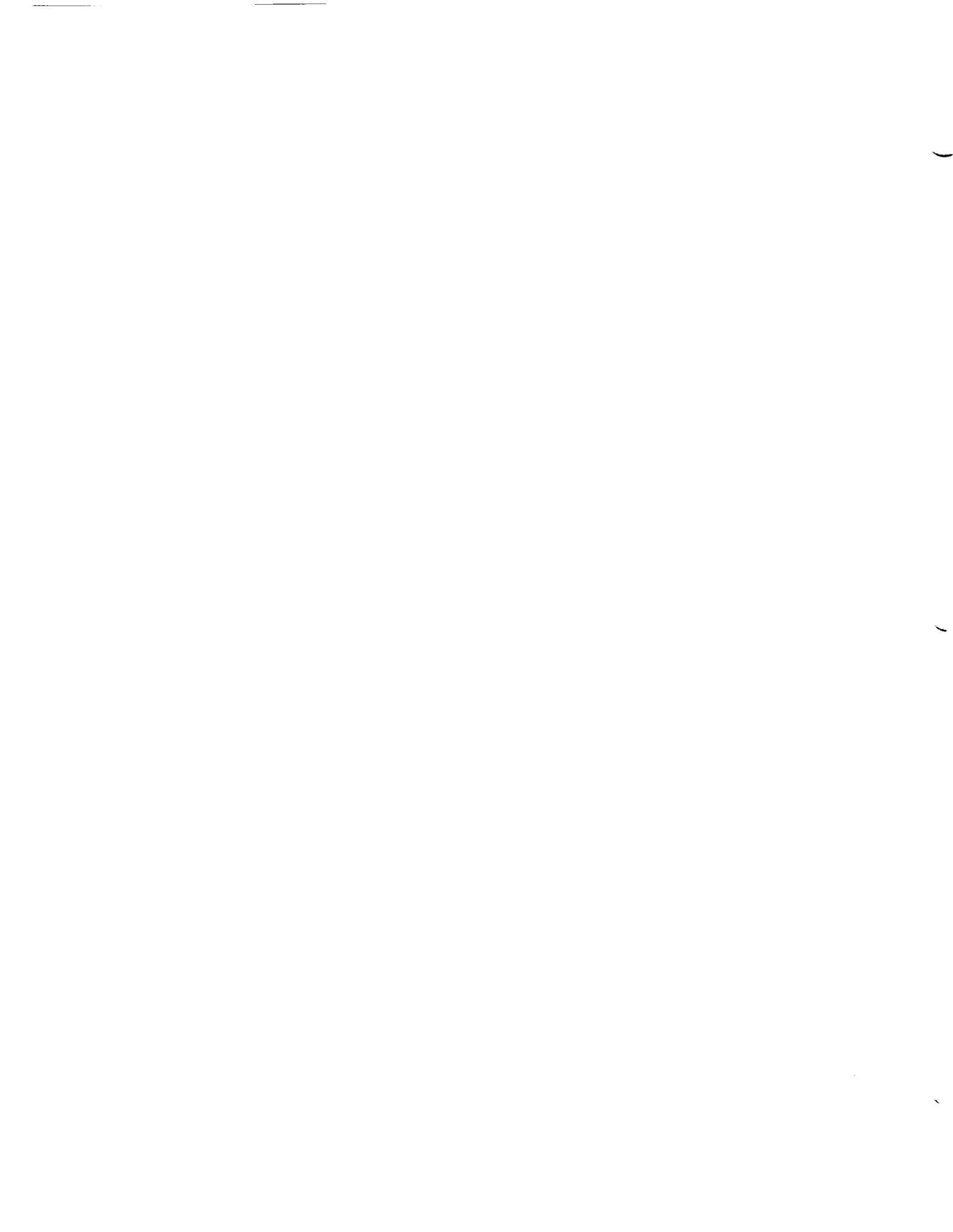
01:39



02:03

Photo 17: -Y Thrust Panel TPS

Views from SRB video camera just after divoting of -Y thrust panel began and just prior to SRB separation. More divots appeared in the non-vented areas than in the vented section. Also note divots outside of the thrust panel in the stringer areas.



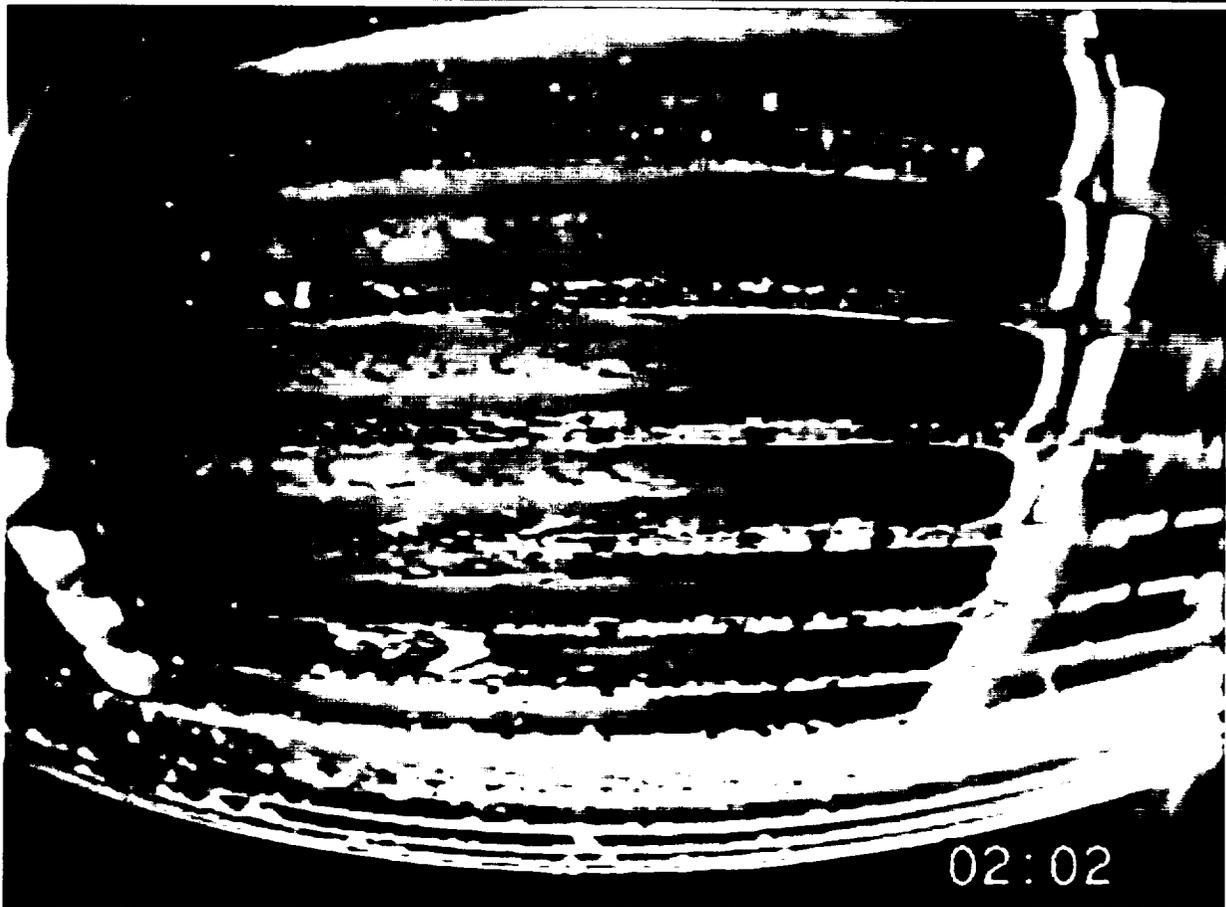
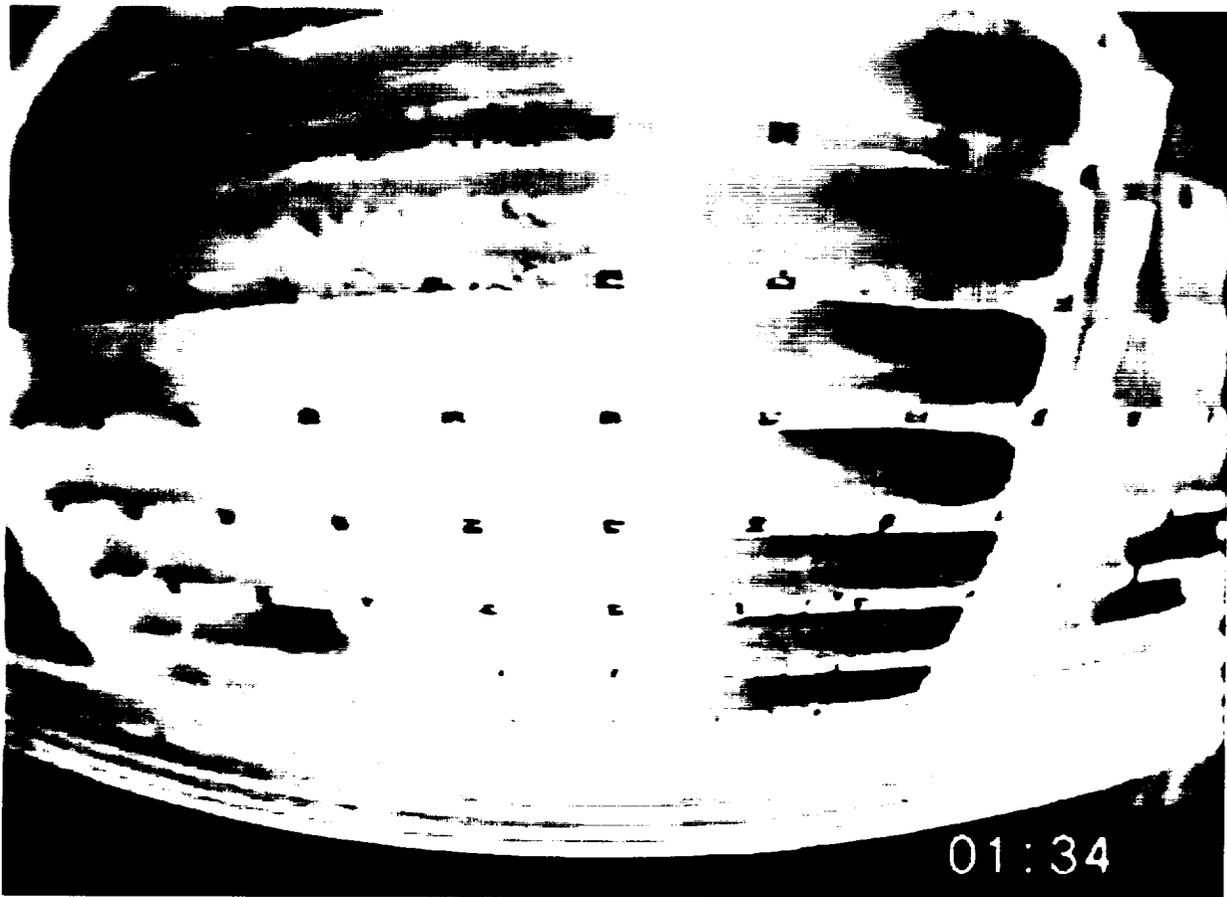
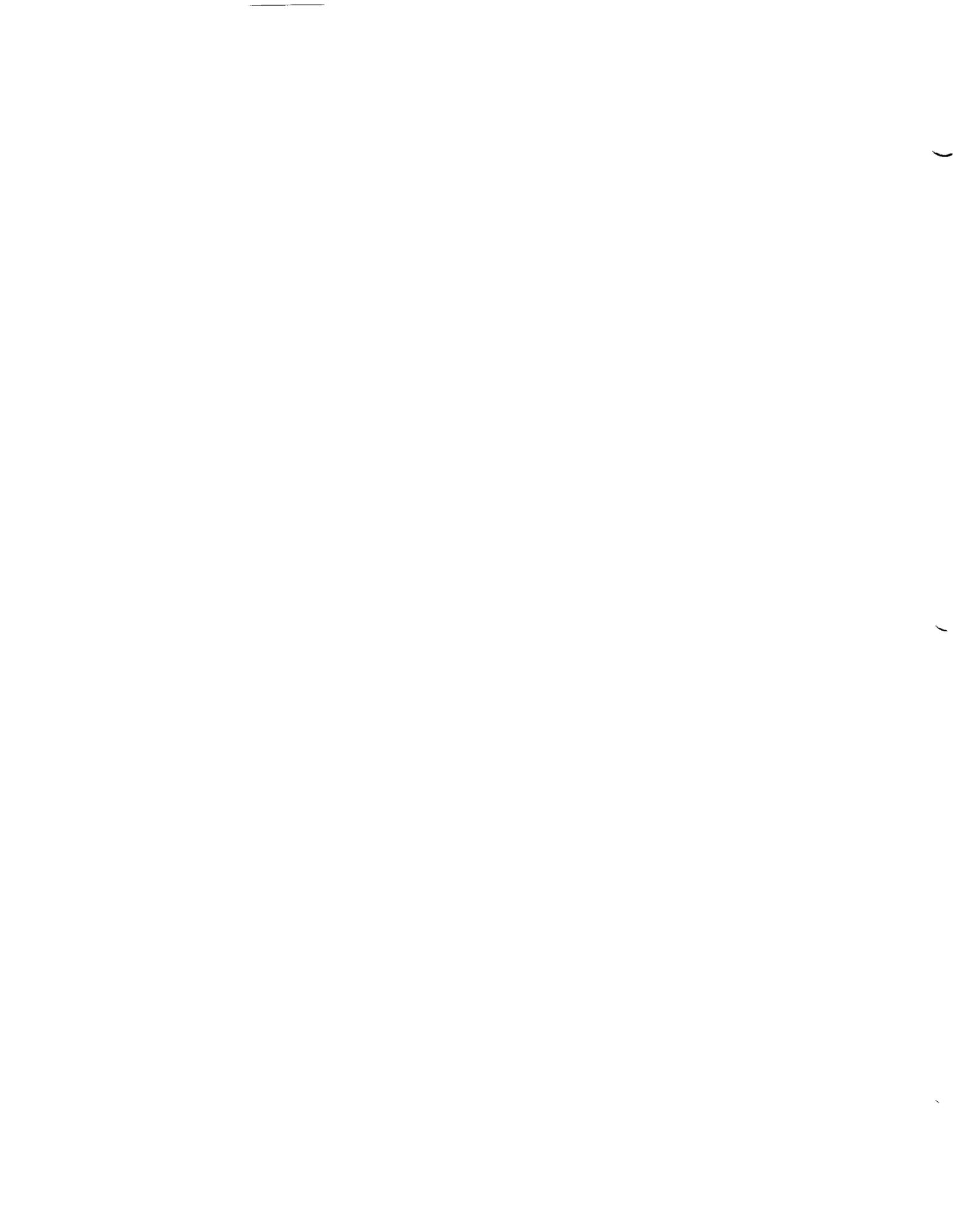


Photo 18: +Y Thrust Panel TPS

Views from SRB video camera just after divoting of +Y thrust panel began and just prior to SRB separation. There were significantly fewer divots in the vented thrust panel area compared to the non-vented stringer area.



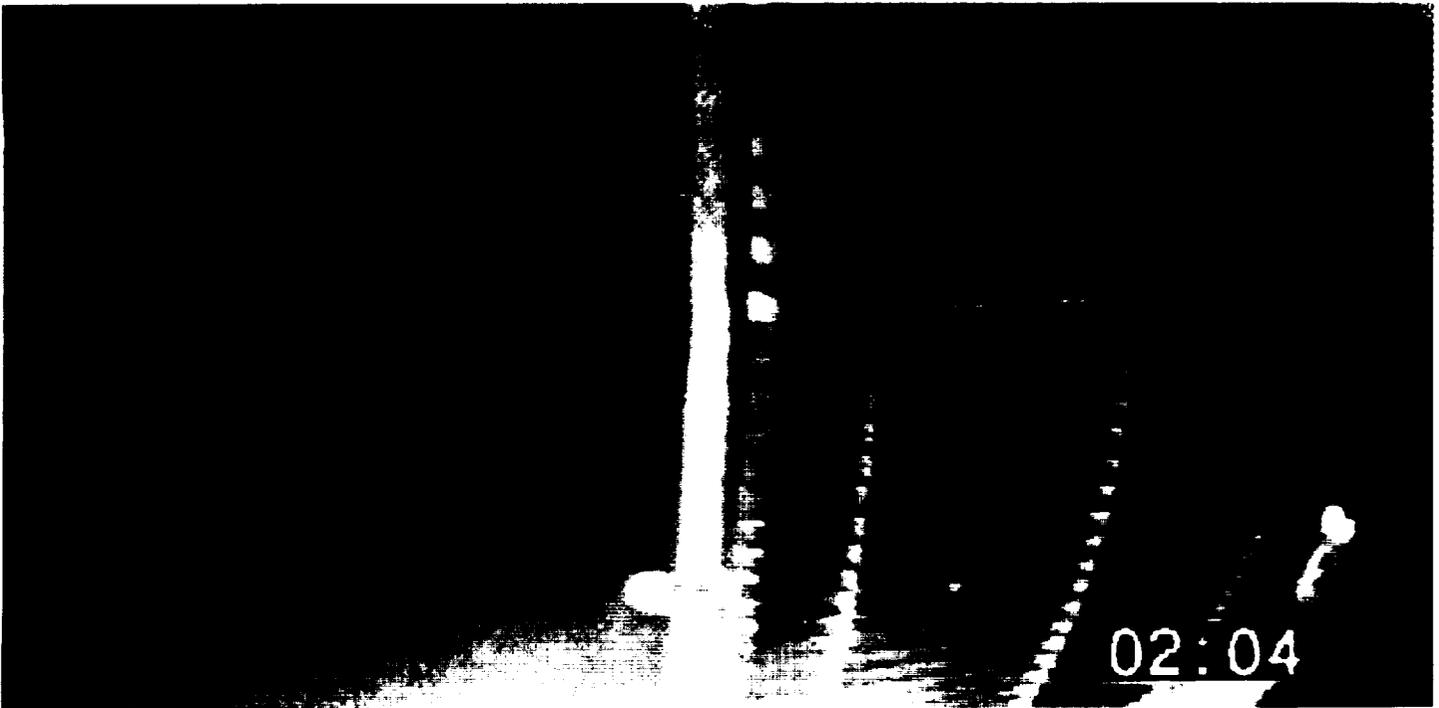
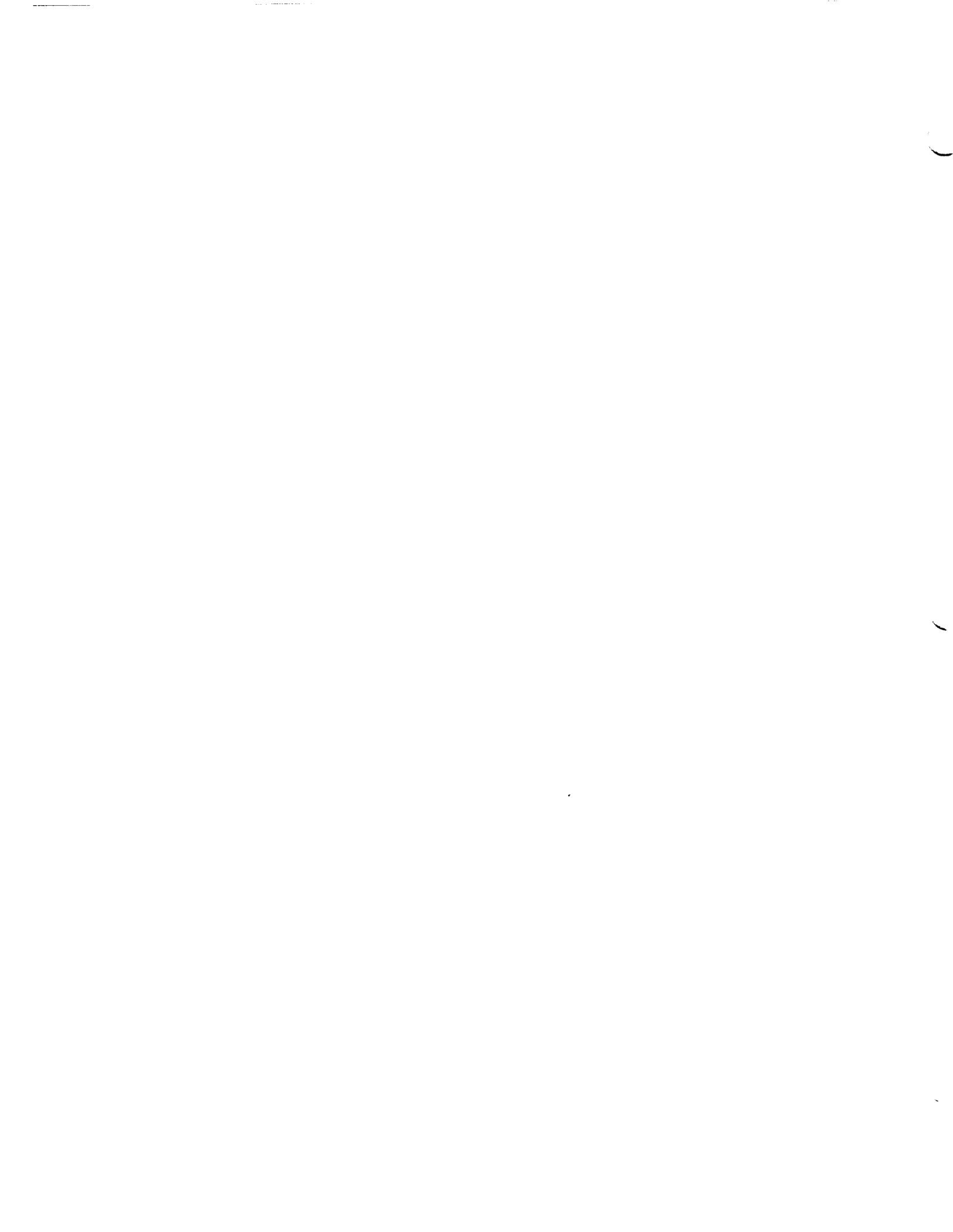


Photo 19: ET LH2 Tank -Z Flange Closeout

Two large divots, one 18" x 9" with substrate exposed and a second divot 8-inches in diameter, were observed after SRB separation in the LH2-to-intertank flange closeout extending into the LH2 tank NCFI.



6.2 ON-ORBIT FILM AND VIDEO SUMMARY

OV-102 was equipped to carry ET/ORB umbilical cameras: 16mm motion picture with 5mm lens and 16mm motion picture with 10mm lens from the LH2 side; 35mm still views from the LO2 side. The flight crew provided 35 hand held still images and approximately 4 minutes of video from the camcorder. The manual pitch maneuver from the heads-up position was performed to bring the tank into view through the overhead windows

6.2.1 ET/ORB Umbilical Films

SRB separation from the External Tank appeared nominal. Illumination from the SRB exhaust plumes showed typical erosion/flaking of thin layers of TPS from the aft surfaces of the -Y upper strut fairing, -Y vertical strut, and LH2 ET/ORB cable tray. TPS charring and "popcorn" divoting of the aft dome was also typical.

The wide angle ET/ORB LH2 umbilical camera provided a view of the left SRB falling away from the ET. However, the illumination had diminished by the time the forward skirt came into view. Consequently, no detail on frustum/nose cap TPS could be discerned.

ET separation from the Orbiter was not visible due to the night launch with the exception of a very short time period while a portion of the aft dome was silhouetted by RCS thruster firings. Although the flight crew later obtained some hand held images of the ET by waiting until the terminator was crossed, the 16mm film in the umbilical cameras had been expended by this time.

6.2.2 Crew Hand Held Still Images/Video

Thirty-five hand-held still images and almost four minutes of video were acquired by the crew. However, distance from the Orbiter was greater than usual because the crew waited for the ET to cross the terminator and be illuminated by sunlight (26-29 minutes MET). No significant or obvious anomalies were detected

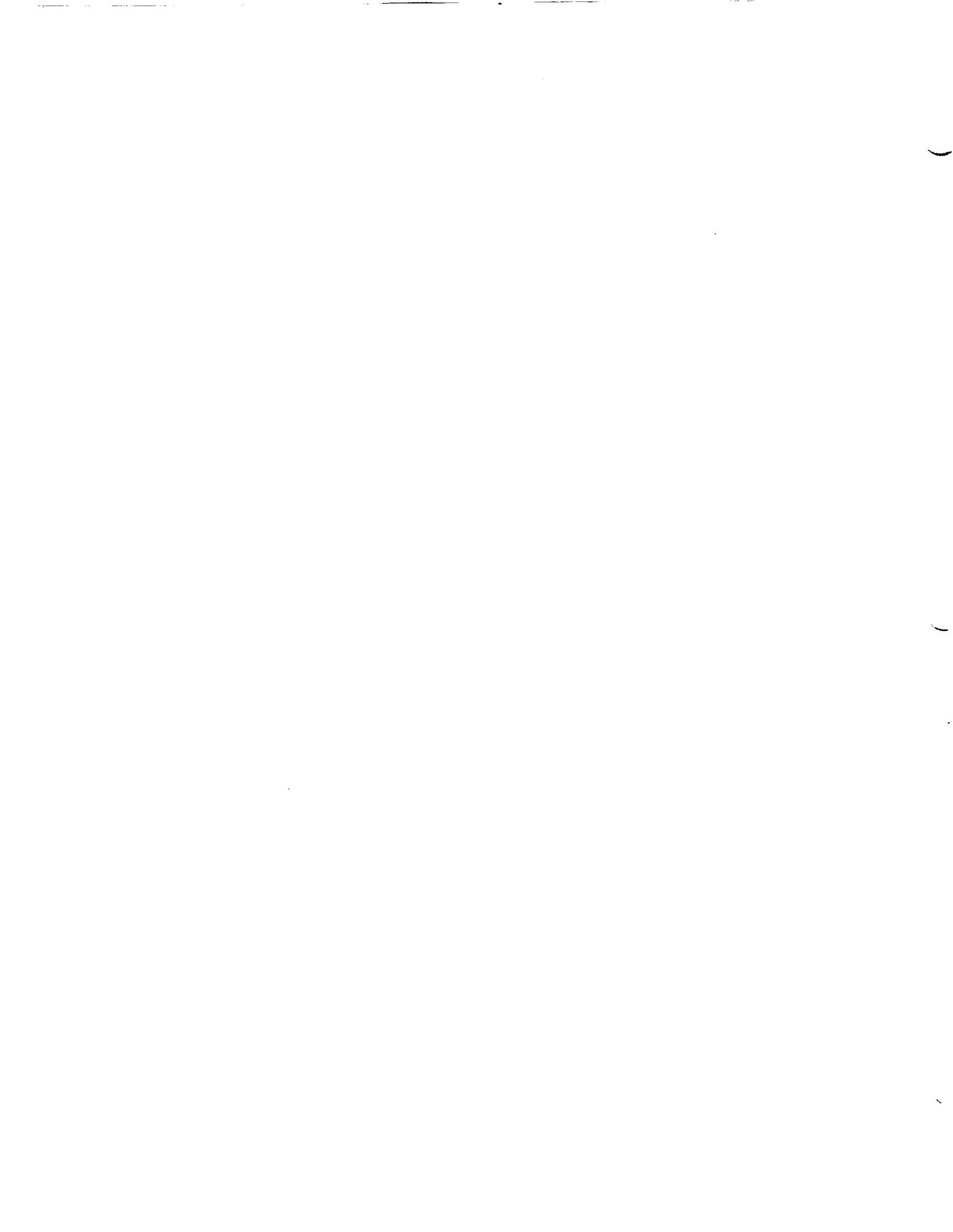
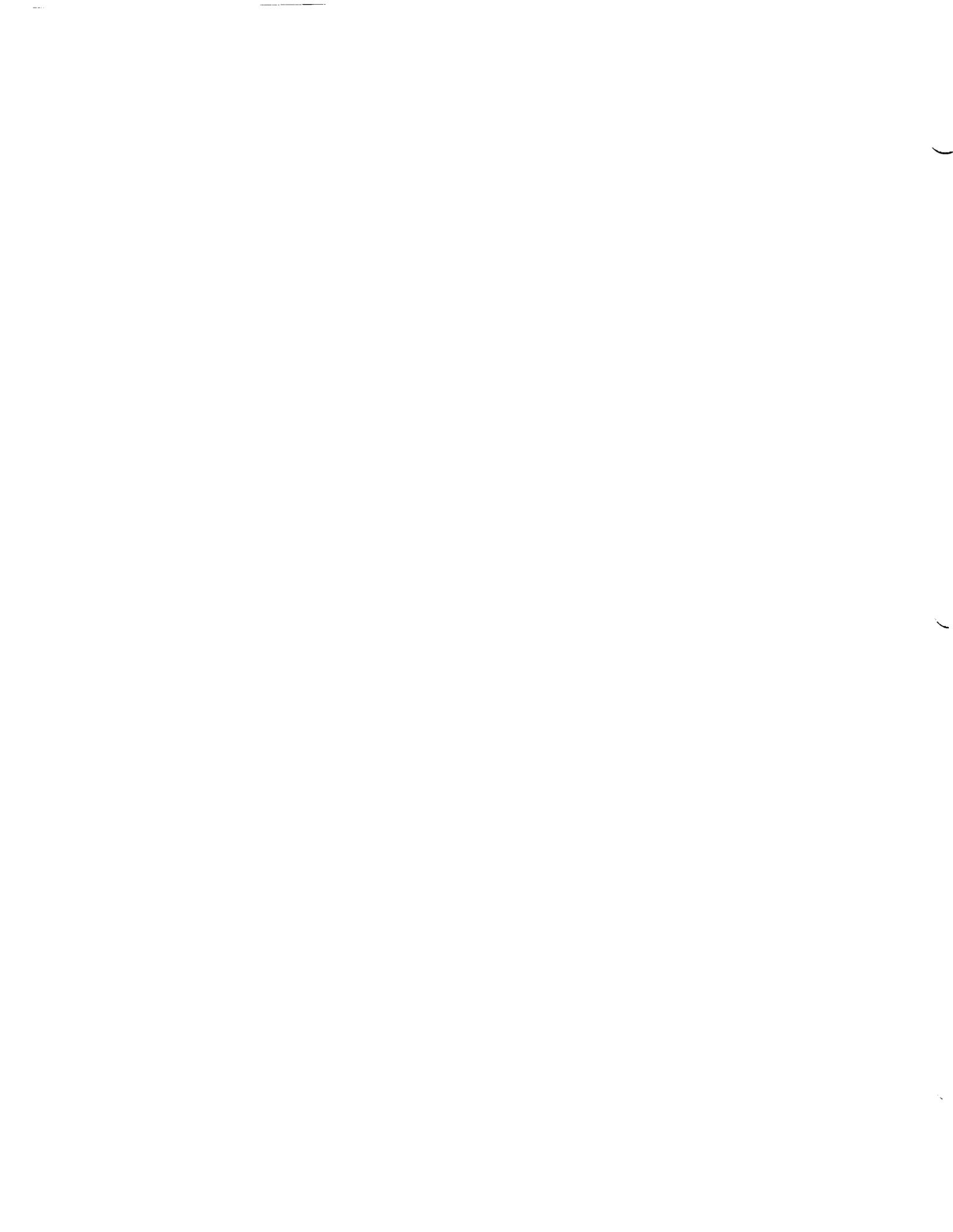




Photo 20: External Tank after Separation from Orbiter

However, distance from the Orbiter was greater than usual because the crew waited for the ET to cross the terminator and be illuminated by sunlight (26-29 minutes MET). No significant or obvious anomalies were detected



6.3 LANDING FILM AND VIDEO SUMMARY

A total of 19 films and videos, which included eight 35mm large format films and eleven videos, were reviewed. There was not much engineering detail due to the dark conditions of a night landing.

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

Drag chute deployment and jettison appeared normal. No anomalies were detected from touch down through rollout.

7.0 SRB POST FLIGHT/RETRIEVAL DEBRIS ASSESSMENT

The BI-097 Solid Rocket Boosters were inspected for debris damage and debris sources at CCAS Hangar AF on 26 July 1999.

Both frustums were in excellent condition. No TPS was missing and no debonds/unbonds were detected over fasteners or acreage. All eight BSM aero heat shield covers had locked in the fully opened position. There were four (4) small areas (size 1.0"x1.0" to 1.0"x2.0") of damaged, missing and/or indented Hypalon and BTA on the molded insulation around the BSM door locations on each frustum. All visible fracture surfaces were slightly darkened or sooted. The damage was caused when the BSM covers impacted the molded insulation.

The forward skirts exhibited no debonds or missing TPS. RSS antennae covers/phenolic base plates were intact. All primary frustum severance ring pins and retainer clips were intact.

The Field Joint Protection System (FJPS) and the System Tunnel Covers closeouts were generally in good condition with no unbonds. The Hypalon topcoat exhibited typical blistering over BTA insulation close-outs.

Separation of the aft ET/SRB struts appeared normal. All six aft booster stiffener rings generally were in good condition with the exception of the LH forward stiffener ring, which was broken off from 206 to 278 degrees by splash down loads. Protective foam aft of both IEA's was missing though the exposed substrate was clean.

TPS on the external surface of both aft skirts was in good condition with typical blistering over BTA insulation closeouts.

The holddown post Debris Containment Systems (DCS) appeared to have functioned normally. The plungers on HDP's #1 and #5 were not fully seated and obstructed by ordnance fragments. Launch film review revealed no debris exiting the bores. There was no evidence of a stud hang-up on this launch.

Overall, the external condition of both SRB's was excellent.

8.0 ORBITER POST LANDING DEBRIS ASSESSMENT

After the 11:20 p.m. local/eastern time landing on 27 July 1999, a post landing inspection of OV-102 Columbia was conducted at the Kennedy Space Center on SLF runway 33 and in the Orbiter Processing Facility bay #3. This inspection was performed to identify debris impact damage and, if possible, debris sources.

The area inside the SSME #3 nozzle where the hot wall leak had occurred prior to liftoff was readily visible by a rupture and surrounding discoloration in each of three adjacent cooling tubes. A LO2 post deactivating pin was found to be missing in post flight inspections and believed to be the debris object that impacted the hot-wall cooling tubes causing the rupture.

The Orbiter TPS sustained a total of 208 hits, of which 49 had a major dimension of 1-inch or larger (reference Figures 1-4). This total does not include the numerous hits on the base heat shield attributed to SSME vibration/acoustics and exhaust plume recirculation.

The following table breaks down the STS-93 Orbiter debris damage hits by area:

	<u>HITS > 1"</u>	<u>TOTAL HITS</u>
Lower surface	42	161
Upper surface	0	4
Window Area	5	21
Right side	1	8
Left side	1	5
Right OMS Pod	0	3
Left OMS Pod	0	6
TOTALS	49	208

The Orbiter lower surface sustained 161 total hits, of which 42 had a major dimension of 1-inch or larger. Most of this damage was concentrated from the nose gear to the main landing gear wheel wells on both left and right chines. The outboard damage sites on the chines followed a similar location/damage pattern documented on STS-86, -87, -89, -90, -91, -95, -88, and -96.

Orbiter lower surface tile damage statistics since STS-86 are shown here:

	STS-86	STS-87	STS-89	STS-90	STS-91	STS-95	STS-88	STS-96	STS-93
Lower Surface (total hits)	100	244	95	76	145	139	80	160	161
Lower Surface (hits >1-inch)	27	109	38	11	45	42	21	66	42
Longest damage site (inches)	7	15	2.8	3.0	3.0	4.0	4.5	4.0	6.0
Deepest damage site (inches)	0.4	1.5	0.2	0.25	0.5	0.4	0.5	0.5	0.5

The largest lower surface tile damage site, located on the right chine, measured 6-inches long by 2-inches wide by 0.5-inches deep.

Otherwise, tile damage sites around the LH2 and LO2 ET/ORB umbilicals were typical. This damage is usually caused by impacts from umbilical ice or shredded pieces of umbilical purge barrier material flapping in the airstream.

The main landing gear tires were reported to be in good condition for a landing on the KSC concrete runway. Three of four main gear tires exhibited ply undercutting.

ET/Orbiter separation devices EO-1, EO-2, and EO-3 functioned normally. No ordnance fragments were found on the runway beneath the umbilicals. The EO-2 and EO-3 fitting retainer springs appeared to be in nominal configuration. No umbilical closeout foam or white RTV dam material adhered to the umbilical plate near the LH2 recirculation line disconnect.

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.

No unusual tile damage occurred on the leading edges of the OMS pods and vertical stabilizer. A 2-inch x 0.75-inch x 0.25-inch deep damage site on the +Y side of the vertical stabilizer near the root attach point may have been caused by SSME start-up vibration.

Hazing and streaking of forward-facing Orbiter windows was moderate. Damage sites on the window perimeter tiles were less than usual in quantity and size.

The post landing walkdown of Runway 33 was performed immediately after landing. No debris concerns were identified. All components of the drag chute were recovered and appeared to have functioned normally. Both reefing line cutter pyrotechnic devices were expended.

In summary, both the total number of Orbiter TPS debris hits and the number of hits 1-inch or larger is significantly greater than the cumulative fleet average when compared to previous missions. Since the damage pattern and majority of hits are related to the loss of TPS from the ET thrust panels, and therefore an identified debris source, these data will not be added to the cumulative table of random hits and averages, but are reflected in the Upper Control Limit charts (Figures 5-7). IFA STS-87-T-01 documenting loss of ET foam is still open.

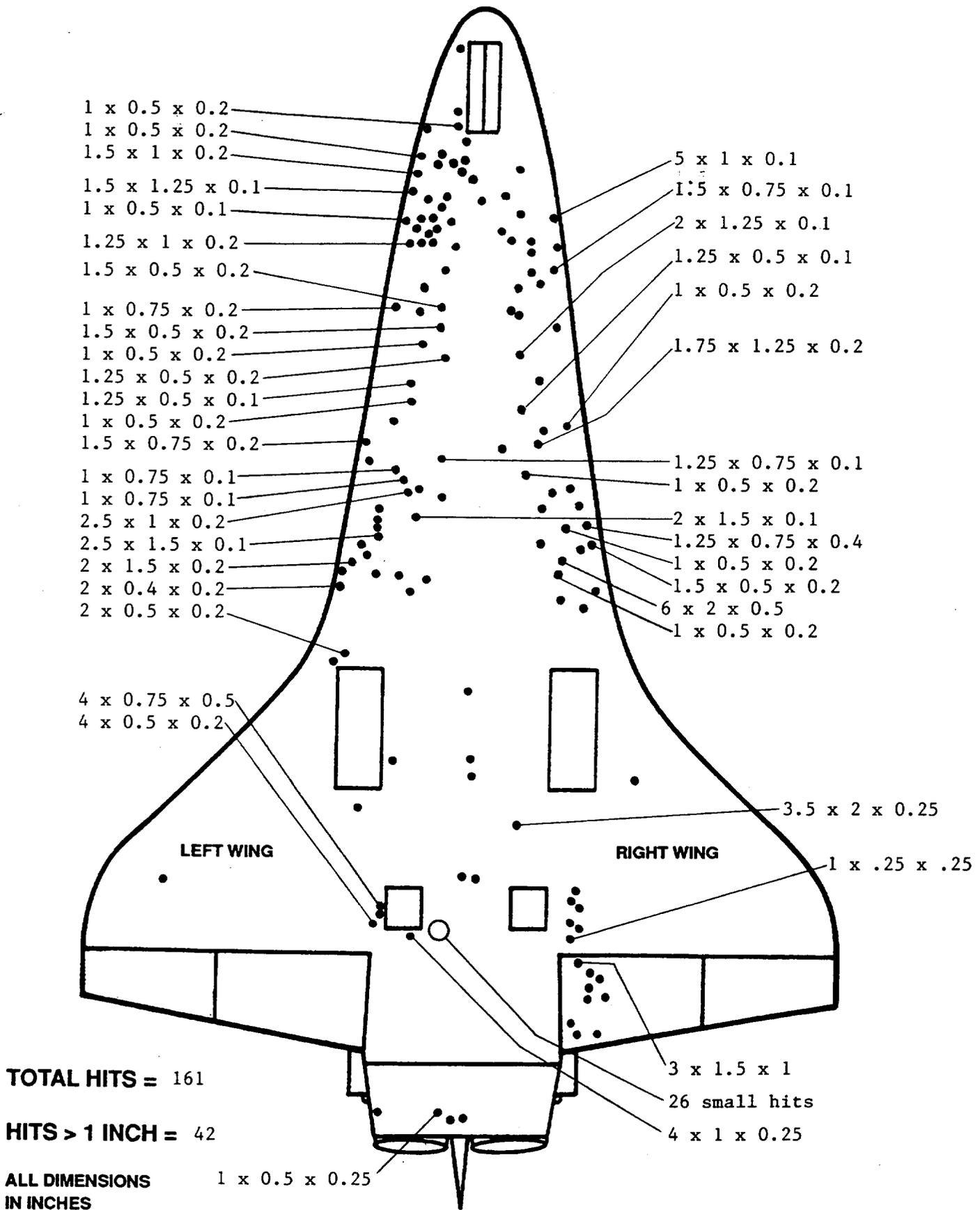


Figure 1: Orbiter Lower Surface Debris Damage Map

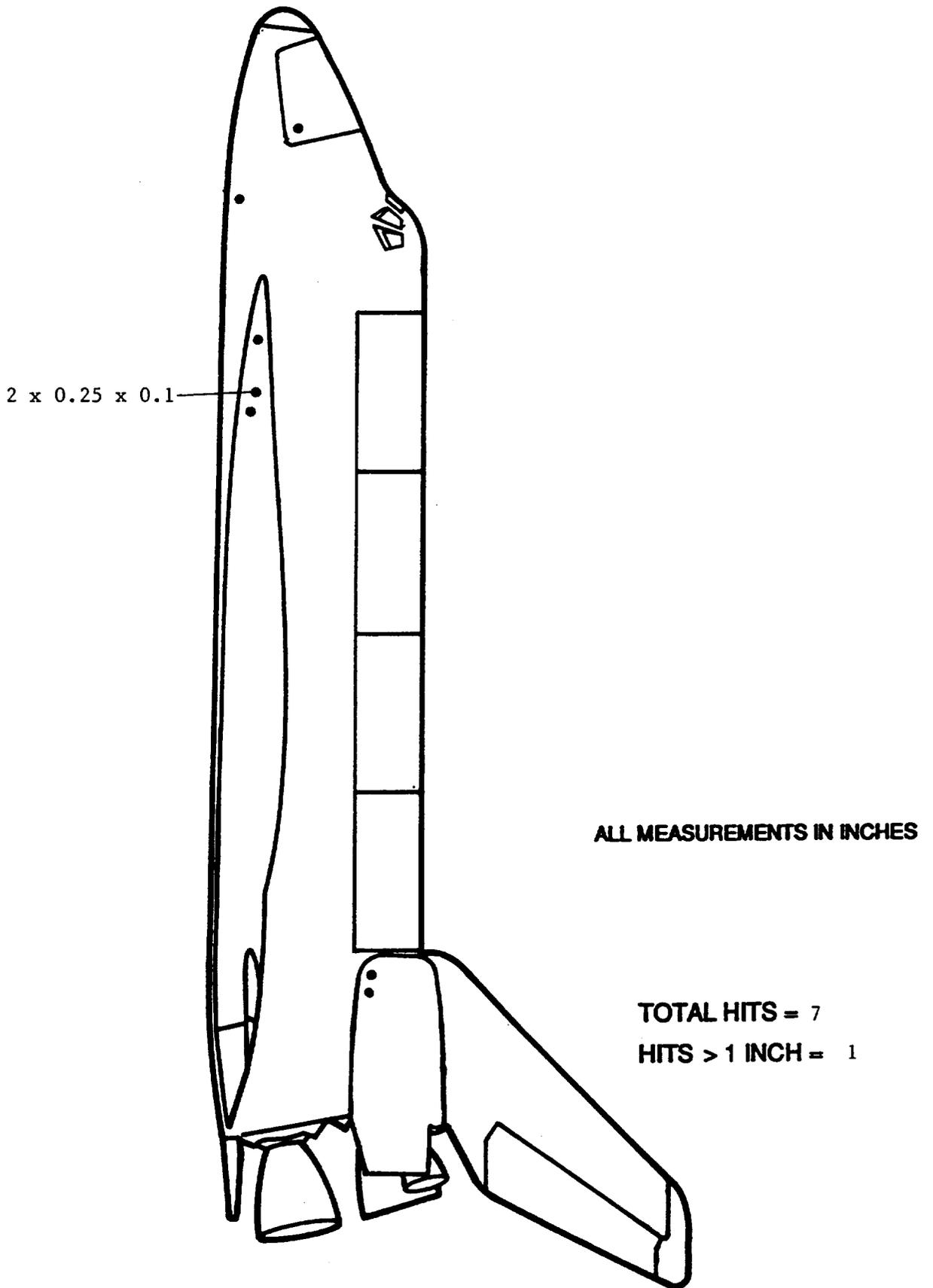
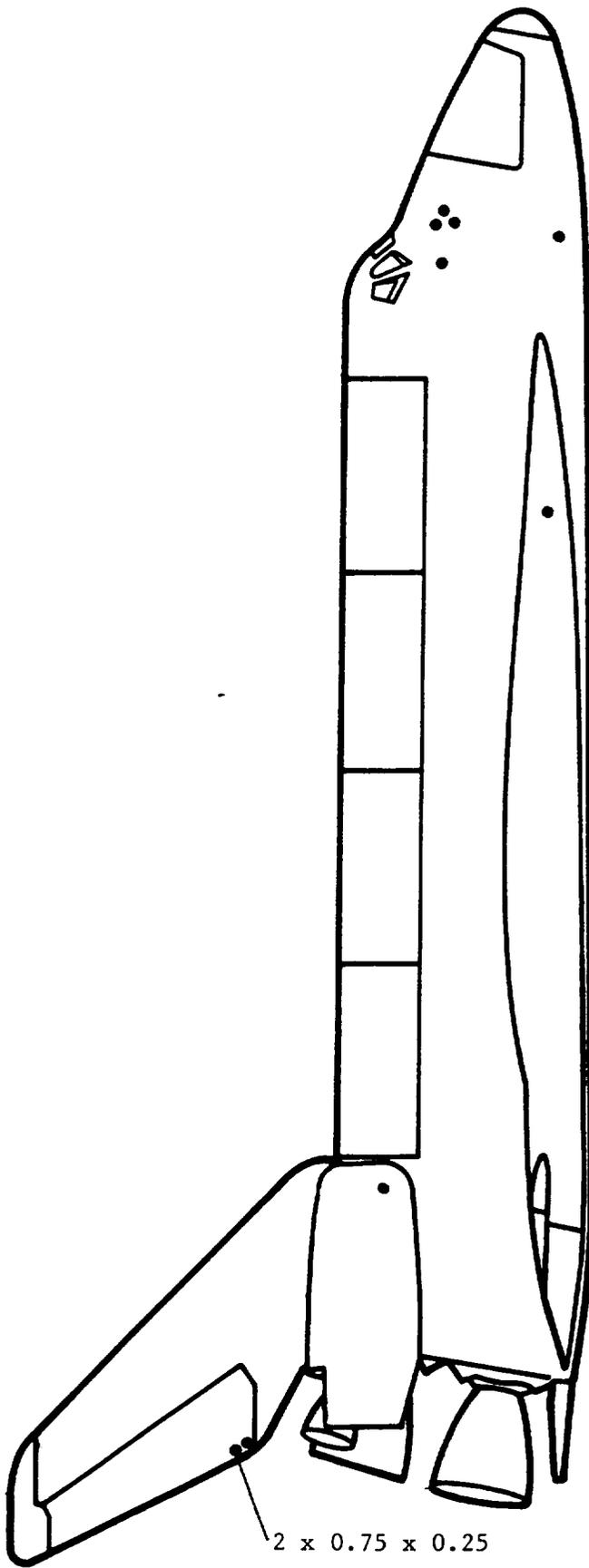


Figure 2: Orbiter Left Side Debris Damage Map



TOTAL HITS = 9
HITS > 1 INCH = 1

Figure 3: Orbiter Right Side Debris Damage Map

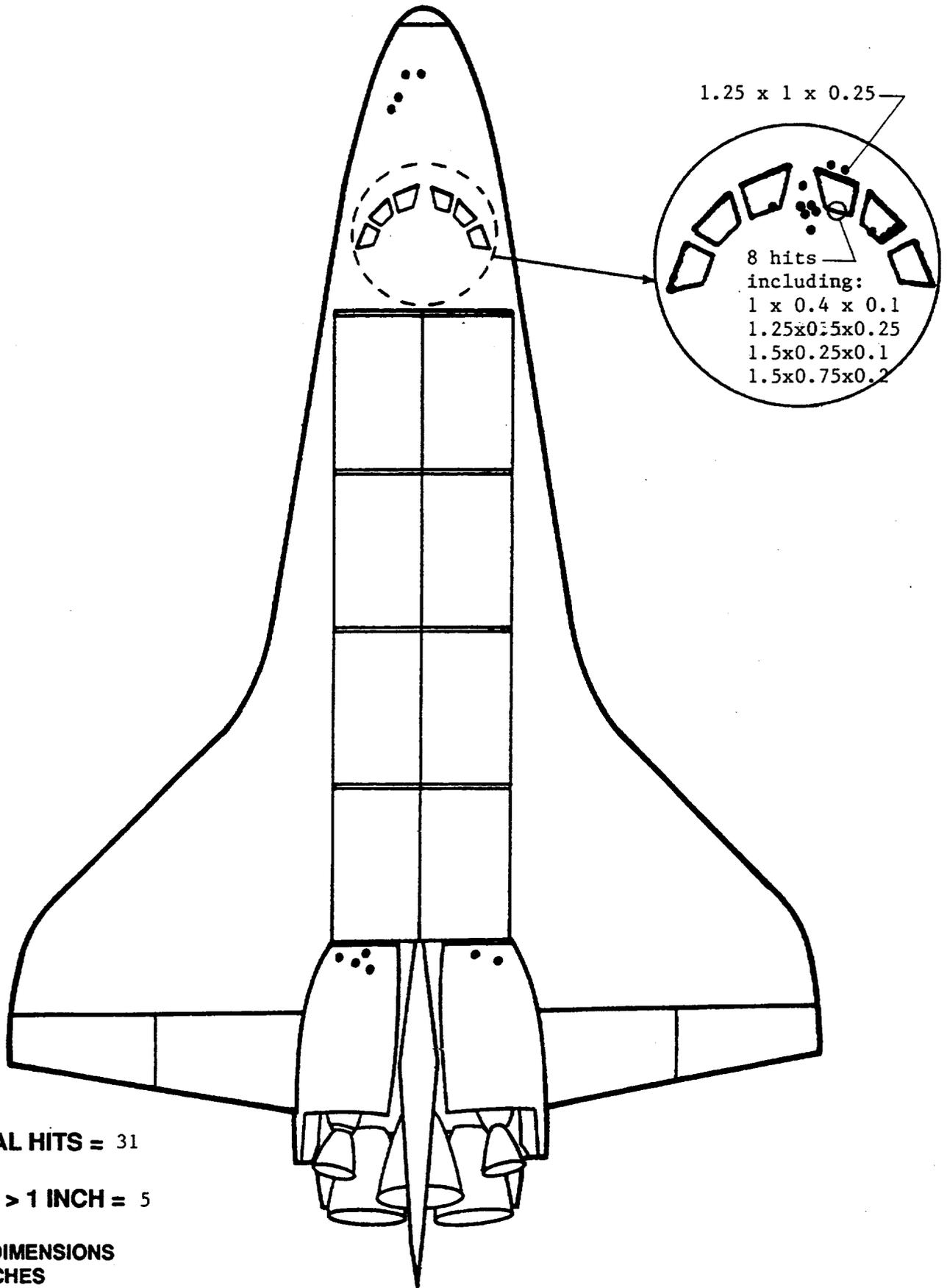


Figure 4: Orbiter Upper Surface Debris Damage Map

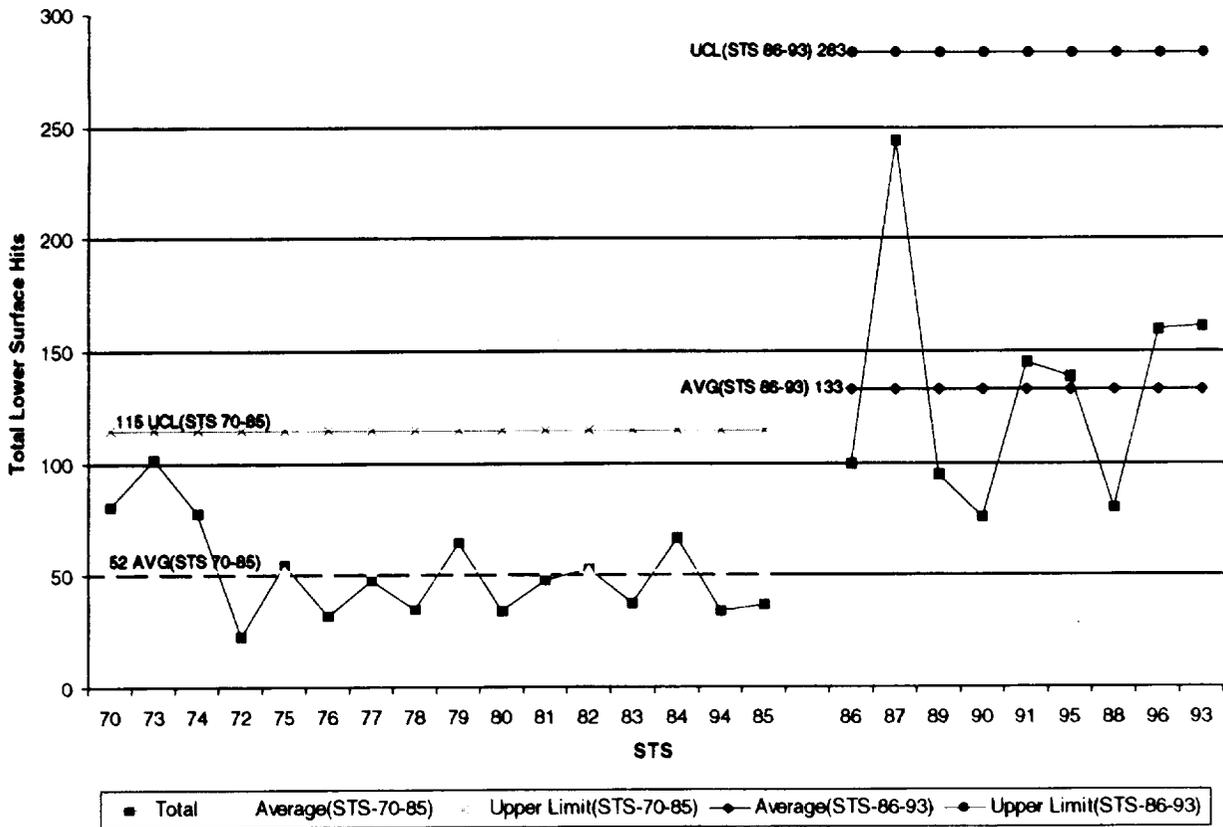
	LOWER SURFACE			ENTIRE SURFACE			LOWER SURFACE			ENTIRE SURFACE		
	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS
STS-6	21	89	36	120	STS-55	10	128	13	143			
STS-8	3	29	7	56	STS-57	10	75	12	106			
STS-9 (41-A)	9	49	14	58	STS-51	8	100	18	154			
STS-11 (41-B)	11	19	34	63	STS-58	23	78	26	155			
STS-13 (41-C)	5	27	8	36	STS-61	7	59	13	120			
STS-14 (41-D)	10	44	30	111	STS-60	4	48	15	106			
STS-17 (41-G)	25	69	36	154	STS-62	7	36	16	97			
STS-19 (51-A)	14	66	20	87	STS-59	10	47	19	77			
STS-20 (51-C)	24	67	28	81	STS-65	17	123	21	151			
STS-27 (51-I)	21	96	33	141	STS-64	18	116	19	150			
STS-28 (51-J)	7	66	17	111	STS-68	9	59	15	110			
STS-30 (61-A)	24	129	34	183	STS-66	22	111	28	148			
STS-31 (61-B)	37	177	55	257	STS-63	7	84	14	125			
STS-32 (61-C)	20	134	39	193	STS-67	11	47	13	76			
STS-29	18	100	23	132	STS-71	24	149	25	164			
STS-28R	13	60	20	76	STS-70	5	81	9	127			
STS-34	17	51	18	53	STS-69	22	175	27	198			
STS-33R	21	107	21	118	STS-73	17	102	26	147			
STS-32R	13	111	15	120	STS-74	17	78	21	116			
STS-36	17	61	19	81	STS-72	3	23	6	55			
STS-31R	13	47	14	63	STS-75	11	55	17	96			
STS-41	13	64	16	76	STS-76	5	32	15	69			
STS-38	7	70	8	81	STS-77	15	48	17	81			
STS-35	15	132	17	147	STS-78	5	35	12	85			
STS-37	7	91	10	113	STS-79	8	65	11	103			
STS-39	14	217	16	238	STS-80	4	34	8	93			
STS-40	23	153	25	197	STS-81	14	48	15	100			
STS-43	24	122	25	131	STS-82	14	53	18	103			
STS-48	14	100	25	182	STS-83	7	38	13	81			
STS-44	6	74	9	101	STS-84	10	67	13	103			
STS-45	18	122	22	172	STS-94	11	34	12	90			
STS-49	6	55	11	114	STS-85	6	37	13	102			
STS-50	28	141	45	184								
STS-46	11	186	22	236								
STS-47	3	48	11	108	AVERAGE	13.3	83.2	19.6	124.3			
STS-52	6	152	16	290	SIGMA	7.1	43.9	9.5	51.9			
STS-53	11	145	23	240								
STS-54	14	80	14	131	STS-93	42	161	49	208			
STS-56	18	94	36	156								

MISSIONS STS-23,24,25,26,26R,27R,30R,42,86,87,89,90,91,95,88,96 AND 93 ARE NOT INCLUDED
SINCE THESE MISSIONS HAD SIGNIFICANT DAMAGE CAUSED BY KNOWN DEBRIS SOURCES

Figure 5: Orbiter Post Flight Debris Damage Summary



Orbiter Post Flight Debris Damage Lower Surface Total Hits



Orbiter Post Flight Debris Damage Lower Surface Hits > 1 inch

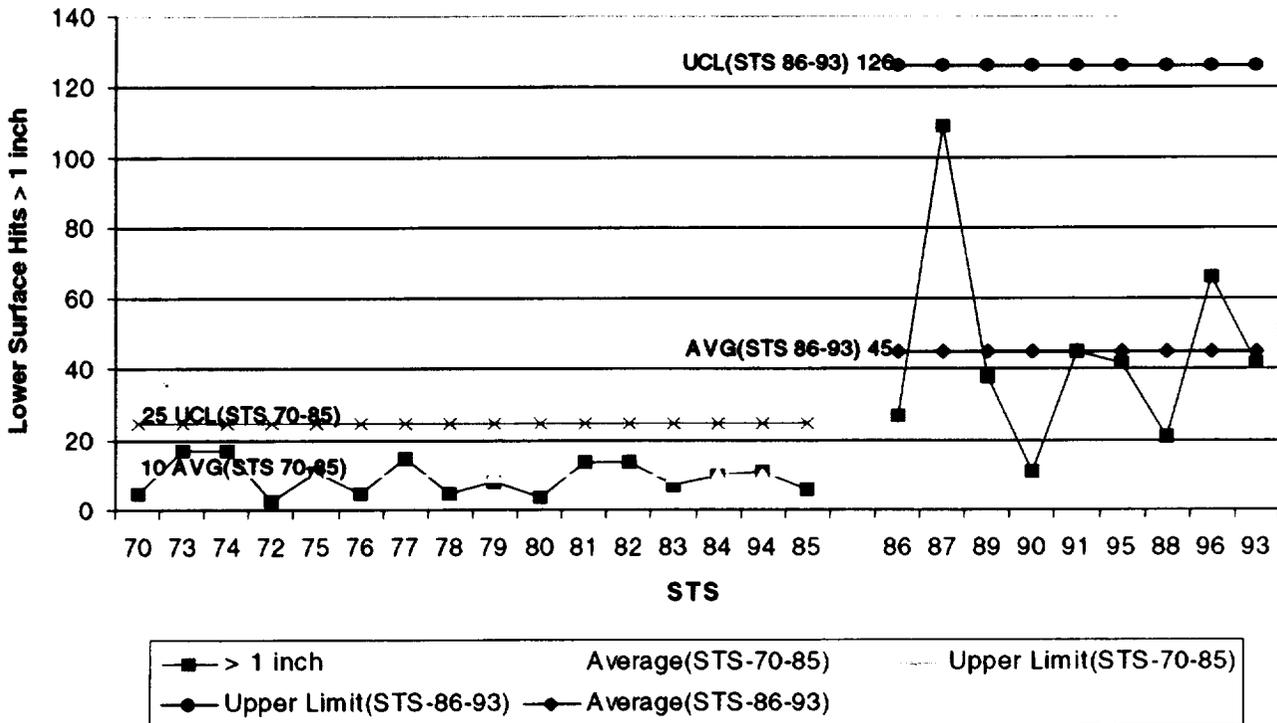
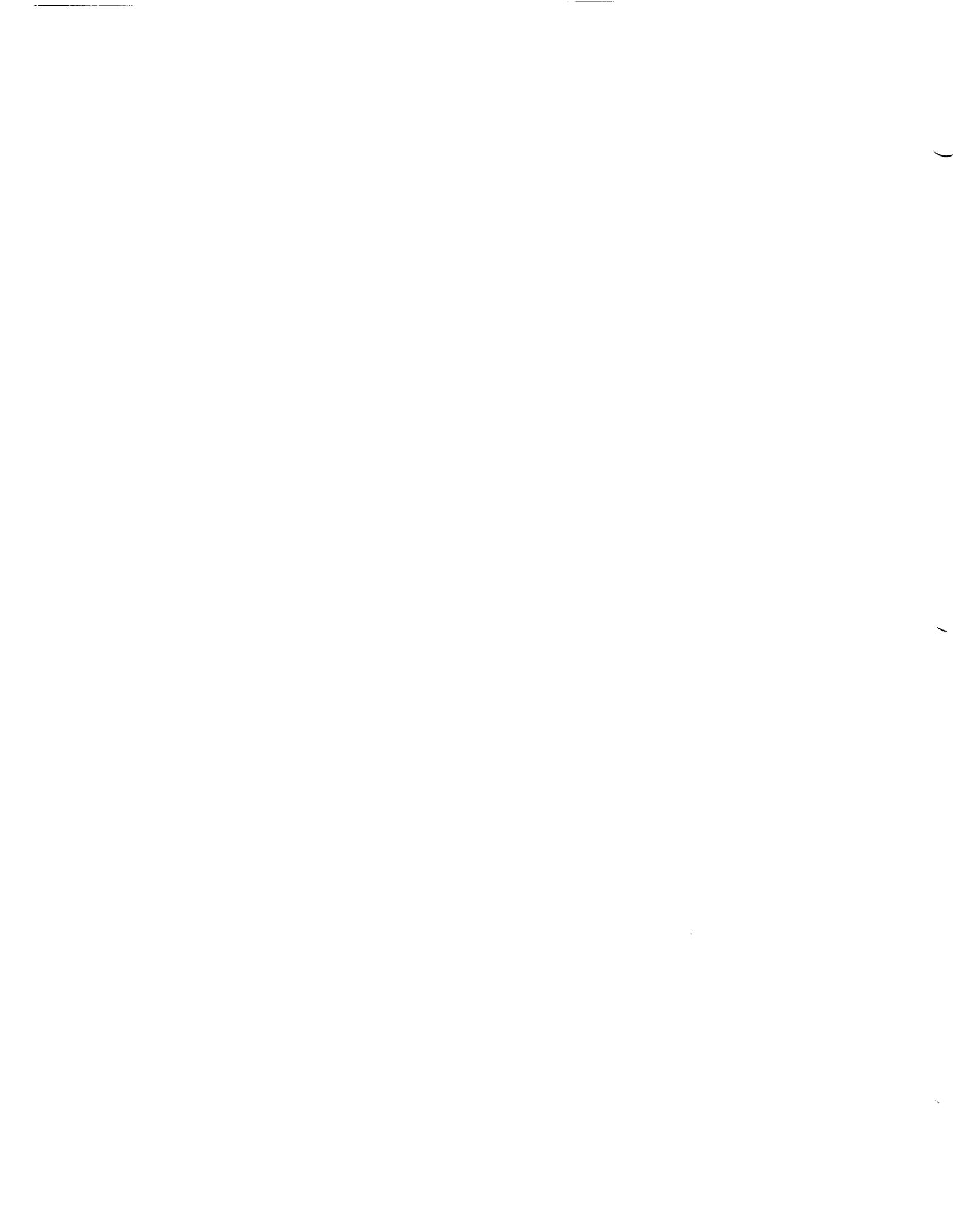
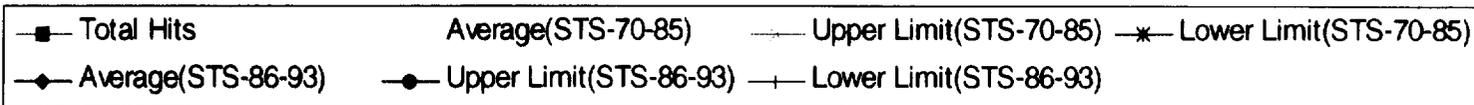
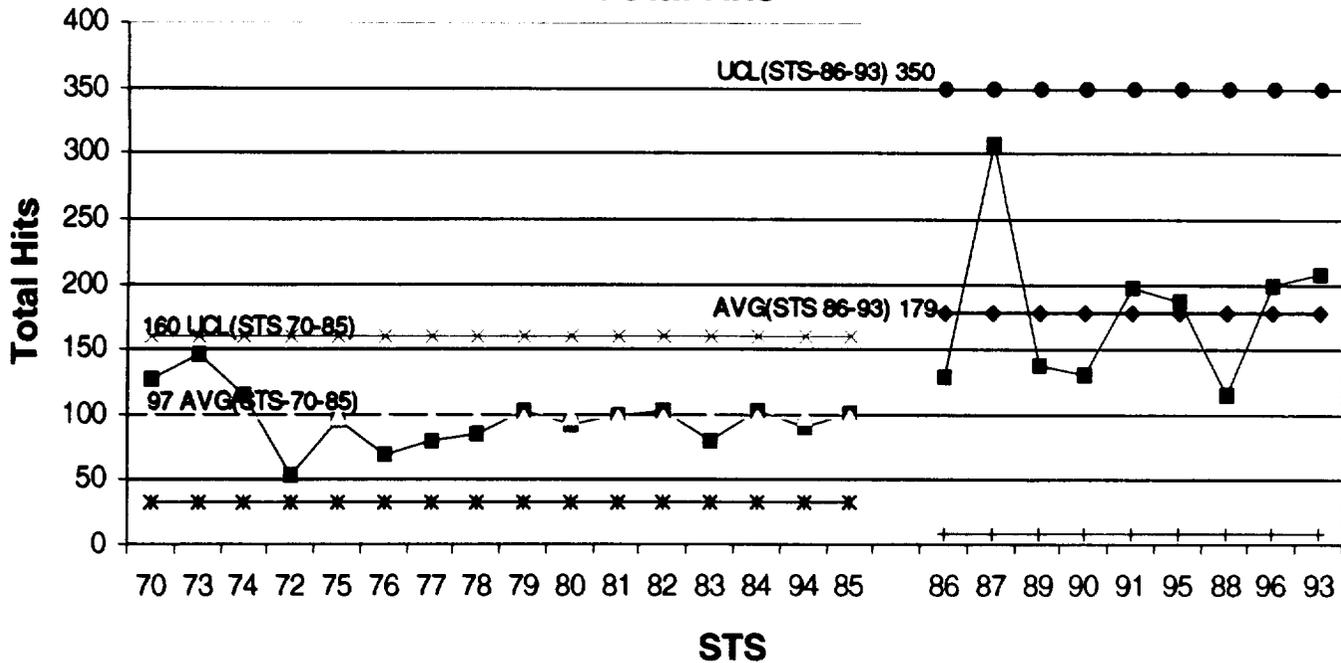


Figure 6: Control Limits for Lower Surface Hits



Orbiter Post Flight Debris Damage Total Hits



Orbiter Post Flight Debris Damage Total Hits > 1 Inch

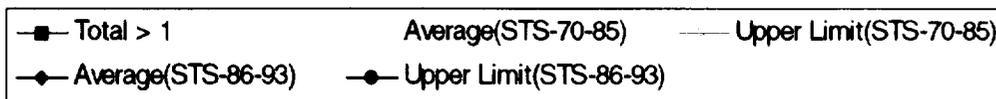
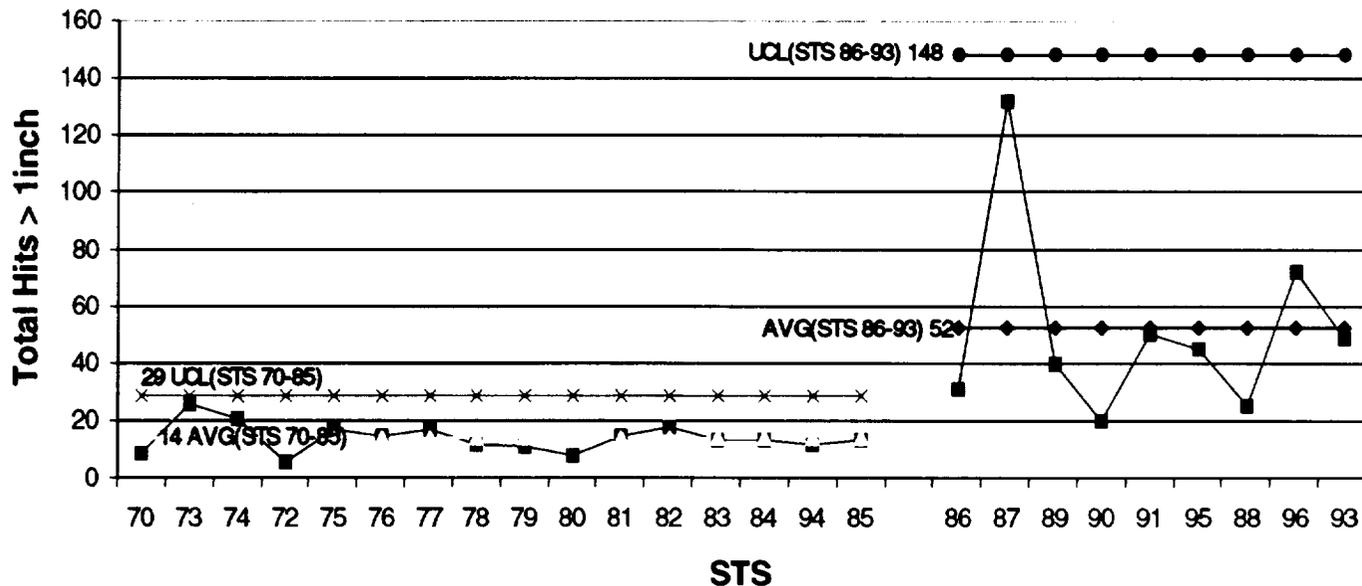
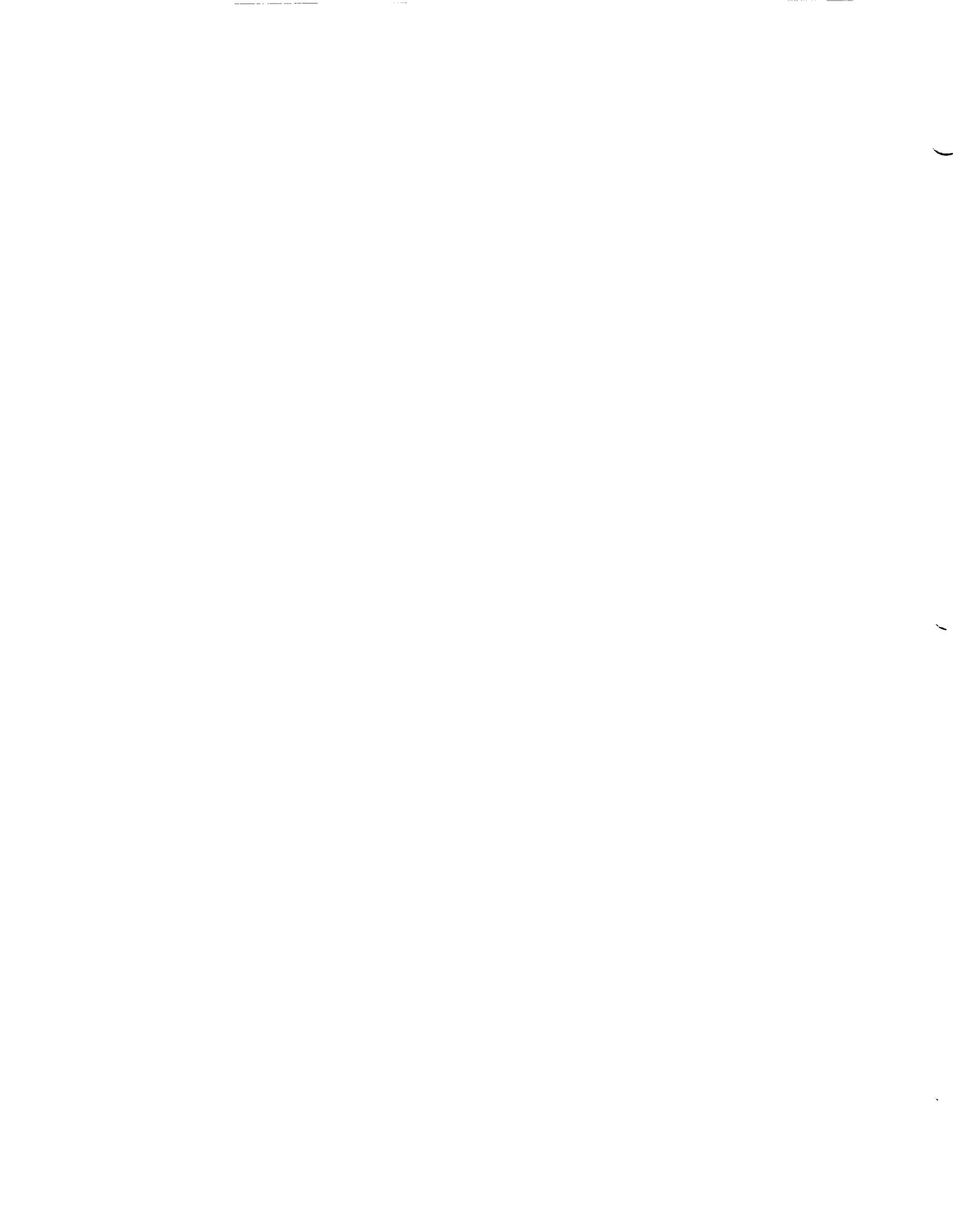


Figure 7: Control Limits for Total Hits



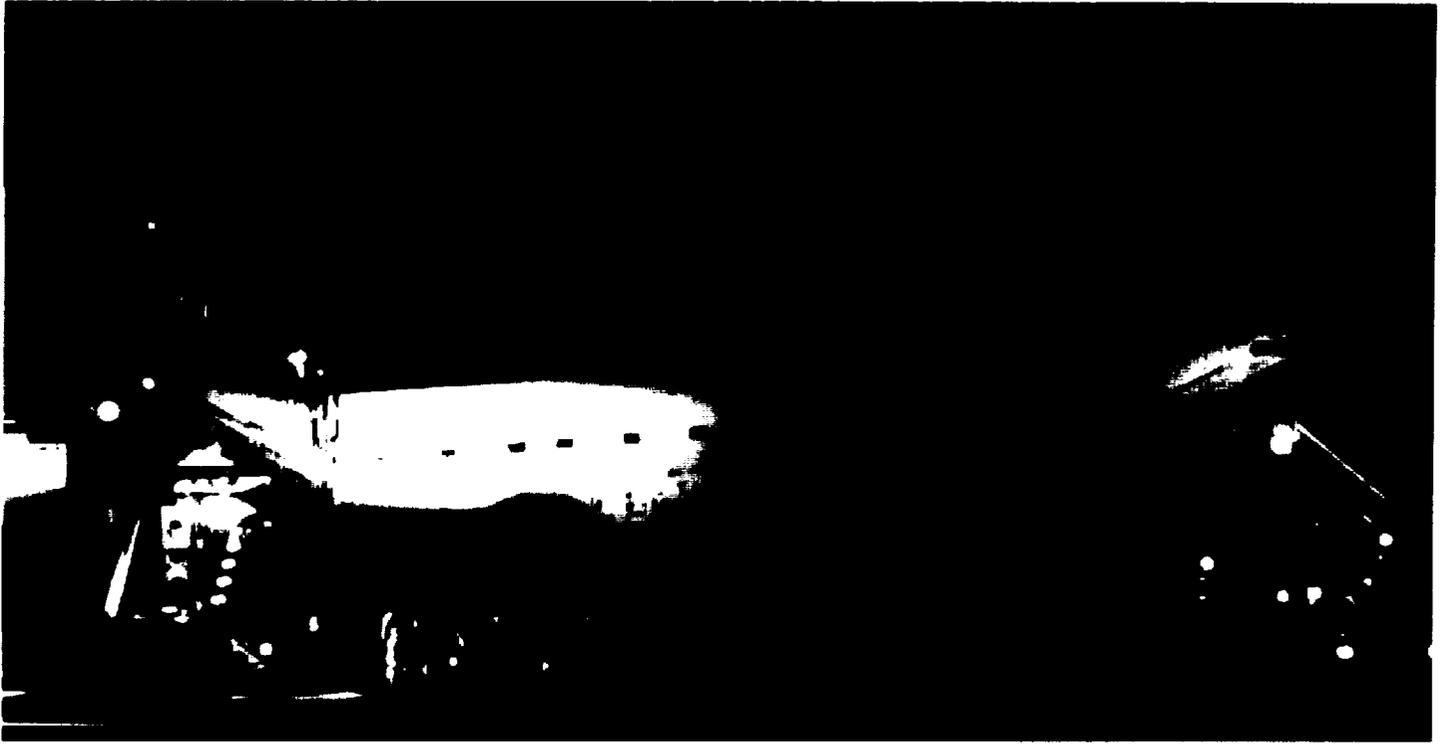


Photo 21: Overall View of Orbiter Sides

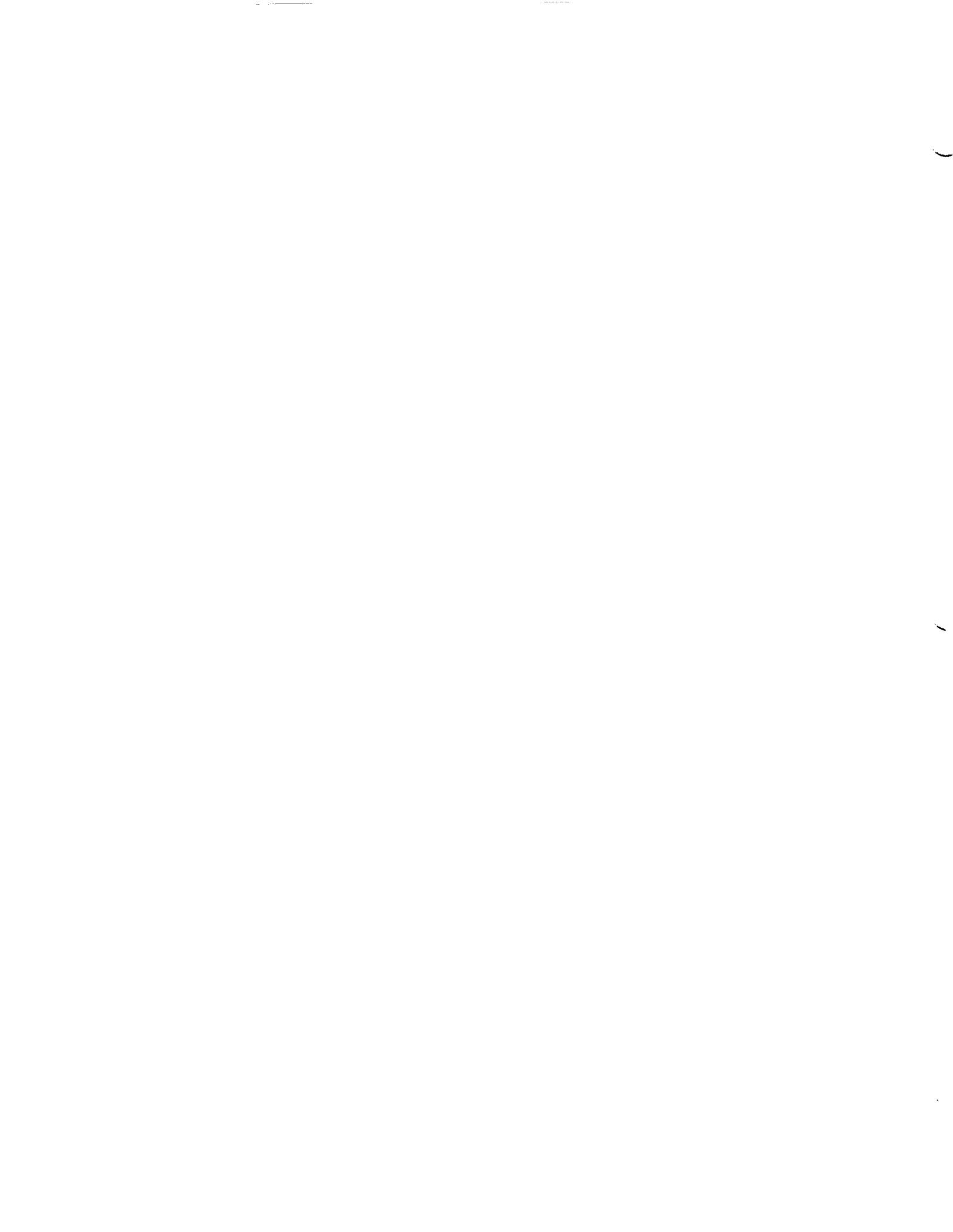




Photo 22: Lower Surface Tile Damage

The Orbiter lower surface sustained 161 total hits, of which 42 had a major dimension of 1-inch or larger. Most of this damage was concentrated from the nose gear to the main landing gear wheel wells on both left and right chines. The outboard damage sites on the chines followed a similar location/damage pattern documented on STS-86, -87, -89, -90, -91, -95, -88, and -96.





Photo 23: Lower Surface Tile Damage

The largest lower surface tile damage site, located on the right chine, measured 6-inches long by 2-inches wide by 0.5-inches deep.

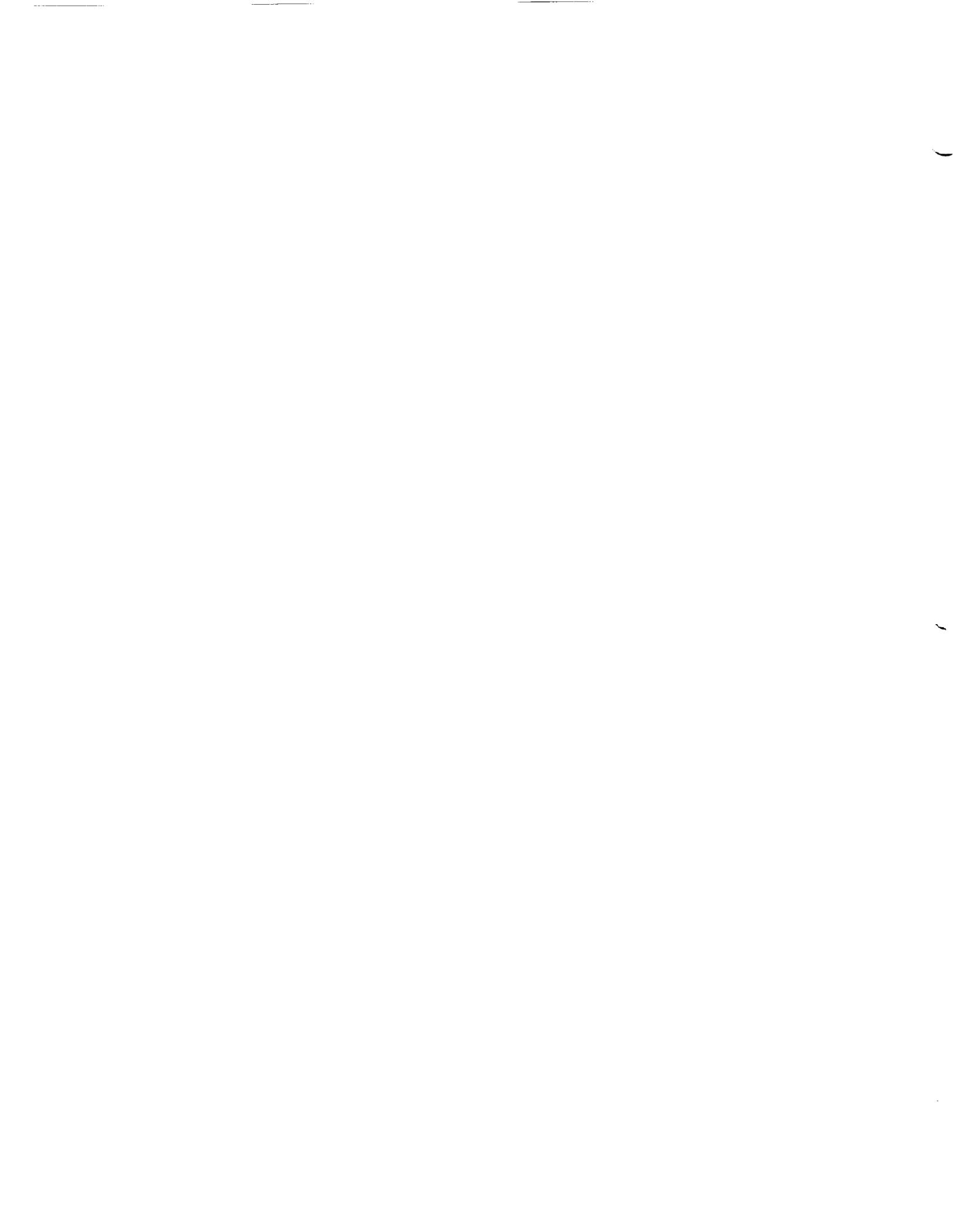
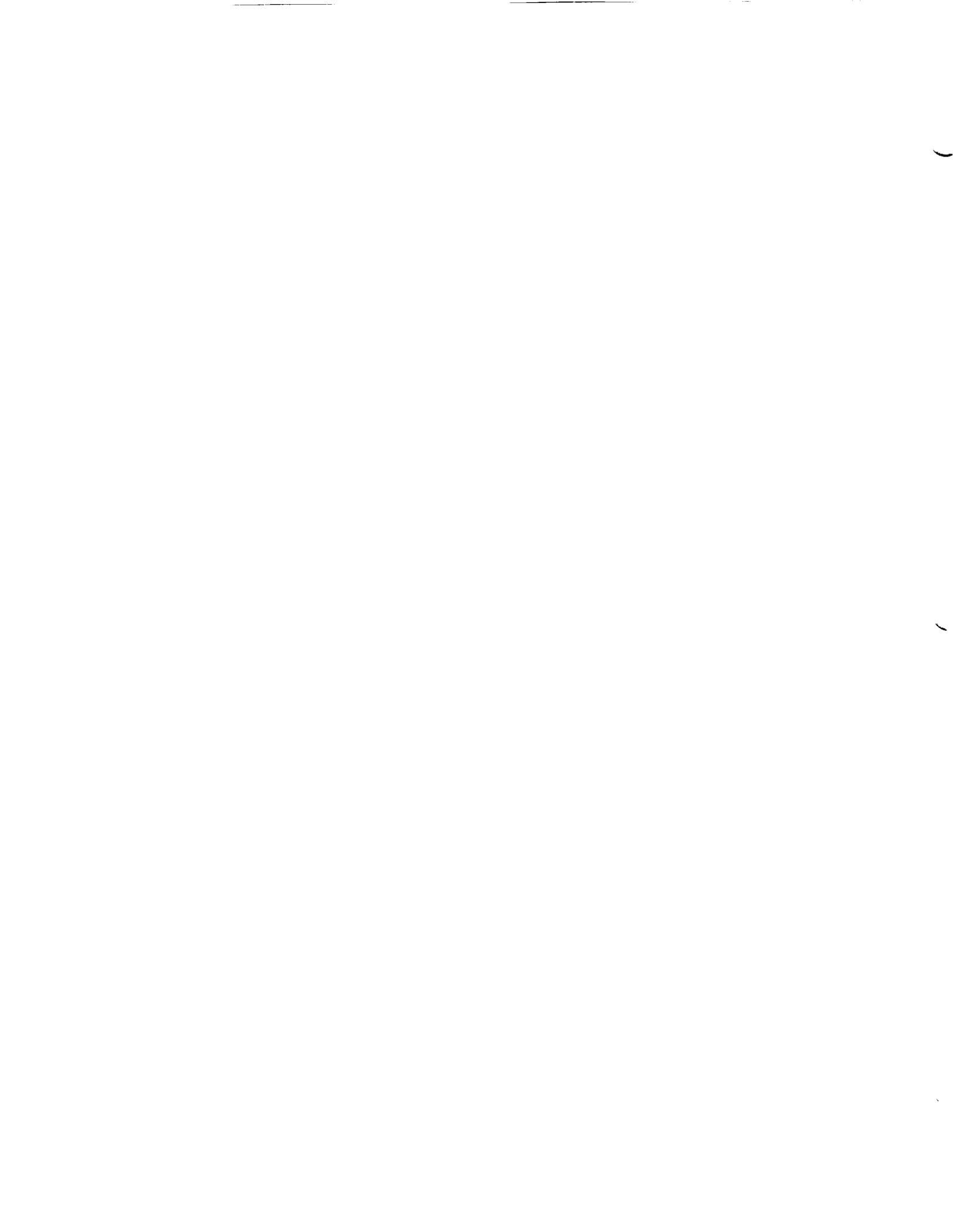




Photo 24: Location of SSME #3 Hydrogen Leak



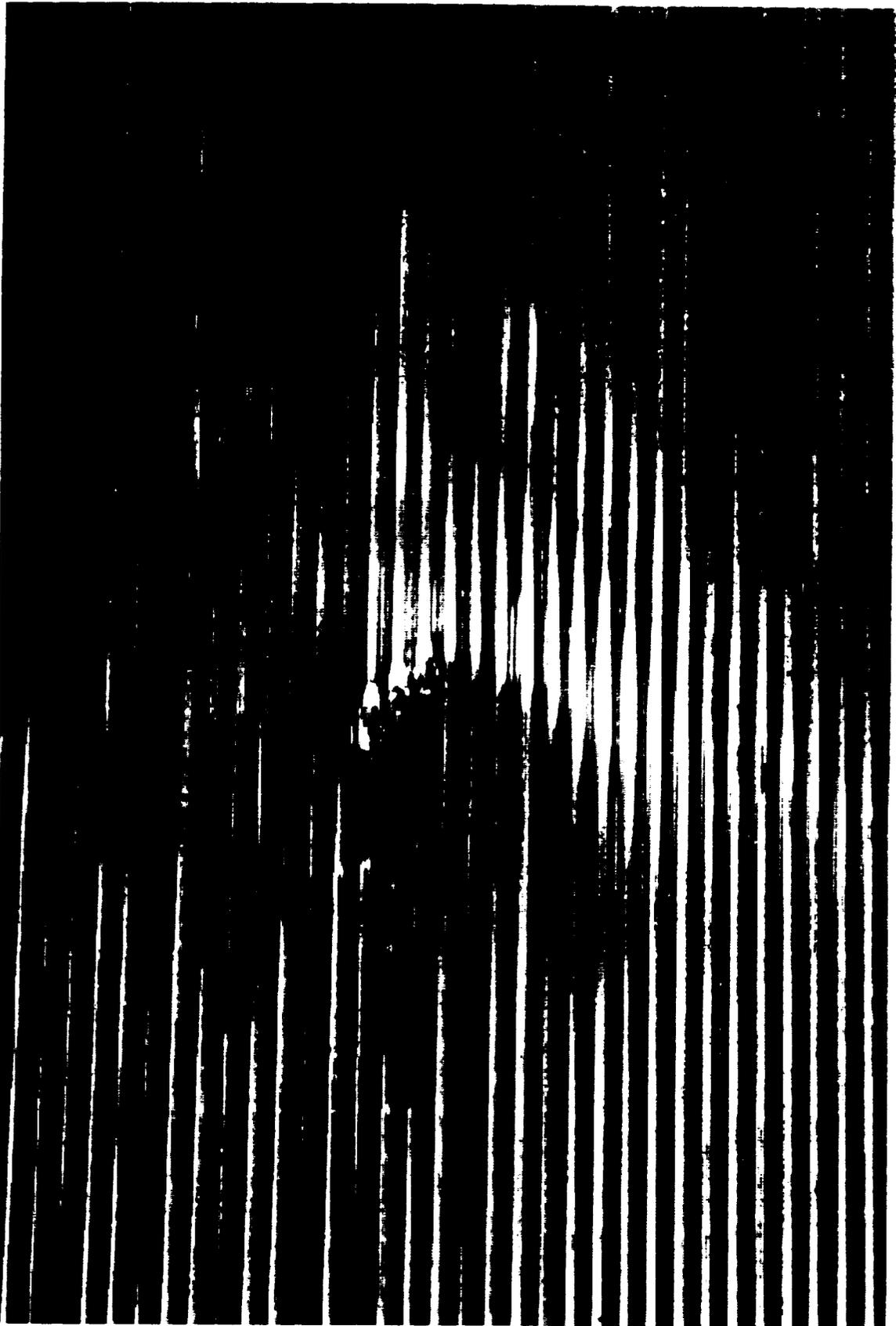


Photo 25: Cooling Tube Ruptures

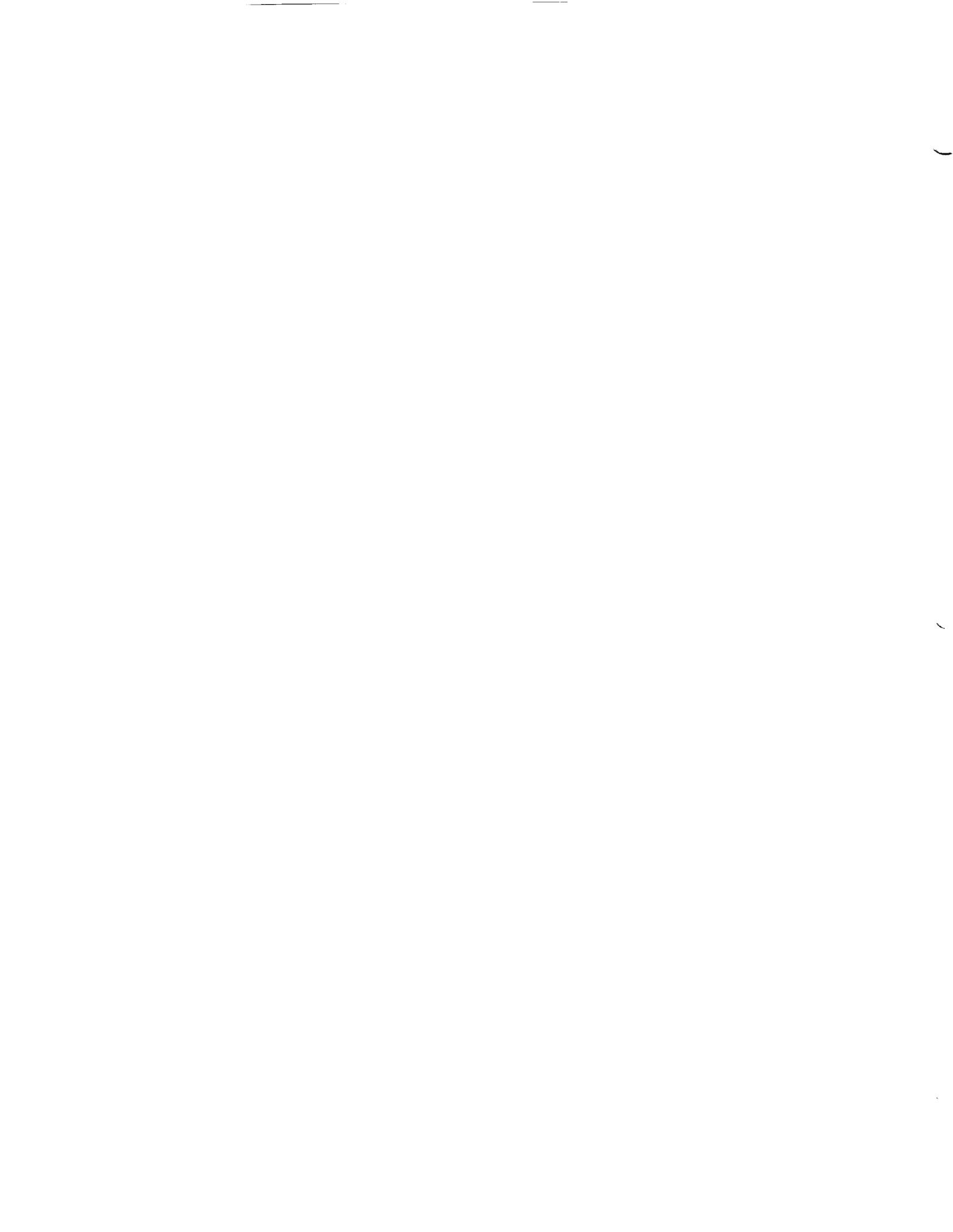
The area inside the SSME #3 nozzle where the hot wall leak had occurred prior to liftoff was readily visible by a rupture and surrounding discoloration in each of three adjacent cooling tubes.





Photo 26: LO2 Post Deactivating Pin

A LO2 post deactivating pin, similar to that pictured here, was found to be missing in post flight inspections and believed to be the debris object that impacted the hot-wall cooling tubes causing the rupture.



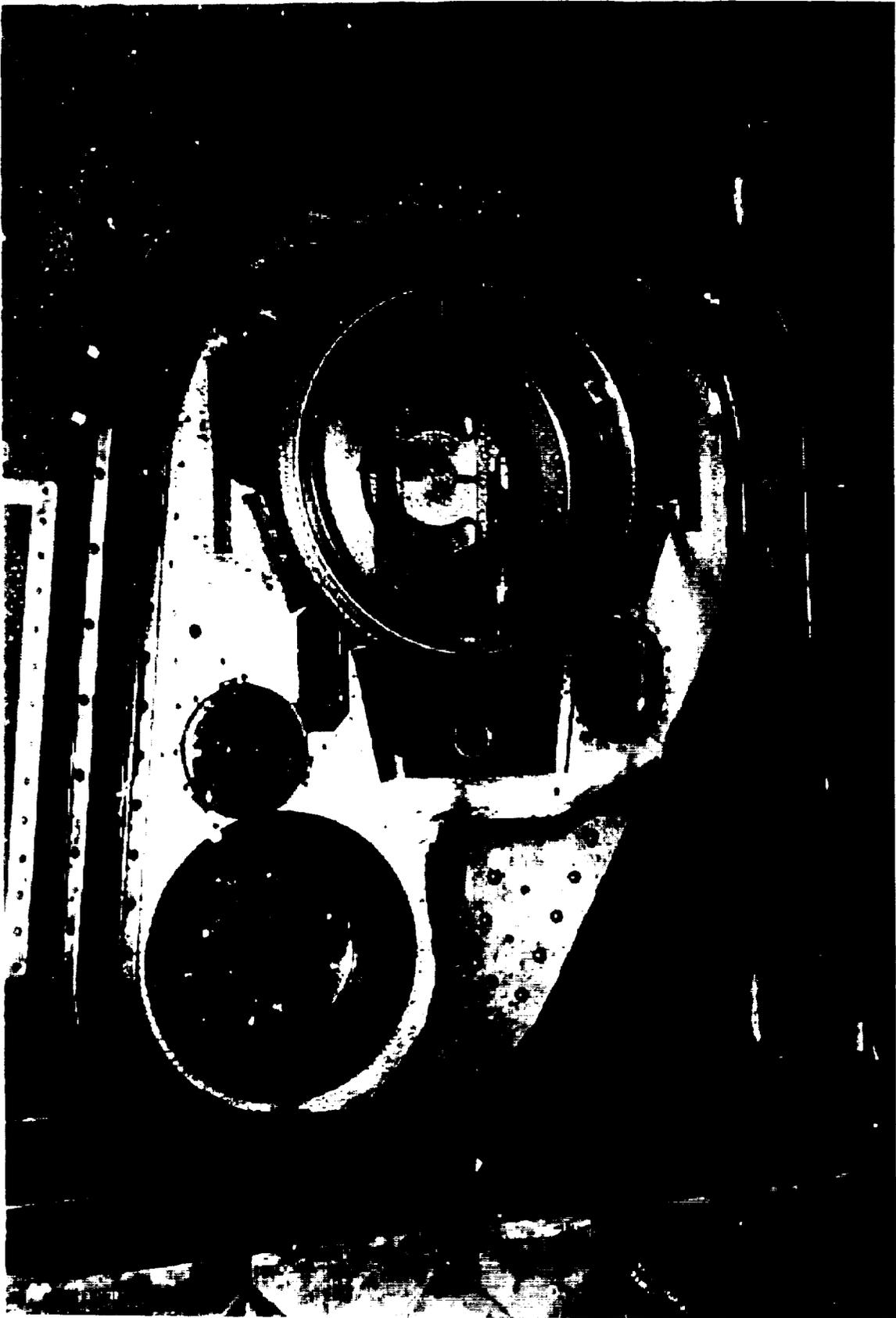
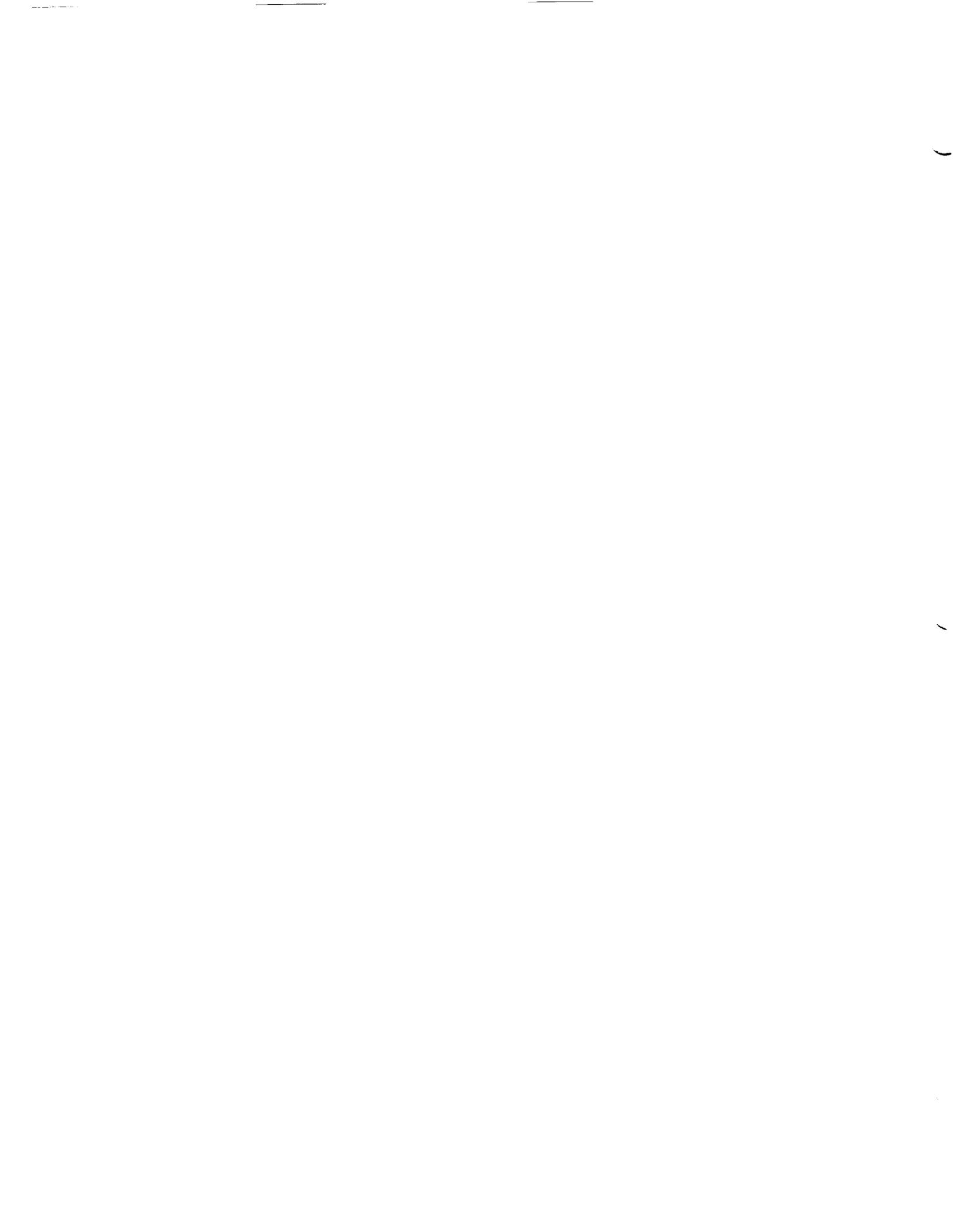


Photo 27: LO2 ET/ORB Umbilical



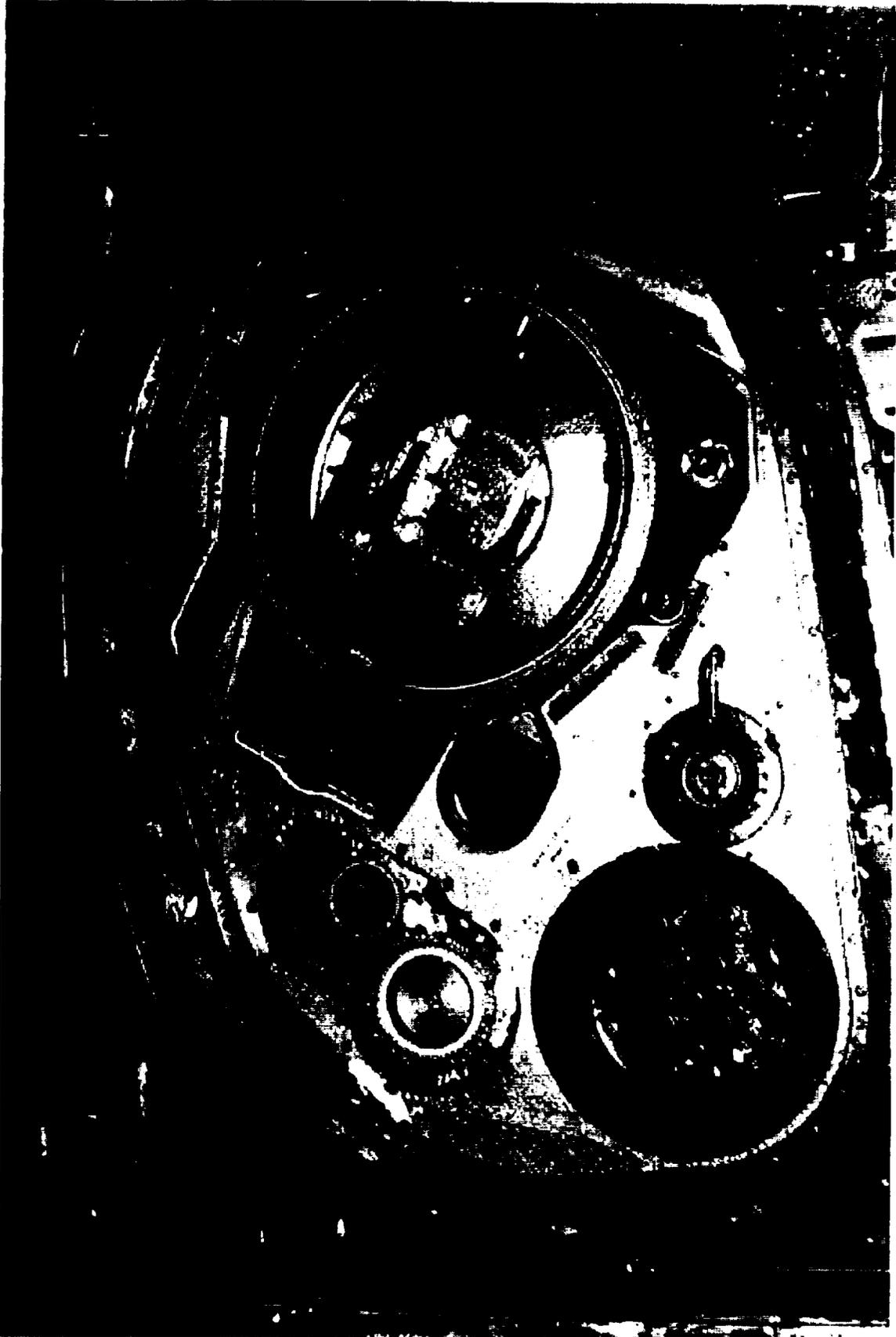


Photo 28: LH2 ET/ORB Umbilical



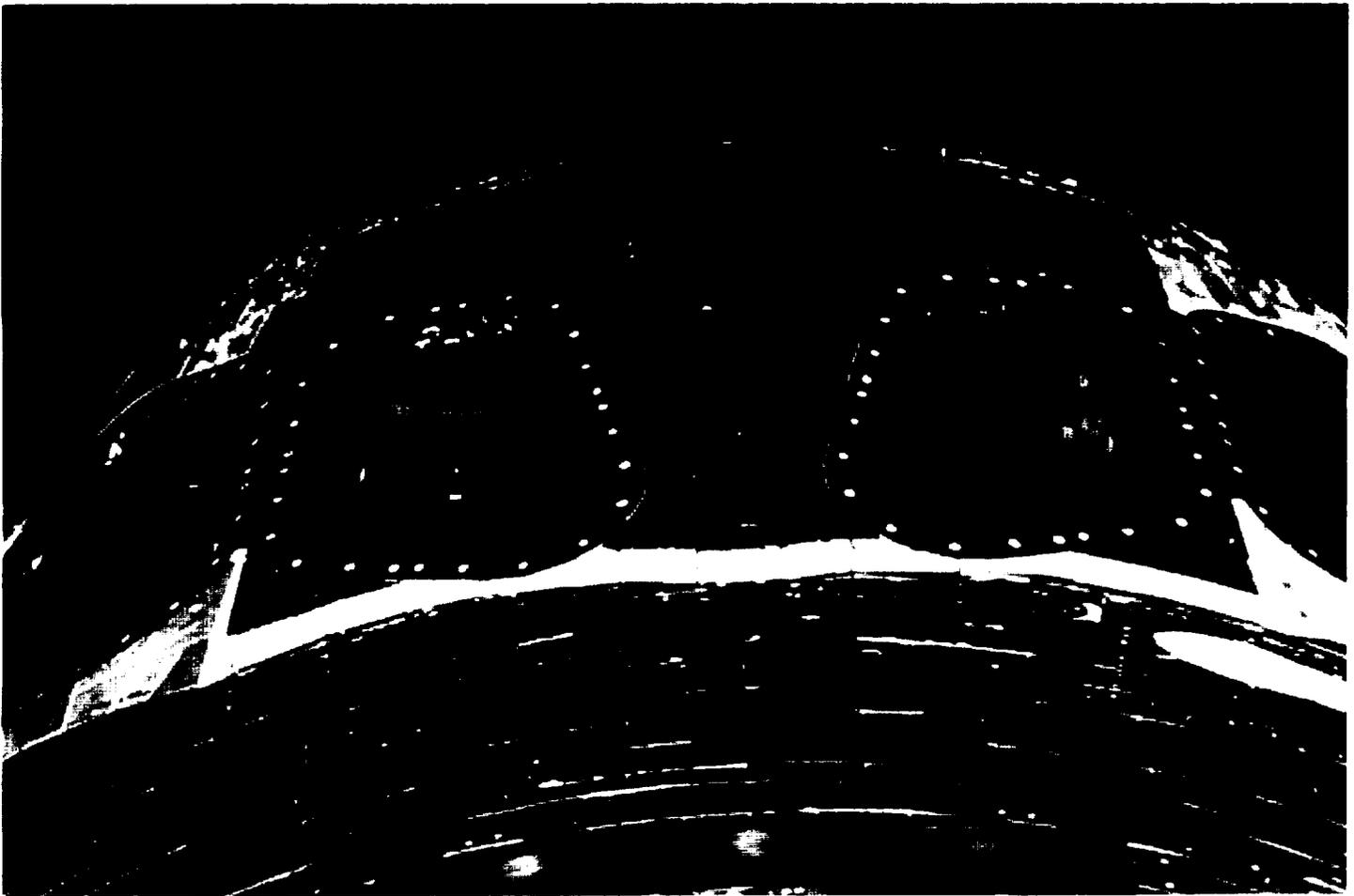
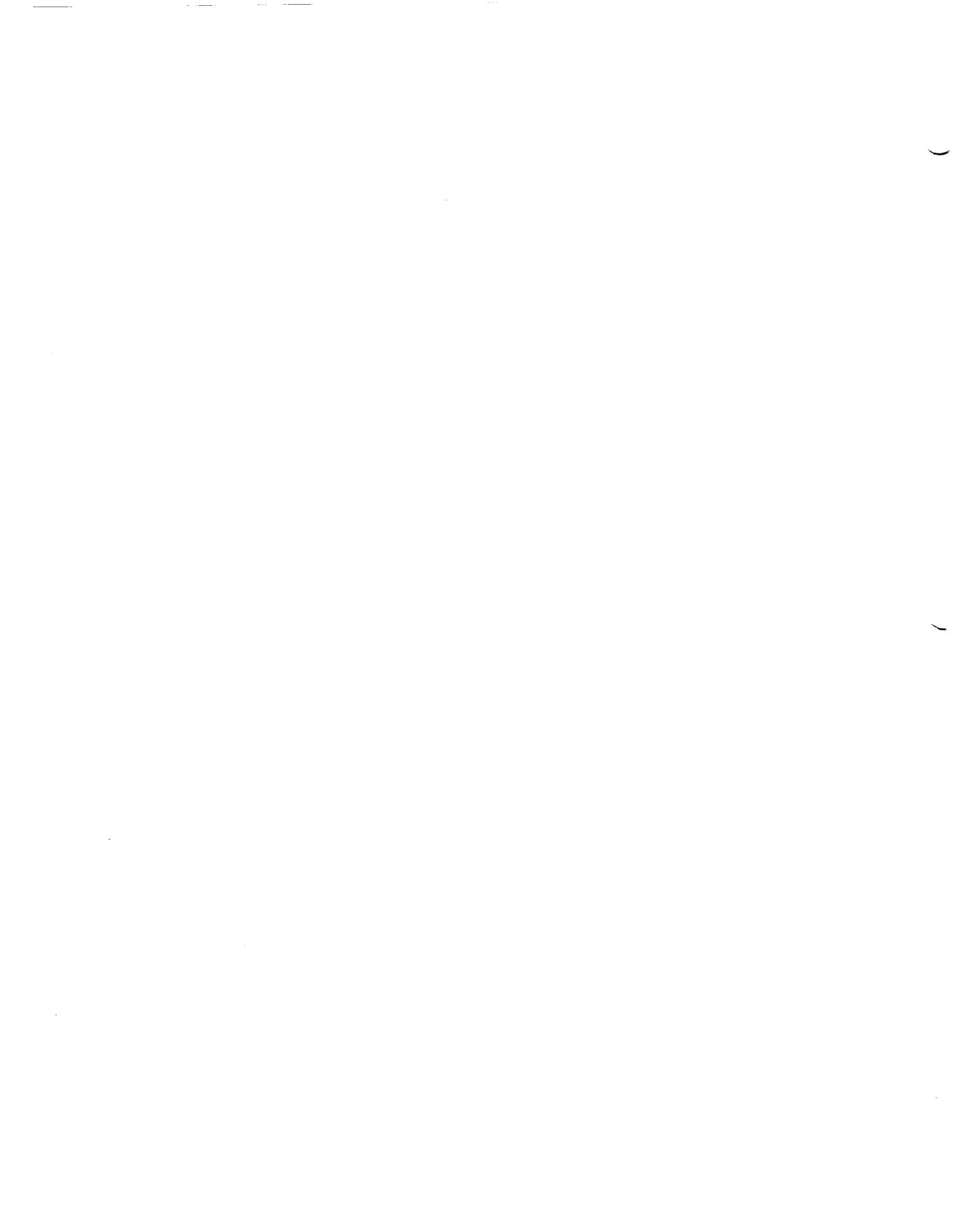


Photo 29: Windows

Hazing and streaking of forward-facing Orbiter windows was moderate. Damage sites on the window perimeter tiles were less than usual in quantity and size.



APPENDIX A. JSC PHOTOGRAPHIC ANALYSIS SUMMARY

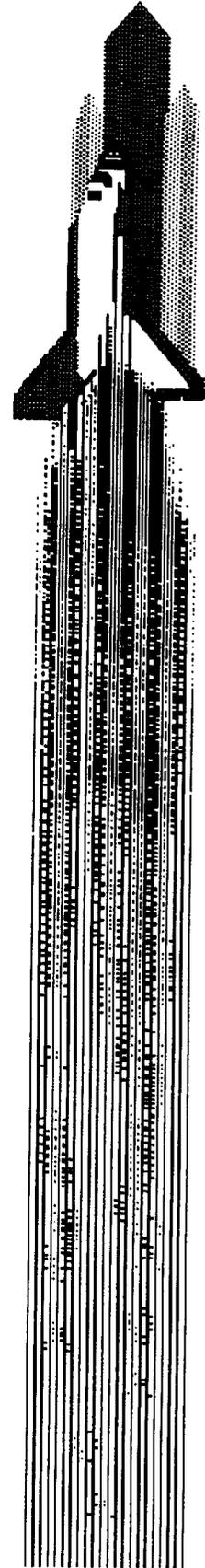




Space Science Branch

STS-93 Summary of Significant Events

August 30, 1999







Space Shuttle STS-93 Summary of Significant Events

Project Work Order - SN3CS

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Table of Contents

1. STS-93 (OV-102): FILM/VIDEO SCREENING AND TIMING	
SUMMARY	A5
1.1 SCREENING ACTIVITIES	A5
1.1.1 Launch	A5
1.1.2 On-Orbit	A5
1.1.3 Landing	A5
1.2 LANDING EVENTS TIMING.....	A5
2. SUMMARY OF SIGNIFICANT EVENTS	A7
2.1 DEBRIS FROM SSME IGNITION THROUGH LIFTOFF	A7
2.2 DEBRIS DURING ASCENT.....	A8
2.3 MOBILE LAUNCH PLATFORM (MLP) EVENTS	A10
2.3.1 Mobile Launch Platform Events.....	A10
2.4 ASCENT EVENTS	A14
2.5 ONBOARD PHOTOGRAPHY OF THE EXTERNAL TANK (ET-99)..	A15
2.5.1 Analysis of the Umbilical Well Camera Films	A15
2.5.2 Analysis of the ET Handheld Photography	A16
2.5.3 Analysis of the ET Handheld Video	A19
2.6 ET THRUST PANEL VIDEO.....	A20
2.7 LANDING EVENTS	A24
2.7.1 Landing Sink Rate Analysis	A24
2.8 OTHER	A25
2.8.1 Normal Events	A25
2.8.2 Normal Pad Events.....	A26

Tables and Figures

Table 1.2	Landing Event Times	A6
Table 2.3.1	SSME Mach Diamond Formation Times	A13
Table 2.5.2	Description of the Handheld ET Film Views.....	A18
Table 2.5.3	ET Tumble and Separation Rates	A20
Table 2.7.1	Main Gear Sink Rate.....	A24
Figure 2.1	Debris from +Y ET / Orbiter Thrust Strut	A7
Figure 2.2 (A)	Flare in SSME Exhaust Plume	A8
Figure 2.2 (B)	Debris Near Left OMS Pod	A9
Figure 2.3.1 (A)	SSME #3 Nozzle Hot-wall Propellant Leak	A10
Figure 2.3.1 (B)	Orange Flash seen from SSME#3.....	A11
Figure 2.3.1 (C)	Ruptured Coolant Tubes in SSME #3 Nozzle	A12
Figure 2.3.1 (D)	Orange Vapors Forward of SSME Rims	A12
Figure 2.4 (A)	SSME #3 Hot-wall Leak During Ascent (Starboard View)	A14
Figure 2.4 (B)	SSME #3 Hot-wall Leak During Ascent (Port View)	A15
Figure 2.5.2 (A)	ET +Y View.....	A16
Figure 2.5.2 (B)	ET -Y View	A17
Figure 2.5.3	Video View of ET	A19
Figure 2.6 (A)	LSRB View of ET Thrust Panel.....	A21
Figure 2.6 (B)	RSRB View of ET Thrust Panel.....	A21
Figure 2.6 (C)	STS-95, STS-96 and STS-93 -Y Thrust Panel Comparisons.....	A22
Figure 2.6 (D)	STS-96 and STS-93 +Y Thrust Panel Comparison.....	A23
Figure 2.7.1	Main Gear Landing Sink Rate	A25

STS-93 (OV-102) Film/Video Screening and Timing Summary

1. STS-93 (OV-102): FILM/VIDEO SCREENING AND TIMING SUMMARY

1.1 SCREENING ACTIVITIES

1.1.1 Launch

The STS-93 launch of Columbia (OV-102) from Pad B occurred on Friday, July 23, 1999 at approximately 204:04:30:59.994 UTC as seen on camera E13. SRB separation occurred at approximately 04:33:03.24 UTC as seen on camera ET207. (STS-93 launched on the third attempt. The first attempt, on July 20, was scrubbed due to an erroneous hydrogen concentration reading in the Orbiter aft compartment. The second launch attempt, on July 22, was waved off due to weather.)

On launch day, 24 of the 24 expected videos were received and screened.

Twenty-two launch films were screened on July 25, 1999. Twenty-one additional films were received for contingency support and anomaly resolution but were not screened.

Umbilical well cameras flew on OV-102 during STS-93. Photography of the left SRB, the LSRB/ET aft attach, and the External Tank (ET-99) aft dome was acquired using umbilical well camera films during SRB separation. Photography of the ET was not acquired during ET separation because of night conditions. Handheld video and still photography of the ET were acquired following separation.

Video of the External Tank +Y and -Y thrust panels was acquired during ascent from cameras mounted on the left and right SRBs.

1.1.2 On-Orbit

No unplanned on-orbit Shuttle analysis support was requested.

1.1.3 Landing

Columbia made a night landing on runway 33 at the KSC Shuttle Landing Facility on July 28, 1999 at 03:20:34 UTC. Eleven videos and six 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 2.7). The drag chute deploy sequence appeared normal on the landing imagery.

According to the pre-mission agreement, the STS-93 landing film was not screened due to budgetary constraints.

1.2 LANDING EVENTS TIMING

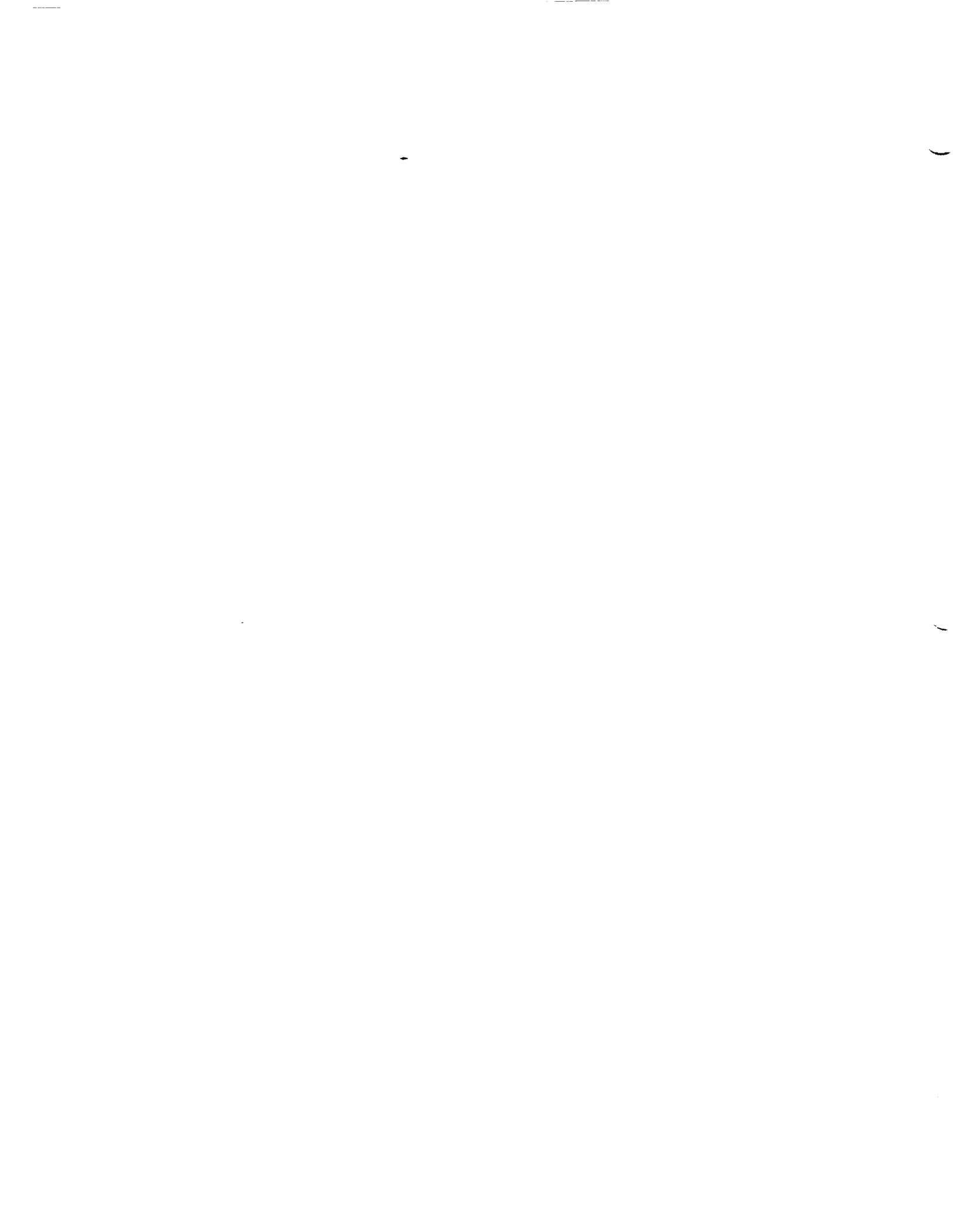
The time codes from videos and films were used to identify specific events during the screening process. The landing event times are provided in Table 1.2.

STS-93 (OV-102) Film/Video Screening and Timing Summary

Event Description	Time (UTC)	Camera
Main gear door opening	Not Seen from Available Views	-
Left main gear inboard tire touchdown	209:03:20:34.375	EL18 IR
Left main gear outboard tire touchdown	209:03:20:34.408	EL18 IR
Right main gear inboard tire touchdown	209:03:20:34.642	EL18 IR
Right main gear outboard tire touchdown	209:03:20:34.692	EL18 IR
*2nd left main gear tire touchdown	209:03:20:35.261	EL18 IR
Pilot chute at full inflation	209:03:20:37.966	KTV33L
Bag release	Noted	KTV33L
Drag chute inflation in reefed configuration	209:03:20:39.669	KTV33L
Drag chute inflation in disreefed configuration	209:03:20:43.055	KTV33L
Nose gear tire touchdown	209:03:20:43.694	EL18R
Drag chute release	209:03:21:05.194	KTV33L
Wheel stop	209:03:21:15	KTV33L

*Note: The left main gear tires are seen lifting off the runway and touching down again at the time provided.

Table 1.2 Landing Event Times



Summary of Significant Events

2. SUMMARY OF SIGNIFICANT EVENTS

2.1 DEBRIS FROM SSME IGNITION THROUGH LIFTOFF

As observed on previous missions, numerous light-colored pieces of debris (umbilical ice debris, RCS paper, SRB flame duct debris, and water baffle debris) were seen aft of the launch vehicle before, during, and after the roll maneuver.

Multiple pieces of ice debris were seen falling from the ET/Orbiter umbilicals along the body flap during SSME ignition. Three pieces of ice debris were seen to contact the LH2 umbilical well door sill (04:30:56.67, 04:30:56.92, and 04:30:57.27 UTC). No damage to the launch vehicle was noted. (Cameras OTV109, OTV154, OTV163, KTV7, E5, E19, E31, E34, E76)

A small dark debris object was seen between the camera and the LO2 TSM moving toward the Orbiter during SSME ignition (04:30:56.393 UTC). The debris was not seen to contact the vehicle. (Camera OTV149, E5)



Figure 2.1 Debris from +Y ET / Orbiter Thrust Strut

A single piece of white-colored debris (probably ice) was seen falling from the forward end of the +Y ET/Orbiter thrust strut and contacted the ET/Orbiter aft attach brace after SSME ignition (04:30:56.59 UTC). (Camera OTV154)



Summary of Significant Events

Multiple pieces of dark-colored debris (probably paint chips) were seen between the LH2 TSM and the RSRB aft skirt during lift off (04:31:02.63). Similarly, multiple pieces of light and dark-colored debris were seen between the LO2 TSM and the LSRB aft skirt during lift off (04:31:01.91 UTC). (Camera OTV150, E20)

A single piece of light-colored debris was seen aft of the ET/RSRB aft attach at liftoff (04:31:01.07UTC). The origin of this debris was not determined. (Camera E2)

Four light-colored pieces of debris (probably SRB aft skirt instafoam) were seen north of the MLP during liftoff (04:31:01.13 UTC). (Camera KTV4)

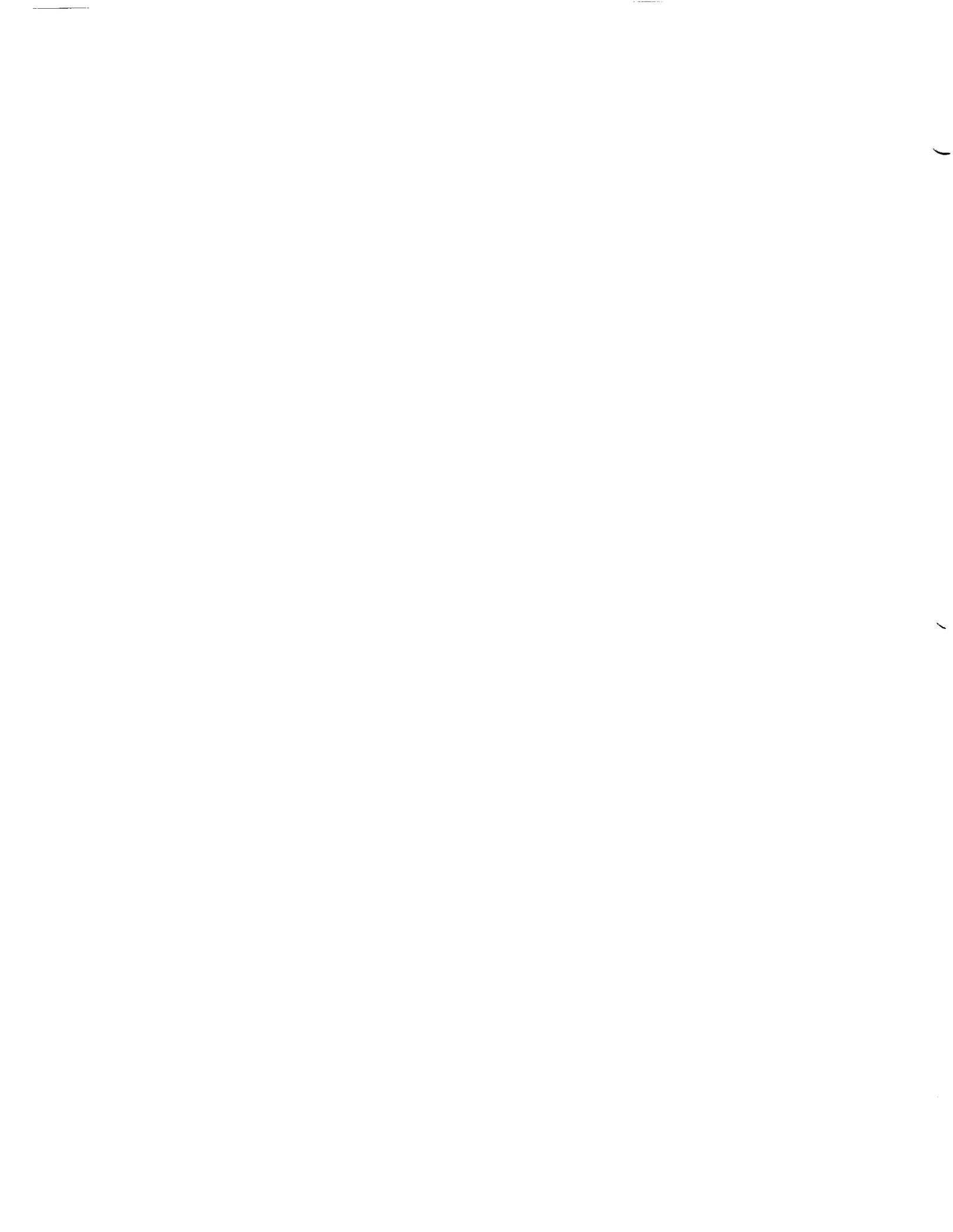
A single piece of light-colored debris was seen falling along the LO2 feedline during liftoff. This debris may have been ice from the forward end of the LO2 feedline. (Camera E34)

2.2 DEBRIS DURING ASCENT



Figure 2.2 (A) Flare in SSME Exhaust Plume

Multiple pieces of ET/Orbiter umbilical well ice and RCS paper debris were seen near the Orbiter during the roll maneuver and early ascent (04:32:00.97 UTC). Two orange-colored flares (probably debris induced) were seen in the SSME exhaust plume during ascent (04:31:23.31 and 04:31:27.32 UTC). (Cameras KTV4, KTV13, KTV21B, ET207, ET212, E52, E54, E207, E212, E222, E223, E224)



Summary of Significant Events

A single piece of debris was seen forward of the LSRB aft skirt during ascent (04:31:13.24 UTC). (Camera KTV4)

A single piece of light-colored debris first seen near the SRB exhaust plume appeared to move in a forward direction toward the vehicle (04:31:36.07 UTC). The apparent forward motion may have been due to the position of the debris relative to the camera (Camera KTV2). On camera KTV4 and KTV13, debris was seen near the SRB exhaust plume at 04:32:20.16 and 04:32:54.69 UTC. Also on camera KTV4, four pieces of light-colored debris were seen near the SRB exhaust plume (probably instafoam from the SRB aft skirts) prior to SRB separation (04:33:01.05 UTC).

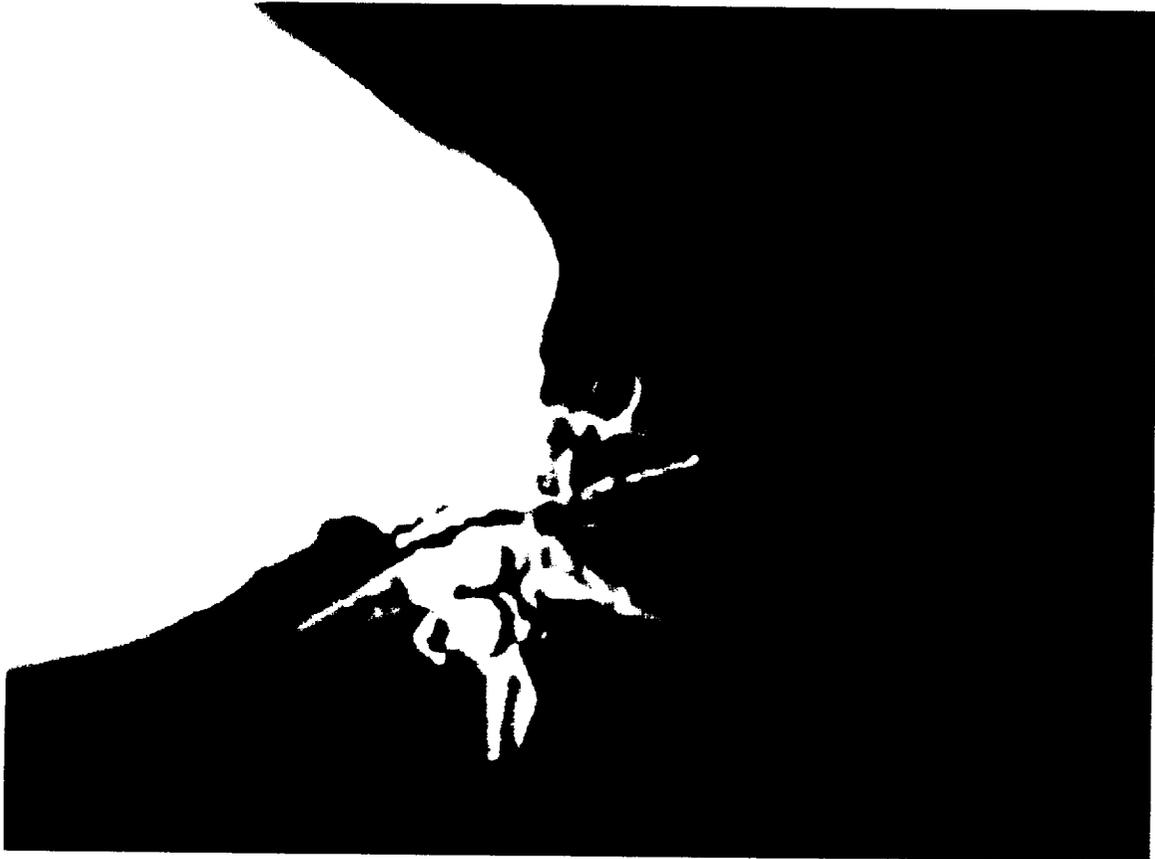
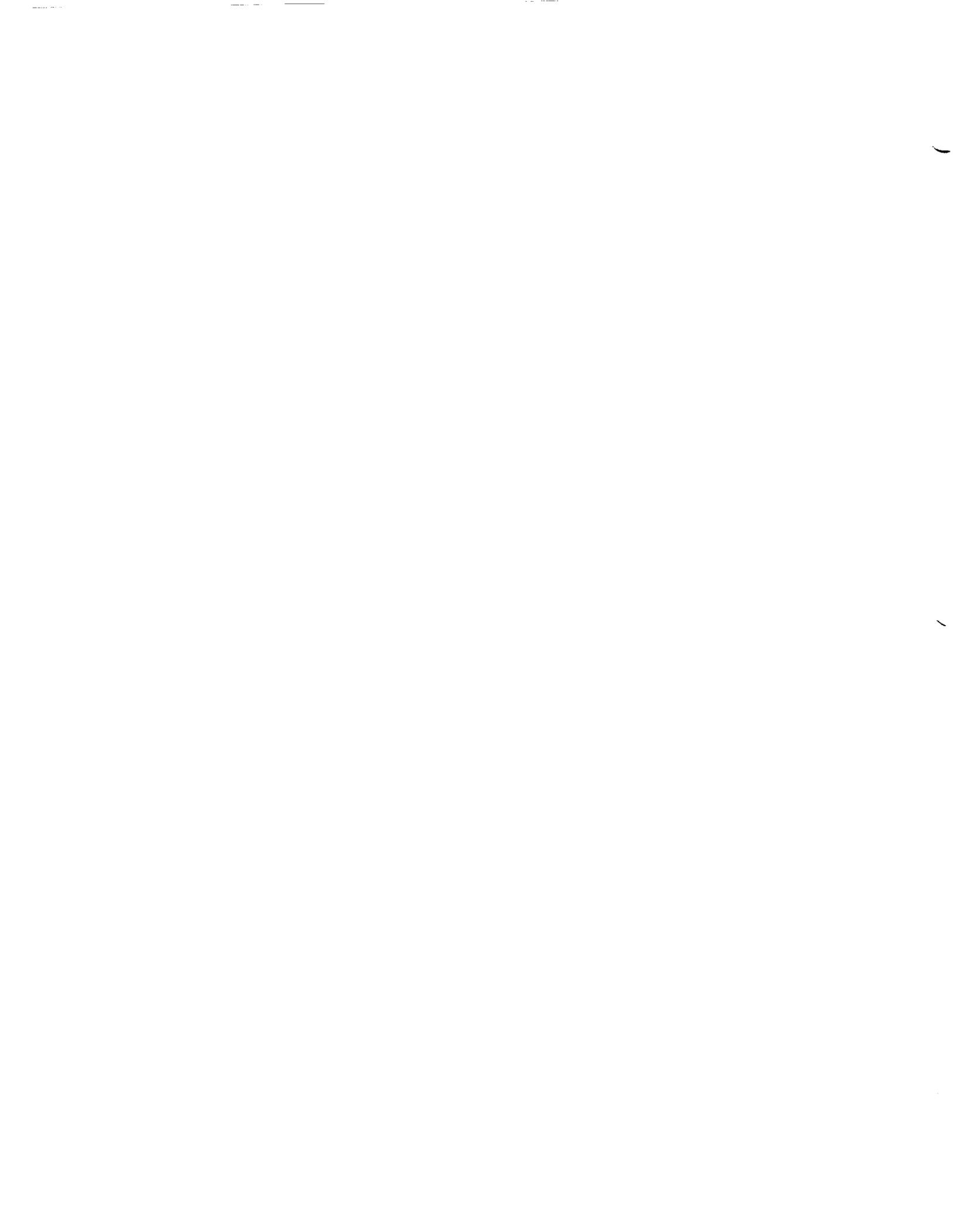


Figure 2.2 (B) Debris Near Left OMS Pod

A single piece of light-colored debris was first seen by the forward edge of the left OMS pod and fell aft near the vertical stabilizer (04:33:00.16 UTC). (Camera KTV13)



Summary of Significant Events

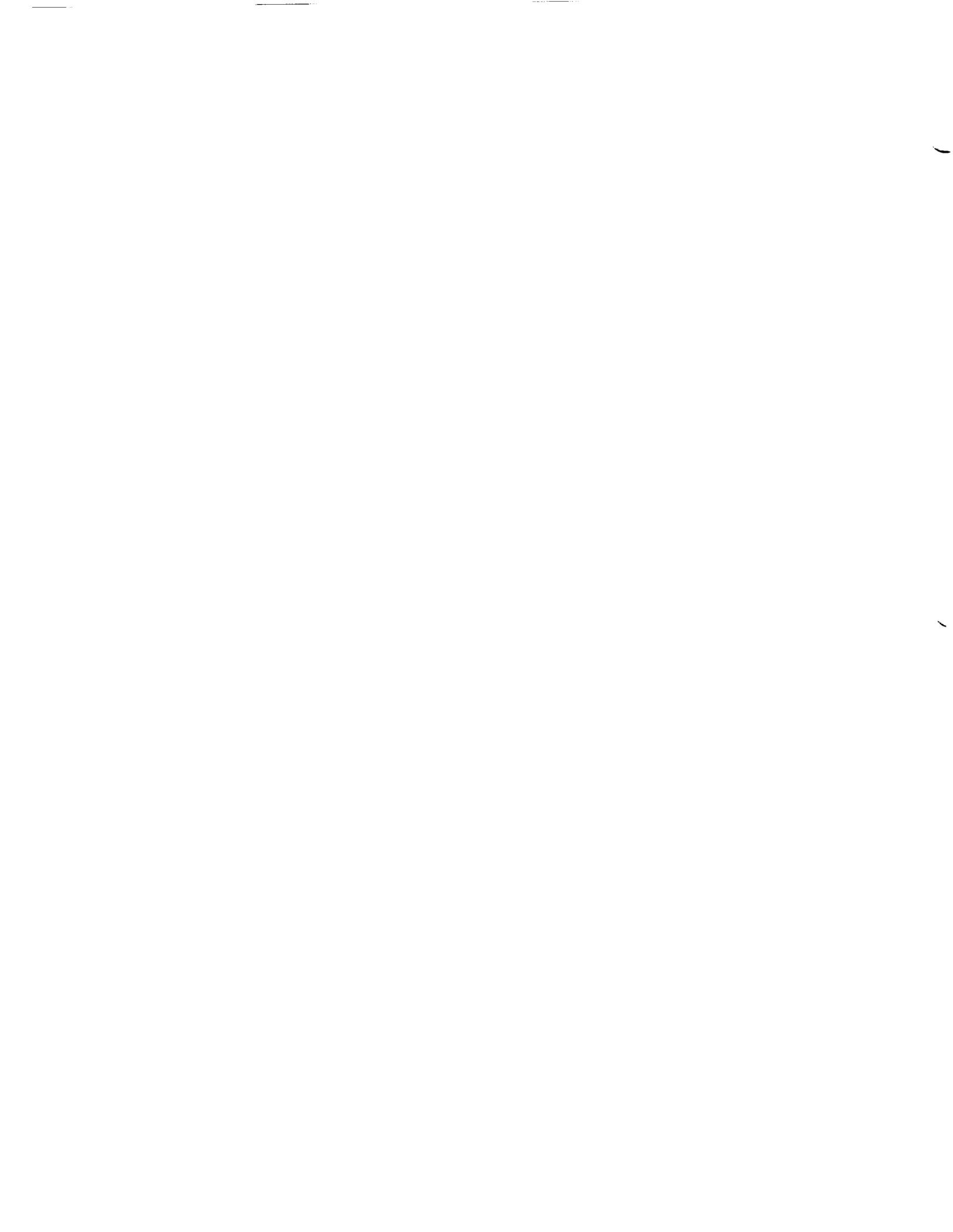
2.3 MOBILE LAUNCH PLATFORM (MLP) EVENTS

2.3.1 Mobile Launch Platform Events



Figure 2.3.1 (A) SSME #3 Nozzle Hot-wall Propellant Leak with Irregular Mach Diamond Formation

After SSME ignition, a SSME #3 nozzle hot-wall propellant leak was visible on the interior of the engine nozzle at approximately the 9 o'clock position on the high-speed (up to 400 fps) launch pad films (Cameras E2, E3, E5, E15, E19, E20, E52, E77). A green-colored streak was visible extending aft of the rim of the SSME #3 rim between the 8 and 10 o'clock positions at 04:30:58.030 UTC.



Summary of Significant Events

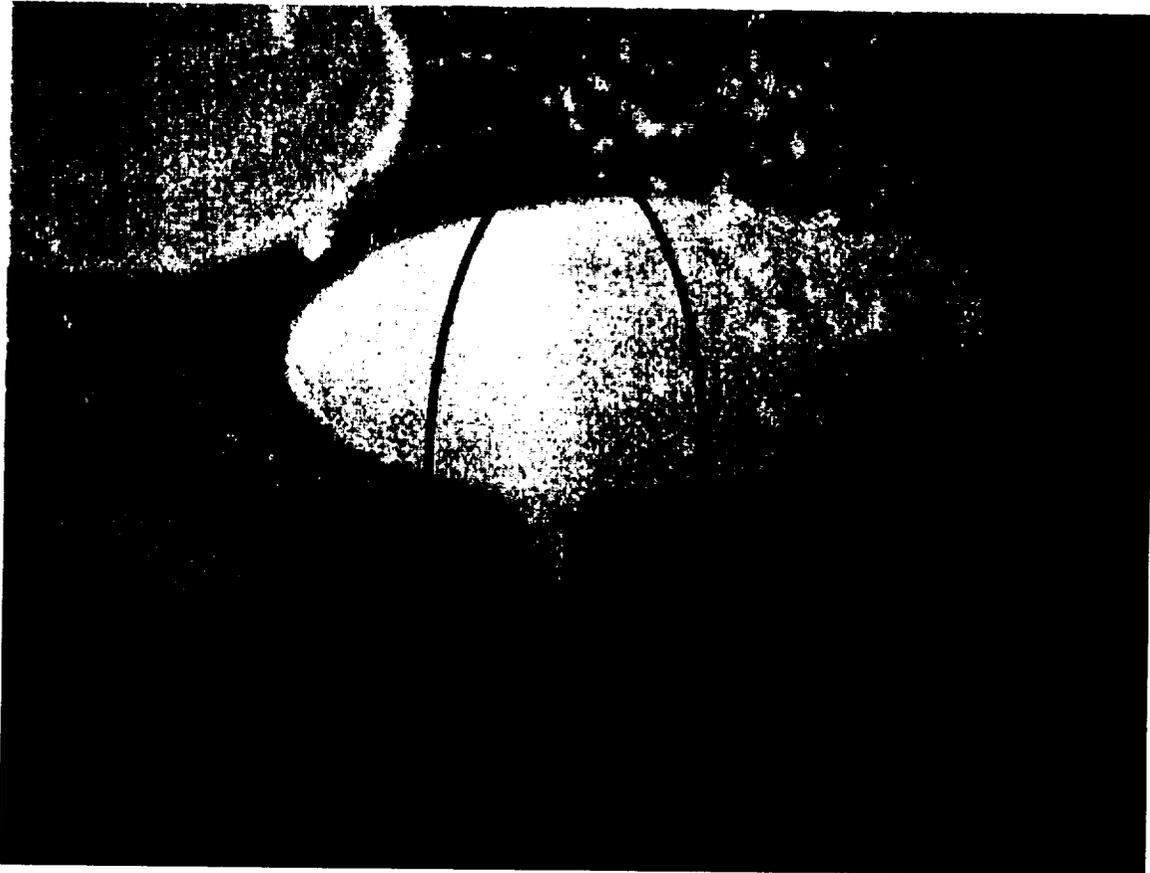


Figure 2.3.1 (B) Orange Flash seen from SSME#3

An orange-colored flash was visible at the same location at 04:30:58.515 UTC. The orange-colored flash was visible over three sequential frames on camera E19. At almost the same time, indications of the SSME #3 hot-wall leak were first seen after SSME ignition (Mach diamond formation) at 04:30:58.520 UTC on camera E19. When the hot-wall propellant leak became visible, the SSME #3 Mach diamond appeared to diminish in size and became irregular shaped compared to the SSME #1 and #2 Mach diamonds. White-colored vapors were visible on the outside of the SSME #3 rim at the same time as the orange flash (camera E15). These vapors appeared to be at the 6 o'clock position on the SSME #3 rim and did not appear to be associated with the nozzle hot-wall leak (similar vapors are normally seen on the exterior surface of the engine nozzles prior to liftoff). Excessive vibrations were not detected in the engine bells during SSME ignition and the engine start-up motions appeared similar to previous missions.



Summary of Significant Events



Figure 2.3.1 (C) Ruptured Coolant Tubes in SSME #3 Nozzle

Ruptures in three adjacent coolant tubes in the SSME #3 nozzle were found during the post-landing inspections. Shuttle program engineers concluded that these ruptures resulted in the small hydrogen leak that occurred during launch. The ruptures were caused by a small metal pin that had dislodged upstream in the fuel manifold.

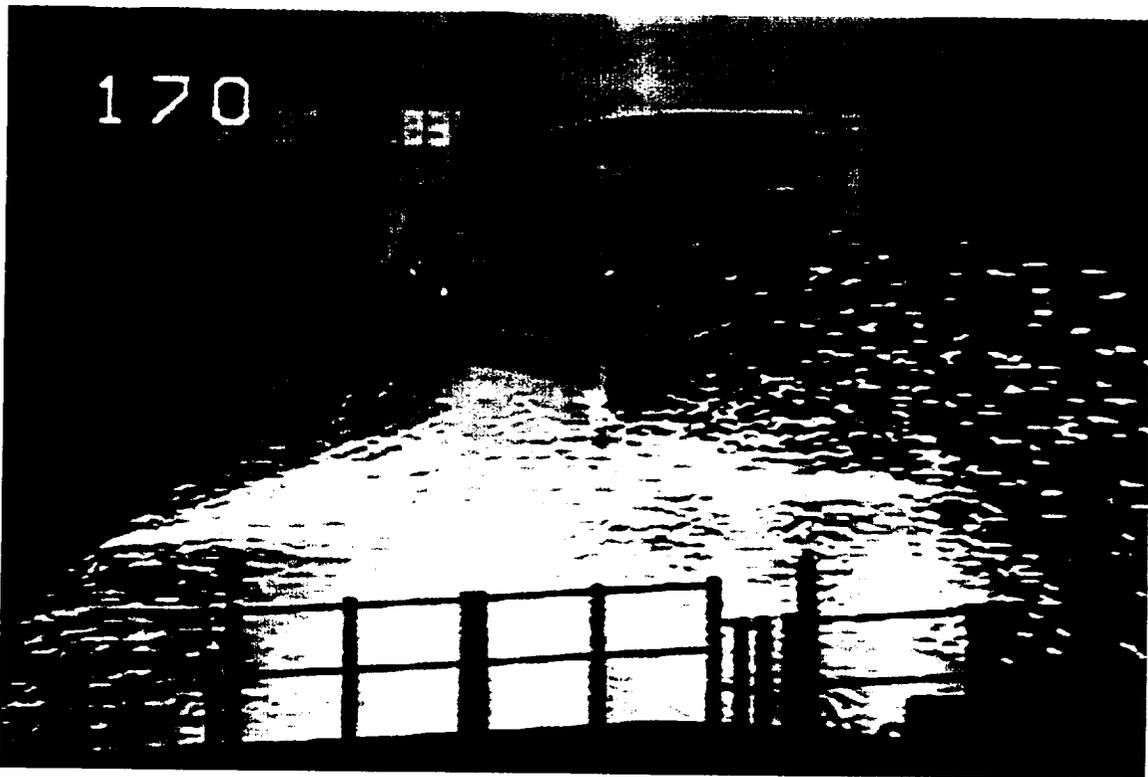
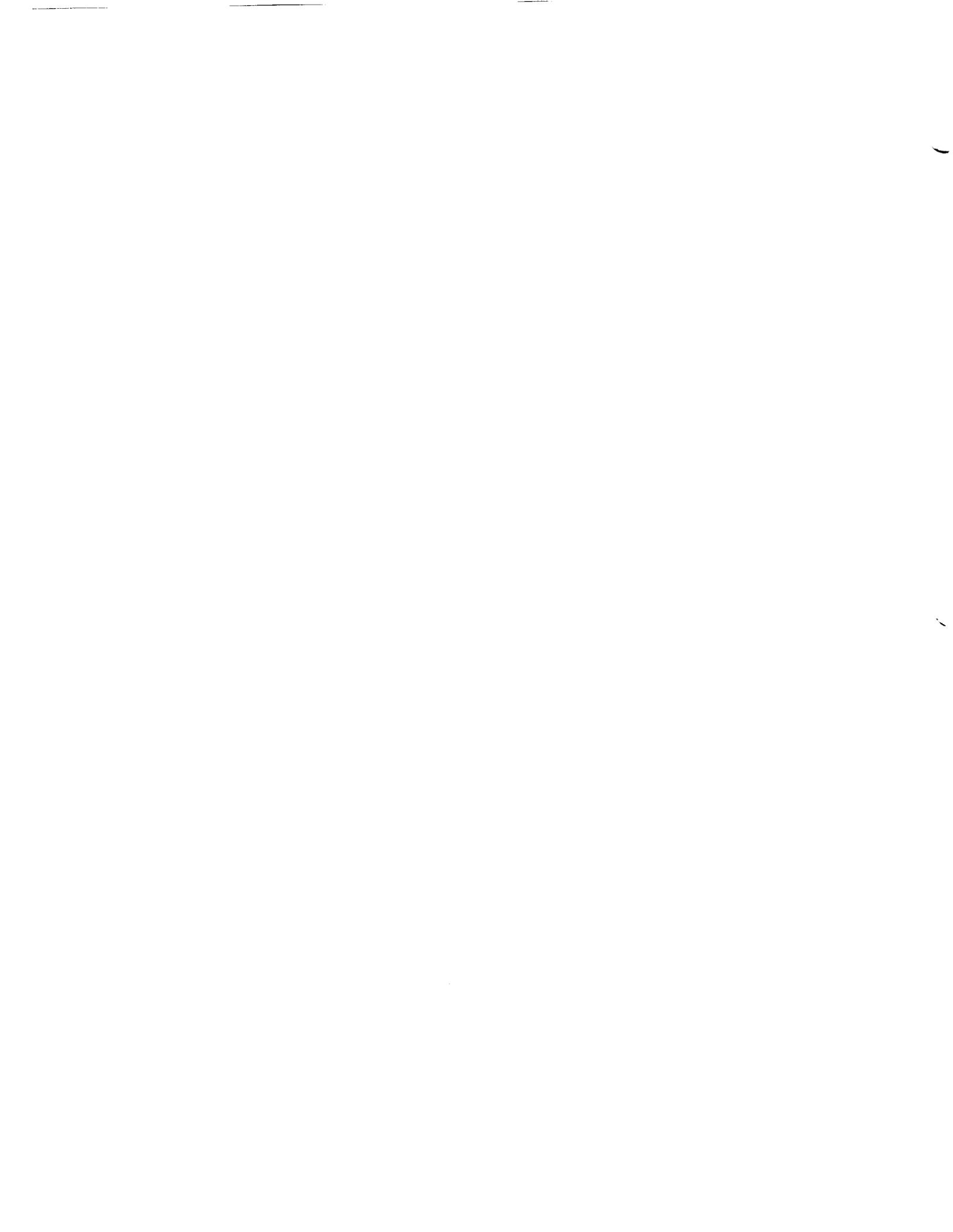


Figure 2.3.1 (D) Orange Vapors Forward of SSME Rims



Summary of Significant Events

An extensive amount of orange vapor (possibly free burning hydrogen) was seen forward of the SSME rims, forward of the base of the OMS pods, and near the base of the vertical stabilizer during SSME ignition (04:30:54.66 UTC). Orange vapors are typically seen on night launches, but possibly not to the extent seen on this mission. (Cameras OTV163, OTV170, OTV171, KTV7, KTV21B, E2, E5, E15, E17, E18, E19, E20, E36, E52, E54, E63, E76, E77)

A stream of white vapor was seen falling aft from a location forward of the -Y ET/Orbiter aft attach brace after SSME ignition (04:30:58.71 UTC). (Cameras OTV109, OTV163, E31, E36.) On the camera E41 view, these vapors were seen to originate from a single point source on the forward end of the ET -Y longeron (04:30:56.956 UTC). On camera OTV154, a similar appearing stream of white vapor was seen near the +Y ET/Orbiter aft attach (04:30:57.40 UTC).

Small areas of tile surface coating material erosion were seen during SSME ignition on the base of the left RCS stinger and on the base heat shield outboard of SSME #2 and SSME #3. (Cameras E2, E19, E20, E63, E76)

The SSME ignition appeared normal on the high-speed engineering films. SSME #1 and SSME #3 engine bell motion was apparent during ignition. The SSME Mach diamonds appeared to form in the expected sequence (3, 2, 1). The times for the Mach diamond formation given below are from camera film E19. (Cameras OTV151, OTV170, E2, E19, E20, E63, E76)

SSME	TIME (UTC)
SSME #3	04:30:56.719 UTC
SSME #2	04:30:56.884 UTC
SSME #1	04:30:56.968 UTC

Table 2.3.1 SSME Mach Diamond Formation Times

No vibration of the drag chute door was detected during SSME ignition. STS-93 was the second flight using new inconol shear pins to hold the drag chute door in position during launch. (Cameras E19, E20)

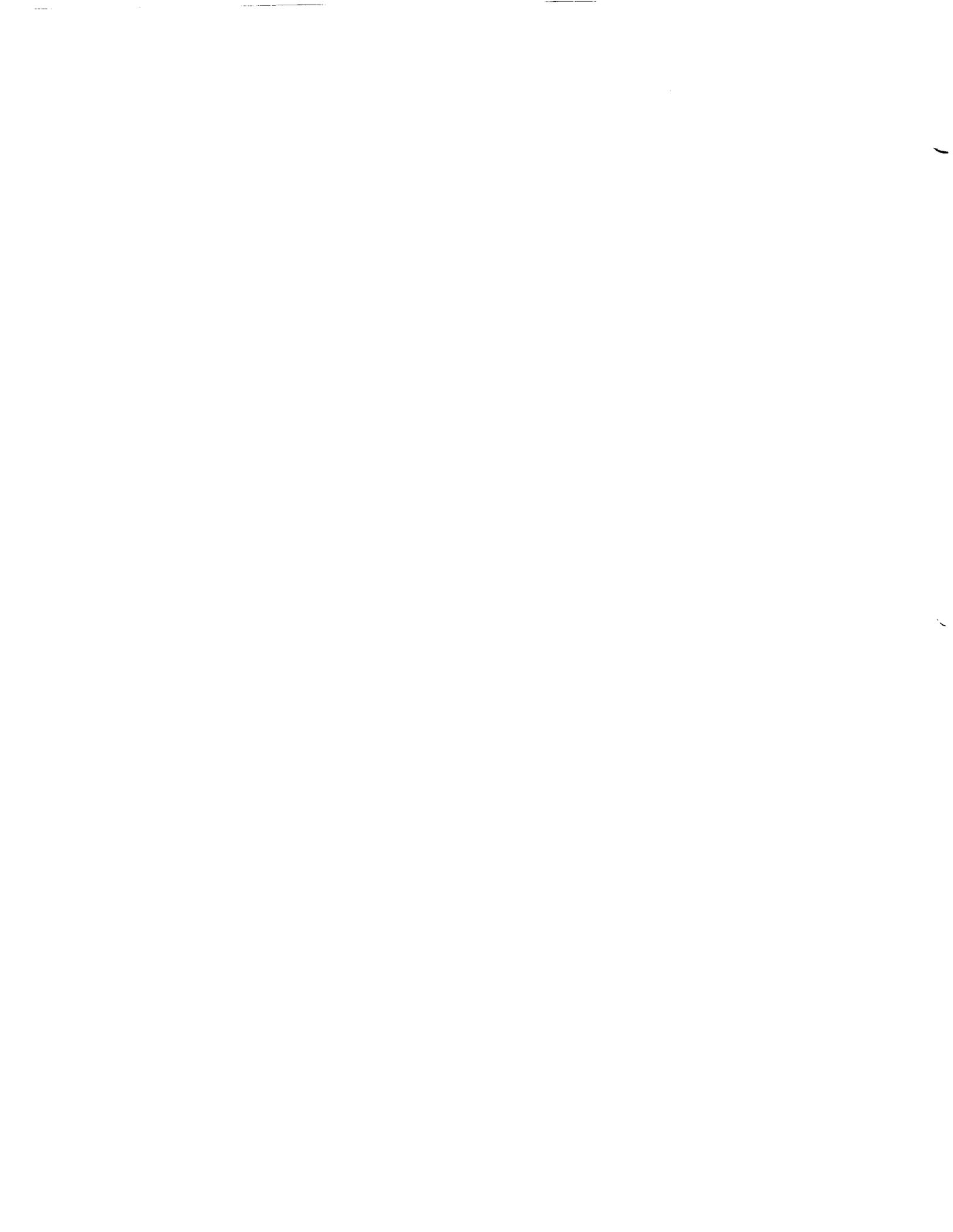


2.4 ASCENT EVENTS



Figure 2.4 (A) SSME #3 Hot-wall Leak During Ascent (Starboard View)

The SSME #3 hot-wall leak was also visible on the interior of the SSME #3 engine nozzle during ascent on the long range tracking cameras (cameras E52, E54, E207, E212, and E223). A white-colored area was seen extending aft of the SSME #3 engine bell rim indicating a substance was streaming aft.



Summary of Significant Events



Figure 2.4 (B) SSME #3 Hot-wall Leak During Ascent (Port View)

White-colored vapor (probably water) was seen streaming from the drain hole at the mid-level of the trailing edge of the rudder speed brake during liftoff and early ascent. This event has been seen on previous missions. (Cameras E52, E224)

Body flap motion was seen during ascent (04:31:25.7 – 04:31:50.1 UTC). The amplitude and frequency of the body flap motion appeared similar to that seen on previous mission imagery. No follow-up action was requested. (Cameras E207, ET207)

2.5 ONBOARD PHOTOGRAPHY OF THE EXTERNAL TANK (ET-99)

2.5.1 Analysis of the Umbilical Well Camera Films

Three umbilical well cameras (one 35mm and two 16mm cameras) flew on OV-102 during STS-93. The +X translation maneuver was not performed on STS-96 due to darkness. OV-102 did not provide timing data to the 16mm umbilical well cameras.

35mm Umbilical Well Camera Film

As expected, the STS-93 35mm umbilical well film was blank and of no use because of the night conditions when the photographs were taken.



Summary of Significant Events

16mm Umbilical Well Camera Films

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 irregular-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 detaching 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 noted. Ablation of the TPS on the aft dome was typical of previous missions. The SRB nose caps were not visible during SRB separation due to the poor lighting.

2.5.2 Analysis of the ET Handheld Photography

The STS-93 crew performed a manual pitch maneuver from the heads-up position to bring the ET into the view of the Orbiter's overhead windows for the handheld photography and video. STS-93 was the eighth flight to use the roll-to-heads-up maneuver.

Thirty-five images of the ET were acquired using the handheld 35mm Nikon camera with a 400mm lens (roll 316). Views of the nose, aft dome, and all sides of the ET were obtained. Approximately twelve of the thirty-five ET views are of the shadowed side of the tank and are very dark.

A description of the ET views of the handheld film is given in Table 2.5.2. Timing data is present on the film.

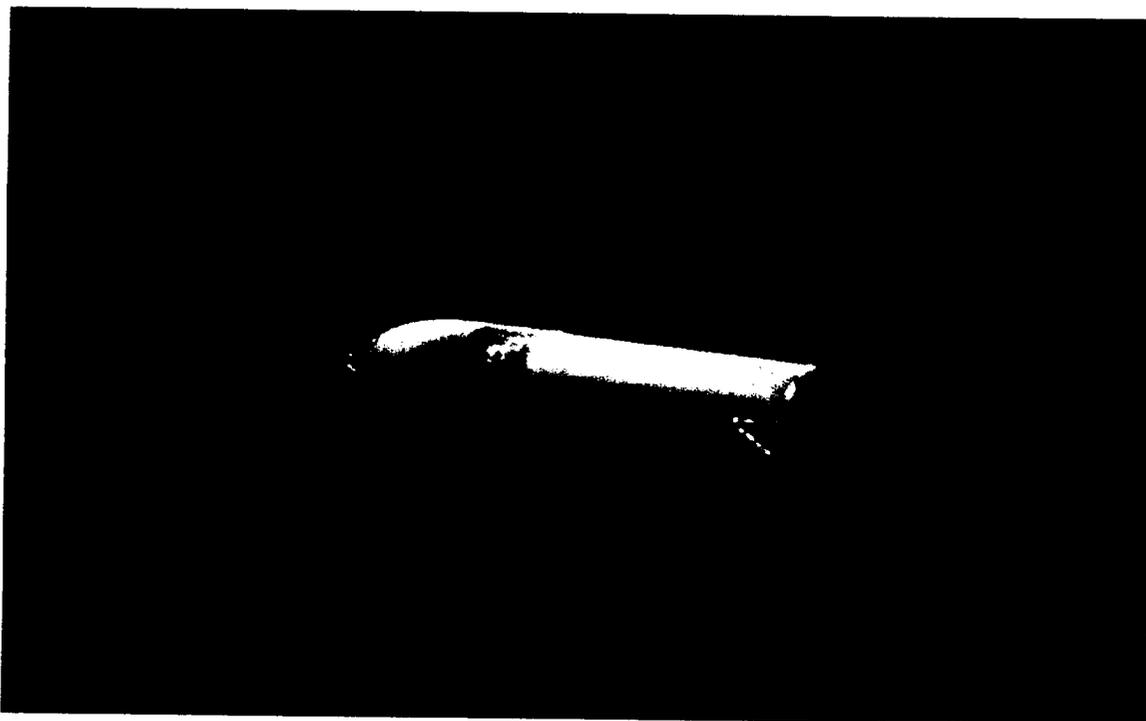


Figure 2.5.2 (A) ET +Y View



Summary of Significant Events

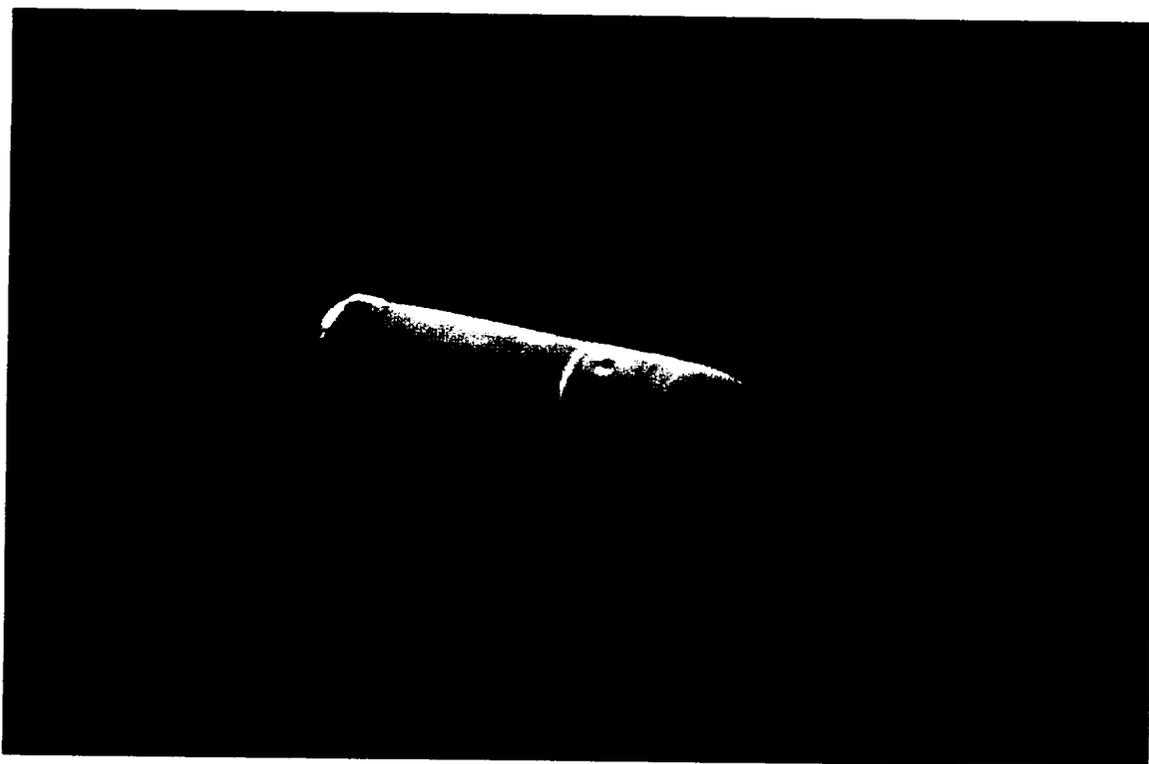


Figure 2.5.2 (B) ET -Y View

The ET is further away than previous (typical) missions because the crew had to wait until the ET came into sunlight before acquiring the imagery (approximately 26 minutes MET). The increased distance resulted in reduced resolution (greater than ten inches on the better views). The ET was in partial shadow on many frames. The distance from the camera to the ET could not be accurately calculated due to the shadowing of the ET. Because of the distance of the ET from the camera (>4 km), the level of detail visible on the imagery was insufficient to detect TPS erosion and the smaller divots seen on the STS-93 SRB thrust panel video. No anomalies on the ET surface were confirmed from the handheld ET film views. The two light-colored marks visible on the ET nose (-Z axis) were visible on the launch video prior to liftoff.

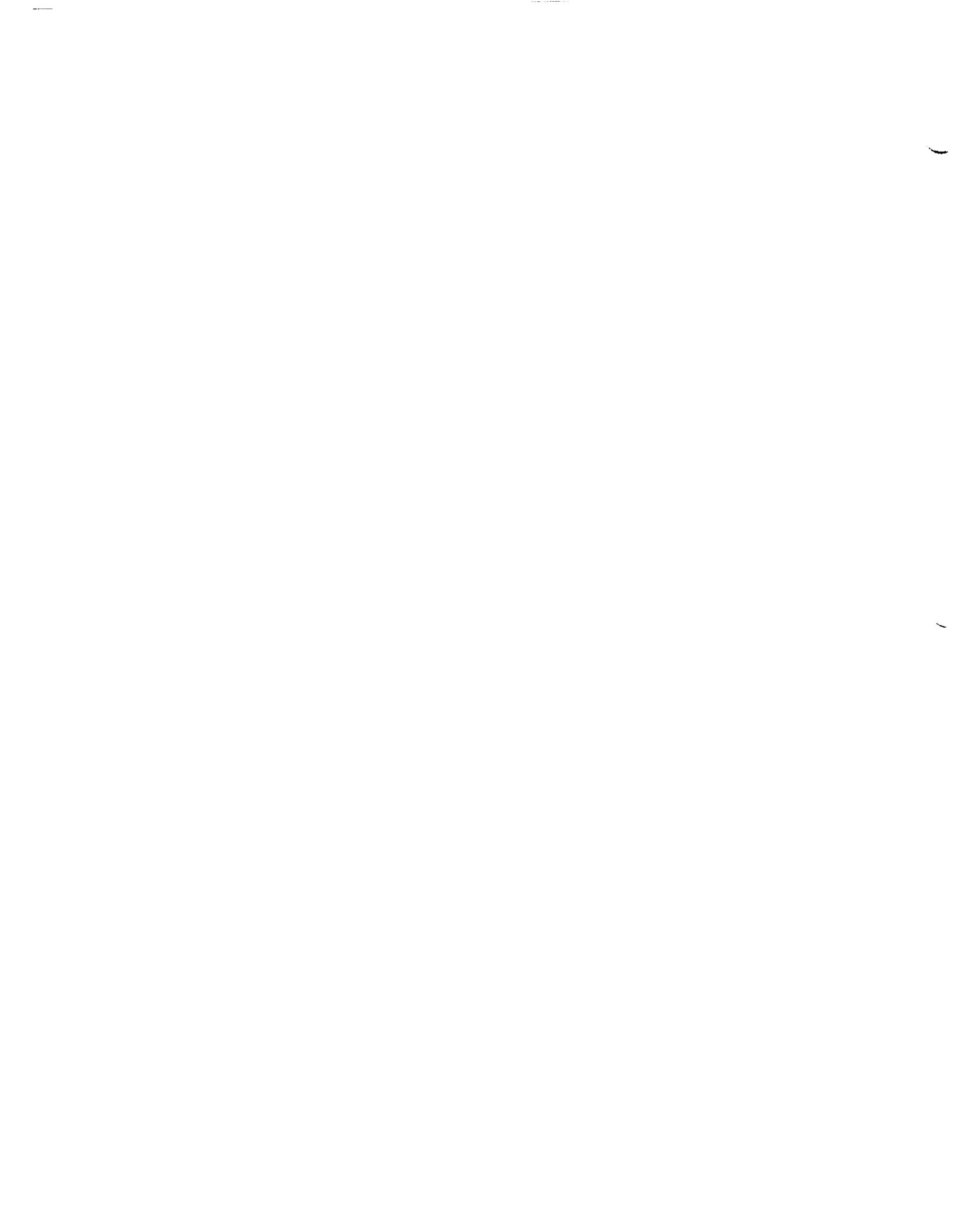
The normal SRB separation burn scars and aero-heating marks were noted on the ET nose and intertank TPS. No venting was seen on the ET film images.



Summary of Significant Events

STS-93					
External Tank: Handheld Pictures (35 mm Film)					
Screening Information and Calculations					
Roll # 316					
Frame No	GMT (hh:mm:ss)	MET (mm:ss)	Delta Time	Cum. Time	View
1	04:57:30	26:30	00:00	00:00	Blank
2	04:57:30	26:30	00:00	00:00	Blank
3	04:57:30	26:30	00:00	00:00	Nose
4	04:57:33	26:33	00:03	00:03	Side of ET
5	04:57:38	26:38	00:05	00:08	-Z, -Y Axis
6	04:57:41	26:41	00:03	00:11	Aft dome, +Z Axis
7	04:57:48	26:48	00:07	00:18	+Y, -Z, Intertank
8	04:57:57	26:57	00:09	00:27	Nose, LH2 Tank, -Y, -Y Thrust Panel
9	04:58:04	27:04	00:07	00:34	Aft Dome
10	04:58:08	27:08	00:04	00:38	Nose, +Z, -Y
11	04:58:21	27:21	00:13	00:51	Nose
12	04:58:24	27:24	00:03	00:54	-Y Axis
13	04:58:26	27:26	00:02	00:56	-Y Axis
14	04:58:39	27:39	00:13	01:09	+Y Axis
15	04:58:58	27:58	00:19	01:28	Aft Dome
16	04:59:03	28:03	00:05	01:33	-Y, -Y Thrust Panel
17	04:59:08	28:08	00:05	01:38	Side of ET
18	04:59:20	28:20	00:12	01:50	Aft Dome, Side of ET
19	04:59:31	28:31	00:11	02:01	Side of ET
20	04:59:40	28:40	00:09	02:10	-Y, -Y Thrust Panel
21	04:59:46	28:46	00:06	02:16	Aft Dome, Side of ET
22	04:59:59	28:59	00:13	02:29	Nose, Side of ET
23	05:00:07	29:07	00:08	02:37	-Y Axis
24	05:00:32	29:32	00:25	03:02	-Y Axis
25	05:00:45	29:45	00:13	03:15	+Y Axis
26	05:00:49	29:49	00:04	03:19	Side of ET
27	05:00:57	29:57	00:08	03:27	Side of ET
28	05:01:02	30:02	00:05	03:32	Side of ET
29	05:01:20	30:20	00:18	03:50	Nose, -Y Axis
30	05:01:33	30:33	00:13	04:03	+Y, +Y Thrust Panel
31	05:01:57	30:57	00:24	04:27	+Y, +Y Thrust Panel
32	05:02:00	31:00	00:03	04:30	-Z Side of ET
33	05:02:10	31:10	00:10	04:40	-Y, LH2 Tank, Nose
34	05:02:24	31:24	00:14	04:54	-Z Axis
35	05:02:31	31:31	00:07	05:01	Nose, -Y Axis
36	05:02:45	31:45	00:14	05:15	+Y Axis
37	05:02:56	31:56	00:11	05:26	-Y Axis

Table 2.5.2 Description of the Handheld ET Film Views



Summary of Significant Events

2.5.3 Analysis of the ET Handheld Video

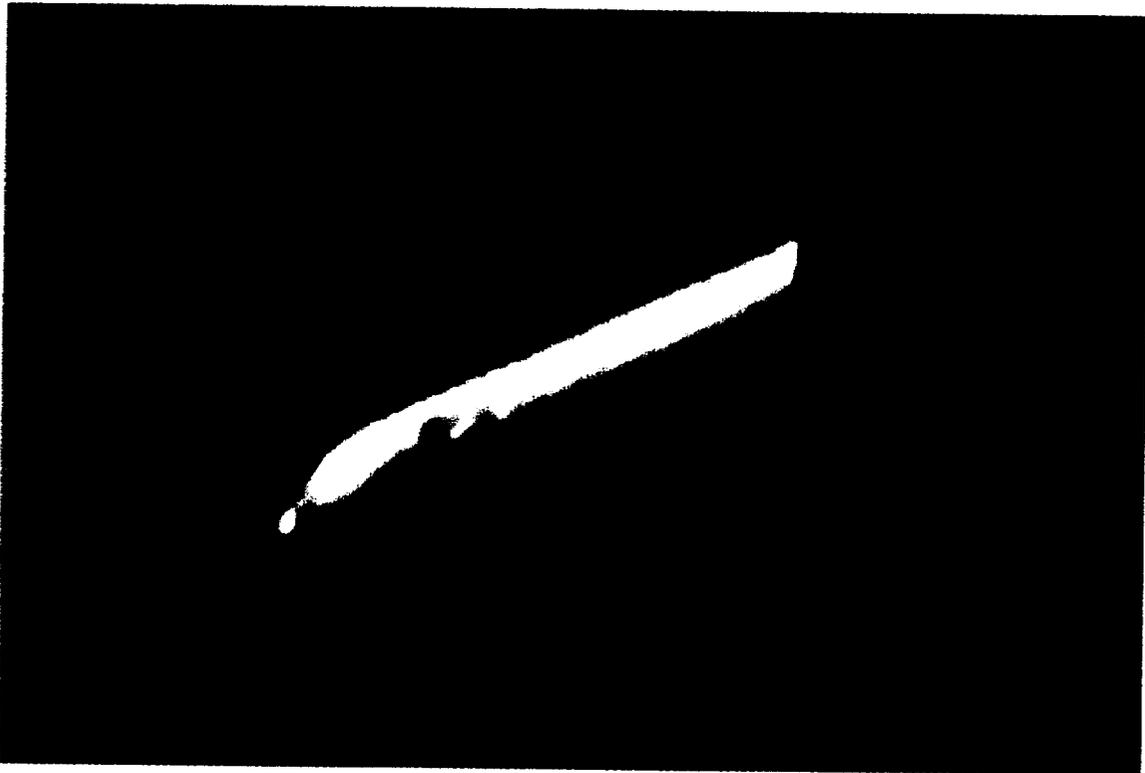


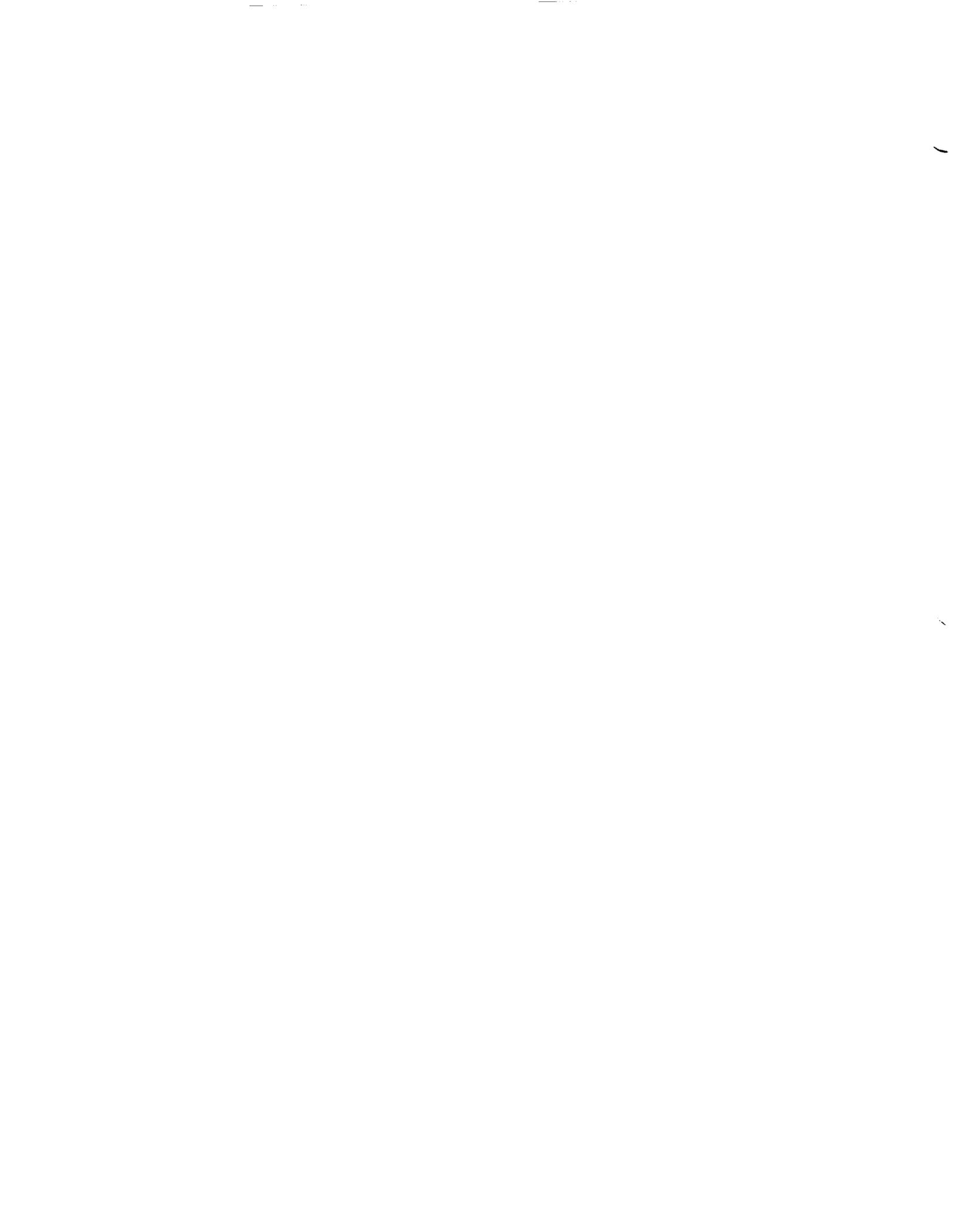
Figure 2.5.3 Video View of ET

Handheld video of the STS-93 ET was obtained. The ET was first acquired at 28.8 minutes MET and the recording continued for 3.7 minutes. The ET is further away than previous (typical) missions because the crew had to wait until the ET came into sunlight before acquiring the imagery. The increased distance resulted in reduced resolution. No TPS damage was confirmed. Views of all aspects of the ET were acquired. The normal SRB separation burn scars and aero-heating marks are visible on the intertank and nose TPS of the ET.

The overall quality of the video is good. The focus and exposure is generally good.

As on STS-88 and STS-96, no venting from the ET was detected on STS-93. (However, venting was seen on the five missions previous to STS-88.)

The tumble rate of the ET (end-to-end rotation of the ET about its center of mass) was greater than that seen on the previous five missions. Table 2.5.3 contains a comparison of the averaged tumble rate measurements for the current and the previous seven Space Shuttle missions.



Summary of Significant Events

MISSION	Tumble Rate (deg/sec)	Separation Rate (m/sec)	MET (mm:ss)	Venting
STS-87	11	--	17:23 - 18:08	Yes
STS-89	12	--	31:42 - 35:27	Yes
STS-90	3	--	14:30*	Yes
STS-91	11	--	16:29 - 18:46	Yes
STS-95	< 1	5.5 (prior to venting)	13:40 - 20:50	Yes
STS-88	2	6.2	15:39 - 22:44	No
STS-96	1.3	6.5	13:21 - 18:21	No
STS-93	14.7	Not Determined	28:56 - 32:56	No

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

Table 2.5.3 ET Tumble and Separation Rates

2.6 ET THRUST PANEL VIDEO

Good quality views of the left and right STS-93 ET thrust panels during ascent were acquired with the SRB video cameras. However, light reflections and shadows hindered the analysis of the damaged TPS. The lighting was from the SRB exhaust plumes because of the night launch.

Similar to the STS-95 and STS-96 thrust panel video views, the divots were seen on or near the rib heads. Very few divots were noted in the valleys between the ribs. The divots were shallow and no primed substrate was noted (Figures 2.6 (A) and 2.6 (B)). Compared to the previous mission videos of the ET thrust panels, fewer total divots appeared to be present on the STS-93 thrust panels (Figures 2.6 (C) and 2.6 (D)). The divots first began to appear at approximately 100 seconds MET, which was similar to the time when the divots formed on the previous mission (STS-95 and STS-96) thrust panel videos.

In addition, multiple divots were seen outboard of both thrust panels on the intertank stringers. Some of the intertank stringer divots were greater than one inch in size. Two large divots were also seen on the LH2 tank TPS and extended across the LH2 tank-to-intertank closeout flange. The largest of these two divots was estimated to be twenty inches in size. From the thrust panel videos, both the left and right SRB nose caps were confirmed to be in place after SRB separation.



Summary of Significant Events

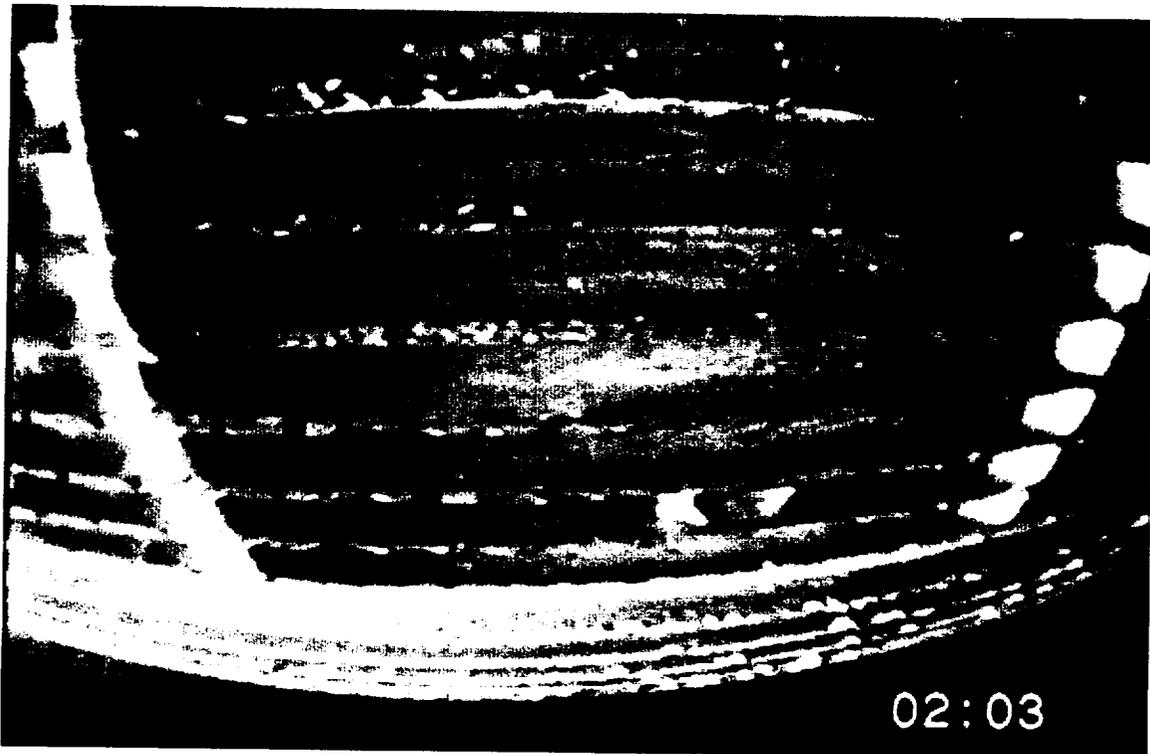


Figure 2.6 (A) LSRB View of ET Thrust Panel

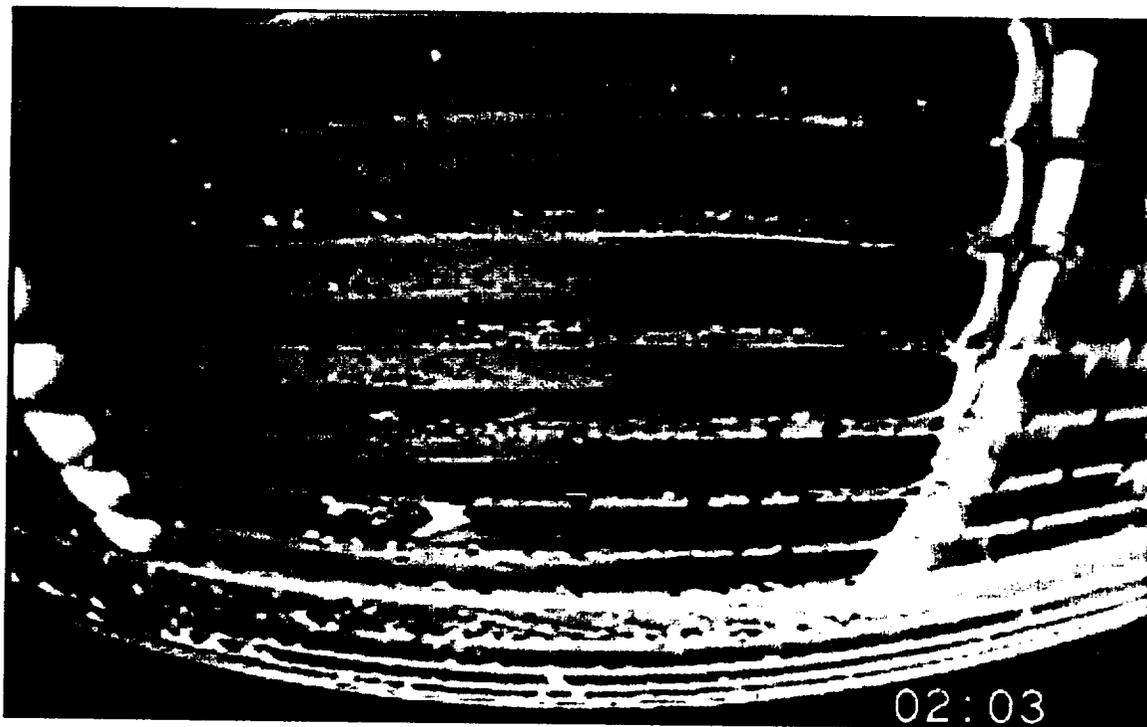


Figure 2.6 (B) RSRB View of ET Thrust Panel

Figures 2.6 (A) and 2.6 (B) contain views of the STS-93 ET thrust panels just before SRB separation (02:03 MET).





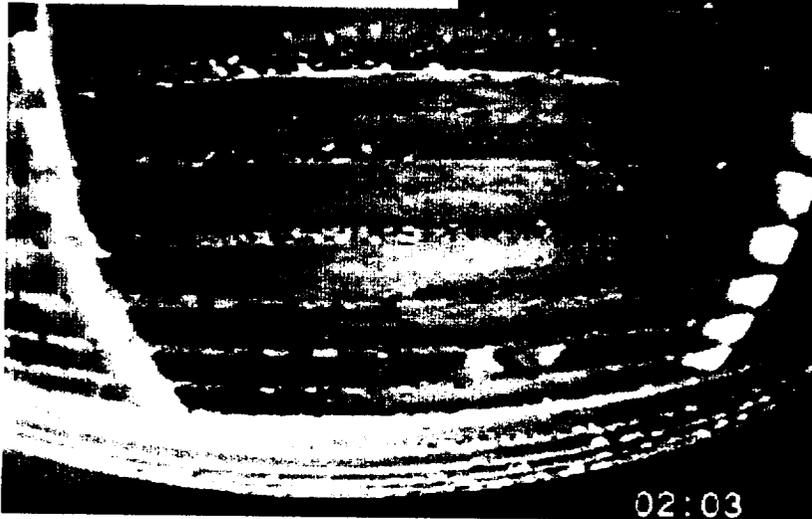
**LEFT ET
Thrust Panel
Comparison**

STS-95



STS-96

STS-93



**Image Science and
Analysis Group
NASA-JSC/SN3**

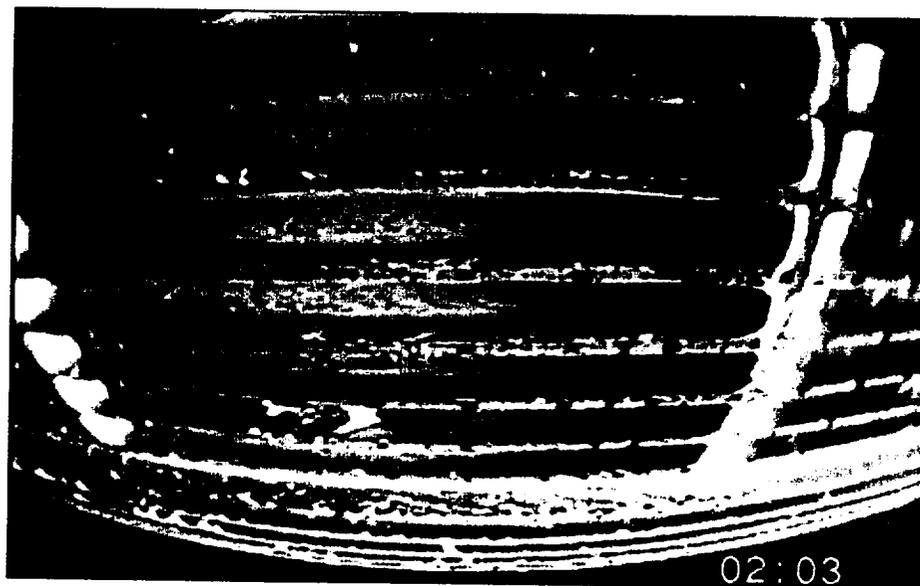
Figure 2.6 (C) STS-95, STS-96 and STS-93 -Y Thrust Panel Comparisons



Right ET Thrust Panel Comparison



STS-96



STS-93

Figure 2.6 (D) STS-96 and STS-93 +Y Thrust Panel Comparison



Summary of Significant Events

2.7 LANDING EVENTS

2.7.1 Landing Sink Rate Analysis

Image data from the centerline video camera at the approach end of runway 33 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 (31 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 (272 inches) 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. A trendline was determined considering the height of the Orbiter above ground with respect to time. Sink rate equals the slope of this regression line.

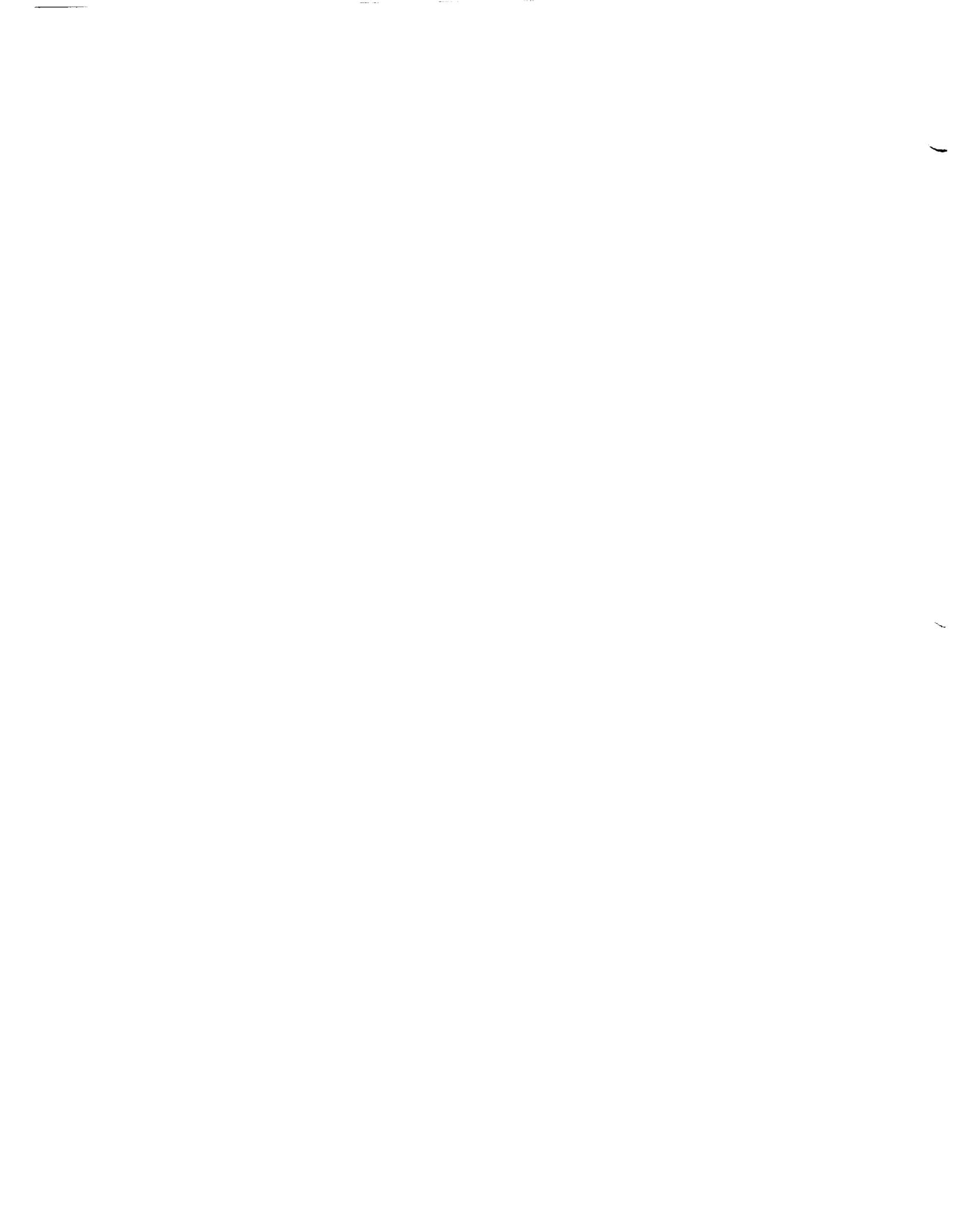
The left main gear sink rate for STS-93 landing at one second, at half a second, and at a one quarter of a second are provided in the following table. A plot describing these sinkrates is enclosed. Due to the night landing resulting in dark images and the degraded resolution of video compared to film, the sink rate estimates for STS-93 are not as accurate as in previous missions. No significant correlation could be determined for the regression of the data during the last 0.25 seconds of the landing. Error estimates during this time are imprecise at best.

Time Prior to Touchdown	1.00 Sec.	0.50 Sec.	0.25 Sec.
Left Main Gear Sink Rate	0.4 ft/sec	0.4 ft/sec	0.3 ft/sec
Estimated Error (1σ)	± 0.1 ft/sec	± 0.2 ft/sec	± 0.6 ft/sec

Left Main Gear Touchdown = 209:03:20:34.375 (UTC)

Table 2.7.1 Main Gear 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-93 vehicle was estimated to be 202,721 lbs.



Summary of Significant Events

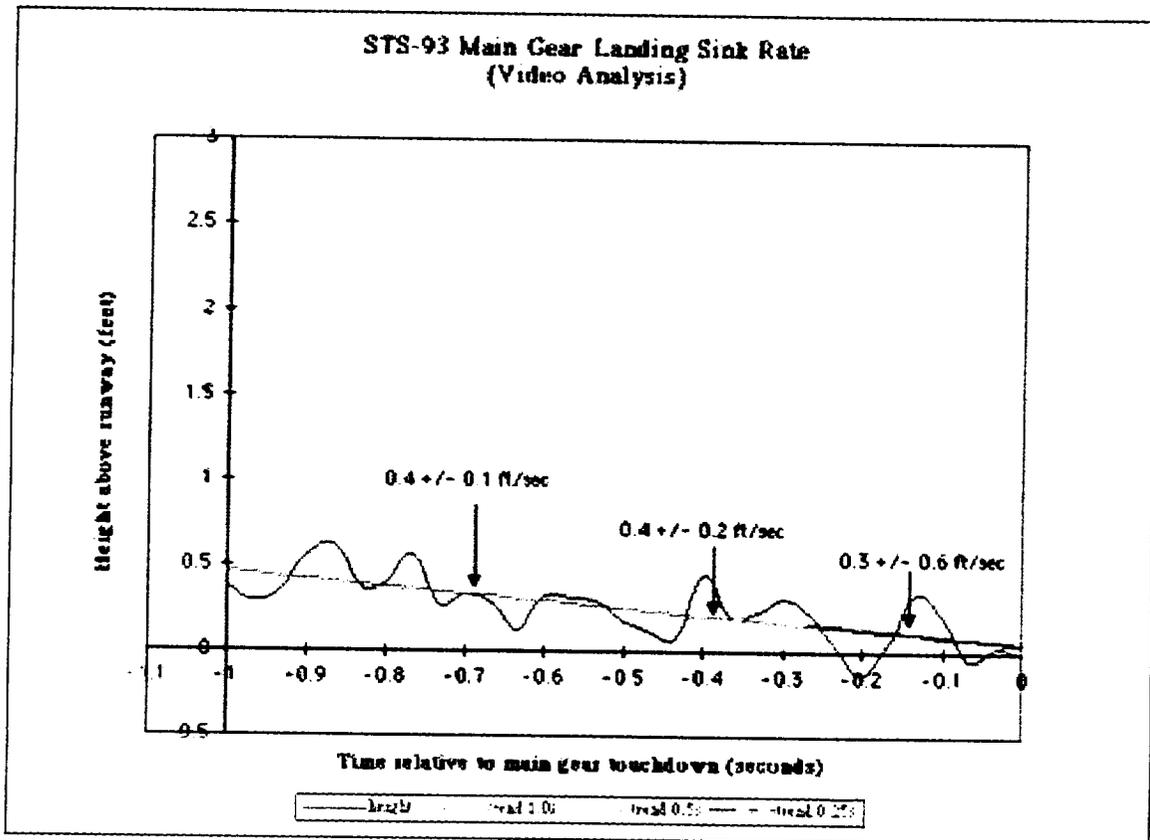


Figure 2.7.1 Main Gear Landing Sink Rate

2.8 OTHER

2.8.1 Normal Events

Normal events observed included:

- vapors from the ET vent louver prior to liftoff
- elevon 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 umbilical 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
- white-colored flashes in the SSME exhaust plume after liftoff
- vapor off the SRB stiffener rings

Summary of Significant Events

- charring of the ET aft dome
- ET aft dome outgassing
- condensation on the Shuttle launch vehicle during ascent
- linear optical effects
- recirculation
- SRB plume brightening
- SRB slag debris before, during, and after SRB separation

2.8.2 Normal Pad Events

Normal pad events observed included:

- hydrogen burn ignitor operation
- FSS and MLP deluge water activation
- sound suppression system water operation
- GH2 vent arm retraction
- TSM T-0 umbilical operations
- LH2 and LO2 TSM door closures



APPENDIX B. MSFC PHOTOGRAPHIC ANALYSIS SUMMARY





STS-93 Engineering Photographic Analysis Report

Table of Contents

- Introduction
- Engineering analysis objectives
- Camera coverage assessment
 - Ground camera coverage
 - Onboard camera coverage
- Anomalies
- Observations
- Engineering data results
 - T-0 times
 - SRB separation time
- Appendix A - Individual film camera assessments
- Appendix B - Individual video camera assessments
- Appendix C - Definitions and acronyms

Introduction

The launch of space shuttle mission STS-93, the twenty-sixth flight of the Orbiter Columbia occurred July 22, 1999, at approximately 11:31PM Central Daylight Time from launch complex 39B, Kennedy Space Center (KSC), Florida. Launch time reported as 204:04:30:59.984 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), perimeter sites, Eastern Test Range tracking sites and onboard the vehicle.

Engineering Analysis Objectives

The planned engineering photographic and video analysis objectives for STS-93 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



- o Free hydrogen ignitors
- o Booster separation motors

- Camera Coverage Assessment

The following table illustrates the camera coverage expected at MSFC for STS-93.

	16mm	35mm	Video
MLP	19	0	4
FSS	5	0	3
Perimeter	0	7	5
Tracking	0	9	12
Onboard	0	0	2
Totals	24	16	24

Total number of film and videos received to date: 66

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

Anomalies

Hot wall leak observed on SSME #3 nozzle.

Observations





SSME #3 hot wall leak seen from camera ET-207.



Engine streak seen from camera ET-213.



Engine streak seen from camera OTV-170.



A number of engine streaks as well as the SSME #3 hot-wall leak were seen from camera E-19.



A number of the engine streaks were also seen from camera E-20.



An engine streak in SSME #2 observed approximately 23 seconds MET.

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	204:04:30:59.993
M-2	E8	204:04:30:59.991
M-5	E12	204:04:30:59.992
M-6	E13	204:04:30:59.992

SRB Separation Time

SRB separation as recorded by observations of the BSM combustion products from long-range film and video cameras. Video cameras ET207 and ET208 both recorded SRB separation at about 204:04:33:03.27 +/-0.033 UTC. High speed film camera E208 recorded SRB separation time at 204:04:33:03.284 UTC.

Appendix A - Individual film camera assessments



Appendix B - Individual video camera assessments

Appendix C - Definitions and acronyms

Individual film/video summary report

 [Return to Engineering Photographic Analysis Reports](#)

 [Return to MSFC Engineering Photographic Analysis Home Page](#)

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REPORT DOCUMENTATION PAGE

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Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 1999	3. REPORT TYPE AND DATES COVERED Final July 18-28, 1999	
4. TITLE AND SUBTITLE Debris/Ice/TPS Assessment and Integrated Photographic Analysis of Shuttle Mission STS-93		5. FUNDING NUMBERS OMR00U0	
6. AUTHOR(S) Gregory N. Katnik		8. PERFORMING ORGANIZATION REPORT NUMBER NASA/TM-1999-208555	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA, John F. Kennedy Space Center Process Engineering, Mechanical Systems Division ET/SRB Branch, Mail Code: PK-H Kennedy Space Center, Florida 32899		10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)		11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION / AVAILABILITY STATEMENT Blanket Release		12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A debris/ice/thermal protection system assessment and integrated photographic analysis was conducted for Shuttle mission STS-93. Debris inspections of the flight elements and launch pad were performed before and after launch. Icing conditions on the External Tank were assessed by the use of computer programs and infrared scanned data during cryogenic loading of the vehicle, followed by on-pad visual inspection. High speed photography of the launch was analyzed to identify ice/debris sources and evaluate potential vehicle damage and/or in-flight anomalies. This report documents the ice/debris/thermal protection system conditions and integrated photographic analysis findings of Space Shuttle mission STS-93 and the resulting effect on the Space Shuttle Program.			
14. SUBJECT TERMS SUBJECT CATEGORY: 15, 16 STS-93 Thermal Protection System (TPS) Ice Debris Integrated Photographic Analysis			15. NUMBER OF PAGES
17. SECURITY CLASSIFICATION OF REPORT Unclassified			16. PRICE CODE
18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

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