Debris/Ice/TPS Assessment and Integrated Photographic Analysis of Shuttle Mission STS-88

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DEBRIS/ICE/TPS ASSESSMENT
AND
INTEGRATED PHOTOGRAPHIC ANALYSIS
OF
SHUTTLE MISSION STS-88

4 December 1998

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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-88

1.0 SUMMARY OF SIGNIFICANT EVENTS

STS-88 consisted of OV-105 (13th flight), ET-97 and BI-095 SRB's on MLP-3 and Pad 39A. Endeavour was launched at 338:08:35:34.019 UTC (3:35 a.m. local) on 4 December 1998. Landing was at 10:53 p.m. local/eastern time landing on 15 December 1998.

ET Thrust Panels

In the on-orbit photography, no divots could be discerned in the intertank +Z side acreage, in the area of the bipod jack pad closeouts, and in the LH2 tank-to-intertank flange closeout with the exception of one 10-inch divot in the forward part of the flange and extending forward into the -Y thrust panel acreage.

Two frames of the -Y thrust panel showed the acreage aft of the EB fitting was generally in good condition. Several divots 2 to 3 inches in size could be discerned in thrust panel TPS to the -Z side of the EB fitting and forward of the fitting. The +Y thrust panel was imaged at a time when the ET was more distant and the resolution had degraded. The presence of divots could not be confirmed.

The Orbiter TPS sustained a total of 116 hits, of which 25 had a major dimension of 1-inch or larger. A comparison of these numbers to statistics from previous missions indicates the total number of hits is close to average while the number of hits 1-inch or larger is still greater than the cumulative mission average.

The Orbiter lower surface sustained 80 total hits, of which 21 had a major dimension of 1-inch or larger. Most of this damage was concentrated between the nose gear and the main landing gear wheel wells on both left and right chines though the predominant number of damage sites occurred on the right side. (It should be noted there was no unusual or unexpected accumulations of ice in the ET LO2 feedline bellows and support brackets at the time of launch). The outboard damage sites on the chines followed a similar location/damage pattern documented on STS-86, -87, -89, -90, -91, and -95, though the pattern was not as symmetric as the previously noted flights. It should also be noted that this was the third flight of the new Super Light Weight Tank.

No lower surface tiles were scrapped due to debris damage. The largest lower surface tile damage site, located on the right chine, measured 4.5-inches long by 1.125-inches wide by 0.125-inch deep. The deepest lower surface tile damage sites measured 0.5-inches and were located on the right chine.

The External Tank Project continues to work an IFA to prevent loss of foam from the ET thrust panels and preclude further damage to Orbiter tiles

SSME Nozzle Ablator

Two pieces of SSME nozzle ablator, (6-inches and 4-inches long, respectively, by ¾-inch wide by 3/8-inch thick), were found on Orbiter body flap stub tiles adjacent to the base heat shield beneath SSME #2. No impact damage to the tiles was detected. Inspection of the SSME #2 and #3 nozzles revealed approximately 60 percent of the ablator was missing.

The ablator was bonded to SSME #2 and #3 circumferentially from 45 degrees inboard to 90 degrees outboard on the -Z side of the nozzle to prevent the recurring problem of bluing. This ablator was first used on STS-95.

Post flight assessment of the recovered ablator pieces and nozzle bonding surface reveal the material debonded after the heat of reentry, and therefore after peak heating of the SSME nozzles. Since it is highly unlikely the pieces of ablator could have remained on the body flap tiles during the aerodynamic turbulence and maneuvering of reentry, the material is believed to have shaken loose at main landing gear touchdown. Nevertheless, the ablator, with a density of about 92 pounds per cubic foot, is now considered to be a debris issue. IFA STS-88-I-01 was taken with a constraint to STS-93.

2.0 PRE- LAUNCH BRIEFING

The Debris/Ice/TPS and Photographic Analysis Team briefing for launch activities was conducted on 1 December 1998 at 1500 hours. The following personnel participated in various team activities, assisted in the collection and evaluation of data, and contributed to reports contained in this document.

P. Weber	NASA - KSC	Chief, ET/SRB Mechanical Systems Branch
G. Katnik	NASA - KSC	Shuttle Ice/Debris Systems
R. Speece	NASA - KSC	Thermal Protection Systems
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W. Richards	USA - SPC	ET Mechanical Systems
M. Wollam	USA - SPC	ET Mechanical Systems
G. Fales	USA - SPC	ET Mechanical Systems
T. Ford	USA - SPC	ET Mechanical Systems
J. Stone	BNA - DNY	Shuttle Aerodynamics
R. Oyer	BNA - LSS	Systems Integration
B. St. Aubin	THIO - LSS	SRM Processing
S. Otto	LMSO - LSS	ET Processing
J. Ramirez	LMSO - LSS	ET Processing

3.0 SCRUB

An overall pre-launch debris inspection of the launch pad and Shuttle vehicle was performed on 2 December 1998. The detailed walkdown of Pad 39A and MLP-3 also included the primary flight elements OV-105 Endeavour, ET-97, and BI-095 SRB's. There were no significant vehicle anomalies. A deck bolt and a small Allen wrench were discovered on the MLP deck during this inspection.

Even with a night launch and liftoff time close to 4:00 a.m., local weather conditions were not expected to be a constraint to launch. Ambient weather conditions consisted of temperatures in the low-to-mid 70's, relative humidity averaging 71 percent, and 9 knot winds out of the northeast.

The Final Inspection of the cryoloaded vehicle was performed on 2 December 1998 from 2145 to 2325 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 data base. ET TPS surface temperatures ranged from low to mid 50's. The only TPS item of note concerned a crack in a -Y+Z intertank stringer valley. The crack was approximately 8-10 inches long and was similar to those documented on previous vehicles. Several small internal leaks in Orbiter RCS thrusters (F3D, F1L, F2R, F4R, and R2R) were documented. The paper cover on thruster R2R was very wet and exhibited a liquid level line.

The launch was scrubbed due to a hydraulic system master alarm that could not be resolved prior to the ending of the launch window.

A post drain inspection of the External Tank revealed no anomalies. There were no constraints to the next cryoload.

Photo 2: STS-88 Ready for Launch

STS-88 consisting of OV-105 Endeavour (13th flight), ET-97, and BI-095 SRBs on MLP-3/Pad 39A prior to cryoload

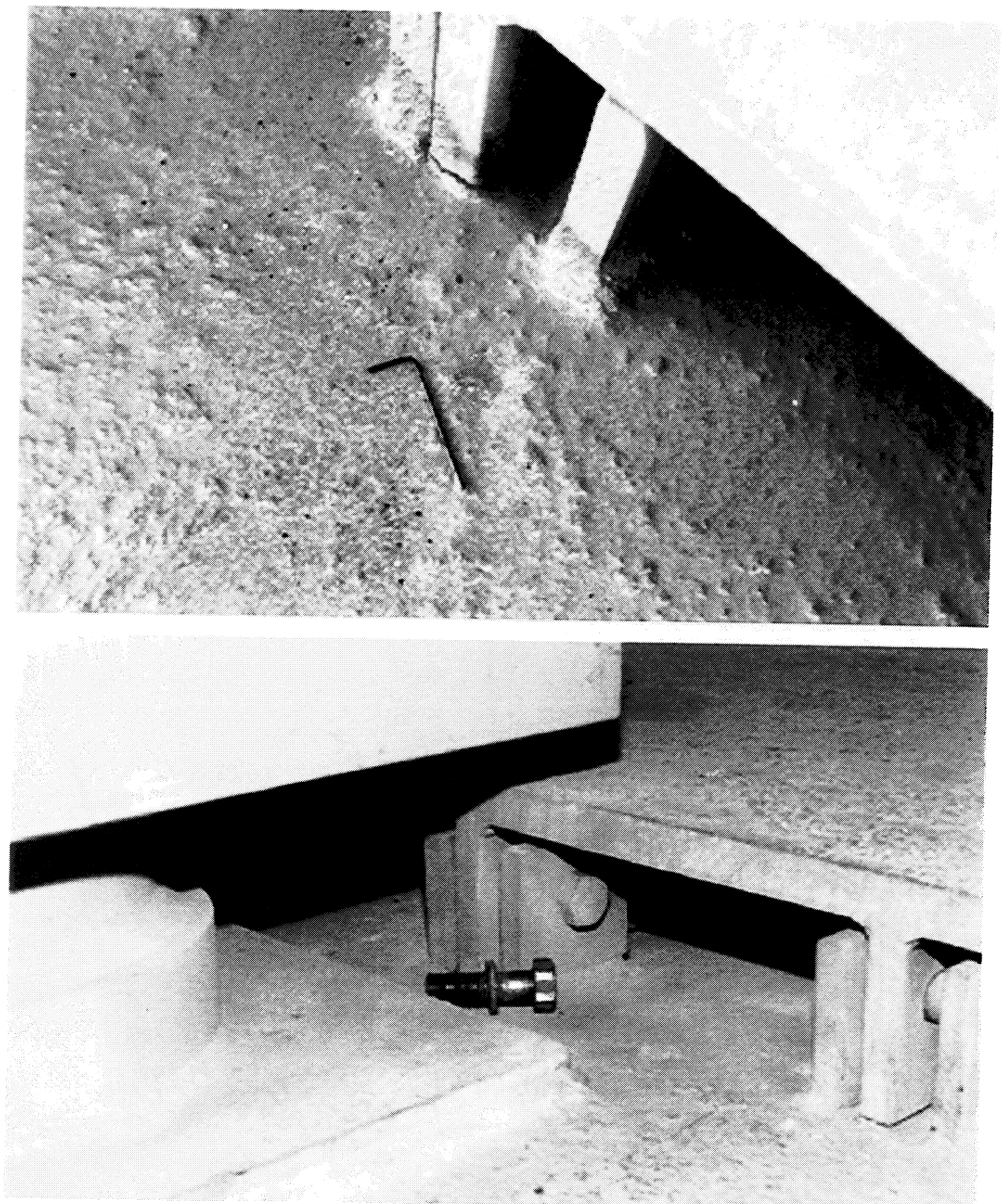


Photo 3: MLP Deck Debris

A small wrench and MLP deck bolt were found during the Pre-Launch Pad Inspection

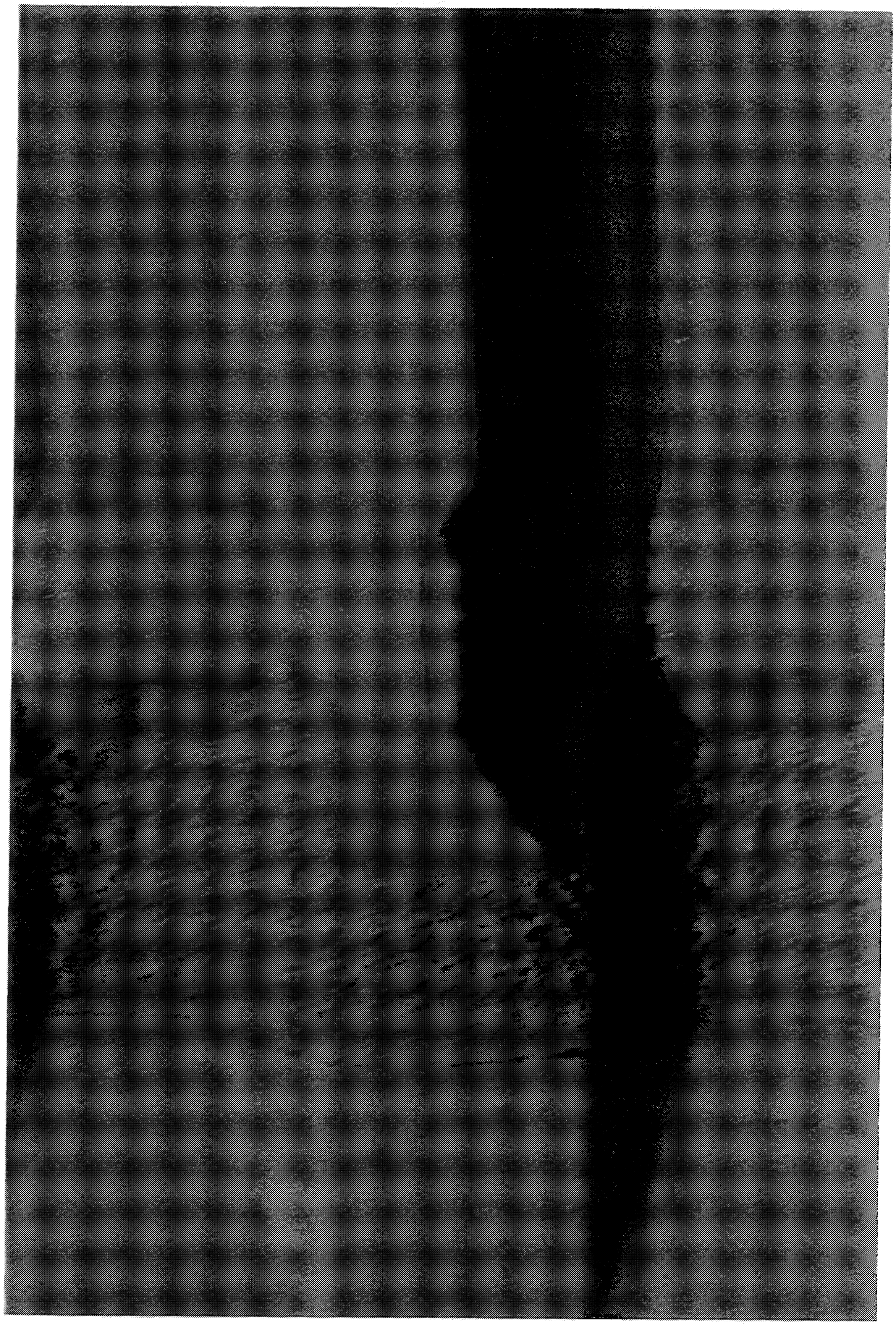


Photo 4: Crack in Intertank Foam

The only TPS item of note concerned a crack in a -Y+Z intertank stringer valley. The crack was approximately 8-10 inches long and was similar to those documented on previous vehicles.

4.0 LAUNCH

STS-88 was launched at 338:08:35:34.019 UTC (3:35 a.m. local) on 4 December 1998.

4.1 PRE-LAUNCH SSV/PAD DEBRIS INSPECTION

A pre-launch debris inspection was accomplished at the same time as the post drain inspection due to the 24 hour scrub turnaround. Weather conditions remained warm with ambient temperatures averaging 74 degrees F, relative humidity at 80 percent, and 9 knot winds out of the east.

4.2 FINAL INSPECTION

The Final Inspection of the cryoloaded vehicle was performed on 3 December 1998 from 1040 to 1150 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 data base.

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 intact. Several small internal leaks (F3D, F1L, F2R, F4R, and R2R) were documented. The paper cover on thruster R2R was very wet and exhibited a liquid level line. Condensate had formed on SSME #1 and #2 heat shield-to-nozzle interfaces. The SSME #3 heat shield was dry. 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 77 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 very light condensate, but no ice or frost accumulations, on the LO2 tank acreage. Surface temperatures averaged 50 degrees Fahrenheit.

One crack was present again in a stringer valley in the intertank -Y+Z quadrant. The crack appeared to originate from the as-sprayed foam at the aft end of the stringer extending forward approximately 10-12 inches from the LH2 tank splice. The crack, which had elongated an additional two inches from that observed during the previous cryoload, was less than 1/16-inch wide with no visible offset or ice/frost formation. The crack was acceptable for flight per the NSTS-08303 criteria and SLWT tanking test IPR rationale.

Numerous frost spots had formed along three intertank stingers near the LO2 tank-to-intertank flange closeout in the -Y-Z quadrant.

The Final Inspection Team observed very light condensate, but no ice or frost accumulations, on the LH2 tank acreage.

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

A 8-inch long by 3/8-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 and frost in the LH2 recirculation line bellows and on both burst disks was typical. The LH2 feedline bellows were wet with condensate.

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. Even with the decrease in ambient temperature, no icing concerns were predicted. 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.

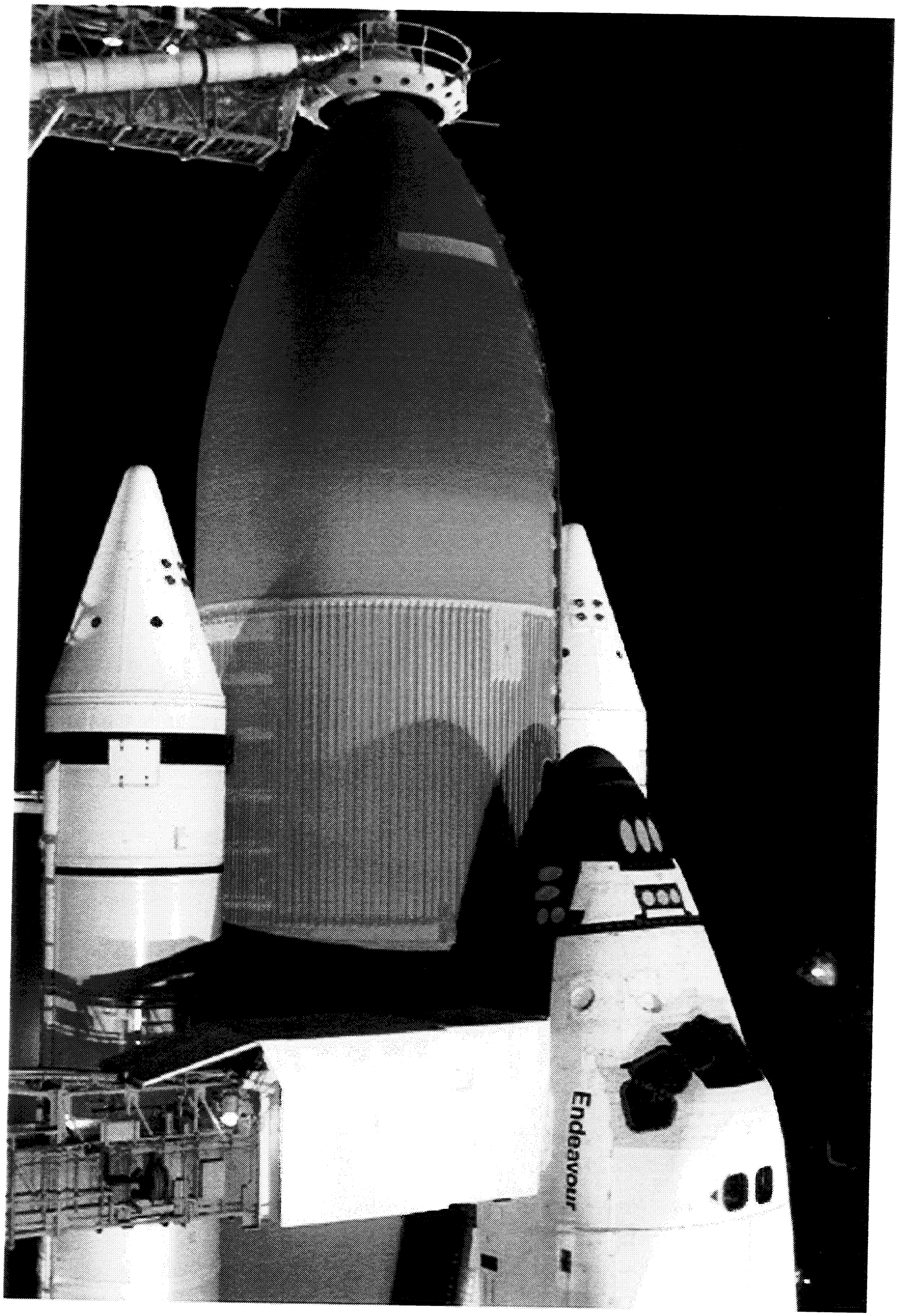


Photo 5: STS-88 Ready for Launch

The Thermal Protection Systems performed nominally during cryoload. The Final Inspection Team observed very light condensate, but no ice or frost accumulations, on the LO2 tank acreage. Surface temperatures averaged 50 degrees Fahrenheit.

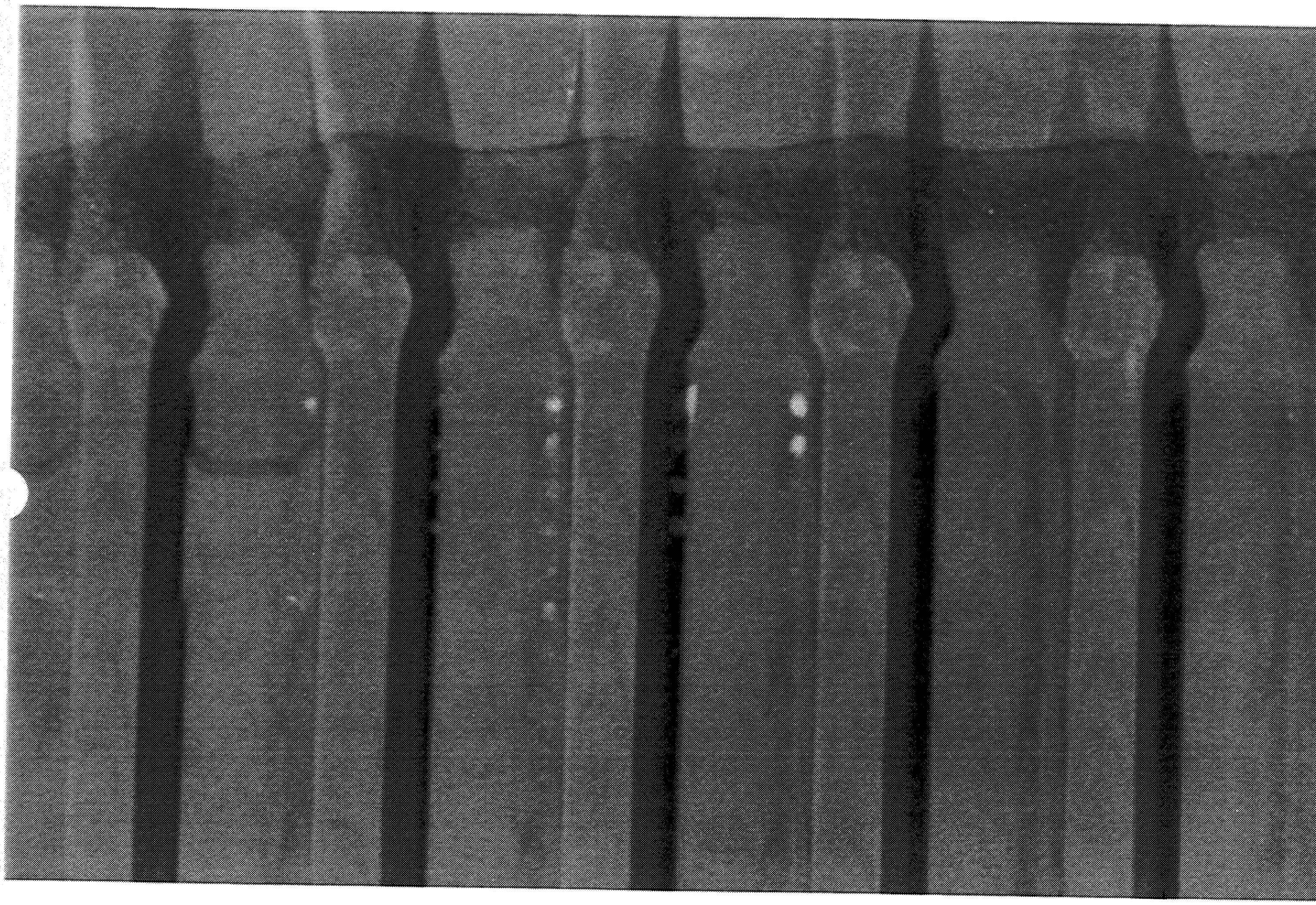


Photo 6: Frost on Intertank

Numerous frost spots had formed along three intertank stingers near the LO2 tank-to-intertank flange closeout in the -Y-Z quadrant.

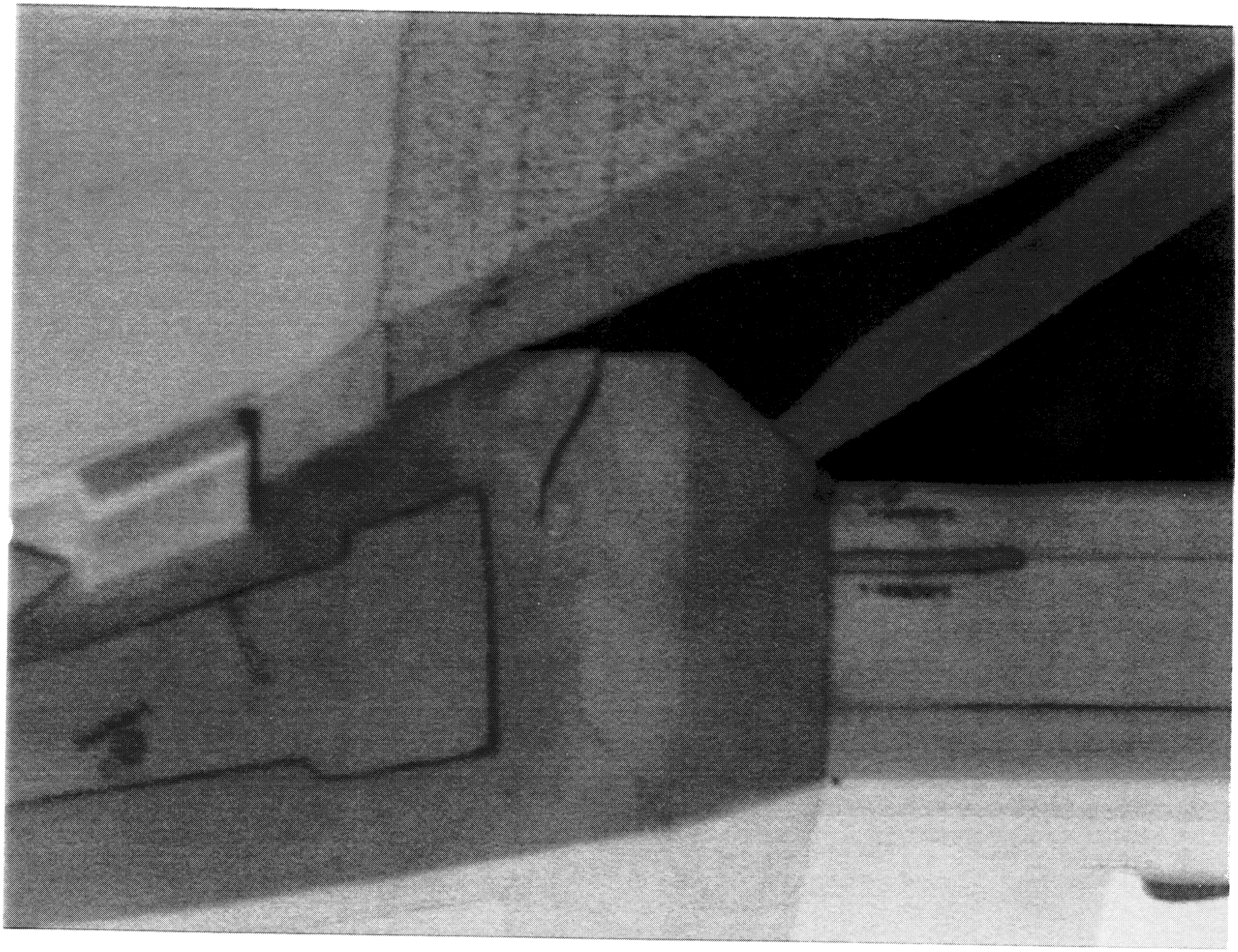


Photo 7: -Y Vertical Strut

A 8-inch long by 3/8-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.

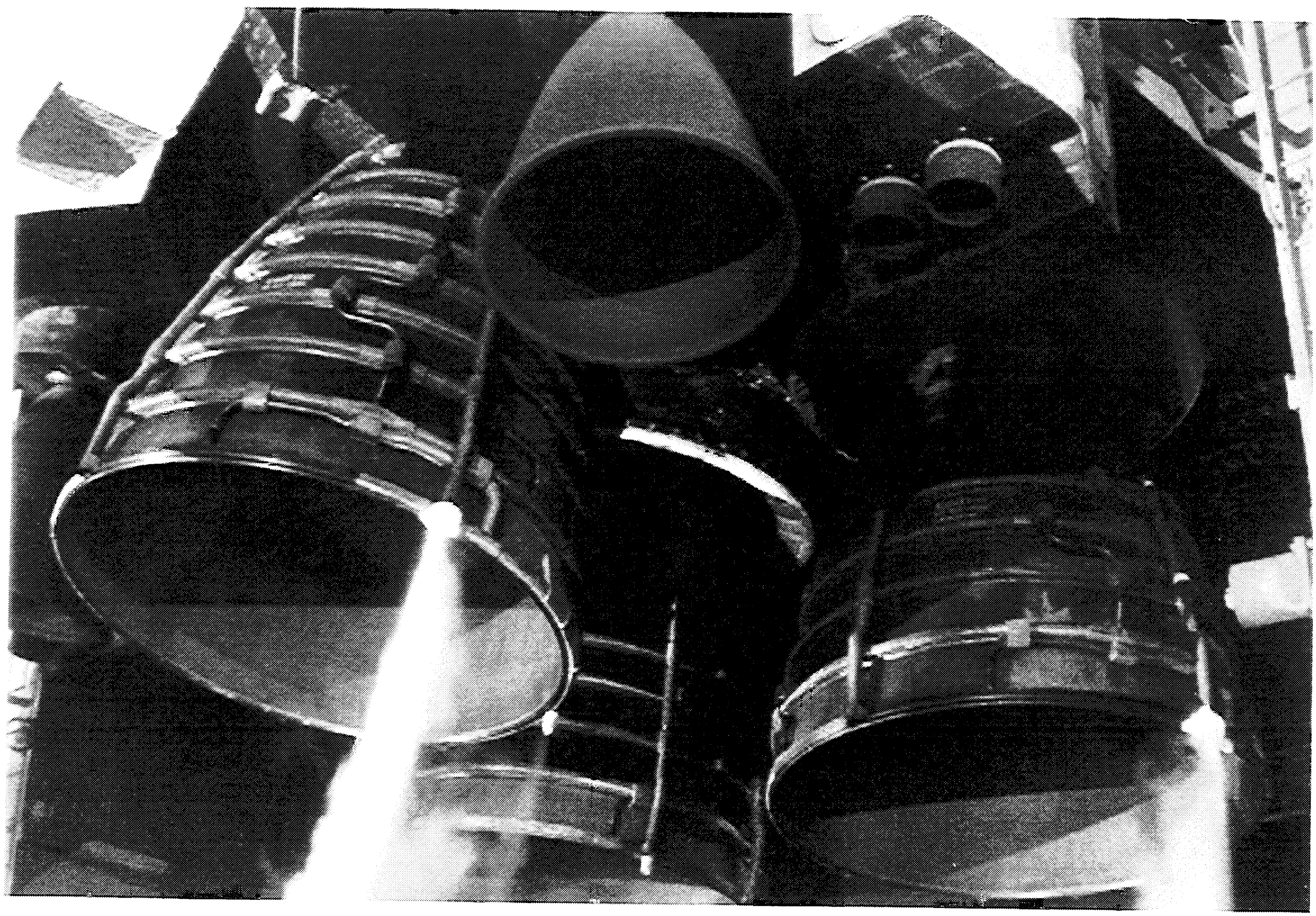


Photo 8: Overall View of SSME's

Photo 9: RCS Thruster R2R

All RCS thruster covers were intact. The paper cover on thruster R2R was very wet and exhibited a liquid level line.

5.0 POST LAUNCH PAD DEBRIS INSPECTION

The post launch inspection of MLP 3, Pad A FSS and RSS was conducted on 4 December 1998 from Launch + 1.5 to 3 hours. No flight hardware was found.

No stud hang-up is expected on this launch. Boeing - Downey reported an Orbiter liftoff lateral acceleration of 0.10 g's, which is below the threshold (0.14 g's) for stud hang-ups. SRB south holddown post erosion was less than usual. North holddown post blast covers and T-0 umbilicals exhibited typical exhaust plume damage. The right SRB aft skirt GN2 purge line was intact, though 80 percent of the protective tape was eroded away and the line was slightly bent at the lower end. The left GN2 purge flex line was also intact though 90 percent of the protective tape had eroded.

The pressure sensor mounted on the handrail south of the SSME #1 position exhibited a damaged cable.

The Tail Service Masts (TSM's) appeared undamaged and the bonnets were closed properly. However, two straps at the top of the LH2 TSM door were loose. Likewise, the Orbiter Access Arm (OAA) seemed to be undamaged.

The GH2 vent line was latched in the eighth of eight tooth of the latching mechanism. The GUCP 7-inch QD surface exhibited no scuff marks. All observations indicated a nominal retraction and latchback, though the SRB exhaust plume had scorched electrical cables and four feet of flex line blanket.

The GOX vent seals were in excellent shape with no indications of plume damage.

Debris findings on the FSS included a missing bolt from the FSS 115 level purge console cover, a loose two inch pipe clamp assembly adjacent to the GH2 vent line pipe on the 195 foot level, an electrical distribution box had separated from the wall mount on the 235 foot level elevator tower west side, a 1-inch diameter pipe coupling and bracket clamp on the west side of 255 foot level, and broken electrical conduit handle on 275 foot level north side.

Overall, damage to the pad appeared to be minimal.

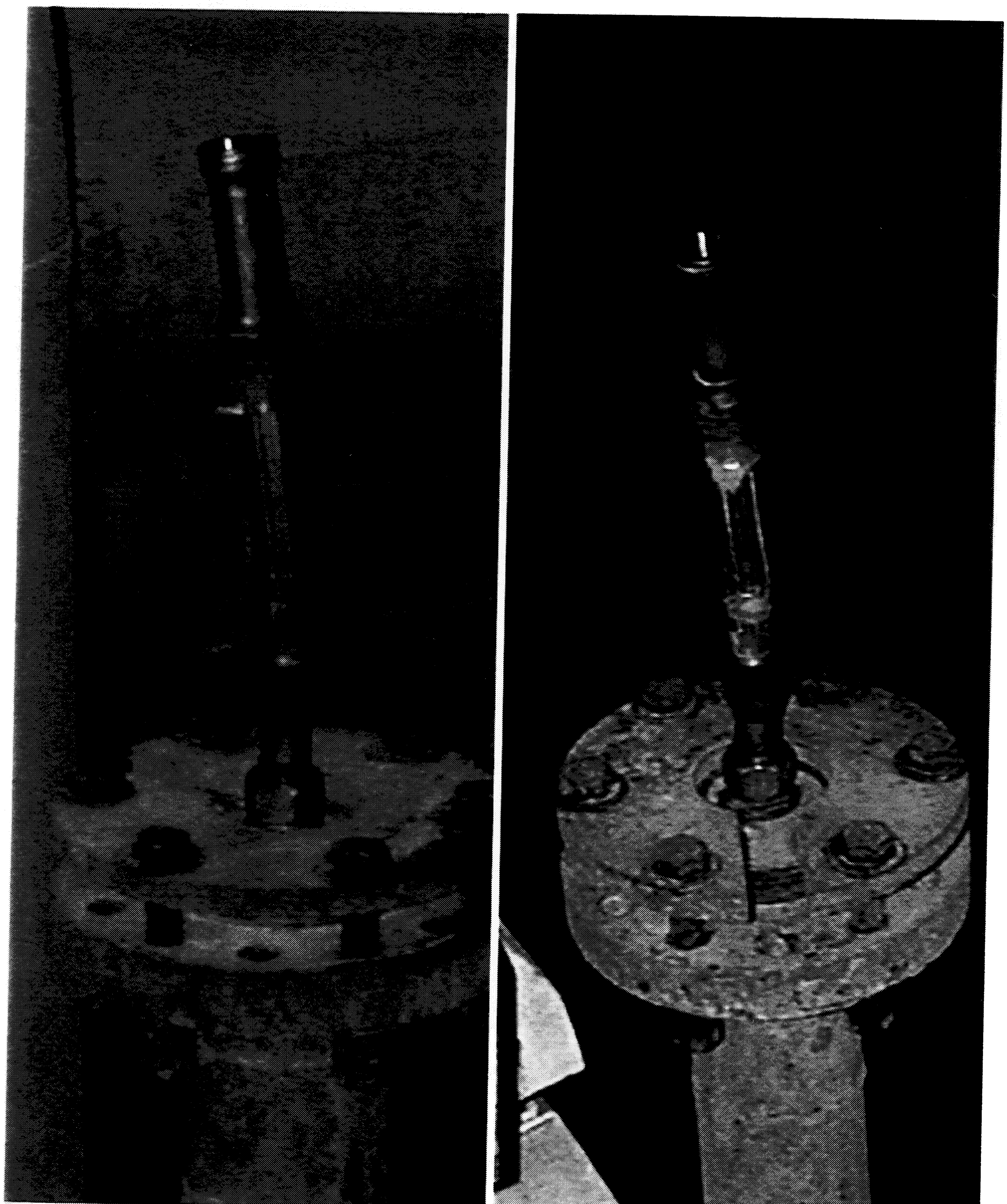


Photo 10: Aft Skirt GN2 Purge Lines

The right SRB aft skirt GN2 purge line was intact, though 80 percent of the protective tape was eroded away and the line was slightly bent at the lower end. The left GN2 purge flex line was also intact though 90 percent of the protective tape had eroded.

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 LAUNCH FILM AND VIDEO SUMMARY

A total of 83 films and videos, which included twenty-seven 16mm films, eighteen 35mm films, and thirty-eight videos, were reviewed starting on launch day.

SSME ignition appeared normal with Mach diamonds forming in a 3-2-1 order (OTV 051).

Free burning hydrogen drifted under the body flap and upward to the base of the vertical stabilizer during SSME ignition (OTV 063, 070, TV-7).

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. Two pieces of umbilical purge barrier mylar tape, one each from inboard and outboard sides of the LH2 ET/ORB umbilical, fell aft (OTV-009, 053, 063).

A thin, white on one side, rectangular object, estimated to be 6 inches long by 3 inches wide, appeared to originate from the body flap hinge near SSME #3 at 08:35:31.778 UTC. This same object could also be seen in film E-19 and E-52 at 08:35:31.831 UTC. Other films of the base heat shield area (from a distance) showed no missing tiles, so the object is believed to be a gap filler or GSE tile shim.

Three streaks occurred in the SSME #1 exhaust plume at 08:35:32.563, 08:35:33.237, and 08:35:33.247 UTC (E-2, -76).

An approximate 2-inch diameter area of surface coating material came loose from an SSME #2 engine mounted heat shield tile during SSME start-up. Tile surface coating material was lost during ignition from four places on the base heat shield near SSME #3, one place on the right ACPS stinger, two places on the aft surface of the left ACPS stinger, and four small areas from base heat shield tiles outboard of SSME #2 (E-17, -19, -20, -76, OTV 050, 070).

RCS thruster R2R was leaking with a visible liquid level line during the Final Inspection. SSME ignition caused the thruster paper cover to rupture and liquid to drain from the thruster nozzle prior to liftoff (OTV 070).

There were no stud hang-ups. A debris object first visible near the HDP #7 blast cover may be a piece of frangible nut web. The object was last seen landing on the HDP shoe (E-11).

A piece of white RTV from the base of HDP #8 was ejected from the SRB exhaust hole after T-0. The piece was estimated to be 14 inches in length by 1 inch wide (E-16).

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).

An object moving away from the vehicle in a northwest direction from the LH SRB aft skirt at 08:35:35.294 UTC was most likely a piece of throat plug material (E-63).

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

Numerous light colored objects falling aft of the vehicle early in flight have been identified as ice particles from the ET/ORB umbilicals, paper covers from the forward and aft RCS thrusters, and pieces of instafoam from SRB aft skirt aft ring closeouts (E-52, -213, -222, -224).

Orbiter body flap motion was readily visible in several films (E-207, -212, -220, -223). Magnitude and frequency appeared to be similar to previous flights.

As many as seven light colored particles, believed to be pieces of SRB aft skirt instafoam, fell along side the SRB exhaust plume from 77.6 to 78.3 seconds MET (TV-4A). These particles are visible in TV-5 from 72 to 76.6 seconds MET.

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

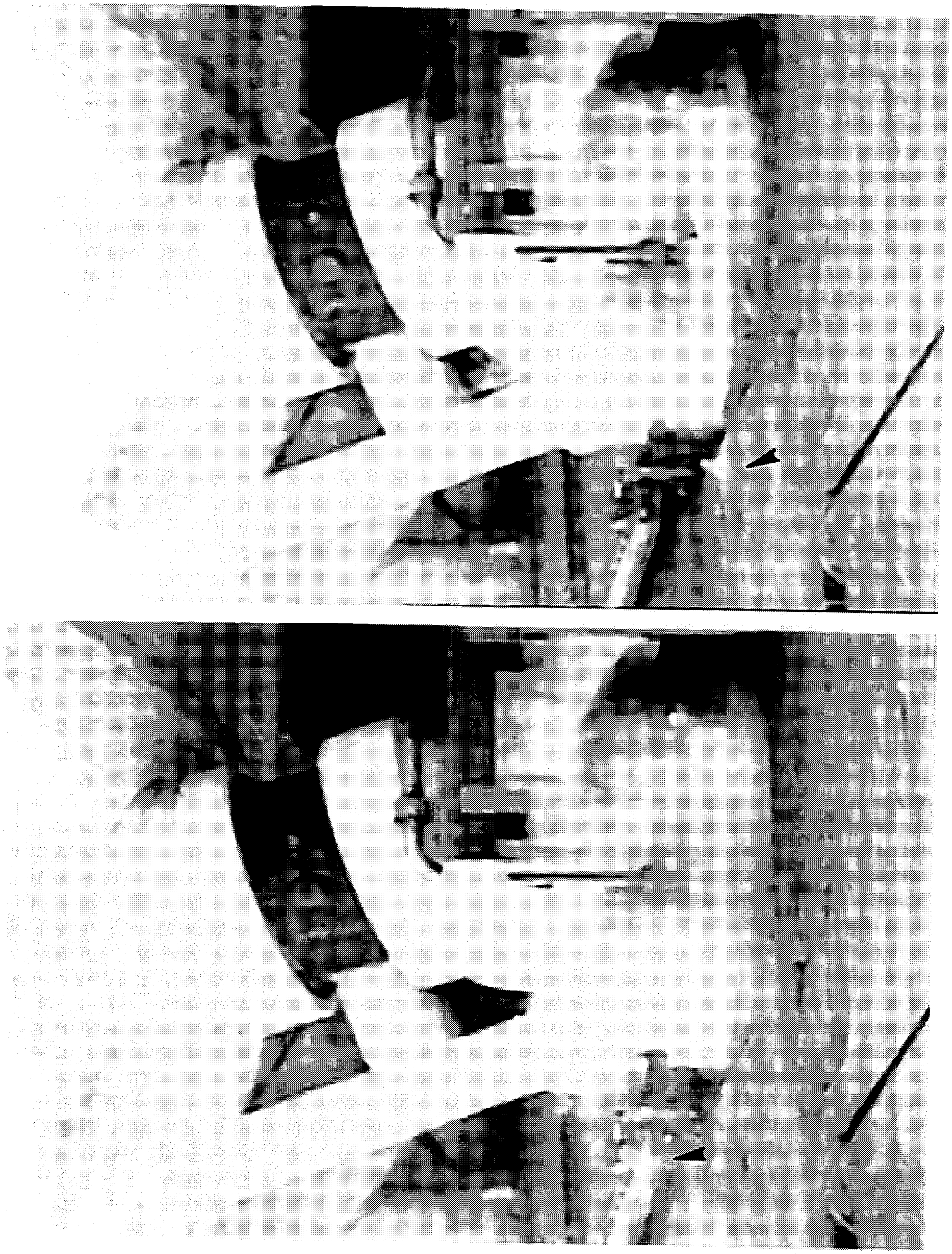


Photo 11: LH2 ET/ORB Umbilical

Two pieces of umbilical purge barrier mylar tape, one each from inboard and outboard sides of the LH2 ET/ORB umbilical, fell aft during SSME ignition

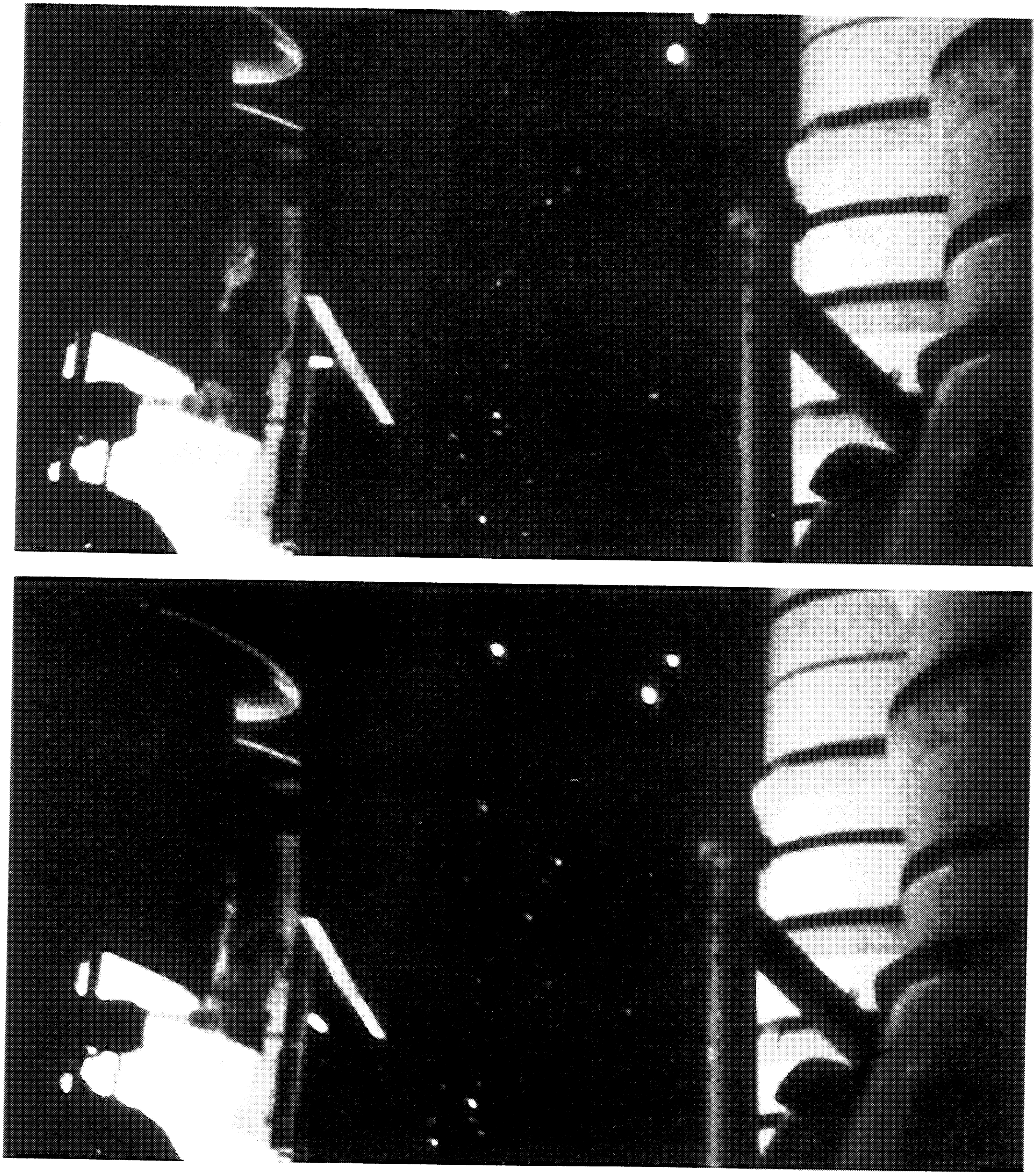


Photo 12: White Object Near Body Flap

A thin, white on one side, rectangular object, estimated to be 6 inches long by 3 inches wide, appeared to originate from the body flap hinge near SSME #3 at 08:35:31.778 UTC. Other films of the base heat shield area (from a distance) showed no missing tiles, so the object is believed to be a gap filler or GSE tile shim.

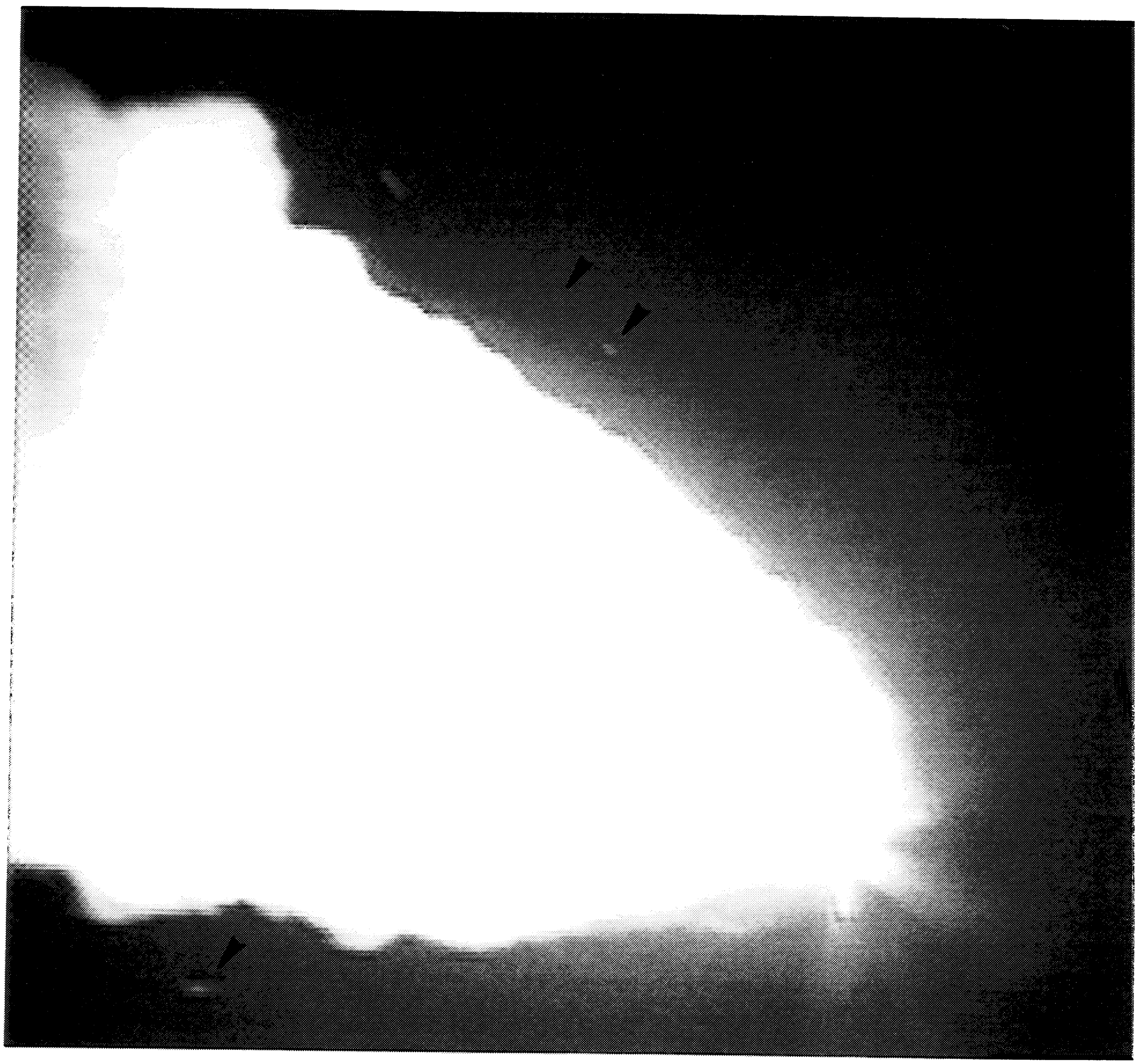


Photo 13: Debris Objects Along SRB Plume

As many as seven light colored particles, believed to be pieces of SRB aft skirt instafoam, fell along side the SRB exhaust plume from 77.6 to 78.3 seconds MET

6.2 ON-ORBIT FILM AND VIDEO SUMMARY

OV-105 was equipped to carry umbilical cameras: 16mm motion picture with 5 mm lens; 16mm motion picture with 10mm lens; 35mm still views. The flight crew provided 36 hand held still images and approximately 15 minutes of video from the camcorder. The +X translation and a manual pitch maneuver from the heads-up position were performed to bring the tank into view through the overhead windows.

6.2.1 ET/ORB Umbilical 16mm Films

SRB separation from the ET was nominal. SRB nose caps were not visible due to the dark conditions of a night launch.

Erosion/ablation of TPS from ET -Y vertical strut and ET/ORB LH2 umbilical cable tray was typical (illuminated by SRB exhaust plume tailoff).

No TPS anomalies occurred on the ET aft dome.

The first few seconds of ET separation from the Orbiter were visible due to Orbiter thruster firings. However, the ET was silhouetted and no detail was discernible.

6.2.2 ET/ORB Umbilical 35mm Film

There were no images due to the night launch.

6.2.3 Crew Hand Held Still Images/Video

For the most part, the still images provided excellent views of the aft dome, aft hard point, LH2 tank acreage, LO2 tank acreage, and nose cone. In one frame, the -Y nose cone louver could be seen. There were no anomalies visible in any of these areas.

No divots could be discerned in the intertank +Z side acreage, in the area of the bipod jack pad closeouts, and on the LH2 tank-to-intertank flange closeout with the exception of one 10-inch divot in the forward part of the flange and extending forward into the -Y thrust panel acreage.

Two frames of the -Y thrust panel showed the acreage aft of the EB fitting was generally in good condition. Several divots 2-3 inches in size could be discerned in thrust panel TPS to the -Z side of the EB fitting and forward of the fitting.

The +Y thrust panel was imaged at a time when the ET was more distant and the resolution had degraded. The presence of divots could not be confirmed.

In the video footage, the ET was overexposed initially. By the time the exposure was adjusted, the ET was more distant. Almost the entire surface area of the ET was recorded. No large divots or obvious anomalies were visible.

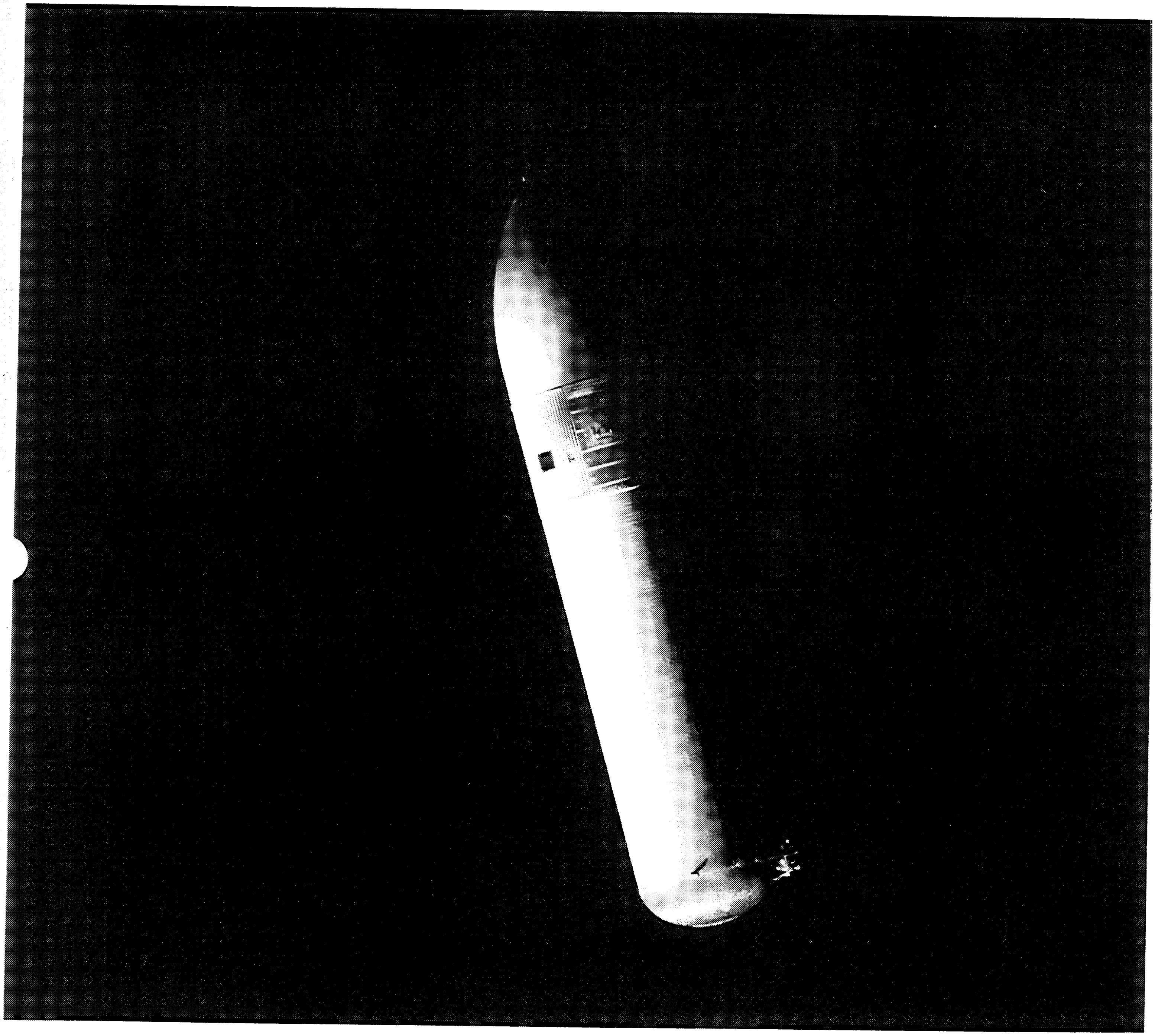


Photo 14: ET -Y Thrust Panel

This view of the -Y thrust panel showed the acreage aft of the EB fitting generally in good condition. Several divots could be discerned in thrust panel TPS to the -Z side of the EB fitting and forward of the fitting. Note the 10-inch divot in the forward part of the LH2 tank-to-intertank flange and extending forward into the -Y thrust panel acreage

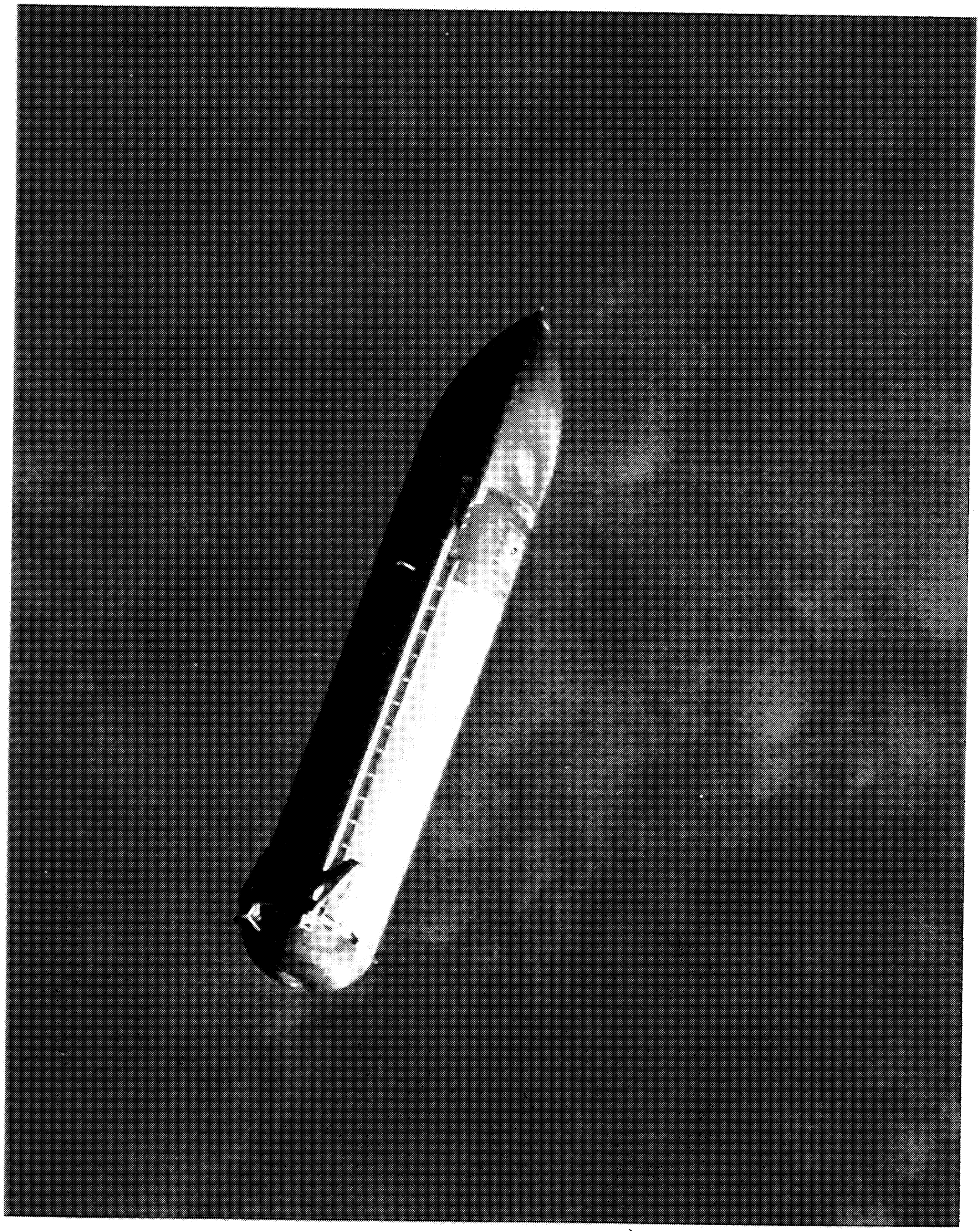


Photo 15: ET +Y Thrust Panel

The +Y thrust panel was imaged at a time when the ET was more distant and the resolution had degraded. The presence of divots could not be confirmed.

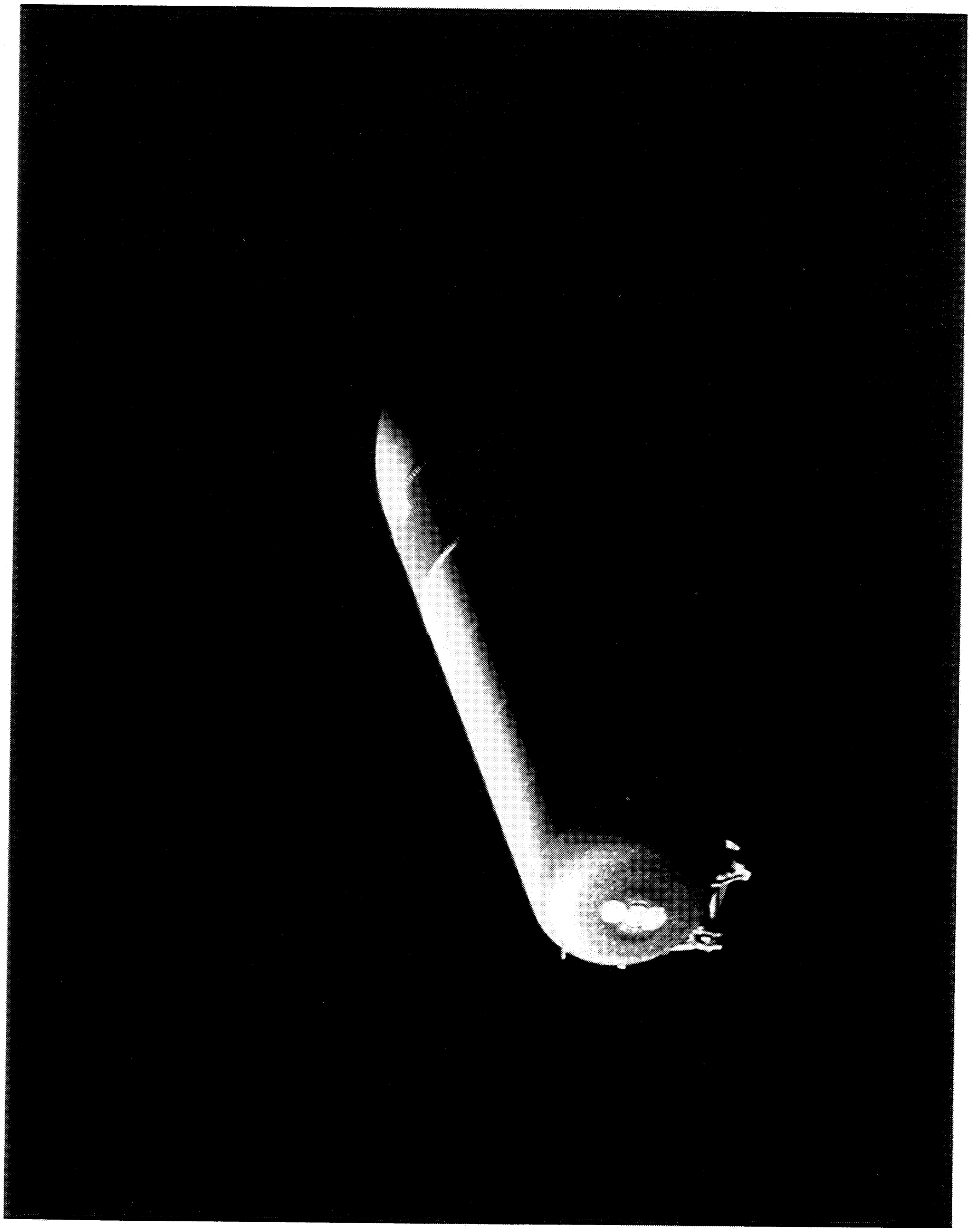


Photo 16: ET Aft dome

For the most part, the still images provided excellent views of the aft dome, aft hard point, LH2 tank acreage, and LO2 tank acreage. There were no anomalies visible in any of these areas.

6.3 LANDING FILM AND VIDEO SUMMARY

A total of 15 films and videos, which included seven 35mm large format films and eight videos, were reviewed.

The landing gear extended properly. The infrared scanners showed no debris falling from the Orbiter during final approach. The main gear tires contacted the runway almost simultaneously.

The drag chute was not flown on this mission. Rollout and wheel stop were uneventful.

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

7.0 SRB POST FLIGHT/RETRIEVAL DEBRIS ASSESSMENT

The BI-095 Solid Rocket Boosters were inspected for debris damage and debris sources at CCAS Hangar AF on 7 December 1998.

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.

The forward skirts exhibited no debonds or missing TPS. RSS antennae covers/phenolic base plates were intact though one layer of phenolic had delaminated on both right and left SRB +Z sides. All primary frustum severance ring pins and retainer clips were intact.

The Field Joint Protection System (FJPS) closeouts were generally in good condition. Trailing edge damage to the FJPS and the GEI cork runs were attributed to debris resulting from severance of the nozzle extension.

Separation of the aft ET/SRB struts appeared normal. All six aft booster stiffener rings sustained water impact damage. In addition, a section of the left SRB ETA ring cover from 100 to 130 degrees was bent and 13 cover bolts were broken. Protective foam aft of both IEA's was missing - the exposed substrate on the left side was clean while the substrate on the right side was darkened and had been subjected to heating in flight.

One unusual finding consisted of a rectangular piece of metal, most likely a nozzle shim, 5-5/8 inches long by 2 inches wide by approximately 1/16 inch thick, imbedded in the right IEA aft surface protective foam close to the upper strut fairing. The shim probably came loose during nozzle severance.

A second unusual finding was a piece of safety wire imbedded in the factory joint of the right SRB aft booster forward of the aft BSM's. The wire most likely came from the HDP Debris Containment System directly aft and closest to this location.

TPS on the external surface of both aft skirts was intact and in good condition.

The holddown post Debris Containment Systems (DCS) appeared to have functioned normally. However, the HDP #8 plunger was obstructed by an ordnance fragment. There was no evidence of a stud hang-up on this launch.

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

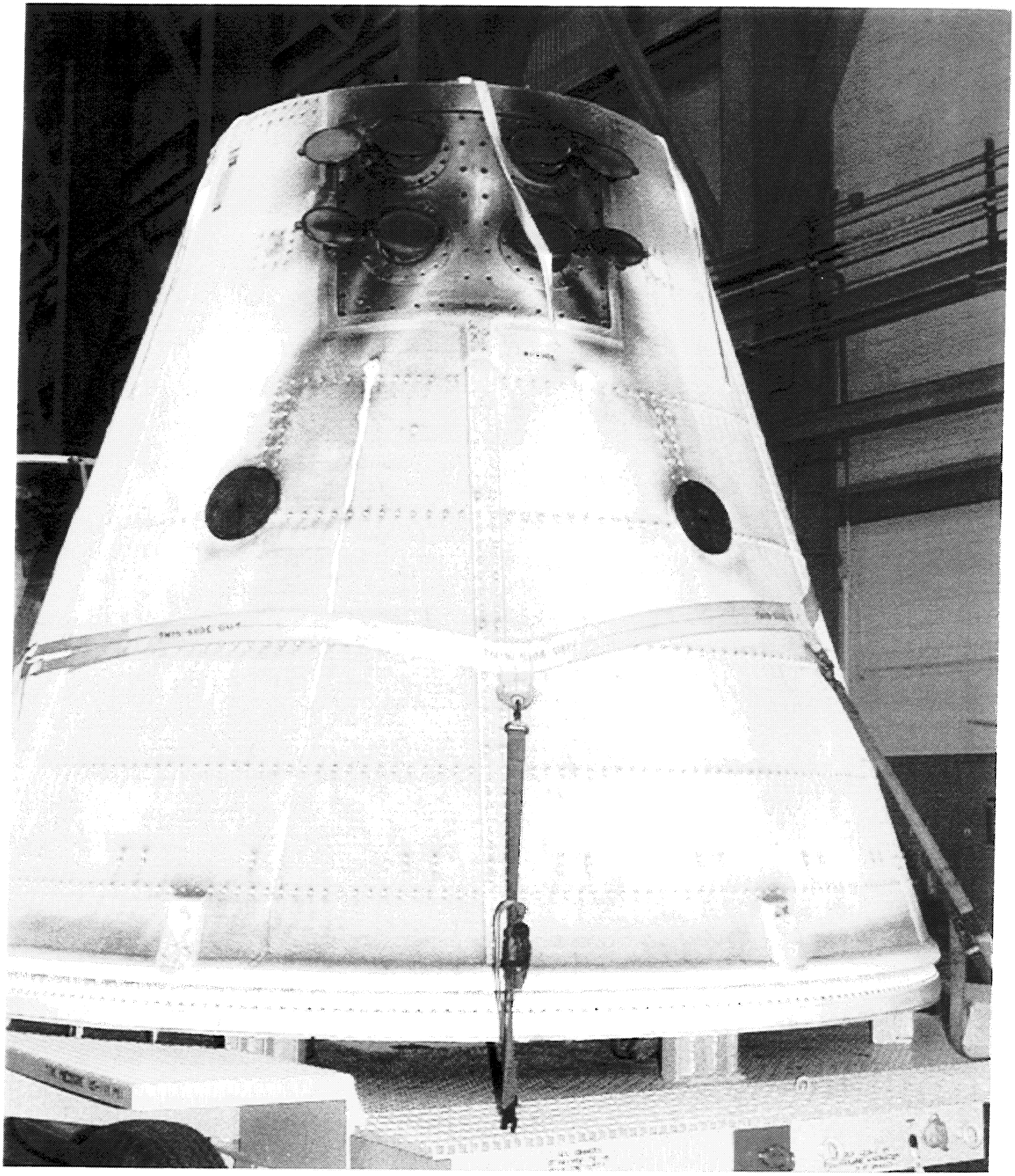


Photo 17: Frustum Post Flight Condition

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.

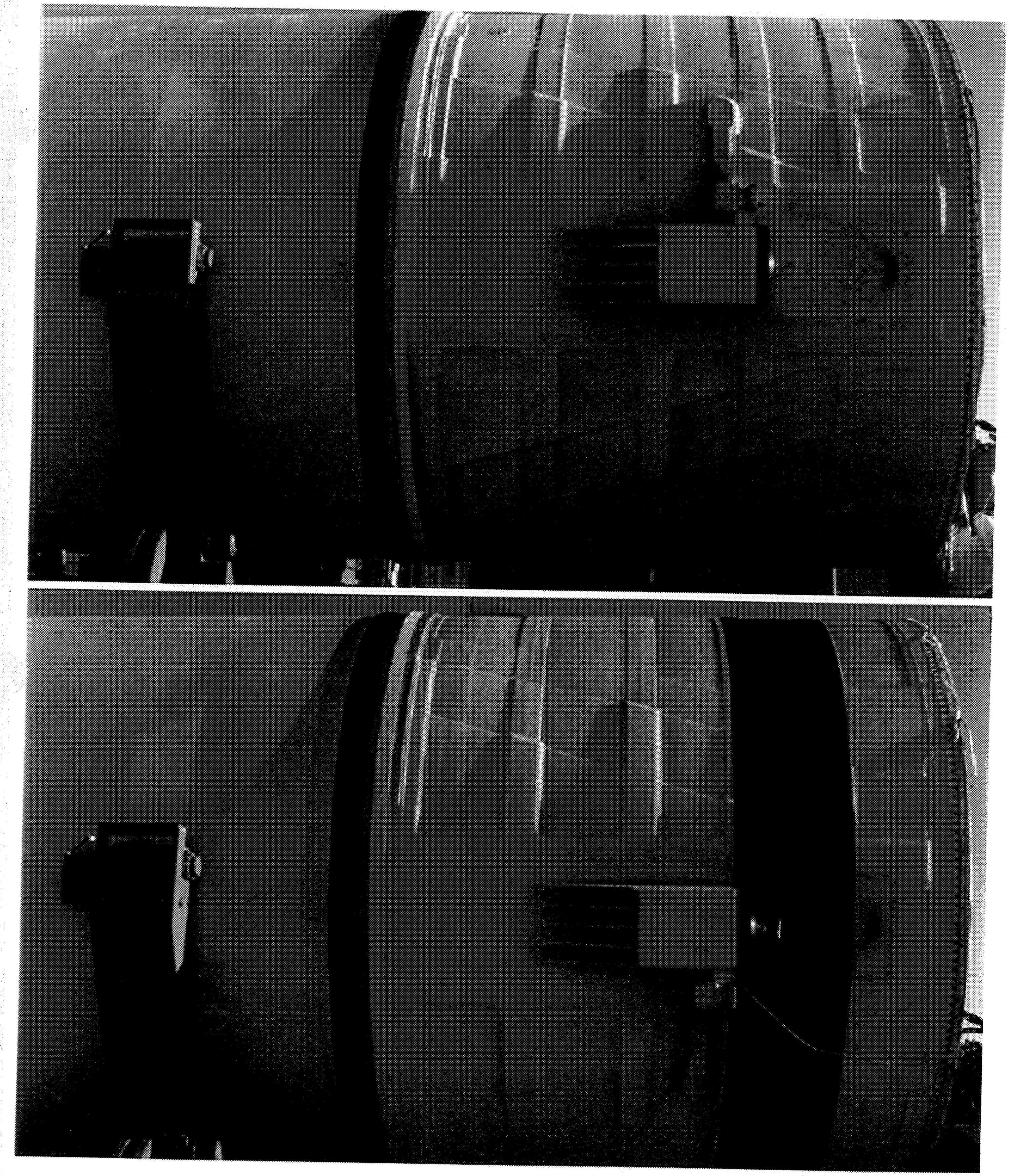


Photo 18: Forward Skirt Post Flight Condition

The forward skirts exhibited no debonds or missing TPS. RSS antennae covers/phenolic base plates were intact though one layer of phenolic had delaminated on both right and left SRB +Z sides. All primary frustum severance ring pins and retainer clips were intact.

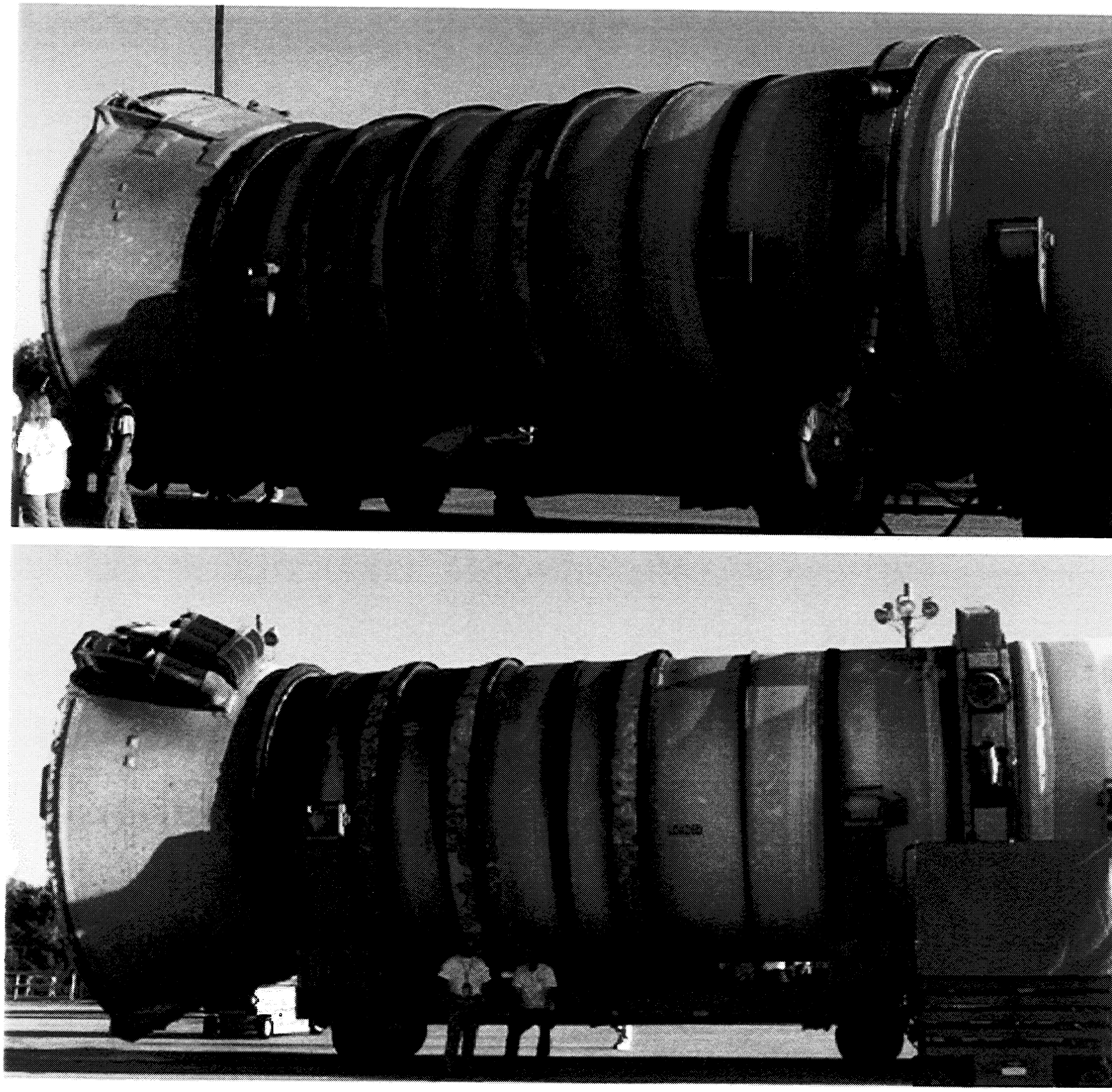


Photo 19: Aft Booster/Aft Skirt Post Flight Condition

Separation of the aft ET/SRB struts appeared normal. TPS on the external surface of both aft skirts was intact and in good condition.

Photo 20: Nozzle Shim

An unusual finding consisted of a rectangular piece of metal, most likely a nozzle shim, 5-5/8 inches long by 2 inches wide by approximately 1/16 inch thick, imbedded in the right IEA aft surface protective foam close to the upper strut fairing. The shim probably came loose during nozzle severance.

8.0 ORBITER POST LANDING DEBRIS ASSESSMENT

After the 10:53 p.m. local/eastern time landing on 15 December 1998, a post landing inspection of OV-105 Endeavour was conducted at the Kennedy Space Center on SLF runway 15 and in the Orbiter Processing Facility bay #2. This inspection was performed to identify debris impact damage and, if possible, debris sources.

The Orbiter TPS sustained a total of 116 hits, of which 25 had a major dimension of 1-inch or larger. This total does not include the numerous hits on the base heat shield attributed to SSME vibration/acoustics and exhaust plume recirculation. A comparison of these numbers to statistics from 71 previous missions of similar configuration (excluding missions STS-23, 24, 25, 26, 26R, 27R, 30, 42, 86, 87, 89, 90, 91, and 95, which all had damage from known debris sources), indicates the total number of hits is close to average while the number of hits 1-inch or larger is still greater than the cumulative mission average. Reference Figures 1-4.

The following table breaks down the STS-88 Orbiter debris damage hits by area:

	HITS > 1"	TOTAL HITS
Lower surface	21	80
Upper surface	0	4
Window Area	2	15
Right side	0	4
Left side	0	3
Right OMS Pod	1	6
Left OMS Pod	1	4
TOTALS	25	116

The Orbiter lower surface sustained 80 total hits, of which 21 had a major dimension of 1-inch or larger. Most of this damage was concentrated between the nose gear and the main landing gear wheel wells on both left and right chines though the predominant number of damage sites occurred on the right side. (It should be noted there was no unusual or unexpected accumulations of ice in the ET LO2 feedline bellows and support brackets at the time of launch). The outboard damage sites on the chines followed a similar location/damage pattern documented on STS-86, -87, -89, -90, -91, and -95, though the pattern was not as symmetric as the previously noted flights. It should also be noted that this was the third flight of the new Super Light Weight Tank.

A comparison of Orbiter lower surface tile damage statistics since STS-86:

	STS-86	STS-87	STS-89	STS-90	STS-91	STS-95	STS-88
Lower surface total hits	100	244	95	76	145	139	80
Lower surface hits > 1-inch	27	109	38	11	45	42	21
Longest damage site	7 in.	15 in.	2.8 in.	3.0 in.	3.0 in.	4.0 in.	4.5 in.
Deepest damage site	0.4 in.	1.5 in.	0.2 in.	0.25 in.	0.5 in.	0.4 in.	0.5 in.

No lower surface tiles were scrapped due to debris damage. The largest lower surface tile damage site, located on the right chine, measured 4.5-inches long by 1.125-inches wide by 0.125-inch deep. The deepest lower surface tile damage sites measured 0.5-inches and were located on the right chine.

Tile damage sites around and aft of the LH2 and LO2 ET/ORB umbilicals were much less than usual. 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 reasonably good condition for a landing on the KSC concrete runway.

ET/Orbiter separation devices EO-1, EO-2, and EO-3 functioned normally. No ordnance fragments were found on the runway beneath the umbilical cavities. The EO-2 fitting retainer springs were in nominal configuration while the spherical washer and retainer springs in the EO-3 fitting were offset/displaced. A total of three clips were missing from EO-2 and -3 "salad bowls". Virtually no umbilical closeout foam or white RT.V dam material adhered to the umbilical plate near the LH2 recirculation line disconnect.

Typical amounts of tile damage occurred on the base heat shield. All SSME Dome Mounted Heat Shield (DMHS) closeout blankets were in excellent condition with the exception of frayed, torn, and missing material on the SSME #3 blanket at the 9-11:00 o'clock position.

Two pieces of SSME nozzle ablator, (6-inches and 4-inches long, respectively, by ¾-inch wide by 3/8-inch thick), were found on Orbiter body flap stub tiles adjacent to the base heat shield beneath SSME #2. No impact damage to the tiles was detected. Inspection of the SSME #2 and #3 nozzles revealed approximately 60 percent of the material was missing.

The ablator was bonded to SSME #2 and #3 circumferentially from 45 degrees inboard to 90 degrees outboard on the -Z side of the nozzle to prevent the recurring problem of bluing. This ablator was first used on STS-95.

Post flight assessment of the recovered ablator pieces and nozzle bonding surface reveal the material debonded after the heat of reentry, and therefore after peak heating of the SSME nozzles. Since it is highly unlikely the pieces of ablator could have remained on the body flap tiles during the aerodynamic turbulence and maneuvering of reentry, the material is believed to have shaken loose at main landing gear touchdown. Nevertheless, the ablator, with a density of about 92 pounds per cubic foot, is now considered to be a debris issue. IFA STS-88-I-01 was taken with a constraint to STS-93.

No unusual tile damage was detected on the leading edges of the OMS pods and vertical stabilizer.

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

The post landing walkdown of Runway 15 was performed immediately after landing. No debris concerns were identified. The drag chute was not utilized for this landing.

In summary, the total number of Orbiter TPS debris hits is close to the fleet average while the number of hits 1-inch or larger is greater than the cumulative fleet average when compared to previous missions (reference Figure 5). 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.

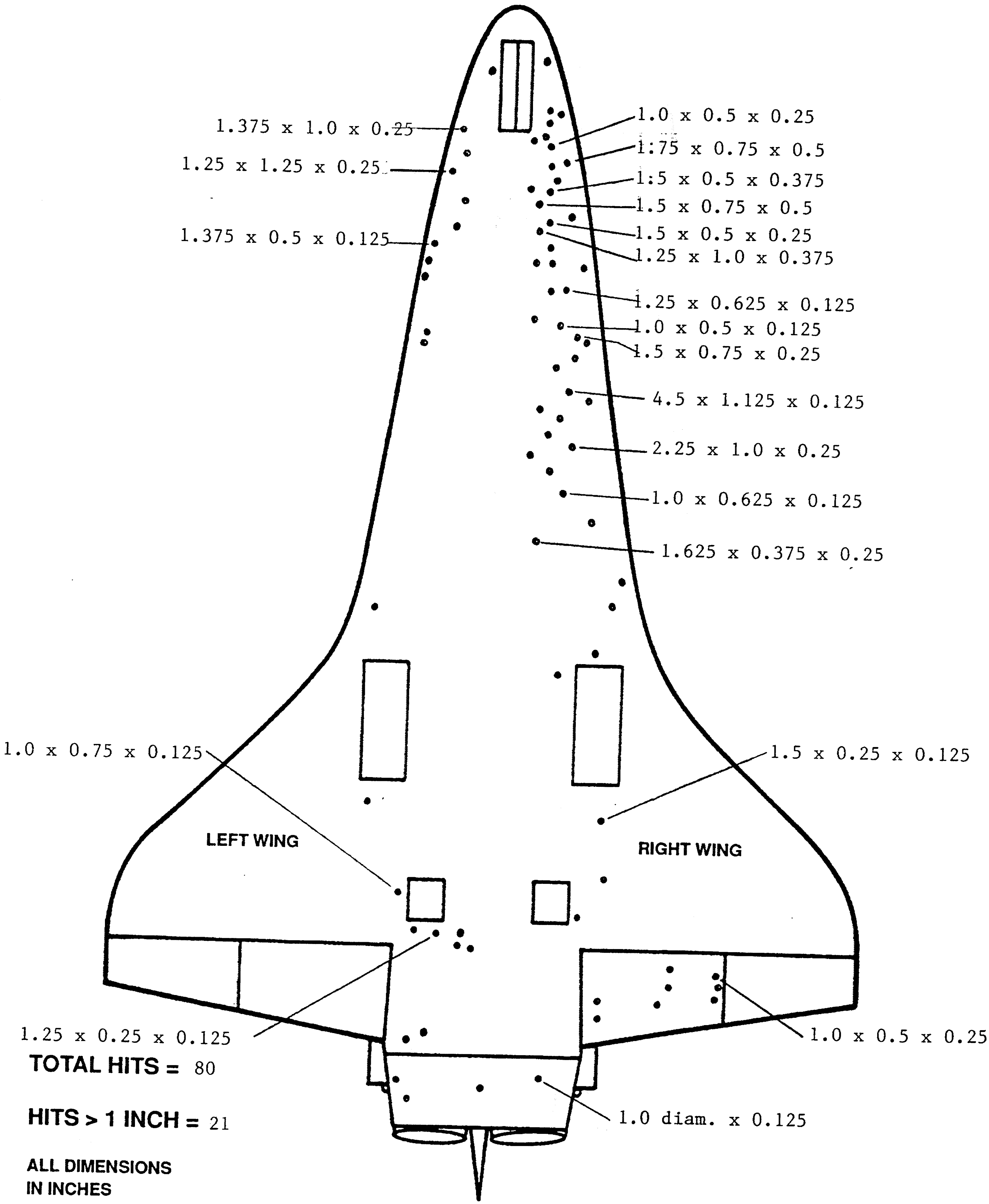


Figure 1: Orbiter Lower Surface Debris Damage Map

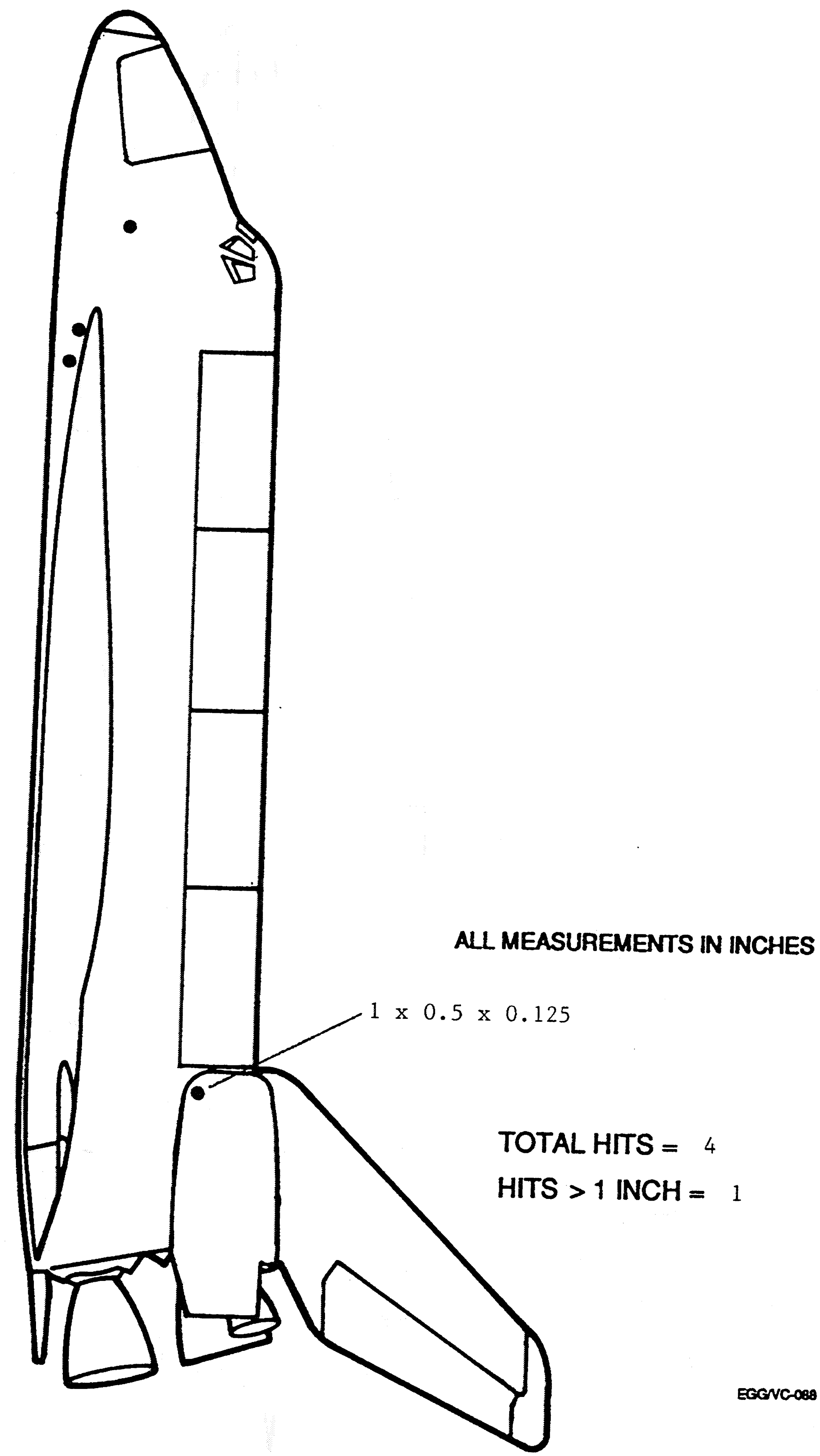


Figure 2: Orbiter Left Side Debris Damage Map

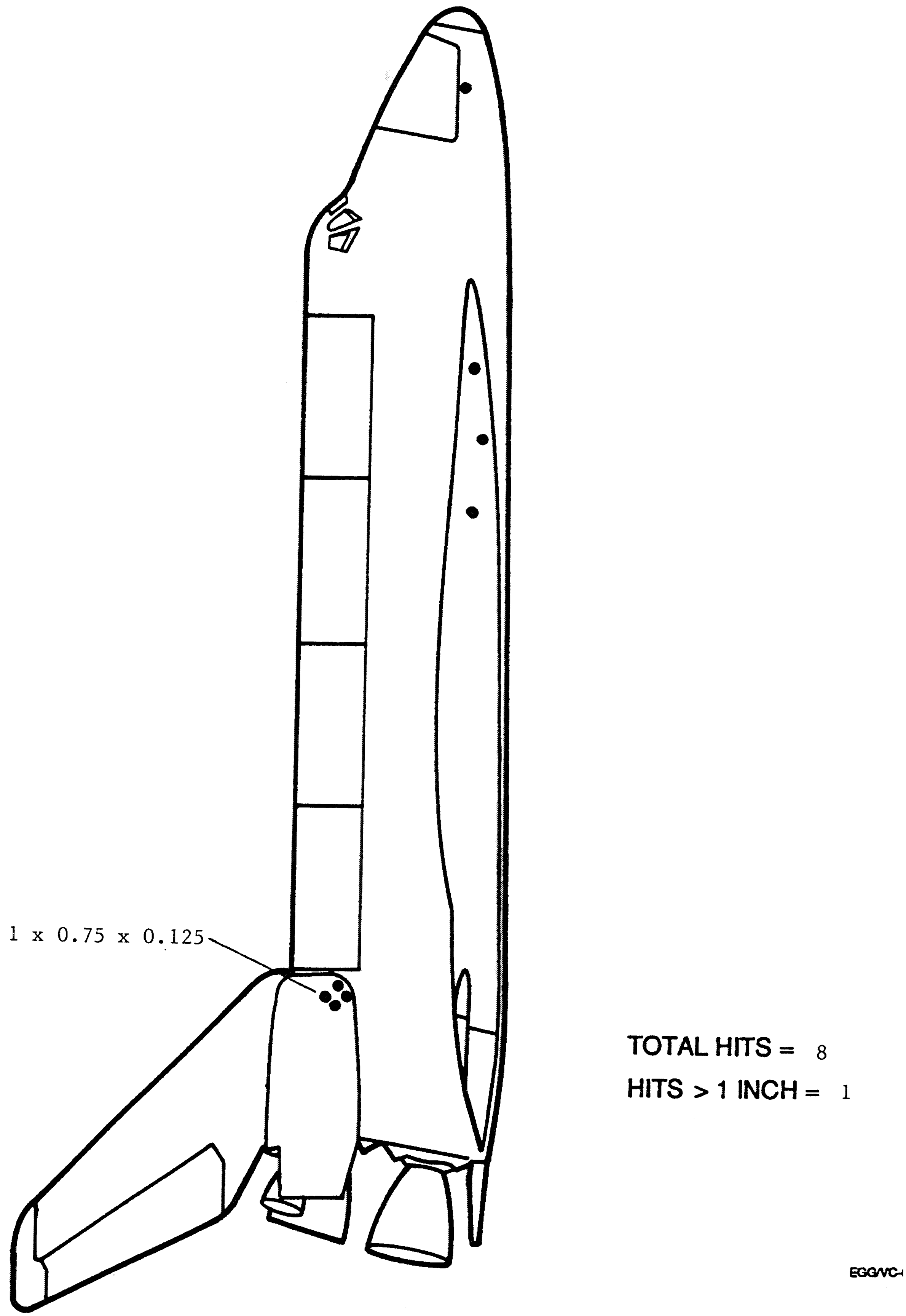


Figure 3: Orbiter Right Side Debris Damage Map

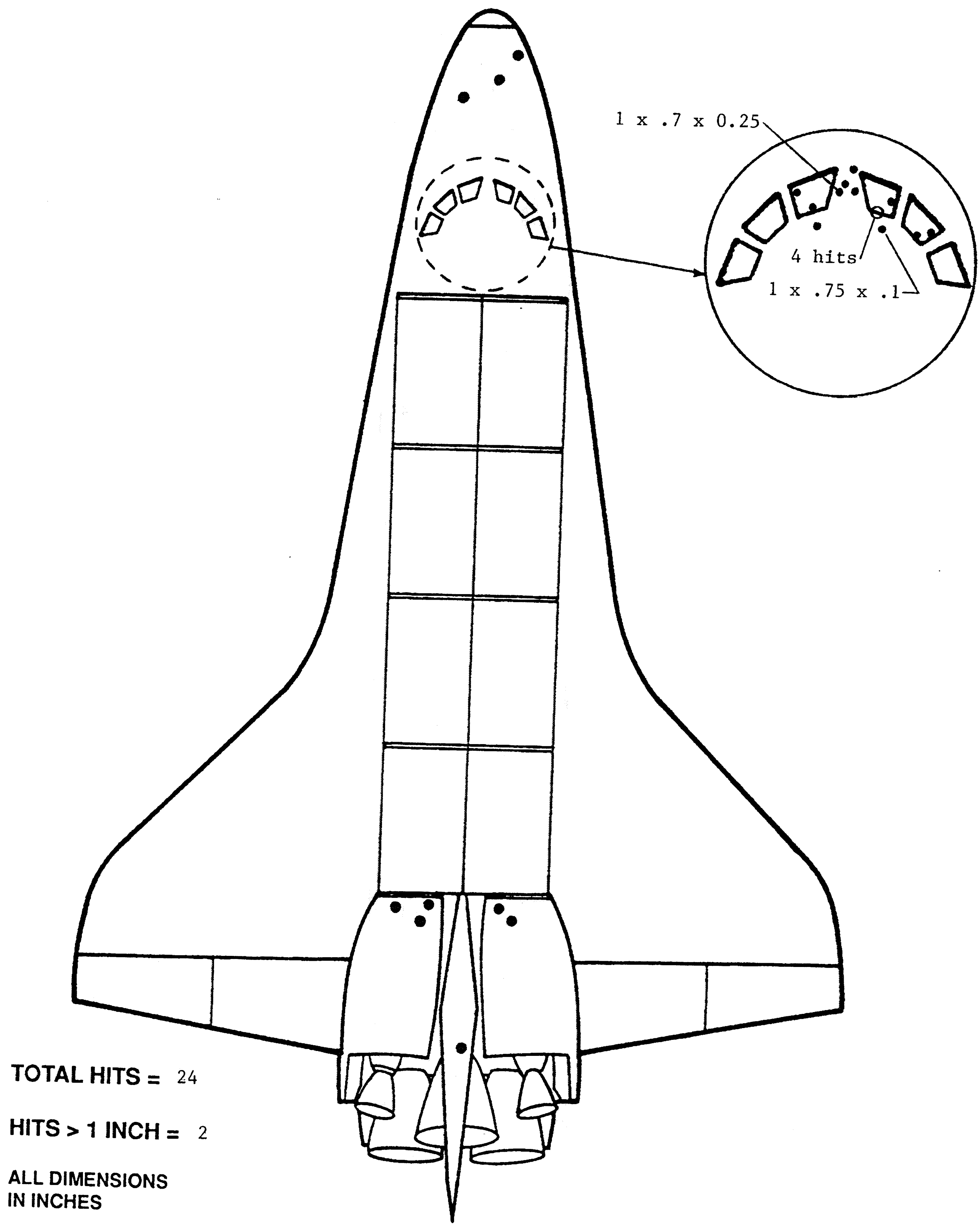


Figure 4: Orbiter Upper Surface Debris Damage Map

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

	LOWER SURFACE		ENTIRE SURFACE	
	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS
STS-55	10	128	13	143
STS-57	10	75	12	106
STS-51	8	100	18	154
STS-58	23	78	26	155
STS-61	7	59	13	120
STS-60	4	48	15	106
STS-62	7	36	16	97
STS-59	10	47	19	77
STS-65	17	123	21	151
STS-64	18	116	19	150
STS-68	9	59	15	110
STS-66	22	111	28	148
STS-63	7	84	14	125
STS-67	11	47	13	76
STS-71	24	149	25	164
STS-70	5	81	9	127
STS-69	22	175	27	198
STS-73	17	102	26	147
STS-74	17	78	21	116
STS-72	3	23	6	55
STS-75	11	55	17	96
STS-76	5	32	15	69
STS-77	15	48	17	81
STS-78	5	35	12	85
STS-79	8	65	11	103
STS-80	4	34	8	93
STS-81	14	48	15	100
STS-82	14	53	18	103
STS-83	7	38	13	81
STS-84	10	67	13	103
STS-94	11	34	12	90
STS-85	6	37	13	102
AVERAGE	13.3	83.2	19.6	124.3
SIGMA	7.1	43.9	9.5	51.9
STS-88	21	80	25	116

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

Figure 5: Orbiter Post Flight Debris Damage Summary

Photo 21: Overall View of Orbiter Sides

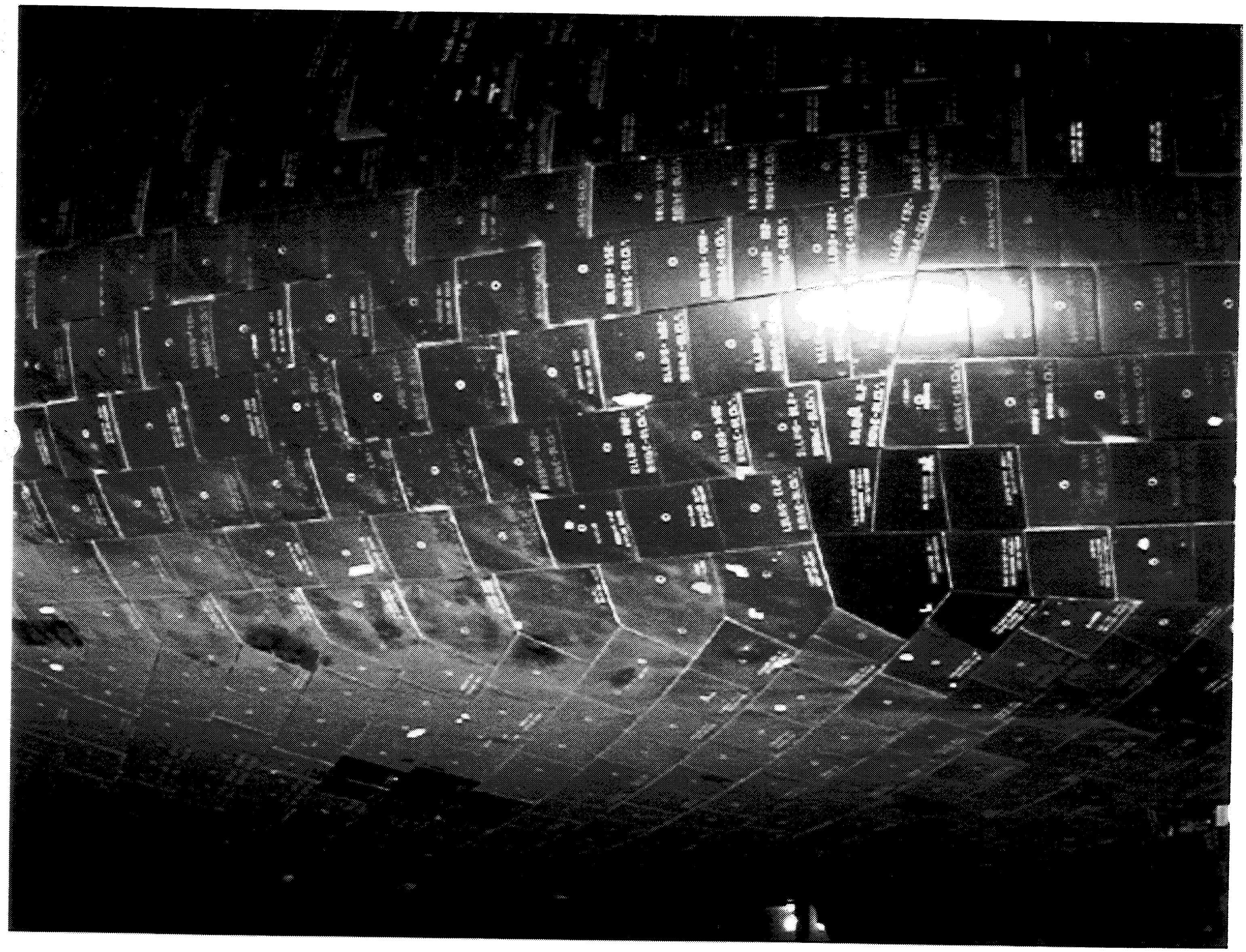


Photo 22: Lower Surface Tile Damage

The Orbiter lower surface sustained 80 total hits, of which 21 had a major dimension of 1-inch or larger. Most of this damage was concentrated between the nose gear and the main landing gear wheel wells on both left and right chines though the predominant number of damage sites occurred on the right side. Virtually no damage occurred on the Orbiter centerline.

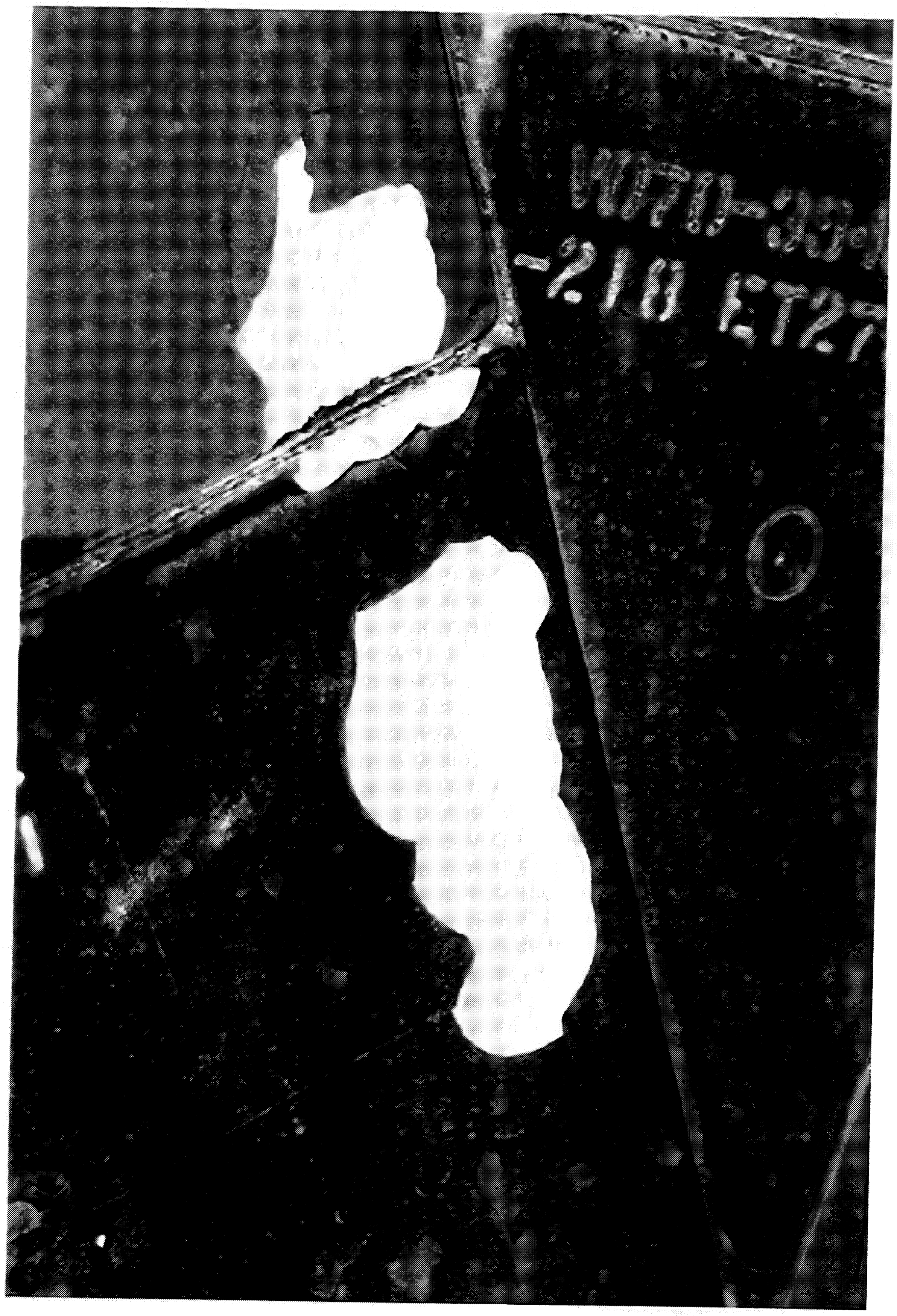


Photo 23: Lower Surface Tile Damage

The largest lower surface tile damage site, located on the right chine, measured 4.5-inches long by 1.125-inches wide by 0.125-inch deep. The deepest lower surface tile damage sites measured 0.5-inches and were located on the right chine.

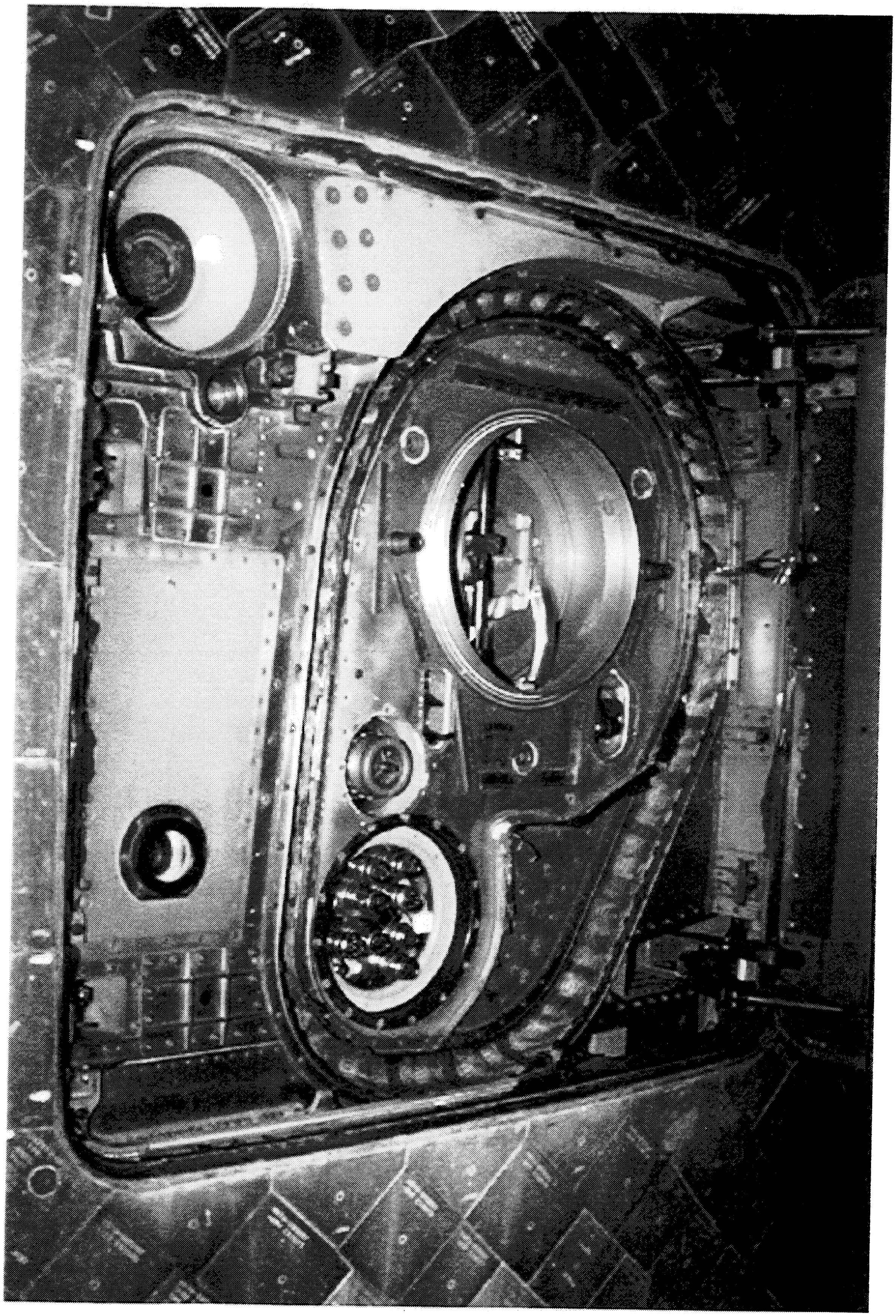


Photo 24: LO2 ET/ORB Umbilical

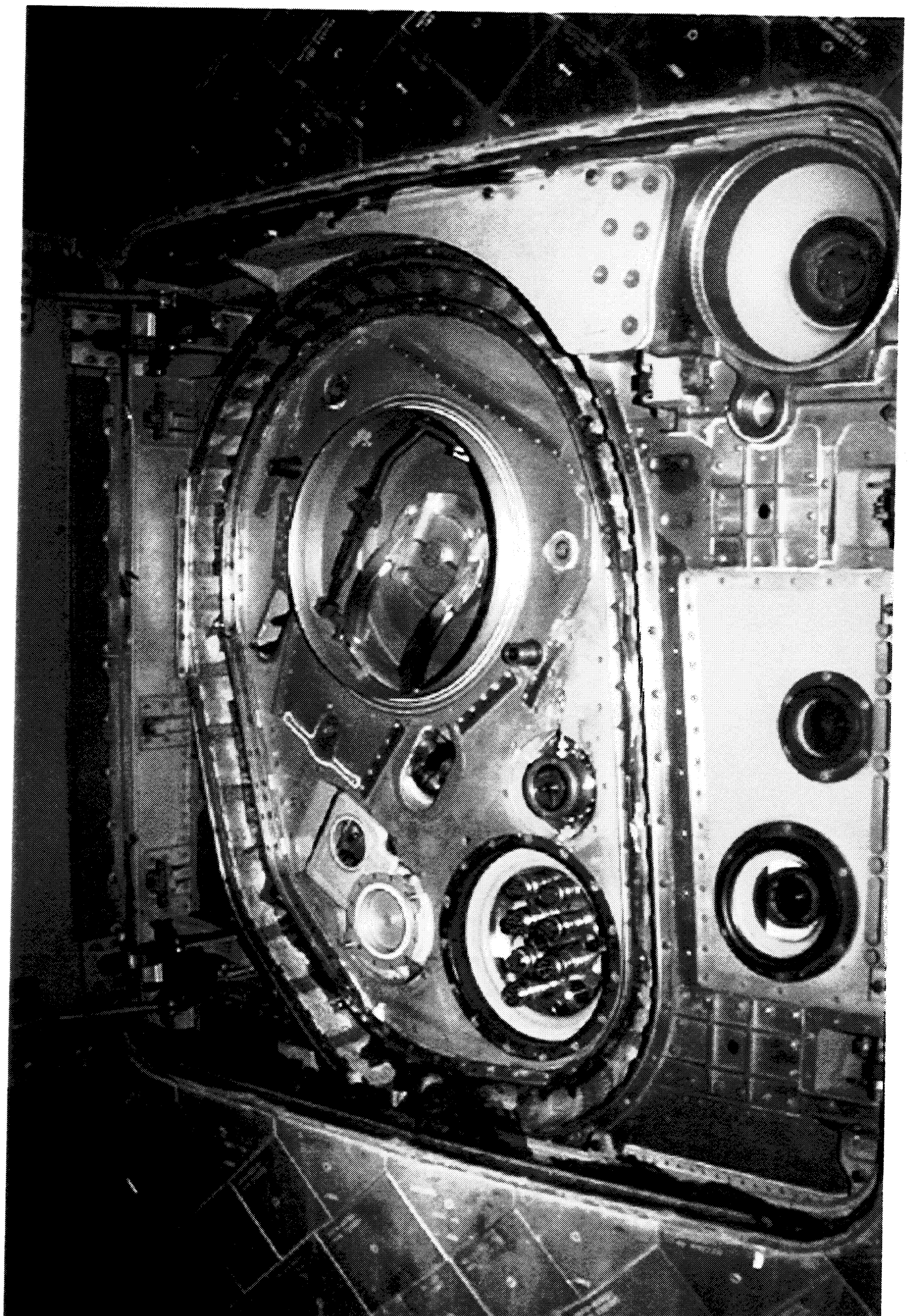


Photo 25: LH2 ET/ORB Umbilical

Photo 26: SSME Nozzle Ablator

Pieces of SSME nozzle ablator were found on Orbiter body flap stub tiles adjacent to the base heat shield beneath SSME #2. No impact damage to the tiles was detected. Inspection of the SSME #2 and #3 nozzles revealed approximately 60 percent of the ablator was missing. The ablator was bonded to SSME #2 and #3 circumferentially from 45 degrees inboard to 90 degrees outboard on the -Z side of the nozzle to prevent the recurring problem of bluing.

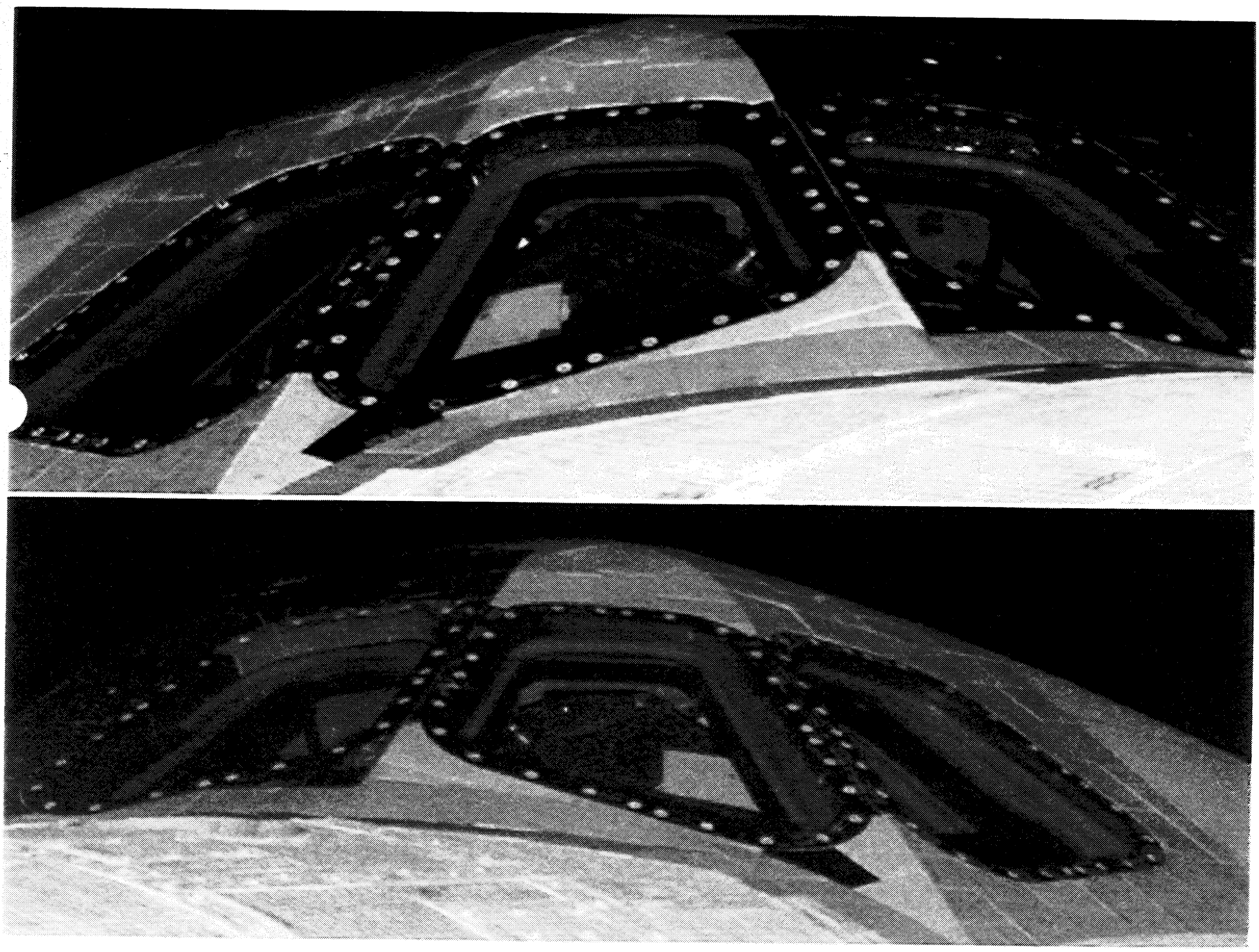
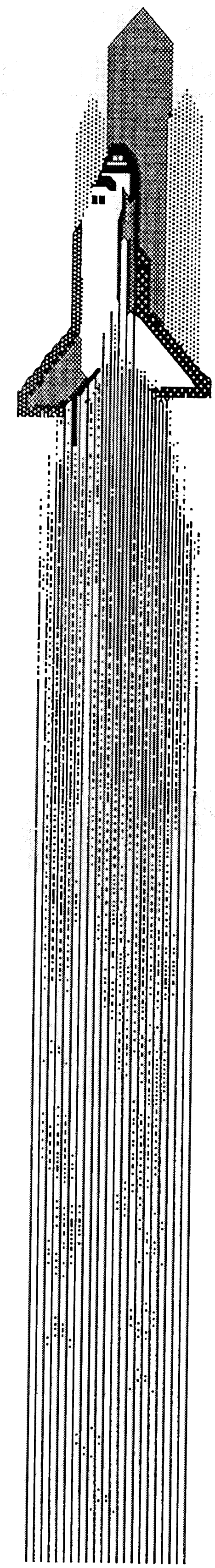


Photo 27: Windows

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

APPENDIX A. JSC PHOTOGRAPHIC ANALYSIS SUMMARY

Space Science Branch
Image Science and Analysis Group



STS-88 Summary of Significant Events

February 16, 1999

Space Shuttle
Image Science and Analysis Group
STS-88 Summary of Significant Events

Project Work Order - SN3CS

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Space Science Branch
Earth Sciences and Solar System Exploration Division
Space and Life Sciences Directorate

Table of Contents

Tables and Figures

1. STS-88 (OV-105): FILM/VIDEO SCREENING AND TIMING SUMMARY

1.1 SCREENING ACTIVITIES

1.1.1 Launch

The STS-88 launch of Endeavour (OV-105) from Pad A occurred on Friday, December 4, 1998 at approximately 338:08:35:34.031 UTC as seen on camera E9. SRB separation occurred at approximately 08:37:37.75 UTC as seen on camera ET207.

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

Twenty launch films were screened on December 7, 1998. Twenty-two additional films were received for contingency support and anomaly resolution, but were not screened.

Photography of the left SRB and the LSRB/ET aft attach and the external tank aft dome was acquired using umbilical well camera films. Handheld still photography of the ET was acquired.

1.1.2 On-Orbit

No unplanned on-orbit Shuttle analysis support was requested. Analysis support (both planned and unplanned) was provided to the ISS AF-2A Space Station photographic and television external survey. The Space Station image analysis support will be documented in the AF-2A Imagery Overview Report.

1.1.3 Landing

Endeavour made a night-time landing on runway 15 at the KSC Shuttle Landing Facility on December 15, 1998 at 10:53 p.m. EST. Ten 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 2.6). The drag chute was not deployed.

According to the pre-mission agreement, the STS-88 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.

Event Description	Time (UTC)	Camera
Main Gear Door Opening	350:03:53:06.412	EL17 IR
Main Gear Touchdown	350:03:53:28.386	EL17 IR
Nose Gear Touchdown	350:03:53:37.588	EL17 IR
Drag Chute Sequence	Not Performed	
Wheel Stop	350:03:54:11	EL17 IR

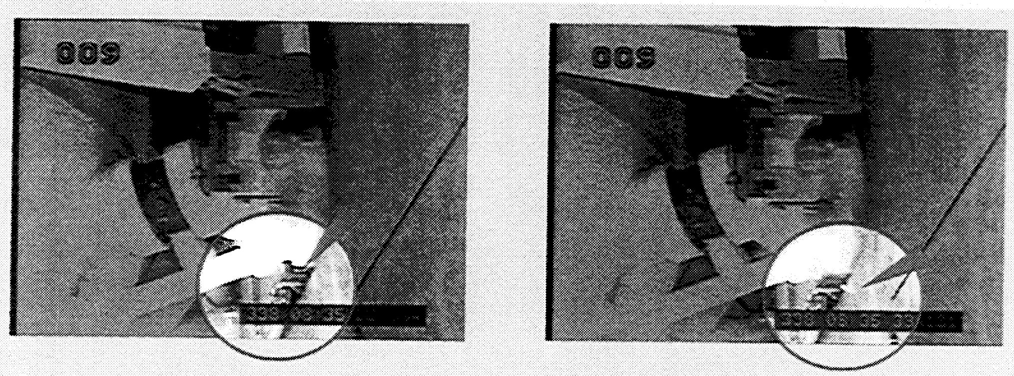
Notes:
(1) The left and right main gear tires appeared to touchdown simultaneously on the videos.
(2) Wheel stop was difficult to time accurately on the night-time views.

Table 1.2 Landing Events Timing

2. SUMMARY OF SIGNIFICANT EVENTS

2.1 DEBRIS FROM SSME IGNITION THROUGH LIFTOFF

As on previous missions, numerous light-colored pieces of debris were seen aft of the launch vehicle before, during, and after the roll maneuver (umbilical ice debris, RCS paper, SRB flame duct debris, and water baffle debris). Multiple pieces of ice debris were seen falling from the ET/Orbiter umbilicals along the body flap during SSME ignition. Two pieces of ice debris were seen to contact the LH2 umbilical well door sill (08:35:29.86, 08:35:31.00 UTC). ET/Orbiter umbilical ice debris was also seen to contact an Orbiter lower surface tile (08:35:33.39 UTC). No damage to the launch vehicle was noted.



Camera OTV009
Light Colored Flexible Debris (Unidentified)
From LH2 Umbilical Area

Figure 2.1 (A) Debris Near LH2 Umbilical

In the above figure, a rectangular-shaped piece of light-colored-flexible debris (probably purge barrier tape) fell from the LH2 umbilical area and contacted the LH2 umbilical well door sill (08:35:33.131 UTC). (Cameras OTV009, OTV054, OTV063, E5, E17, E31, E34)

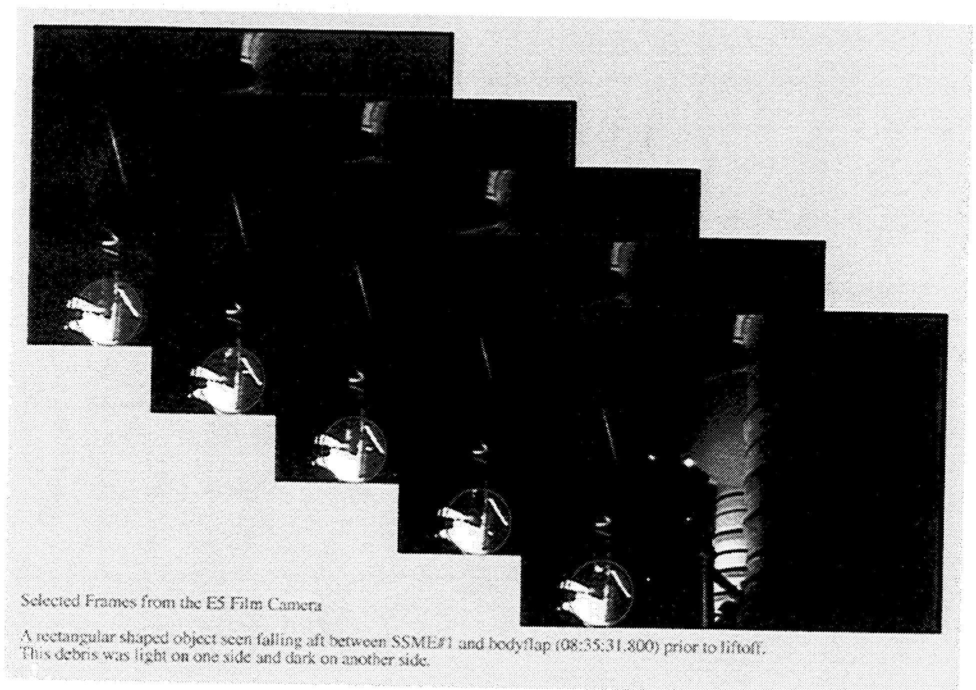


Figure 2.1 (B) Rectangular Shaped Debris between SSME # 1 and Body Flap

A thin, white-colored rectangular shaped piece of debris was seen between the body flap and SSME #3 prior to liftoff (08:35:31.800 UTC). The origin and identification of this debris was not determined. (Camera E5)

A single piece of white-colored debris (probably RCS paper) was seen between the body flap, SSME #2, and SSME #3 (08:35:33.970 UTC). (Camera E5)

A single piece of debris was seen traveling from the RSRB flame duct area at liftoff (08:35:34.59 UTC). (Camera OTV070)

A single piece of light-colored debris (probably SRB throat plug material) was seen traveling in a northerly direction from the base of the SRB's at liftoff (08:35:35.283 UTC). (Cameras E52, E63)

2.2 DEBRIS DURING ASCENT

Probably because of the contrast against the night sky, more than the usual amount of debris was seen aft of the launch vehicle during ascent. Multiple pieces of ET/Orbiter umbilical ice debris and RCS paper debris (too numerous to count) were seen near the SSME rims, near the vertical stabilizer, and aft of the vehicle from liftoff, through the roll maneuver, and beyond.

A light-colored piece of debris appeared to be near the right Orbiter wing tip from the camera E54 perspective (08:35:53.932 UTC). This debris was probably RCS paper.

Multiple pieces of ET/Orbiter umbilical well ice and RCS paper debris were seen near the Orbiter during the roll maneuver and early ascent (08:35:46.6 through 08:36:07.0 UTC). Two orange-colored flares (probably debris induced)

were seen in the SSME exhaust plume during ascent (08:36:07.53, 08:36:12.77 UTC). (Cameras ET207, E223)

On camera E224, a single piece of debris was seen near the -Z side of the aft end of the ET. This debris appeared that it could have possibly originated from the intertank region of the ET (08:36:16.762 UTC).

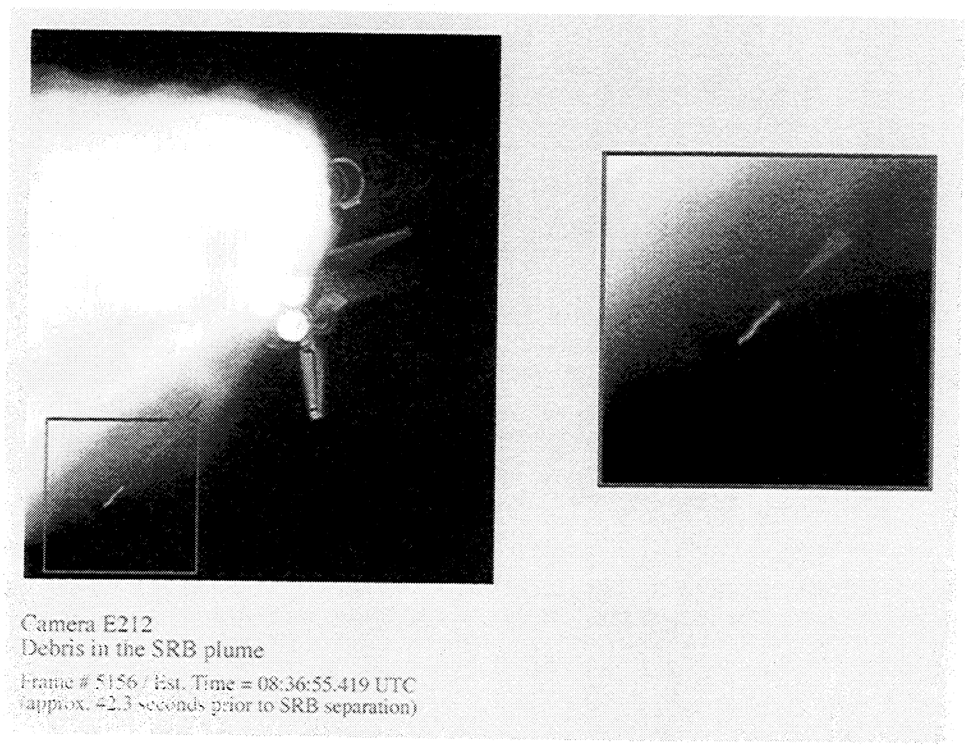
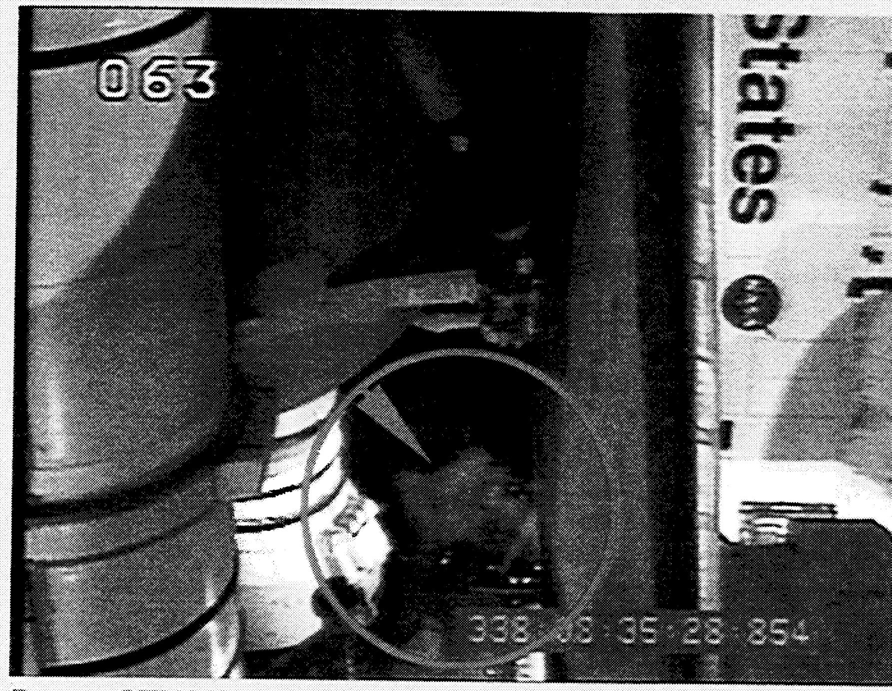


Figure 2.2 Linear Shaped Debris Near SRB Exhaust Plume

Approximately nine pieces of debris (probably SRB aft skirt instafoam) were seen near the SRB exhaust plume during ascent (08:36:45.59, 08:36:50.67, 08:36:52.17, 08:36:52.87, 08:36:53.24 UTC). Several of these debris appeared linear shaped, possibly due to image motion smear. On camera E212, a single large appearing piece of debris was seen falling from near the aft end of the LSRB. (Cameras KTV4A, KTV5A, ET212, E52, E54, E207, E212, E222, E223, E224)

2.3 MOBILE LAUNCH PLATFORM (MLP) EVENTS

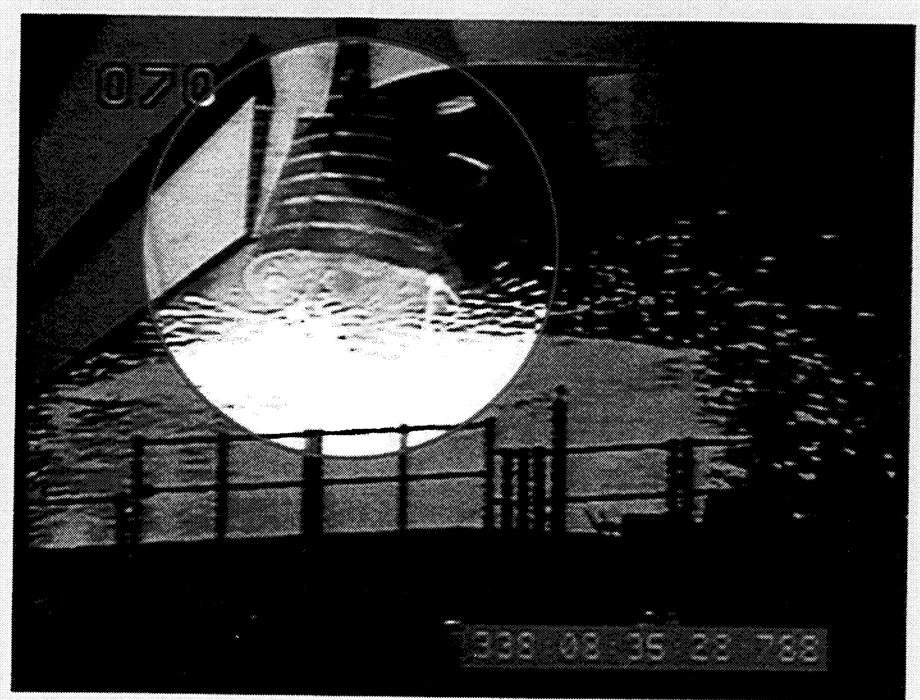
2.3.1 Mobile Launch Platform Events



Camera OTV063 - Orange Vapor

Figure 2.3.1 (A) Orange Vapor between RSRB and Body flap

Orange vapor, probably free burning hydrogen, was clearly visible moving forward along the north-side of the bodyflap during SSME ignition.



Camera OTV070
Orange Vapor above SSME#1

Figure 2.3.1 (B) Orange Vapor forward of SSME # 1 Rim

Orange vapor was visible drifting forward from the aft end of the vehicle near the SSME rims toward the base of the vertical stabilizer during SSME ignition. Orange vapor has been observed on previous missions. (Cameras E2, E17, E18, E20, E36, OTV063, OTV070, OTV071, KTV21A)

The SSME ignition appeared normal on the high-speed engineering films. The SSME Mach diamonds formed in the expected sequence. The times for the Mach diamond formation given below are from camera film E19.

SSME	TIME (UTC)
SSME #3	08:35:30.776 UTC
SSME #2	08:35:30.918 UTC
SSME #1	08:35:31.086 UTC

Table 2.3.2 SSME Mach Diamond Formation Times

Small areas of tile surface coating material erosion were seen during SSME ignition on the SSME #2 Dome Mounted Heat Shield (DMHS), on the base heat shield near SSME #3, and on the base of the right RCS stinger. A small area of tile surface coating material was seen to detach from the base heat shield near the base of SSME #2 during SSME ignition (08:35:29.29 UTC). (Cameras E17, E18, E76, OTV070)

Several light-orange-colored flashes were seen in the SSME #1 exhaust plume prior to liftoff (08:35:32.563, 08:35:32.625, 08:35:33.237, and 08:35:33.247 UTC). (Cameras E2, E76)

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 (08:35:41.885 UTC). This event has been seen on previous missions. (Camera E52)

2.4 ASCENT EVENTS

Body flap motion was visible during ascent (08:36:06.6 - 08:36:40.5 UTC). The body flap motion appeared similar to that seen on previous mission imagery. (Cameras E207, ET207)

2.5 ONBOARD PHOTOGRAPHY OF THE EXTERNAL TANK (ET)

2.5.1 Analysis of the Umbilical Well Camera Films

Two rolls of 16 mm umbilical well film, and one roll of 35 mm umbilical well film were received. The +X translation maneuver was performed on STS-88 to facilitate the imaging of the ET with the umbilical well cameras.

35 mm Umbilical Well Camera Film

Due to total darkness at the time of ET separation, the 35mm Umbilical well camera film was dark and unuseable.

16 mm Umbilical Well Camera Film

The 16mm coverage of the ET separation was unuseable due to the dark lighting conditions.

The LSRB separation was visible on the 16mm films because of the light from the SRB's. The LSRB separation appeared normal on the 16mm umbilical well camera films. Numerous light-colored pieces of debris (insulation), and dark debris (charred insulation) were seen throughout the SRB separation film sequence. Typical ablation and charring of the ET/Orbiter LH2 umbilical electric cable tray and the aft surface of the -Y upper strut fairing prior to SRB separation were seen. Numerous irregularly-shaped pieces of debris (charred insulation) were noted near the base of the LSRB electric cable tray prior to SRB separation. Pieces of TPS were seen to detach from the aft surface of the horizontal section of the -Y ET vertical strut. Normal blistering of the fire barrier material on the outboard side of the LH2 umbilical was seen. Ablation of the TPS on the aft dome was typical of that seen on previous missions. The left SRB nose cap was visible during SRB separation. The right SRB nose cap appeared to be present, but this could not be comfirmed because of darkness.

Timing data was present on both of the 16mm umbilical well camera films.

2.5.2 Analysis of the ET Handheld Photography

The STS-88 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-88 was the sixth flight to use the roll-to-heads-up maneuver).

The crew obtained External Tank (ET) photography with a 35 mm handheld camera (Nikon-F4 w/400 mm lens). A total of 36 excellent quality pictures of the ET were obtained (roll number 333). Timing data was present on all frames.

Image	Time (GMT) (hh:mm:ss)	Time (MET) (mm:ss)	Distance from the Orbiter (estimated)
First Image	08:51:13	15:39	1.6 km
Last Image	08:58:18	22:44	4.2 km

Table 2.5.2 (A) ET Timing Information

Frame No	GMT (hh:mm:ss)	MET (mm:ss)	Delta Time	Cum. Time	View	Percent Shadow / Dark	Distance in km
1	08:51:13	15:39	00:00	00:00	-Y, -Z, -Y Thrust Panel	40%	1.61
2	08:51:24	15:50	00:11	00:11	-Y, -Z, -Y Thrust Panel	50%	1.61
3	08:51:44	16:10	00:20	00:31	Aft dome, -Z	60%	1.69
4	08:51:54	16:20	00:10	00:41	Aft dome. -Z	70%	1.78
5	08:52:09	16:35	00:15	00:56	Aft dome	60%	1.88
6	08:52:21	16:47	00:12	01:08	Aft dome	50%	1.88
7	08:52:33	16:59	00:12	01:20	LO2 Feedline, +Y	dark	1.99
8	08:52:46	17:12	00:13	01:33	LO2 Feedline, +Y, +Z	dark	2.11
9	08:52:59	17:25	00:13	01:46	LO2 Feedline, +Y, +Z. Bipod	dark	2.26
10	08:53:09	17:35	00:10	01:56	Umb Att, LO2 Feedline, Bipod, +Z	20%	2.26
11	08:53:25	17:51	00:16	02:12	Umb Att, LO2 Feedline, Bipod, +Z, Ojive, Nose	30%	2.42
12	08:53:36	18:02	00:11	02:23	Umb Att, LO2 Feedline, Intertank, +Z, Ojive, Nose	40%	2.42
13	08:53:47	18:13	00:11	02:34	Umb Att, LO2 Feedline, Intertank, +Z, Ojive, Nose	50%	2.60
14	08:53:58	18:24	00:11	02:45	Umb Att, LO2 Feedline, Intertank, +Z, Ojive, Nose	60%	2.60
15	08:54:07	18:33	00:09	02:54	LO2 Feedline, Nose	70%	2.60
16	08:54:22	18:48	00:15	03:09	-Y , Nose	dark	2.60
17	08:54:37	19:03	00:15	03:24	-Z, Nose	70%	2.71
18	08:54:48	19:14	00:11	03:35	-Z, Intertank, Nose	60%	2.82
19	08:54:59	19:25	00:11	03:46	-Z, Intertank, Access door, Ojive	50%	2.82
20	08:55:07	19:33	00:08	03:54	-Z, Ojive	40%	2.82
21	08:55:21	19:47	00:14	04:08	Aft dome	30%	2.82
22	08:55:32	19:58	00:11	04:19	Aft dome, +Z	40%	3.08
23	08:55:45	20:11	00:13	04:32	Aft dome, LO2 Feedline, +Z	dark	3.08
24	08:55:55	20:21	00:10	04:42	LO2 Feedline, +Y, +Y Thrust Panel, Intertank, Ojive,	50%	3.08
25	08:56:06	20:32	00:11	04:53	LO2 Feedline, +Y, +Y Thrust Panel, Intertank, Ojive,	60%	3.08
26	08:56:21	20:47	00:15	05:08	LO2 Feedline, +Y, +Y Thrust Panel, Intertank, Ojive,	30%	3.22
27	08:56:30	20:56	00:09	05:17	+ Y, nose	60%	3.38
28	08:56:49	21:15	00:19	05:36	-Y, Nose	50%	3.08
29	08:56:57	21:23	00:08	05:44	-Y, -Y Thrust Panel, Intertank, Ojive	40%	3.08
30	08:57:05	21:31	00:08	05:52	-Y, -Y Thrust Panel, Intertank, Ojive	30%	3.56
31	08:57:14	21:40	00:09	06:01	Aft dome, -Y	50%	3.76
32	08:57:24	21:50	00:10	06:11	Aft dome	dark	3.76
33	08:57:40	22:06	00:16	06:27	-Z, Intertank	40%	3.76
34	08:57:50	22:16	00:10	06:37	-Z, Intertank, Nose	30%	3.98
35	08:58:00	22:26	00:10	06:47	-Z, Intertank, Nose	50%	4.23
36	08:58:18	22:44	00:18	07:05	-Y, Nose	dark	4.23

Table 2.5.2 (B) Description of the ET Views

A description of the ET views on the handheld film is given in Table 2.5.2 (B). Views of the +Z, -Y, -Z, and +Y sides of the ET were acquired including views of the +Y and -Y thrust panel. The film images of the ET were silhouetted due to the Sun light incidence angle. This resulted in large areas of dark shadow on the ET.

The normal SRB separation burn scars and aero-heating marks were noted on the +Y and -Y sides of the intertank and nose of the ET. There was no visible damage on the ET intertank surrounding the thrust panel regions of the ET. Enhancements on ten selected views were made to bring out details on the ET thrust panels. See Section 2.5.4 for the findings from the analysis of the ET thrust panel enhancements.

The tumble rate of the ET (end-to-end rotation of the ET about its center of mass) was equivalent or less than that seen on the previous five missions. Table 2.5.2 (C) contains a comparison of the averaged tumble rate measurements for the current and the five previous Space Shuttle missions.

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 deg/sec**	**6.2 m/sec**	**15:39 - 22:44**	**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 2.5.2 (C) ET Tumble and Separation Rates

2.5.3 Enhanced Images of the ET Thrust Panels

Ten 35 mm handheld film views of the ET were enhanced to restore the resolution of the imagery for detailed analysis. Two enhancements of the ET intertank region at a distance of approximately 1.6 km and 3 km from the Orbiter are shown in figures 2.5.3 (A) and 2.5.3 (B).

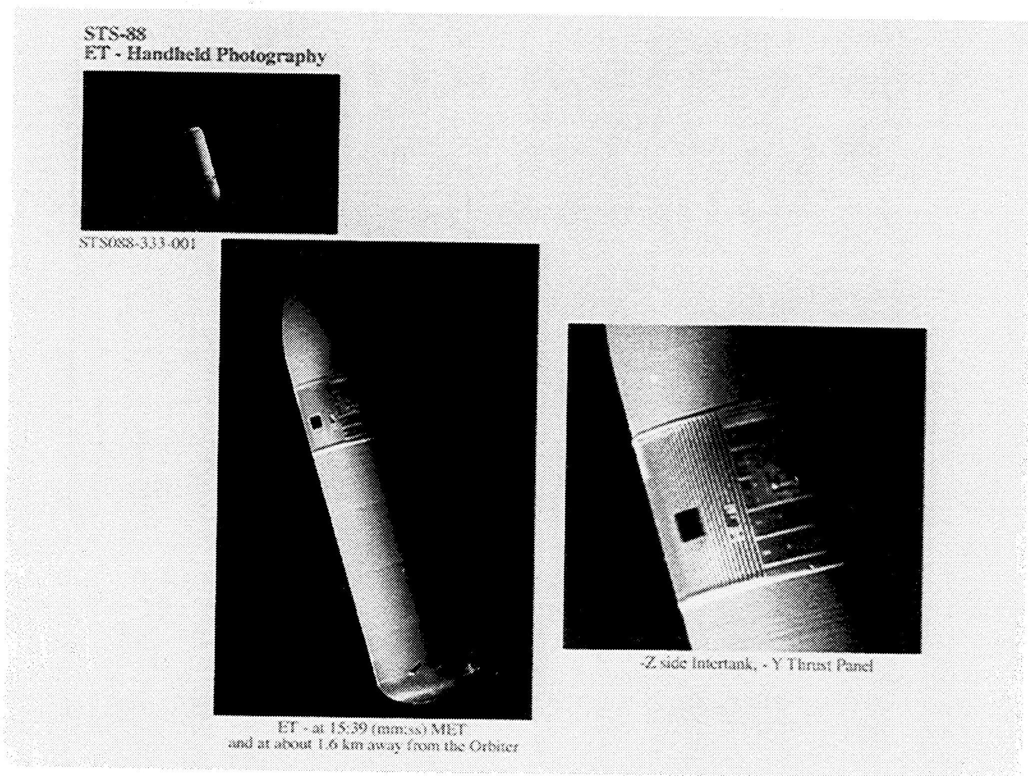


Figure 2.5.3 (A) ET -Y Thrust Panel, ~ 1.6 km Distance from the Orbiter

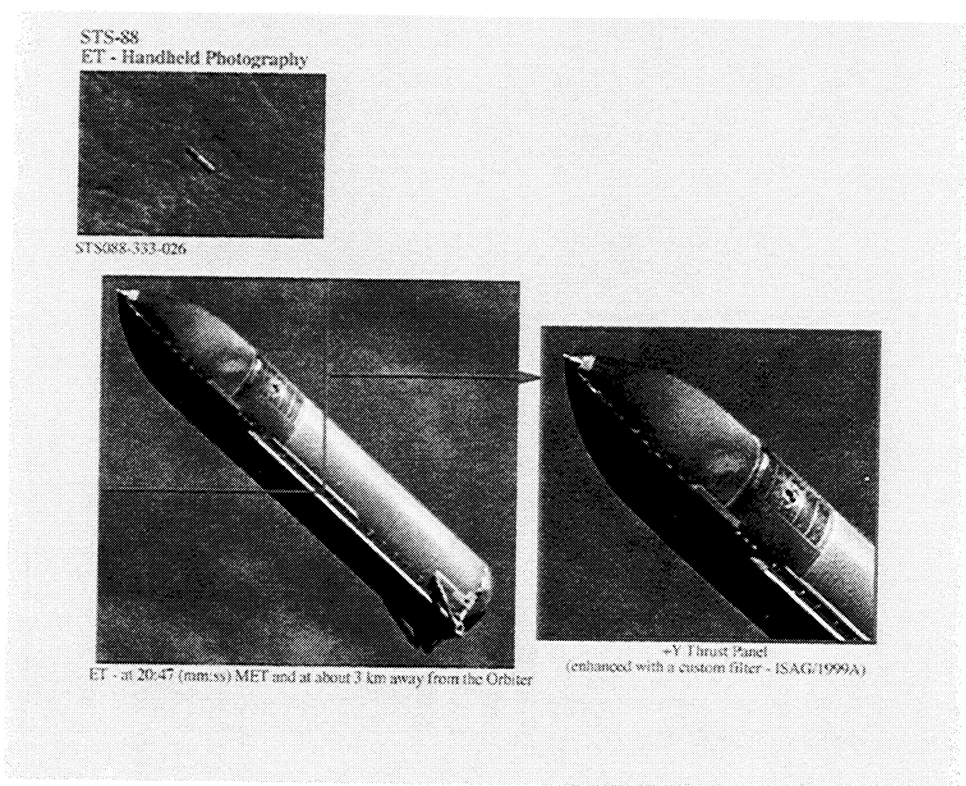


Figure 2.5.3 (B) ET +Y Thrust Panel, ~ 3 km Distance from the Orbiter

2.5.4 Analysis of the ET Thrust Panel Views

An estimate of the minimum resolvable object size on the enhanced views of the thrust panels was made for use in the analysis of possible defects on the thrust panels.

The minimum resolvable object size on the STS-88 400 mm lens images of the ET is ~7 to 8 inches at 3 km using a known 7.3 inch spacing between the intertank stringer heads and the ~9 inch width of the LH2 tank-to-intertank close-out flange for size reference. This compares favorably with the previously calculated ~8 inch theoretical minimum resolvable object size for the Nikon F4 camera w/ 400 mm lens at 3 km.

Overall, both the STS-88 -Y and +Y thrust panel views appear similar to each other with only a few possible divots at the discernible resolution. See Figures 2.5.4 (A) and (B).

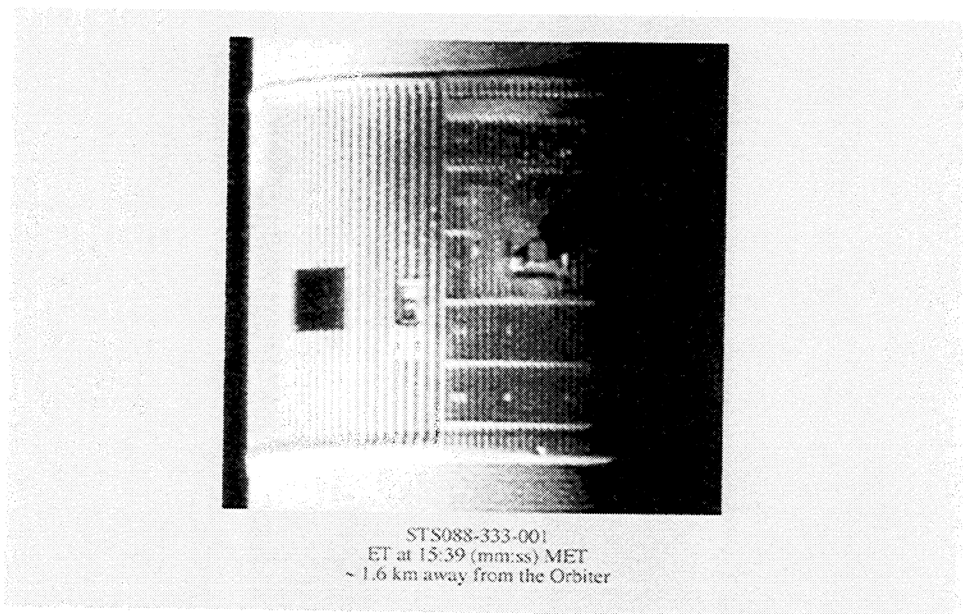


Figure 2.5.4 (A) -Z Intertank and -Y Thrust Panel of the ET at ~ 1.6 km

Figure 2.5.4 (A) is a view of the -Y thrust panel taken at ~1.6 km distance from the Orbiter. The minimum resolvable object size is ~ 3 inches. The -Y thrust panel TPS does not appear significantly damaged at this level of detail. However, an ~ 9 inch divot is visible at the junction of the -Y thrust panel and the LH2 tank-to-intertank close-out flange.

On the ~1.6 km view, a rectangular-shaped, light-colored tone is visible on the TPS immediately surrounding the -Y EO fitting. This area is visible on the pre-launch close-out views.

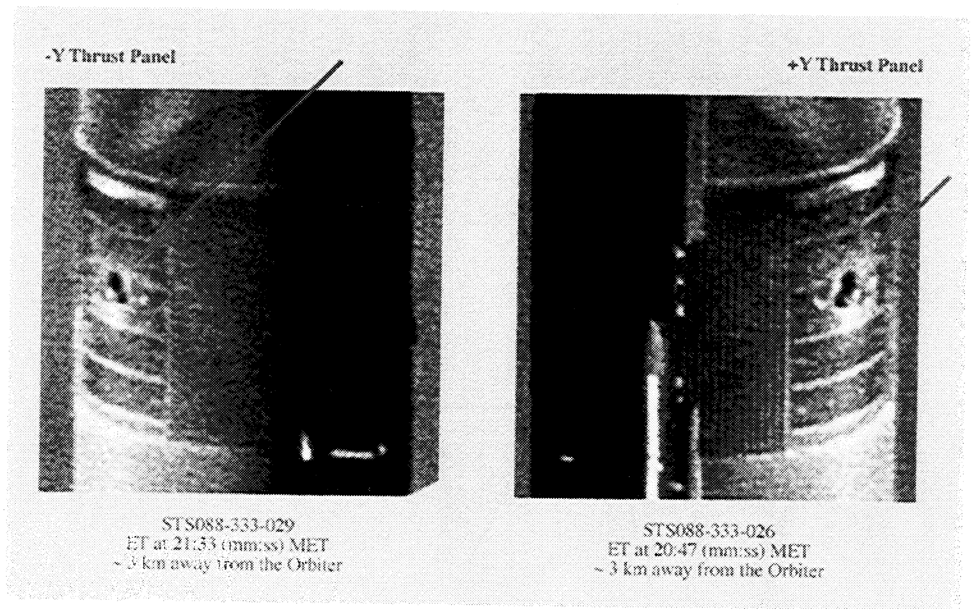


Figure 2.5.4 (B) -Y and +Y Thrust Panels of the ET at ~ 3.0 km

The STS-88 -Y ET thrust panel appears relatively clean on the digitally enhanced and the original negative photography while the +Y thrust panel has somewhat variable appearing tones / textures near the forward attach strut.

The +Y Thrust Panel TPS immediately surrounding and forward of the +Y EO fitting appears to have a coarse texture when compared to the same area on the -Y thrust panel. See arrows in Figure 2.5.4 (B). The course texture could indicate an area of possible divoting (probably less than one or two inches in diameter based on the STS-95 thrust panel video) and/or a TPS texture change on the +Y thrust panel similar to that seen on the STS-95 SRB ET -Y thrust panel separation video. This is not conclusive because of the minimum resolvable object size that is detectable, the slight differences between the two images in resolvable detail, possible slight differences in focus, and the change in Sun light direction across the tank.

2.5.5 Analysis of the ET Handheld Video

Figure 2.5.5 Handheld Video View of the ET

Approximately fifteen minutes of video of the ET was obtained on STS-88. Timing data was present on the on-board tapes which was read from the Cannon L2 camcorder post-flight. No ET venting was detected on the STS-88 imagery (venting was seen on the five previous missions).

2.6 LANDING EVENTS

2.6.1 Landing Sink Rate Analysis

Image data from film camera EL-7 South was used to determine the landing sink rate of the main gear. In the analysis, data from approximately one second of imagery immediately prior to touchdown was considered. Data points defining the main gear struts were collected on every frame (100 frames of the data during the last second prior to touch down). An assumption was made that the line of sight of the camera was perpendicular to the Orbiter's y-axis. The distance between the main gear struts was used as a scaling factor. The main gear height above the runway was calculated by the vertical difference between the main gear struts and the reference point. These heights were then regressed with respect to time and the trendline was determined. Sink rate equals the slope of this regression line.

The left main gear sink rate for STS-88 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.

Time Prior to Touchdown	1.00 Sec.	0.50 Sec.	0.25 Sec.
Left Main Gear Sink Rate	1.7 ft/sec	1.8 ft/sec	2.3 ft/sec
Estimated Error (1σ)	± 0.2 ft/sec	± 0.2 ft/sec	± 0.1 ft/sec

Left Main Gear Touchdown = 350:03:53:28.386 (UTC)

Table 2.6.1 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-88 vehicle was estimated to be 201,606 lbs.

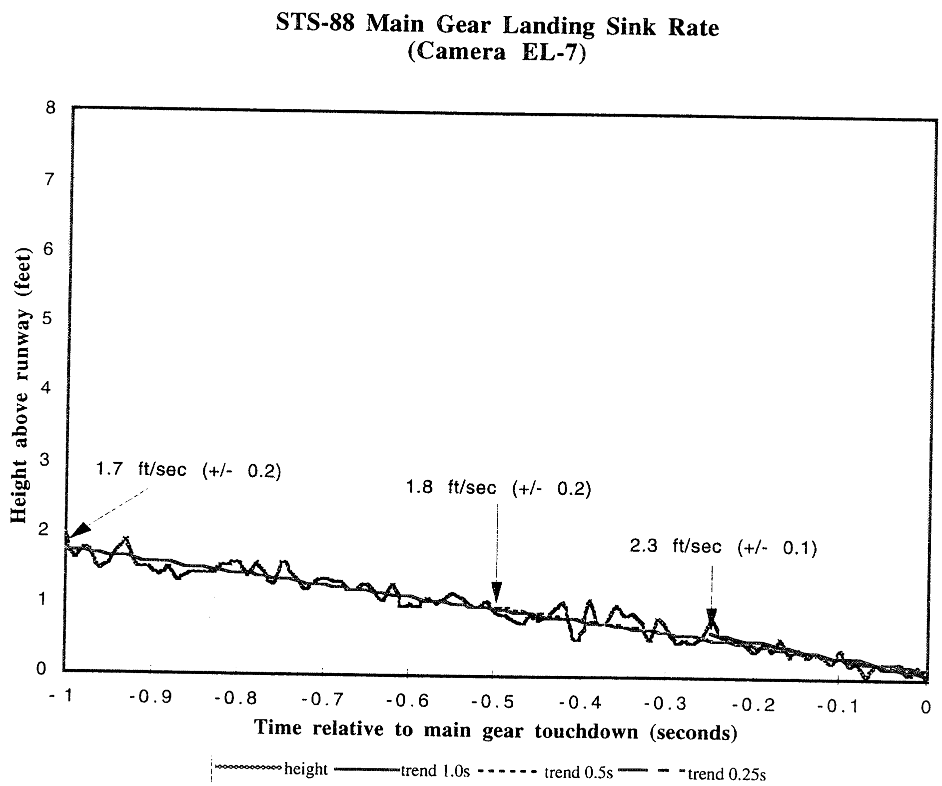


Figure 2.6.1 Main Gear Landing Sink Rate

2.7 OTHER

2.7.1 Normal Events

Normal events observed included 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, vapor off the SRB stiffener rings, charring of the ET aft dome, ET aft dome outgassing, linear optical effects, recirculation, SRB plume brightening, and slag debris before, during, after SRB separation.

2.7.2 Normal Pad Events

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

APPENDIX B. MSFC PHOTOGRAPHIC ANALYSIS SUMMARY

STS-88 Engineering Photographic Analysis Report

Table of Contents

Introduction

The launch of space shuttle mission STS-88, the thirteenth flight of the Orbiter Endeavour occurred on December 4, 1998, at approximately 2:35AM Central Daylight Time from launch complex 39A, Kennedy Space Center (KSC), Florida. Launch time to be reported as 338:08:35:34.019 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-88 include, but are not limited to the following:

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

- Free hydrogen ignitors
- Booster separation motors

Camera Coverage Assessment

The following table illustrates the camera coverage received at MSFC for STS-88.

	16mm	35mm	Video
MLP	17	0	4
FSS	5	0	3
Perimeter	0	7	6
Tracking	0	8	10
Onboard	0	0	0
Totals	22	15	23

Total number of film and videos received to date: 60

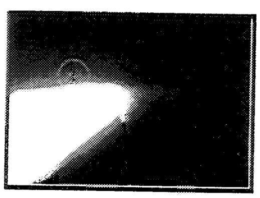
An individual motion picture camera assessment is provided as Appendix A. Appendix B contains detailed assessments of the video products received at MSFC.

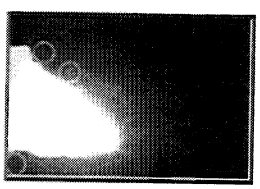
Ground Camera Coverage

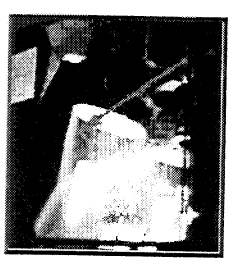
Anomalies

No anomalies observed to date.

Observations


Debris observed falling aft of the vehicle during ascent from camera ET-212.


Debris observed falling aft of the vehicle during ascent from camera TV4a.


A streak in SSME #1 was observed at 338:08:35:33.241 UTC prior to liftoff.

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	08:35:34.029
M-2	E8	Too Dark
M-5	E12	08:35:34.027
M-6	E13	Too Dark

SRB Separation Time

SRB separation as recorded by observations of the BSM combustion products from long-range film camera E-207 occurred at 338:08:37:37.76 UTC.

Appendix A - Individual film camera assessments

Appendix B - Individual video camera assessments

Appendix C - Definitions and acronyms

Individual film/video summary report

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Return to MSFC Engineering Photographic Analysis Home Page

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A debris/ice/thermal protection system assessment and integrated photographic analysis was conducted for Shuttle mission STS-88. 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 of Space Shuttle mission STS-88 and the resulting effect on the Space Shuttle Program.

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