Debris/Ice/TPS Assessment and Integrated Photographic Analysis Of Shuttle Mission STS-98

Robert F. Speece
Process Engineering/Mechanical Systems Division/ET-SRB Branch,
Kennedy Space Center, Florida

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DEBRIS/ICE/TPS ASSESSMENT AND INTEGRATED PHOTOGRAPHIC ANALYSIS OF SHUTTLE MISSION STS-98

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Robert F. Speece
ET/SRB Thermal/Mechanical Systems
NASA - KSC
Mail Code: PH-H2

Peter Chitko
Chief, ET/SRB Mechanical Branch
NASA - KSC
Mail Code: PH-H2

Approved:

Robert F. Speece
ET/SRB Thermal/Mechanical Systems
NASA - KSC
Mail Code: PH-H2

Peter Chitko
Chief, ET/SRB Mechanical Branch
NASA - KSC
Mail Code: PH-H2

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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 analyses 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-98

1.0 SUMMARY OF SIGNIFICANT EVENTS

STS-98 consisted of OV-104 Atlantis (23rd flight), ET-106, and BI-105 SRB's on MLP-2 and Launch Pad 39A. Atlantis was launched at 23:13:02 UTC (6:13 p.m. local) on 7 February 2001. Landing occurred at 20:33:04 UTC (12:33 p.m. local time) on 20 February 2001 at the Edwards Air Force Base (EAFB), California.

Post landing inspection of Orbiter tiles showed a total of 102 hits, of which 13 had a major dimension of 1-inch or larger. The Orbiter lower surface sustained 73 total hits, of which 8 had a major dimension of 1-inch or larger. Some of these damage sites (23 total hits with three larger than 1-inch) were located in the area from the nose gear to the main landing gear wheel wells on both left and right chines, which is consistent with the loss of foam from ET thrust panels. But the overall quantity and average size of the damage sites compared to previous flights was consequently reduced as a result of the pre-launch TPS venting modification. Some of the hits in this area may also be attributed to impacts from LO2 feedline bellows ice particles, with one hit just aft of the nose gear on the left side having material imbedded in the damage site.
Laboratory analysis results show the imbedded material to be tile gap filler.

Tracking films provided view of debris in the region of the vertical stabilizer and left OMS pod prior to SRB separation. The debris was observed to have a profile similar to that of RCS cover paper. This observation was listed on the STS-98 Consolidated Film/Video Report. Subsequently, a damage site on the vertical stabilizer leading edge was observed during on-orbit operations. At Orbiter landing, the damage site had not changed significantly in size and measured 2 by 3 by 0.25 inches in depth. Sample from this damage site provided evidence of tile
materials only when processed in the laboratory, as shown in the analysis report and summary. There were no tiles, blankets or components missing from the vertical stabilizer or OMS pod areas, as might have caused the observed damage.

STS-98 was the first mission in which the up-firing Forward Reaction Control System (FRCS) engines were fired coincident with the Solid Rocket Booster (SRB) Booster Separation Motors (BSM) as a planned event to shield the forward facing Orbiter windows from BSM plume exhaust products and window impact concerns. The event was within view of ground cameras, however, the details of the firing were not readily discernable as the vehicle is being seen through
the plume. Post-landing assessment of the Orbiter windows noted that window hazing appeared to be less than normal. Tile damage in the Orbiter windows area included 18 hits with 3 having a
major dimension of 1-inch or larger.

In summary, both the number of Orbiter TPS debris hits and the number of hits 1-inch or larger were less than average, or "in family." The ET TPS venting modifications continue to provide a reducing effect on the quantity and size of Orbiter TPS damage sites.

2.0 PRE-LAUNCH SSV/PAD DEBRIS BRIEFING

The Debris/Ice/TPS and Photographic Analysis Team briefing for launch activities was conducted at 1500 on 06 February 2001. The following personnel participated in various team activities, assisted in the collection and evaluation of data, and contributed to reports contained in this document.

R. Speece	NASA - KSC	Thermal Protection Systems
A. Oliu	NASA - KSC	Shuttle Photo/Debris Systems
J. Rivera	NASA - KSC	ET Mechanisms/Structures
M. Payne	NASA - KSC	SRB Mechanical Systems
W. Boyter	NASA - KSC	SRB Mechanical Systems
B. Nguyen	NASA - KSC	SRB Mechanical Systems
R. Page	NASA - KSC	SSP Integration
J. Blue	USA - SFOC	ET Mechanical Systems
W. Richards	USA - SFOC	ET Mechanical Systems
M. Wollam	USA - SFOC	ET Mechanical Systems
T. Ford	USA - SFOC	ET Mechanical Systems
R. Seale	USA - SFOC	ET Mechanical Systems
B. Atkinson	Boeing	Systems Integration
T. Wilson	Boeing	Systems Integration
A. Khodadoust	Boeing	Huntington Beach
J. Stone	Boeing	Huntington Beach
S. Otto	LMMSS	ET Processing

3.0 LAUNCH PROCESS

The launch process for debris team activities, consisting of inspection and process monitoring throughout the launch countdown, were completed in a methodical and detailed

3.1 PRE-LAUNCH SSV/PAD DEBRIS INSPECTION

A pre-launch debris inspection of the launch pad and Shuttle vehicle was performed on 06 February 2001. The purpose of this inspection was to identify and resolve any potential debris sources, and perform a detailed inspection of flight hardware prior to final launch countdown preparations. Pad conditions were favorable for the inspection and normal activities associated with final operations for launch were in work. A close-up inspection of the Space Shuttle Vehicle (SSV) and the launch pad facility areas was performed.

The only facility discrepancy noted was a broken pip pin discovered at the Rotating Service Structure (RSS) 207 foot level on the Left Hand Forward Reaction Control System (FRCS) access retractable platform. A piece of the pin was forwarded to the Pad shop personnel, who were found to have the remaining portions. Pin replacement was in work.

A crack-like material surface observation was found on the aft side of the External Tank LH2 recirculation line and was discovered to be a serration cut in the ablator material for substrate shrinkage.

No unresolved issues from this inspection were noted.

Photo 2: Pre-Launch Debris Inspection
ET, Orbiter, and SRB elements were inspected at L-1 day and no unresolved issues or concerns were noted. The Space Shuttle Vehicle was determined to be 'ready for launch.'

3.2 FINAL INSPECTION

The Final Inspection of the cryoloaded vehicle was performed on 07 February 2001 from 1210 to 1340 hours during the two hour built-in-hold at T-3 hours in the countdown. Ambient conditions at the launch pad were 67 degrees F, 78% relative humidity, and winds were 5.9 knots at 11.2 degrees measured at 1300 hours local time. There were no Launch Commit Criteria or OMRS criteria violations. There was no acreage icing concerns. There were also no protuberance icing conditions outside of the established database in NSTS 08303.

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. No unusual temperature indications were noted.

3.2.1 ORBITER

No Orbiter tile or RCC panel anomalies were observed. The RCS thruster paper covers were intact but three covers (F3L, F2U, R1R) were discolored, with no liquid indications observed. Ice/frost had formed on the SSME #1 and #2 heat shield-to-nozzle interfaces, an acceptable condition per the NSTS 08303 criteria. The SSME #3 heat shield was dry.

3.2.2 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 Thiokol was 61 degrees F, which was within the required range of 44-86 degrees F.

3.2.3 EXTERNAL TANK

The ice/frost prediction computer program 'SURFICE' was run and compared to infrared scanner point measurements, both data sets indicated no surface temperature concerns for STS-98 launch.

The Final Inspection Team observed no condensate on the LO2 tank acreage. Surface temperature measured 59-60 degrees F with Infrared and ‘SURFICE’ predicted 47-57 degrees F. There were no TPS anomalies.

No significant anomalies were present in the intertank TPS. A 6-inch long hairline width stringer valley TPS crack was visible in the +Z+Y quadrant in the first machined stringer valley +Y of the cable tray PAL ramp. Surface temperature measured 65 degrees F with Infrared. Ice and frost accumulations on the GUCP were typical.

Light to medium condensate was present on the LH2 tank acreage. Surface temperatures ranged from 54 to 66 degrees F with Infrared and ‘SURFICE’ predicted 42-52 degrees F. There were no acreage TPS anomalies.

Typical amounts of ice/frost had accumulated in the LO2 feedline bellows and support brackets. A two-inch diameter frost spot was observed on the aft side of the +Y vertical strut/longeron closeout.

A 10-inch stress relief crack in the –Y vertical strut TPS forward surface had formed with a width of ¼-inch. This condition has been accepted for flight on previous vehicles and is documented in NSTS 08303.

There were no TPS anomalies on the LO2 ET/ORB umbilical. Ice/frost accumulations were present on the aft and inboard sides. Ice/frost fingers on the separation bolt pyrotechnic canister purge vents were typical and all observations were within NSTS 08303 criteria.

Ice and frost in the LH2 recirculation line bellows and on both burst disks was typical. Likewise, a typical amount of ice/frost had accumulated on the LH2 ET/ORB umbilical purge barrier outboard side, forward, and aft surfaces. 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. All observations were within NSTS 08303 criteria.

Overall, the ET was in excellent condition for the STS-98 launch count and the Final Inspection.

3.2.4 FACILITY

All SRB sound suppression water troughs were filled and properly configured for launch. No leaks were observed on the GUCP or the LO2 and LH2 Orbiter T-0 umbilicals.

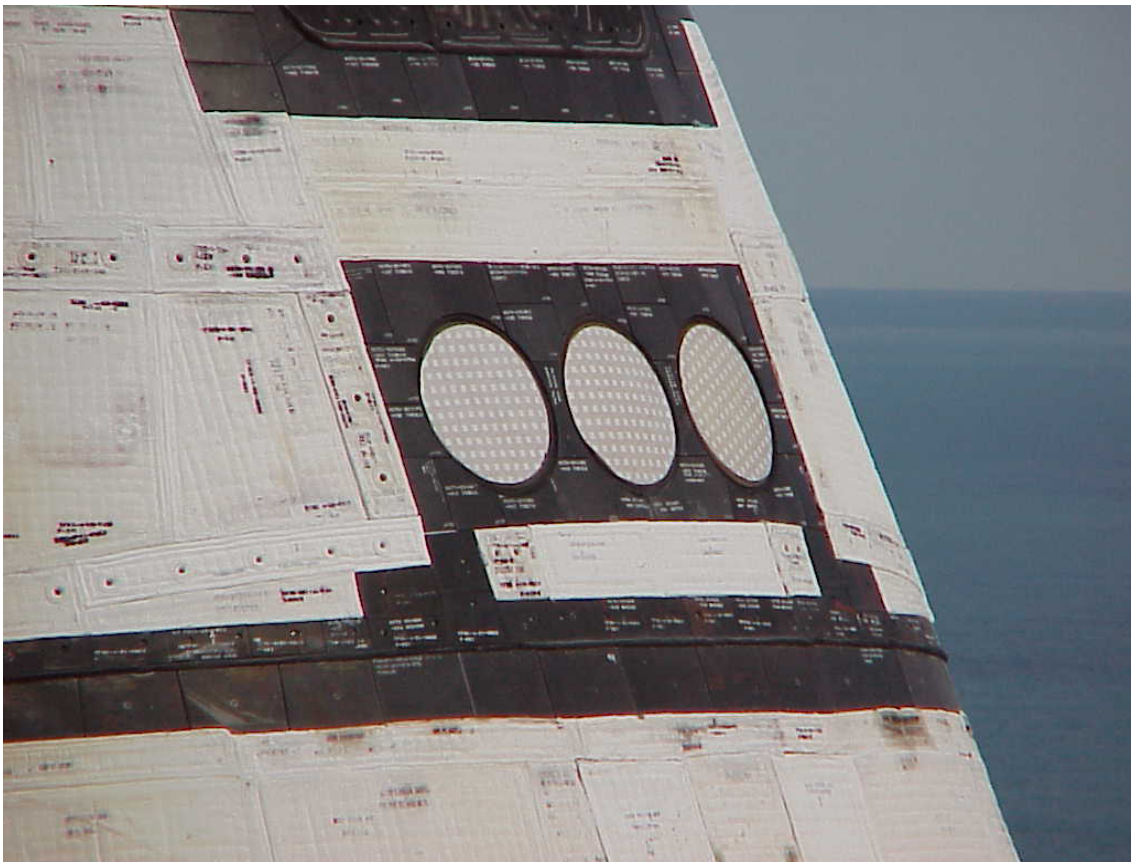
3.3 T-3 HOURS TO LAUNCH

After completion of the Final Inspection on the pad, surveillance continued from the Launch Control Center. Twenty-two remote-controlled television cameras and two infrared radiometers were utilized to perform scans of the vehicle. No ice or frost on the acreage TPS was detected. Protuberance icing previously assessed did not increase. Ambient conditions at the launch pad were 67 degrees F, 72% relative humidity, with winds 6 knots at 71 degrees measured at 1730 hours local time. At T-2:30, the GOX vent seals were deflated and the GOX vent hood lifted. Although frost covered some portions 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-98 was launched at 23:13:02.010 UTC (6:13 p.m. local) on 07 February 2001.

Photo 3: ET LO2 Tank and Intertank

The LOX tank and Intertank acreage foam areas were in excellent condition. No condensate was observed by the Final Inspection Team. Surface temperatures, as measured by Infrared radiometers, averaged 59 degrees Fahrenheit for LOX tank and 65 degrees Fahrenheit for the Intertank.



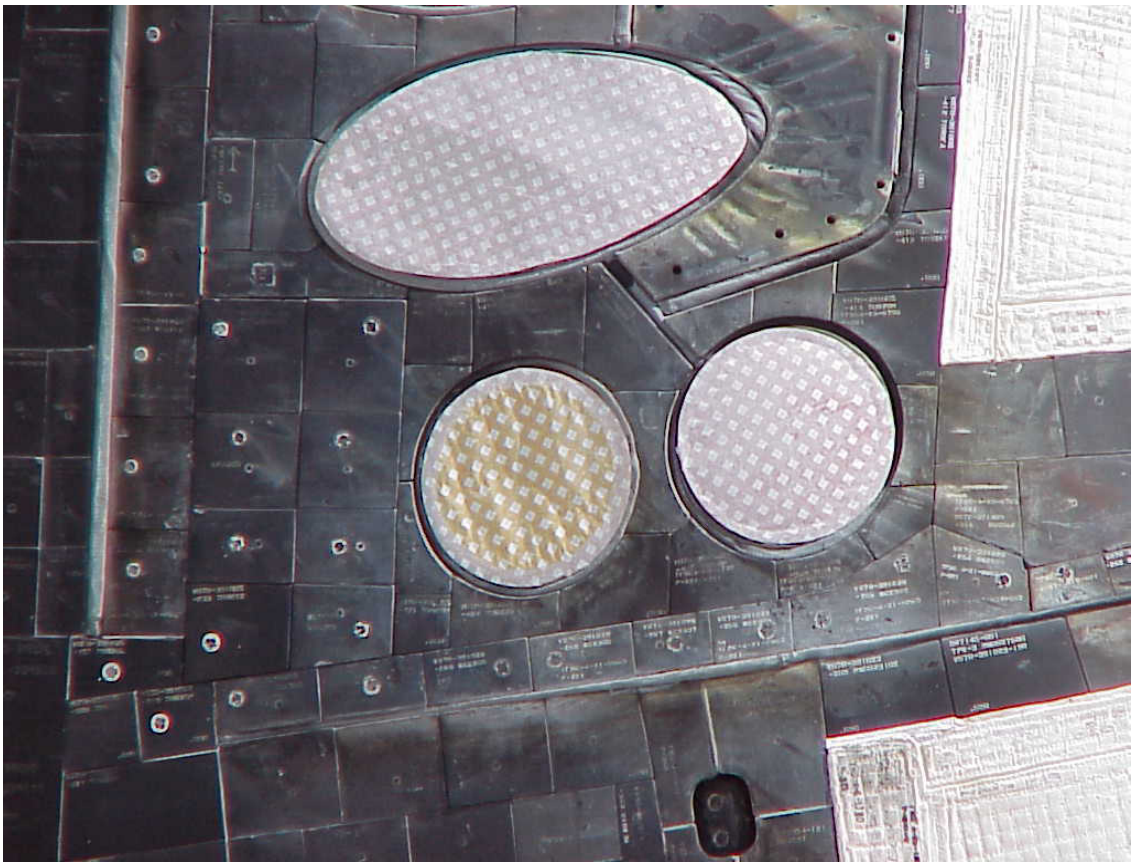


Photo 4 and 5: Orbiter RCS Discolored Thruster Covers
Paper covers for thrusters F2U and F3L were discolored, no liquid was visible behind them.

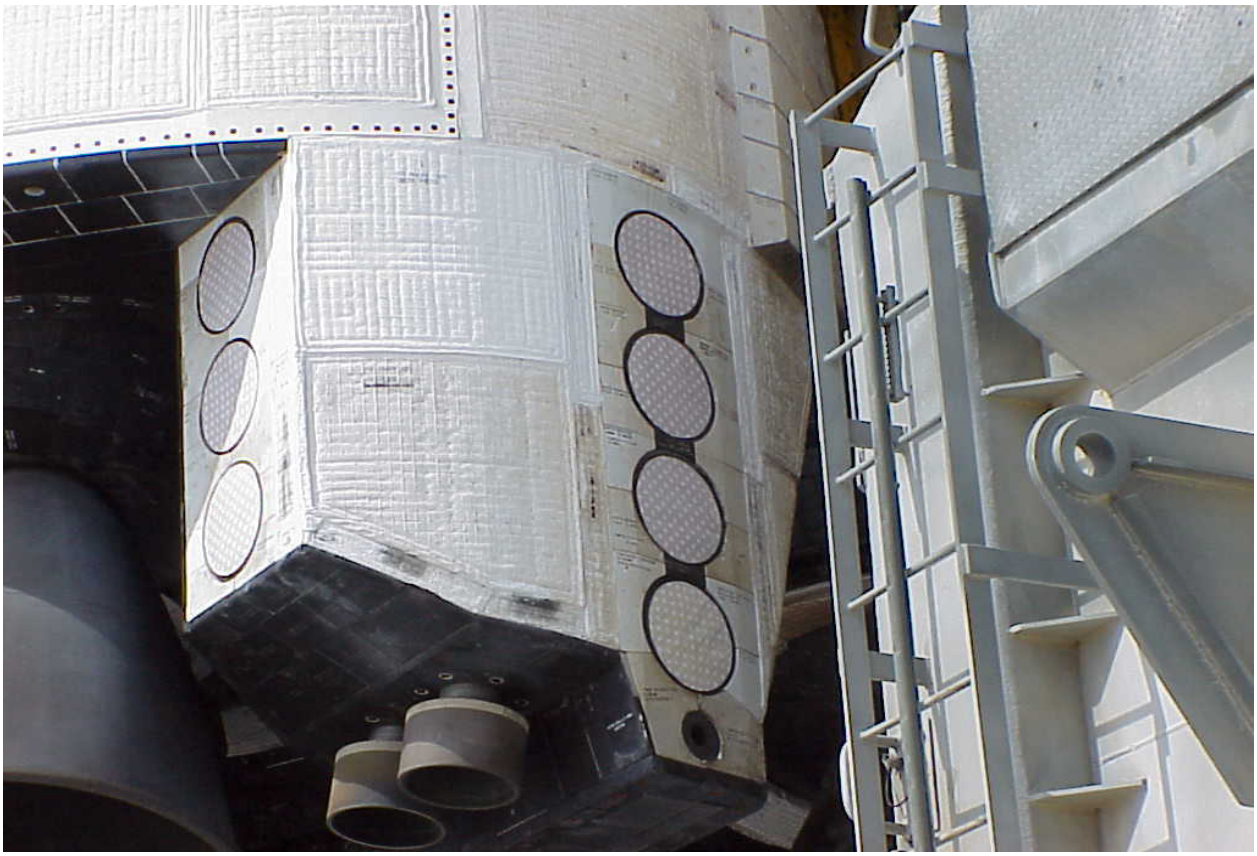


Photo 6: Orbiter RCS Discolored Thruster Cover
Orbiter RCS thruster cover at location R1R is discolored but has no liquid level visible behind it.

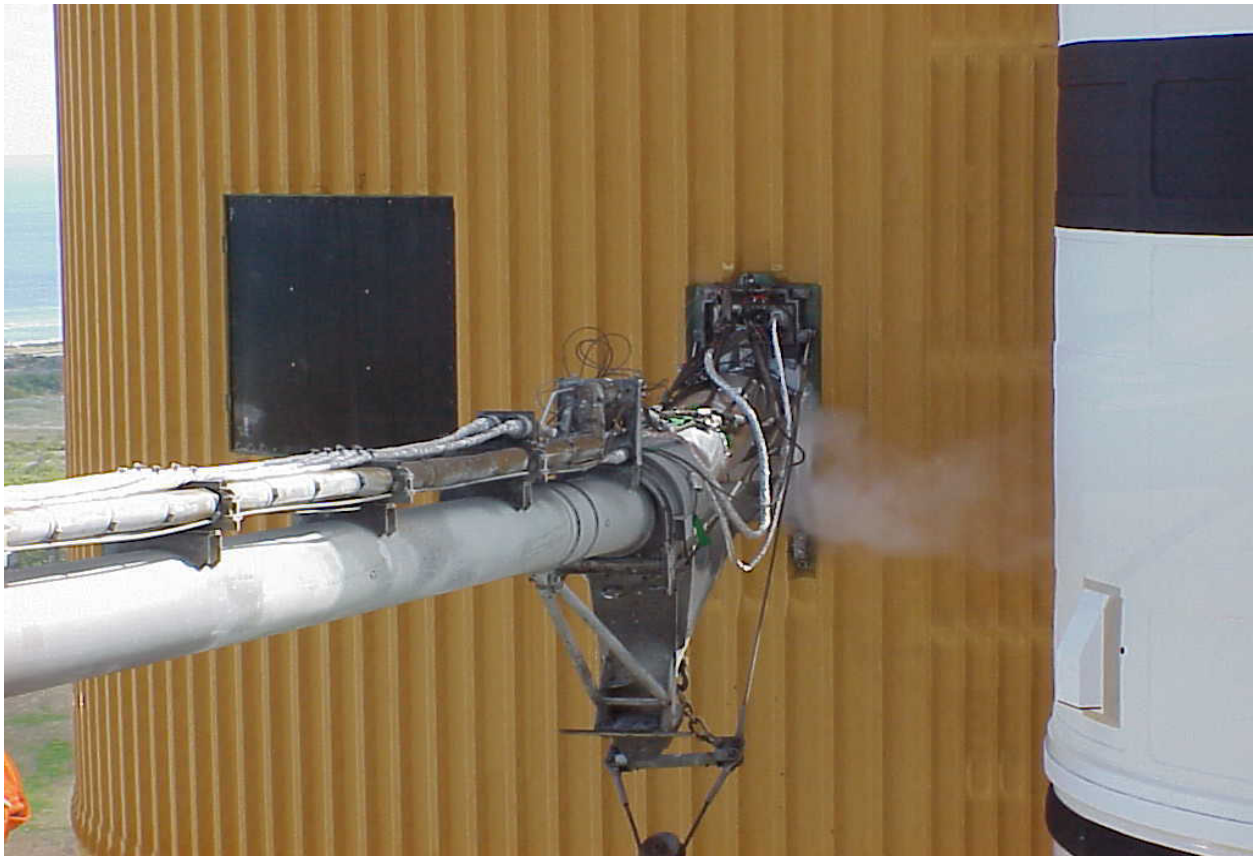


Photo 7: GUCP, Hydrogen Vent Line, and ET Intertank Door
Nominal conditions were visible at the GUCP, Hydrogen vent line, and ET Intertank door when assessed during the Final Inspection Team walkdown. Ice-Frost formation visible at the Ground Umbilical Carrier Plate was noted to be within NSTS 08303 requirements.

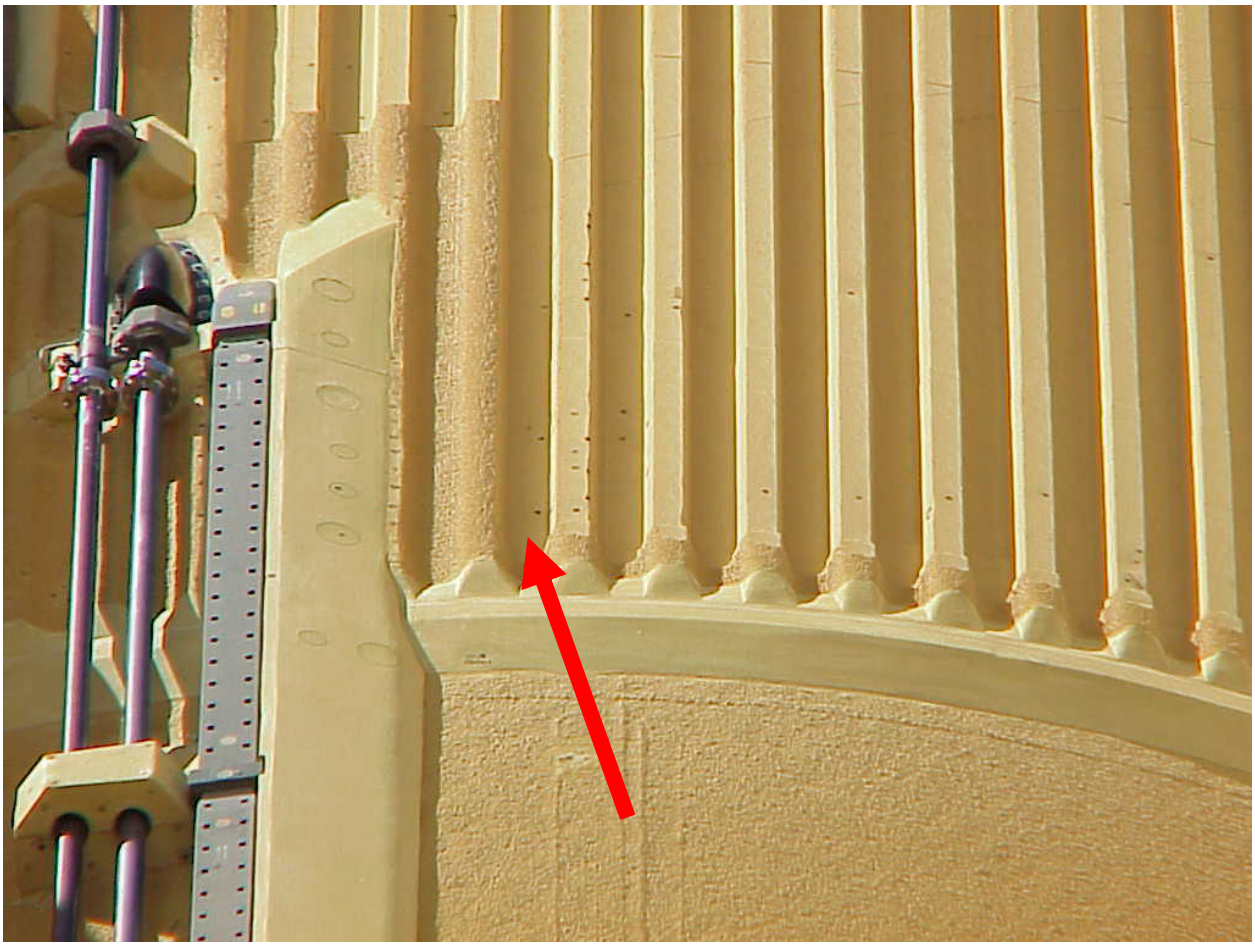


Photo 8: Crack in Intertank Stringer Valley

No significant anomalies were present in the intertank TPS. A hairline crack, 6-inches in length, was noted in the first machined valley +Y of the Protuberance Air Load (PAL) ramp. Cracks in the Intertank TPS had been previously observed and attributed to shrinkage from cryogenic loading and “hoop stresses” in the Intertank structure.

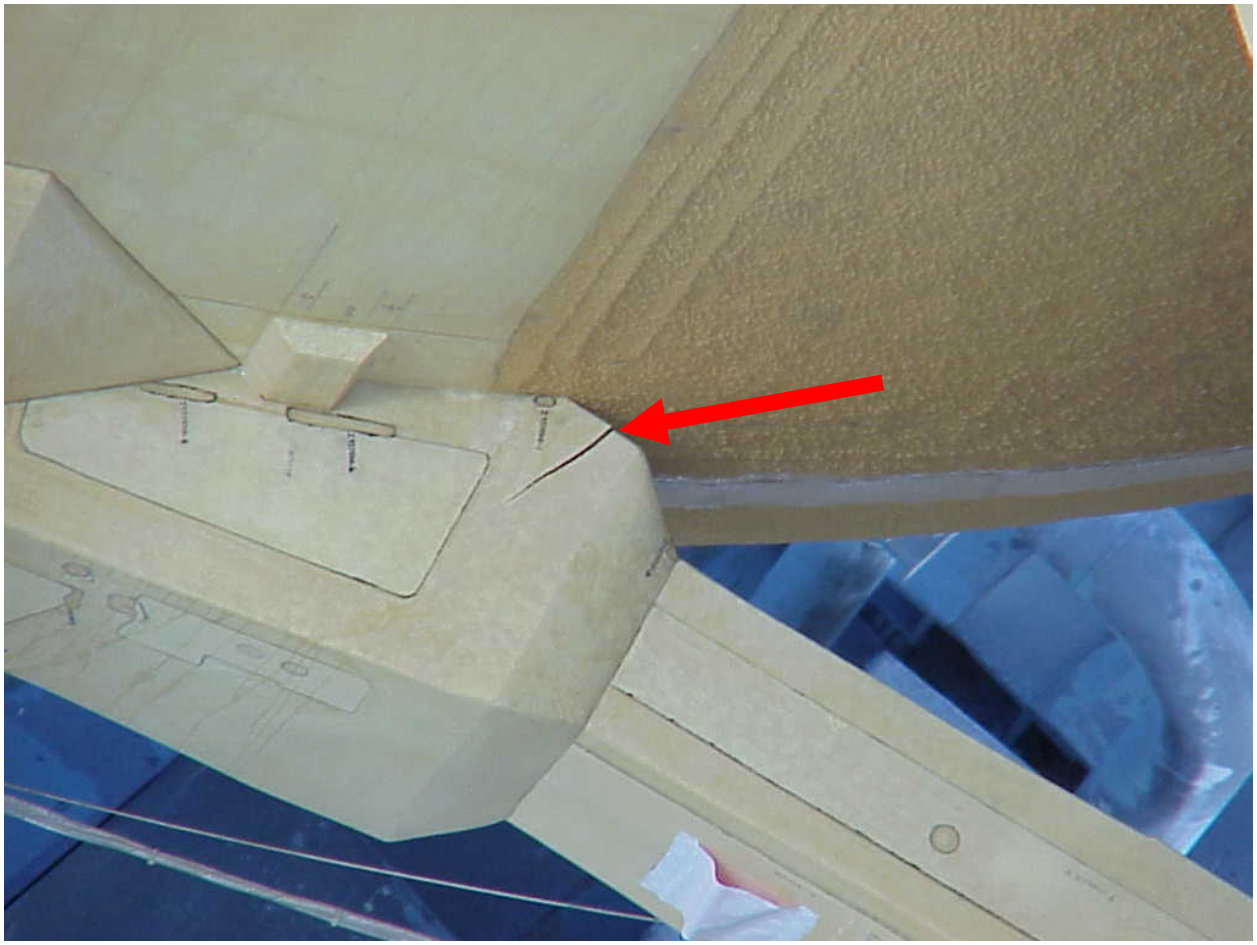


Photo 9: ET -Y Longeron

As typically observed, a crack in the forward surface insulation of the Longeron to ET/SRB cable
tray was present. This crack is due to rotation of the vertical strut as the Hydrogen tank is cryogenically loaded. The crack is approximately 10-inches long and ¼-inch wide, no ice-frost was present. The crack was accepted per the NSTS 08303 criteria. The LH2 tank was observed by the Final Inspection Team and found to be in excellent condition with light to medium condensate visible with measured average temperature of 60 degrees Fahrenheit.

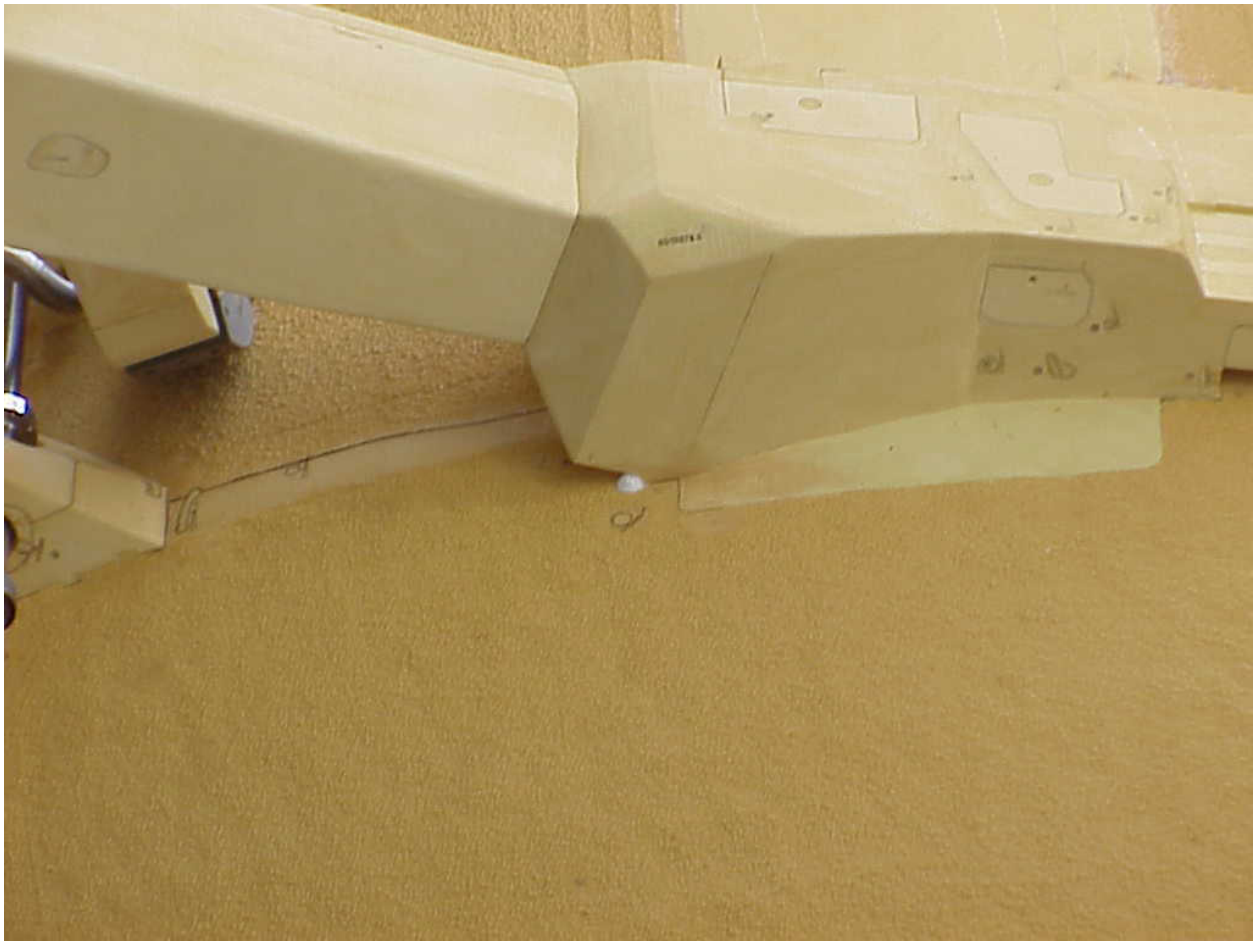


Photo 10: ET +Y Longeron TPS

An ice-frost formation, approximately 2-inches in diameter, located aft of the +Y Longeron was observed by the Final Inspection Team. The ice-frost spot is located adjacent to a foam closeout and is likely caused by a thermal short/crack. This condition is acceptable per NSTS 08303.

Photo 11: LH2 ET-Orbiter Umbilical

Approximate 6-inch long ice-frost 'fingers' were present at the exit points for the pyro-cannister purges and umbilical purge areas with a 1-inch diameter frost spot at the closeout plug for manual actuator access port and is most likely a bond-line thermal short effect. Ice-frost formation was present at the recirculation line bellows and recirculation line to umbilical interface. The purge barrier was wet with condensate and had ice frost formations on the aft, forward, and outboard locations. The LO2 ET-Orbiter umbilical had similar purge exit 'fingers' and condensate/ice-frost on the purge barrier at the inboard and lower locations. There were no acreage LO2 or LH2 umbilical TPS anomalies. All observations were within the NSTS 08303 criteria.

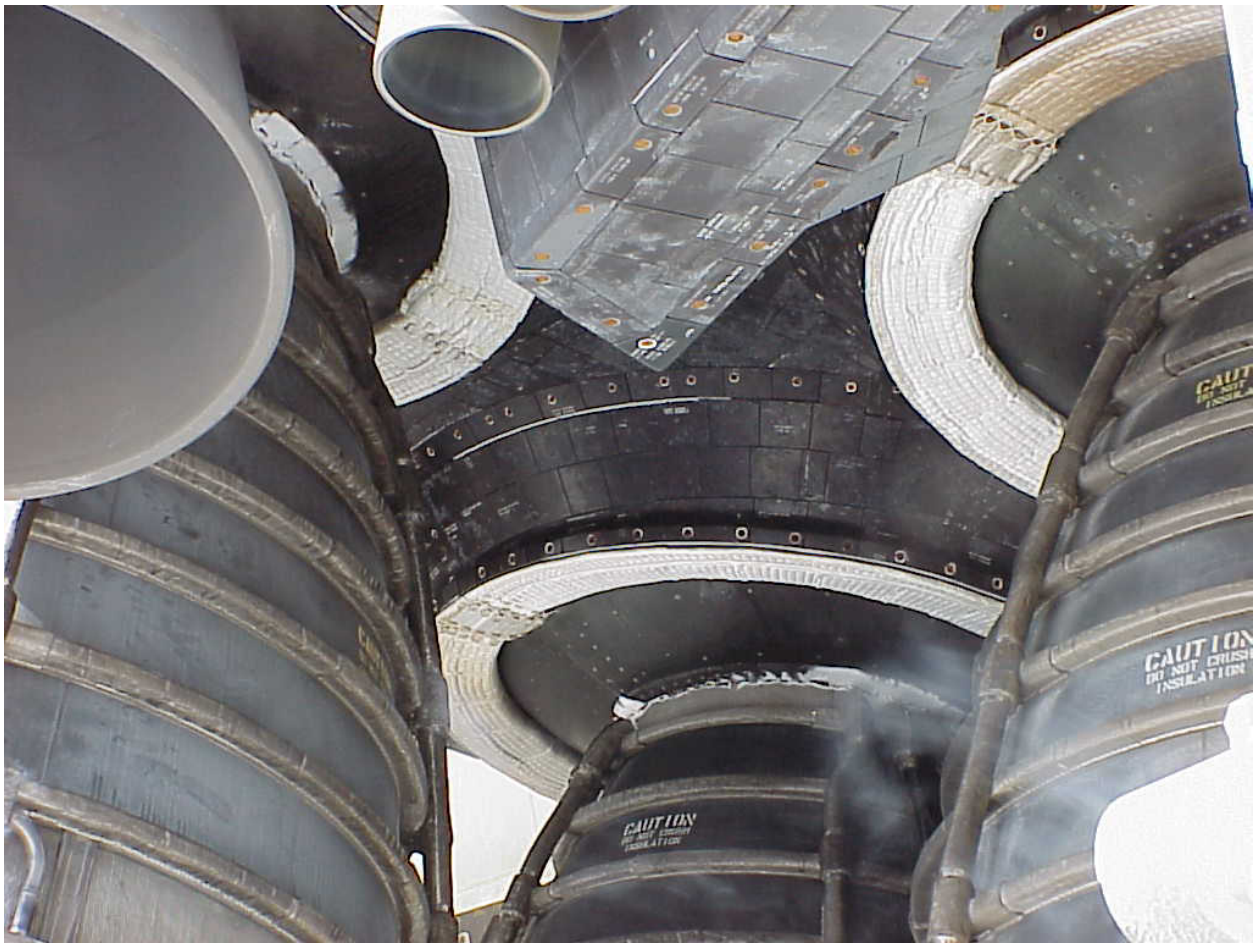


Photo 12: Overall View of SSME Base Heat Shield

The SSME base heat shield is visible and free of defects. Ice-frost formations at the nozzle interface for SSME number 1 and 2 locations were typical.

4.0 POST LAUNCH PAD DEBRIS INSPECTION

The post launch inspection of the MLP-2, Pad A FSS and RSS was conducted on 08 February 2001 from Launch + 12 to 14 hours. No flight hardware was found. The walkdown was delayed due to an IPR condition. The IPR occurred when bus 4A power dropped out just after launch, resulting in the loss of four MLP Hardware Interface Modules.

Orbiter liftoff lateral acceleration data to predict stud hang-ups received from Boeing-Huntington
Beach indicated that a hang-up had not occurred. No signs of stud hang-ups were detected in the visual inspection of the four south posts. Erosion was typical for the north posts. HDP-6 shoe shim material was debonded from the RH side. North holddown post blast covers and T-0 umbilical exhibited typical exhaust plume damage. Both SRB aft skirt GN2 purge lines were intact, protective tape layering was partially eroded.
The LO2 and LH2 Tail Service Masts (TSM) appeared undamaged with the bonnets in a closed position. The MLP deck appeared to be in nominal condition.

The GH2 vent line latched in the number eighth tooth of eight total teeth of the latching mechanism. The GUCP 7 inch QD sealing surface exhibited no damage.
The OAA appeared to be intact with no evidence of plume impingement.
All slidewire emergency egress baskets were secured with no evidence of damage.
The GOX vent arm, hood, ducts and structure appeared to be in nominal condition with no indications of plume damage.

Large pieces of roofing material had come off from the top of the power sub-station building just west of the pad apron. This material impacted a trailer in the boxcar area west of the Pad apron causing major damage to that trailer.

Specific debris findings included:

- South Flame Trench
  - A broken bolt/nut/washer assembly (3" x .75" diameter)
  - A safety shower sign
  - An identification tag (dog tag type)
  - A pipe clamp (2" diameter)
- 115' Level
  - A metal spring 9" x 1" diameter.
- No flight debris was found on the Pad apron.
- No unusual debris items were found on the FSS

Overall, damage to the FSS/RSS and MLP appeared to be minimal. Other than the power sub-station roofing material damage in the boxcar area, nominal debris conditions were noted on the Pad apron.

Photo 13: HDP Erosion and GN2 Purge Line
Erosion affect is clearly visible on the east side of the north HDP; the condition of the SRB aft skirt GN2 purge line is tape-wrap damage; and the south HDP indicates only minimal launch damage. Only nominal post-launch debris conditions exist in the SRB exhaust hole areas of the MLP.

Photo 14 and 15: Trailer Damage, Pad Boxcar Area

Roof material from the top of the power sub-station building located just west of the pad apron came off and impacted this trailer located in the Boxcar area west of the Pad.

5.0 FILM REVIEW

Observations from the Film Review were reported 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. No significant anomalies were observed in the film review. Several pieces of debris were seen to pass (right to left) near the left OMS nozzle, the profile of this is similar to RCS paper cover material. This observation was listed in the STS-98 Consolidated Film/Video Report.

5.1 LAUNCH FILM AND VIDEO SUMMARY

A total of 85 films and videos, which included twenty-eight 16mm films, eighteen 35mm films, and thirty-nine videos, were reviewed starting on launch day.

Tile surface coating material fell during engine startup from: a) orbiter base heat shield inboard of SSME #2 and outboard of SSME #3 (E-76, E-77); and b) body flap upper surface, outboard of SSME #2 (E-77).

Small ice particle from LO2 feedline bellows reported in the first-day video review (OTV-61) observed falling away from orbiter (E-40). Full view of the particle trajectory was obscured by facility backlighting, so orbiter contact was not verified.

Two distinct flashes after SRB separation, as reported in the first-day video review, were not observed during film review (E-207, E-212).

GUCP disconnect from the ET was nominal (E-33, E-34). The small ice formation observed on the –Z side of the GUCP did not induce any TPS loss on the intertank.

Object observed falling from umbilical area towards the SRB (E-36). This object is most likely umbilical purge baggie material.

LH2 and LO2 T-0 disconnections were nominal.

Several flashes were observed in the SSME plume (E-52, E-207, E-222, E-224).

Free-burning GH2 observed rising towards orbiter base (E-52, E-63, E-76, E-77, E-222).

Numerous pieces of SRB throat plug and water trough material ejected from the SRB exhaust hole (E-52, E-63, E-222, E-224).

Particles of SRB aft-skirt instafoam fell along side the SRB plume (E-54, E-63, E-213, E-220, E-222, E-223).

Body flap and elevon movement during ascent were typical (E-31, E-223).

Facility debris observed passing through field of view well after the vehicle had cleared the tower (E-63, E-76, E-77).

Base heat shield movement during SSME ignition was typical (E-76).

Ice particles fell from ET/ORB umbilicals after lift-off.

The forward RCS firing event prior to and during SRB separation was not clearly visible. OMS-assist engine firing was visible (E-212).

Prior to SRB separation, several pieces of debris were observed to pass (right-to-left) behind the left OMS nozzle. They were further observed to separate into multiple pieces outboard of the aft edge of the OMS. There is no appearance of rigidity in these debris pieces. RCS paper cover material has provided a similar debris profile. (E-207)

Throat plug material expelled from the RH-SRB exhaust hole and contacted orbiter lower surface tile just aft (approx. 8 feet) of LOX ET/ORB umbilical (E-5).

Free-burning GH2 was observed rising towards orbiter base during SSME startup.

Several ice particles fell from ET/ORB umbilical during SSME ignition, none of the particles contacted the vehicle.

Slag particles fell out of the SRB plume during tail-off.

SRB HPU exhaust was visible at T-0 and during liftoff (E-15, E-16).

Vapors on ET aft dome and SRB stiffener rings were observed after T-0.

Ice particles fell from LH2 / LO2 TSM T-0 disconnects.

No ordnance fragments fell from the DCS/stud hole in HDP #7 (E-11).

RCS paper covers from forward RCS observed moving downstream over the right wing (E-57).

5.2 FORWARD RCS FIRING AT SRB SEPARATION

The STS-98 mission is the first firing of the Forward Reaction Control System forward firing jets at SRB separation to preclude the effects of Booster Separation Motor impingement affects on the forward Orbiter windows. Film review analysis of this event was inconclusive, only a plume effect was visible when compared to previous missions' SRB separation events. The OMS-assist burn to orbit was clearly visible for the STS-98 mission (item E-212).

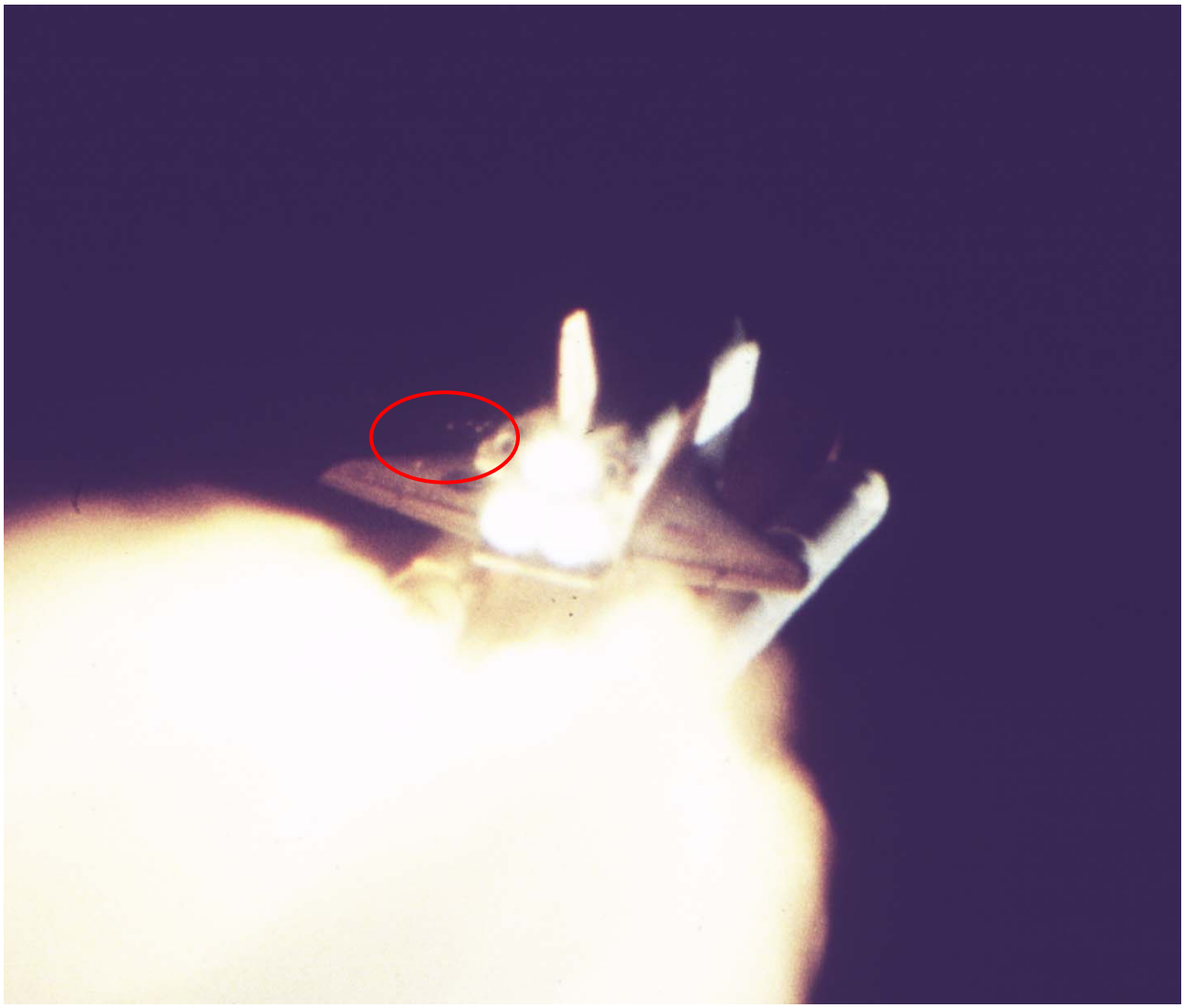


Photo 16: Debris Passing by LH OMS Pod

Approximately 4.6 seconds prior to SRB separation, E-207 shows debris particles passing over the LH wing near the OMS pod. The debris has the profile of RCS paper cover material. No flight hardware damage is visible in these views.

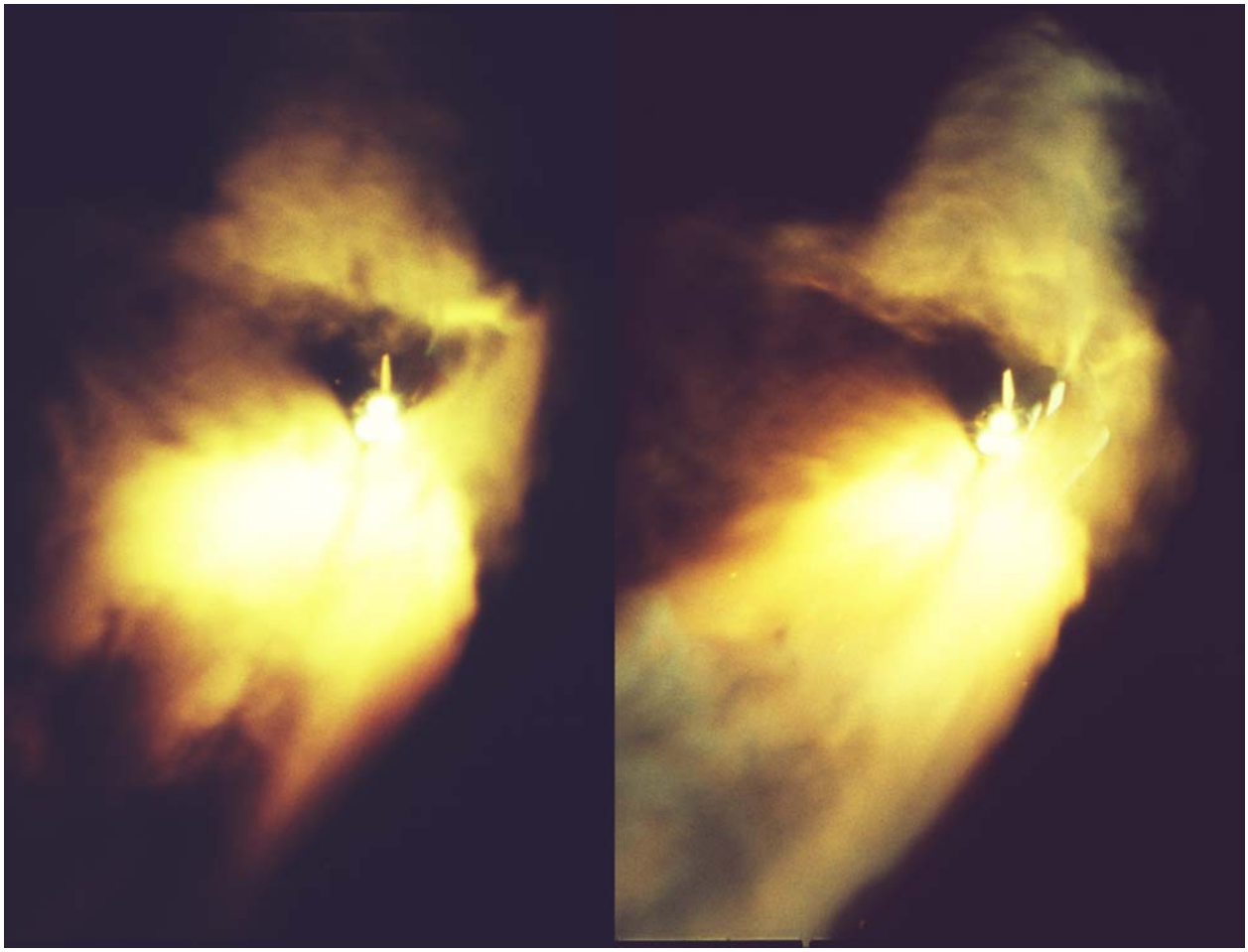


Photo 17: Forward Thruster Firing

These views from E-207 show SRB separation for STS-97 (left) and STS-98 (right) looking for the difference due to FRCS firing. The tracking film does not conclusively show the firing, as can normally be seen for an OMS-assist, only plume effect might be noted.

5.3 ON-ORBIT FILM AND VIDEO SUMMARY

No planned On-Orbit imagery for the STS-98 mission was available due to launch time, the Hardware areas of interest would be in darkness without sunlight. A mission day one video downlink was performed for the tail damage site on the forward face of the vertical stabilizer. This image was made available when the damage site was discovered during mission operations, at the direction of the Mission Management Team a thermal evaluation was performed for this area.

5.3.1 16mm Film Footage

STS-98 had the 16 mm umbilical well cameras disabled preflight due to an electrical short investigation, no imagery available.

5.3.2 35mm Film Footage

No imagery available due to lighting conditions.

5.3.3 Crew Hand-Held Still Images

No video available because of nighttime conditions.

5.4 LANDING FILM AND VIDEO SUMMARY

Three 35mm, four 16mm, and black & white video data from STS-98 landing were reviewed. The landing events of final approach to touchdown, drag chute deploy and landing through rollout and wheel stop were visible. A slight bounce was seen at MLG touchdown. The drag chute deploy was viewed as nominal. The data provided good visibility to all of the events. No anomalies were noted in the landing film and video data.

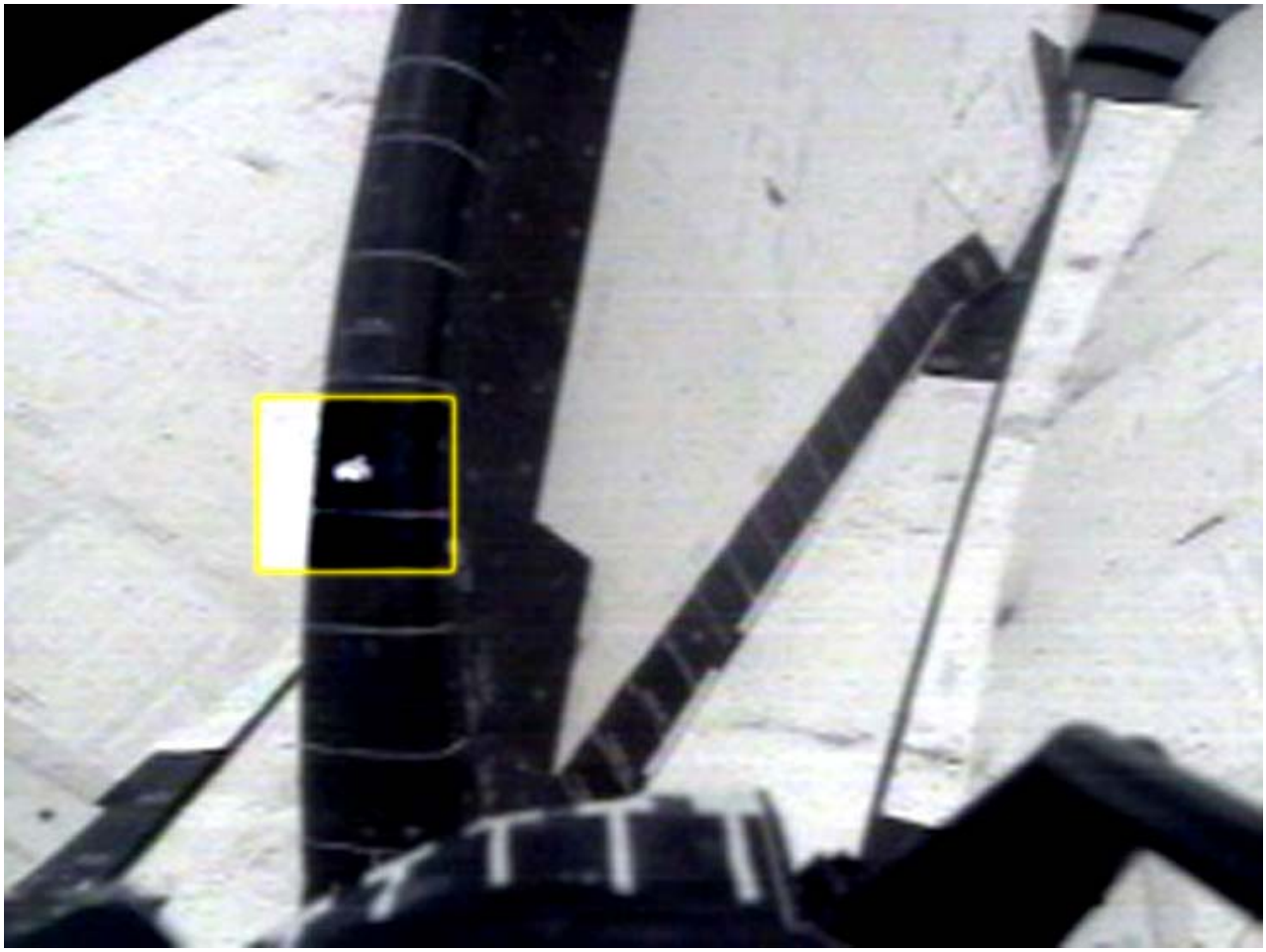


Photo 18: Damage Tile at Vertical Stabilizer

Impact damage to a tile on the leading edge of the vertical tail was seen in on-orbit video. Video analysis was used to estimate the damage size as 2-inches in diameter. The depth of the damage could not be ascertained but was viewed as surface only and thermal analysis indicated sufficient material thickness remained to protect for a nominal reentry.

6.0 SRB POST FLIGHT/RETRIEVAL DEBRIS ASSESSMENT

The BI-105 Solid Rocket Boosters were inspected for debris damage and debris sources at CCAFS Hangar AF on 12 February 2001. Generally, both boosters were in excellent condition.

OBSERVATIONS

The Debris Containment System (DCS) Plunger was not fully seated on HDP No. 7. The plunger had been prevented from seating properly by pieces of frangible nut.

The TPS on both frustums exhibited no debonds/unbonds. There was minor localized blistering of the Hypalon paint.

All eight BSM aero heat shield covers appeared to have fully opened as seen by the visible marks
on Frustum TPS and nozzle, but two of the LH cover attach rings had been bent at the hinge by parachute riser entanglement and had not remained in the fully-open locked position.

The forward skirts exhibited no debonds or missing TPS. The RSS antennas were intact.

The Field Joint Protection System (FJPS) and the System Tunnel Cover closeouts were generally in good condition with no unbonds observed.

Separation of the aft ET/SRB struts appeared normal
.
Aft skirt external surface TPS was in good condition. Typical blistering of Hypalon paint had occurred on the BTA insulation close-outs and GEI cork runs.

The holddown post DCS appeared to have functioned normally except on HDP No. 7 which had some ordnance/nut fragments lodged in the plunger/bore. No indication of stud hang up was observed.

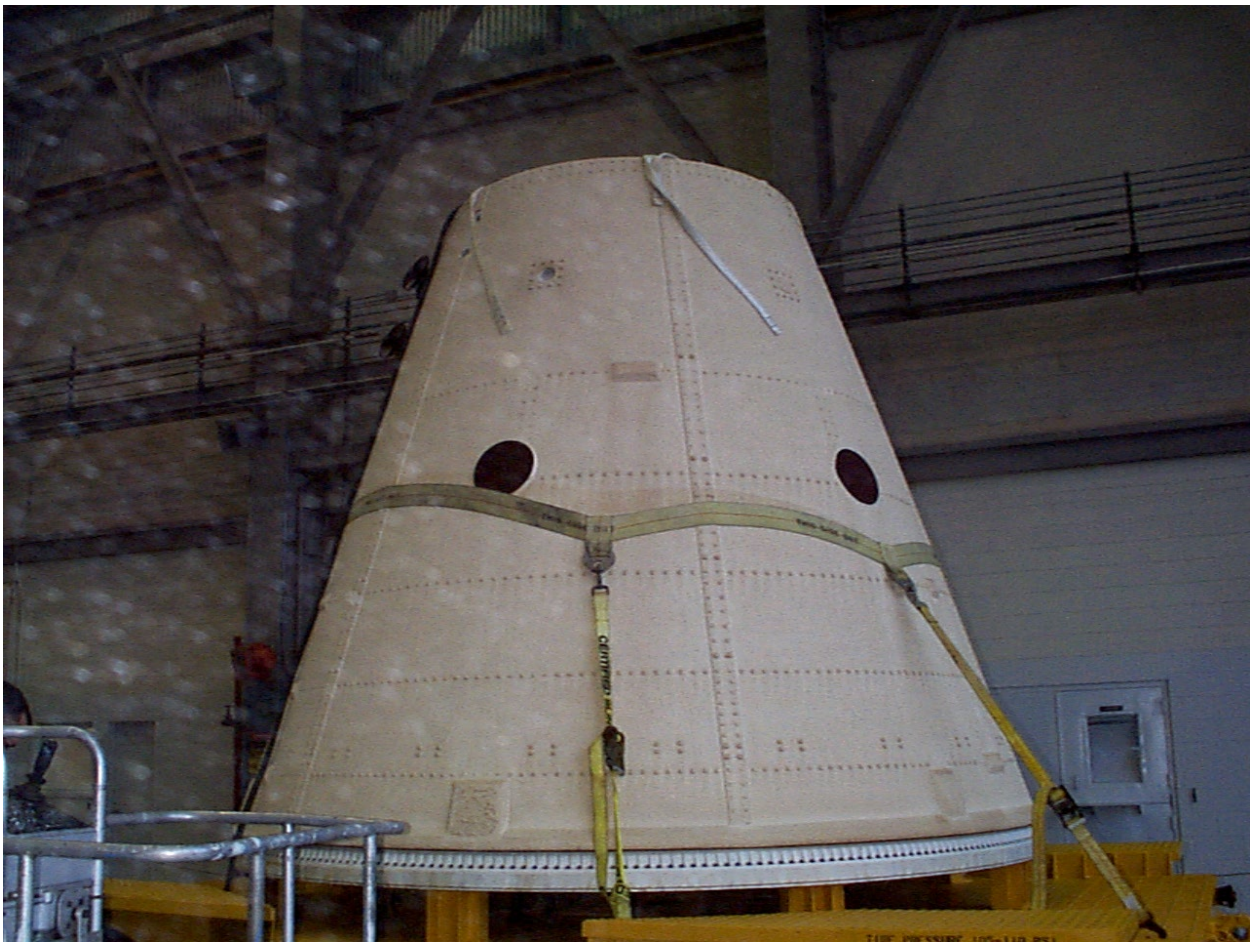


Photo 19: Frustum Post Flight Condition

The frustums exhibited no debonds/unbonds or missing TPS.
All four BSM aero heat shield covers on the Right Hand, and two on the Left Hand had locked in the fully opened position. The LH BSM right side aero heat shields had not remained fully open, all covers had left linear stop marks on the nozzles.

Photo 20: Forward Skirt Post Flight Condition

The forward skirts exhibited no debonds and only minor handling TPS damage sites. RSS antennae covers/phenolic base plates had minor erosion of SLA-220 and the left hand +Z phenolic base plate had minor delamination.

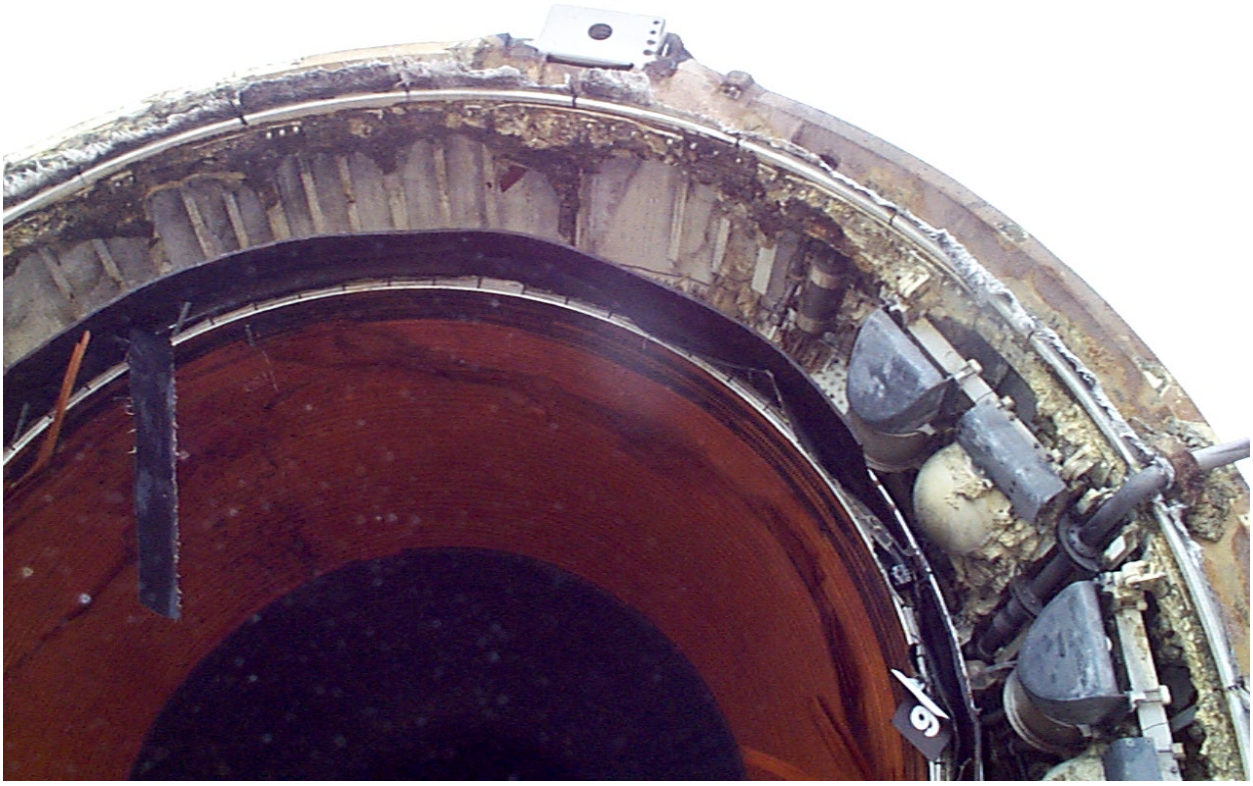


Photo 21: Aft Skirt Post Flight Condition

Aft skirt external surface TPS was in nominally good condition, two areas of missing MSA2 on the attach ring had some sooting evident.

7.0 ORBITER POST LANDING DEBRIS ASSESSMENT

After the 12:33 pm local time landing on 20 February, 2001, a preliminary post landing inspection of OV-104 Atlantis was conducted at the Edwards Air Force Base Runway 22. The final inspection was performed at the Mate Demate Device (MDD) on February 21, 2001.

The Orbiter TPS sustained a total of 102 hits of which 13 had a major dimension of one 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.

The following table lists the STS-98 Orbiter damage hits by area:

	HITS > 1-inch	TOTAL HITS
Lower Surface	8	73
Upper Surface	1	5
Window Area	3	18
Right Side	1	1
Left Side	0	3
Right OMS Pod	0	2
Left OMS Pod	0	0
TOTALS	13	102

The Orbiter lower surface sustained 73 total hits, of which 8 had a major dimension of one inch or larger. Approximately 24 damage sites (with three larger than one inch in a major dimension) were located in the area from the nose gear to the main landing gear wheel wells. The amount and size of damage in this region was less than average. ET intertank TPS venting modifications appear to continue to have a reducing effect on both the quantity and size of the damage sites.

Numerous damage sites around the LH2 ET/ORB umbilical were most likely caused by pieces of the umbilical purge barrier flapping in the airstream and contacting tiles before pulling loose and falling aft.

The largest lower surface tile damage site, located just aft and outboard of the nose landing gear door, measured 2.5 inches long by 2 inches wide by 0.25 inch deep. Slight erosion was observed at this and an adjacent damage site. Imbedded in a third damage site in this area was a fibrous material. This site was sampled and sent for laboratory material analysis and identification.

The second largest hit was located on the lower surface of the left-hand inboard elevon, and measured 2 inches long by 1.5 inches wide by 0.5 inch deep. This damage site showed indications of thermal erosion.

Only two minor hits were observed on the left OMS pod. However, two adjoining edges of an AFRSI blanket near the leading edge of the left OMS pod were observed to be loose and frayed. There were no missing tiles or blankets from the OMS pods that would coincide with the debris observed near the OMS pod prior to SRB separation in film E-207.

There were no tiles or blankets missing from the vertical tail. The vertical tail leading edge damage site observed during on-orbit operations had not changed significantly (2 inches by 3 inches by 0.25 inch). This damage site appeared to have an impact residue embedded in it, the site was sampled and sent for analysis and identification.

This is the first flight using the forward up-firing RCS jet plumes to help prevent BSM particulate impingement on the windows during SRB separation. Window hazing appeared to be less than normal. Streaks were observed on forward facing windows 3 and 4. The streaks are believed to be RTV adhesive used to bond the paper covers to the Orbiter RCS nozzle exits. It was also noted that an AFRSI blanket was slightly protruding from the area immediately aft of the up-firing jets in the forward RCS group.

A total of 18 impact damage sites on the window perimeter tiles were observed with three having a major dimension of one inch or greater. These damage sites are a result of impact by RCS paper covers with RTV adhesive on the back.

The landing gear tires were reported to be in good condition. There was no ply under cutting on the main landing gear tires.

No debris was found beneath the umbilicals after the umbilical doors were opened.

Tile damage on the base heat shield was typical. The SSME Dome Heat Shield closeout blankets were in excellent condition, except for the SSME number one closeout blanket which was torn at the seven-o'clock position.

A post landing walk-down of the runway was performed. No flight hardware was found. All components of the drag chute were recovered and appeared to have functioned normally. Both reefing and line cutter pyrotechnic devices were expended.

In summary, both the total number of Orbiter TPS debris hits (102) and the number of hits one-inch or larger (13) were within the established family totals(family average 103 total hits and 16 one-inch or greater. The total number of Orbiter TPS debris hits, and the number of hits 1-inch or larger, were "in family" when compared to the statistics generated from previous Shuttle missions. These comparisons are shown in table and graphic form in figures 5, 6 and 7.

8.0 POST LANDING LABORATORY SAMPLES

Laboratory samples were obtained from the Orbiter vehicle during post landing turnaround operations. These samples consisted of wipe samples from Orbiter windows 1 through 8, damage site sample from tile V070-293021-088 OCN 008119 (located at the base of the vertical tail) and an Ames gap filler segment removed from tile V070-391035-050 OCN 008034 (located on the lower surface aft of NLGD). These samples were analyzed by the KSC Materials Science Laboratory for material identification and comparison to know material sources. Results of this analysis provided indications of landing site materials, paint, metal and metal corrosion products, and Orbiter Thermal Protection System (TPS) materials. No unusual findings resulted from this analysis and no adverse debris material trends were noted. The laboratory report for this analysis is included in this debris report as figure 1. The conclusion section 4.2 has results for samples 1 and 2 transposed, the gap filler material (glass fiber mat) was sample 2. The sample 1, forward surface damage site of vertical stabilizer, contained tile and tile materials. The sample 2, lower surface damage site aft of NLGD, contained tile gap filler, tile, and tile materials. These results indicate the cause of the damage was tile material (sample 1) or tile gap filler / tile materials (sample 2) or the damaging debris was not retained in the damage site.

NASA
Director of Spaceport Engineering and Technology
Materials Science Laboratory
Kennedy Space Center, Florida 32899

March 6, 2001

KSC-MSL-0109-2001

SUBJECT: STS-98 Post- landing Orbitor Window Wipes, DFRF

CUSTOMER: Robert Speece/NASA/PH-H/861-3637

1.0 REQUEST:

Wipe samples were taken from STS-98 windows 1-8 after landing at Dryden Flight Research Center. The samples consisted of one isopropyl alcohol (IPA) and one dry wipe for each window. The window debris wipes were submitted for analysis and compared to known STS materials. Two additional samples were submitted with the window sample and they were identified as follow:
#1. Sample removed from damage to the VO70-293021-088, OCN 008119, OV104, FLT 23, DFRF, 2/23/01
#2. Ames G/F segment. Removed from VO70-391035-050, OCN: 008034, FLT 23, OV-104, DFRF, 2/23/01

2.0 PROCEDURE:

Particulate was collected from the IPA cloth wipes and put in individual petri dishes. All of the samples were analyzed by optical microscopy (OM). Two typical particulate samples were analyzed by scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS). EDS is used to provide a qualitative and semi-quantitative analysis for all elements in the periodic table above beryllium (4).

3.0 RESULTS:

3.1 The particulate collected on the IPA wipes and the dry wipes were similar in composition and were classified into components on the basis of color and texture by OM. The following table lists estimated volume percentages of each component versus sample number.

Figure 1: Microchemical Analysis Report for STS-98

Component ID	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8
Black	3	4	3	2	T	5	2	3
White	4	5	2	3	T	10	3	3
Clear	5	4	2	4	T	2	1	1
Red	T	T	15	10	2	1	1	1
Metallic	T	T	T	T	T	T	X	T
Gray	X	X	4	8	T	30	T	10
Glass fibr	X	T	X	T	X	X	X	X
Amber flk	T	T	T	3	T	T	T	T
Organic	88	87	74	70	18	52	93	83

T: Trace amount (<1%) X: Not detected

3.2 The samples from windows 3 and 6 were typical, and were considered to be representative of all eight of the window samples. The SEM/EDS analysis results for the samples from windows 3 and 6 are listed in Table 1.

Table 1

Sample Component	Major Elements	Moderate/Minor/Trace Elements	Max Size (um)
Black	Fe,Si,Ca,C	Al,O,Mg,K,Ti	1-180
White	Ca,K,P	C,O,Mg,Cl,Si	1-250
Clear	Si	O,Mg,Al,K,Fe	1-185
Red	Ti,Si	O,Al,S,Cd,Ce	1-280
Metallic	Cu,Zn,Fe,Cr	Ni,Ti	1-150
Gray	Ca,P,Al,Si,K	C,O,Na,Mg,S,Fe	1-250
Glass fibers	Si,Al	O	10
Amber flake	Si,K,Fe	O,Mg,Al,Ca,Ti,Mn	1-150
Organic	ND		

(μm): Micrometers, ND: Not Determined

Figure 1: Microchemical Analysis Report for STS-98

4.0 CONCLUSION:

4.1 The window samples(1 through 8) contained black, white, clear, red, metallic, gray, glass fibers, amber flake, and organic materials.
The results for the particulate analyzed by SEM/EDS are summarized below:

- The black particles were composed of silicon-oxygen rich material (possibly black tile materials) and steel corrosion products.
- The white particles consisted of calcium oxygen rich materials (possibly $CaCO_3$, calcite), calcium-phosporous-carbon rich materials, and silicon rich materials(silica tile).
- The clear materials showed high silicon and minor oxygen which could be silicon dioxide (alpha-quartz, alpha-SiO_2).
- The red particles were steel corrosion products and paint.
- The metallic materials consisted of a 300 series stainless steel and brass.
- The gray particles were composed of silicon-aluminum-oxygen rich materials (possibly insulation filler materials) and calcium phosphorus rich materials.
- The glass fibers were composed of silicon-aluminum rich high temperature insulation type.
- The amber flake was composed of muscovite, $KAl_2 (ALSi_3O_{10}) (OH)_2$.

4.2 The sample number #1 contained glass fiber mat with white to gray colored materials, dark hard tile, and fibrous glass. The sample number #2 contained dark hard tile, fibrous glass, and off-white materials.

- The glass fiber mat were composed of silicon-aluminum rich glass fibers, and the white to gray colored materials appeared to be composed of silicon rich amorphous materials with trace amounts of oxygen.
- The dark hard tile, fibrous glass, off-white materials were composed of silicon rich amorphous materials with small amount of oxygen.

4.3 The particle sizes were in the range of 1 to 280 micrometer.

Equipment: JEOL JSM-6400 Scanning Electron Microscope, MSL cal. 0082
Kevex Sigma 2 Energy Dispersive Spectrometer, MSL cal. 0083

Calibration methodology may vary depending on the type of analysis and equipment. Customers with special accuracy or calibration requirements should contact the Primary Investigator.

Primary Investigator: Hae Soo Kim
Hae Soo Kim, (321) 867-3910

Figure 1: Microchemical Analysis Report for STS-98

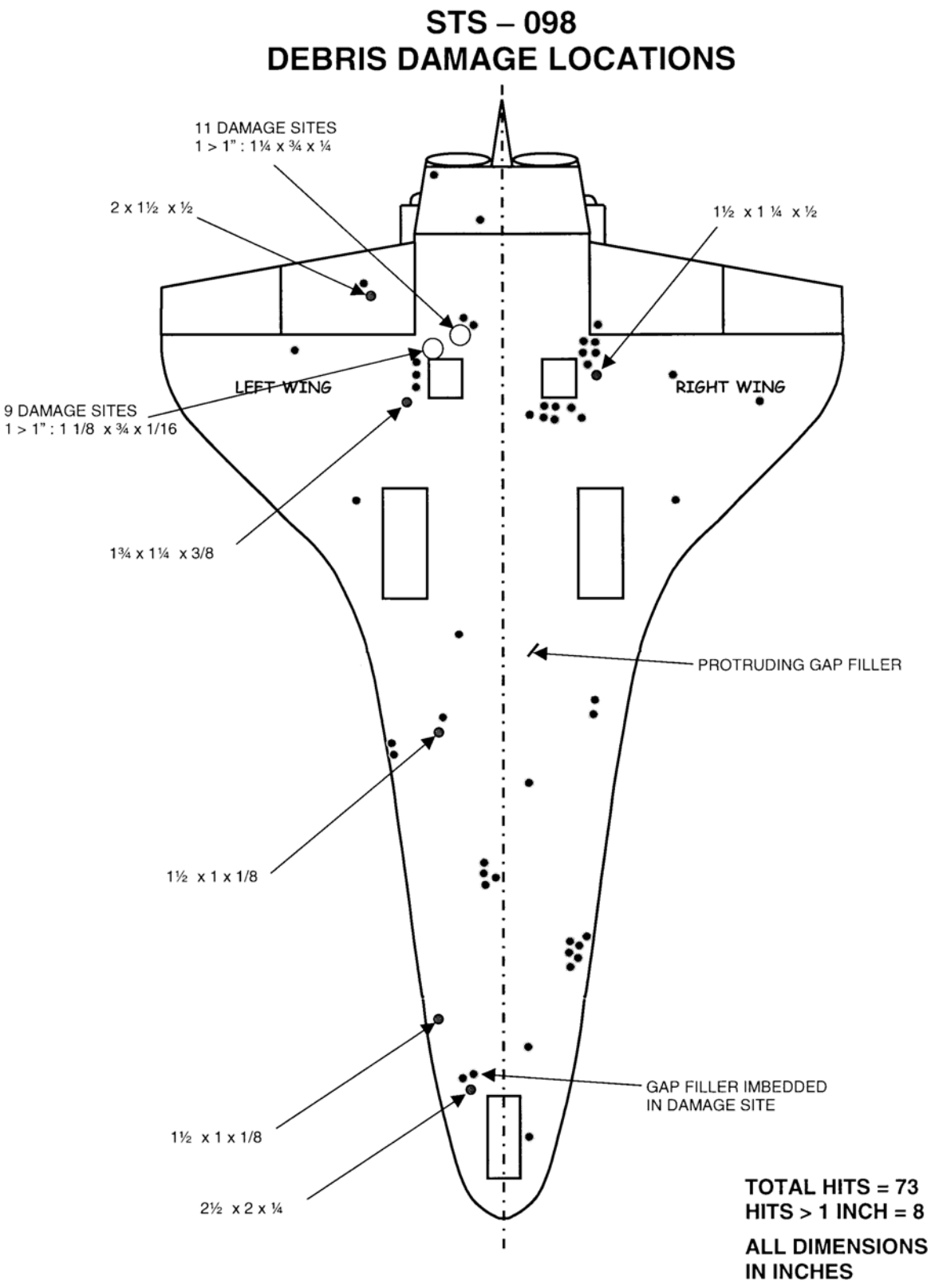


Figure 2: Orbiter Lower Surface Debris Damage Map

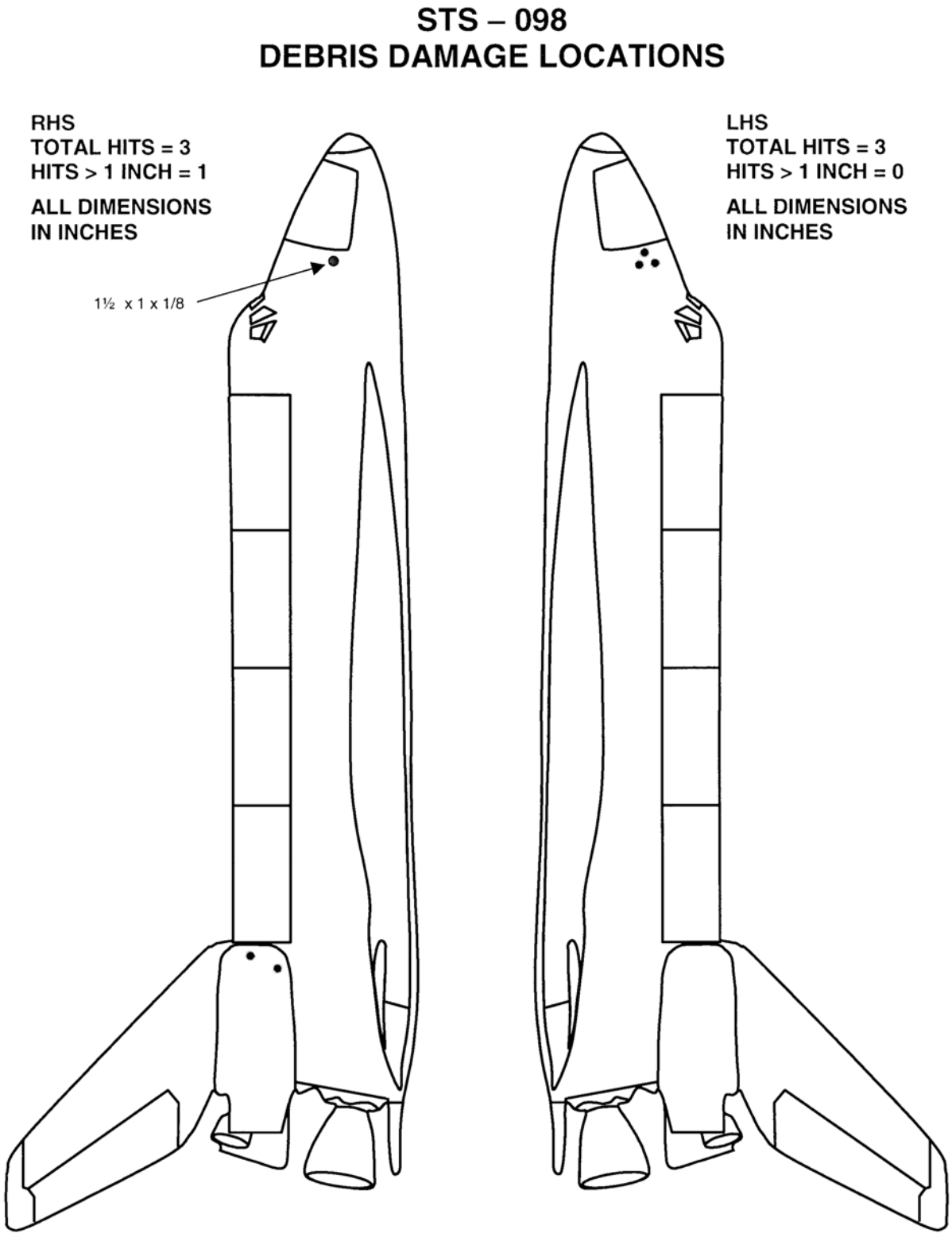


Figure 3: Orbiter Right and Left Side Debris Damage Map

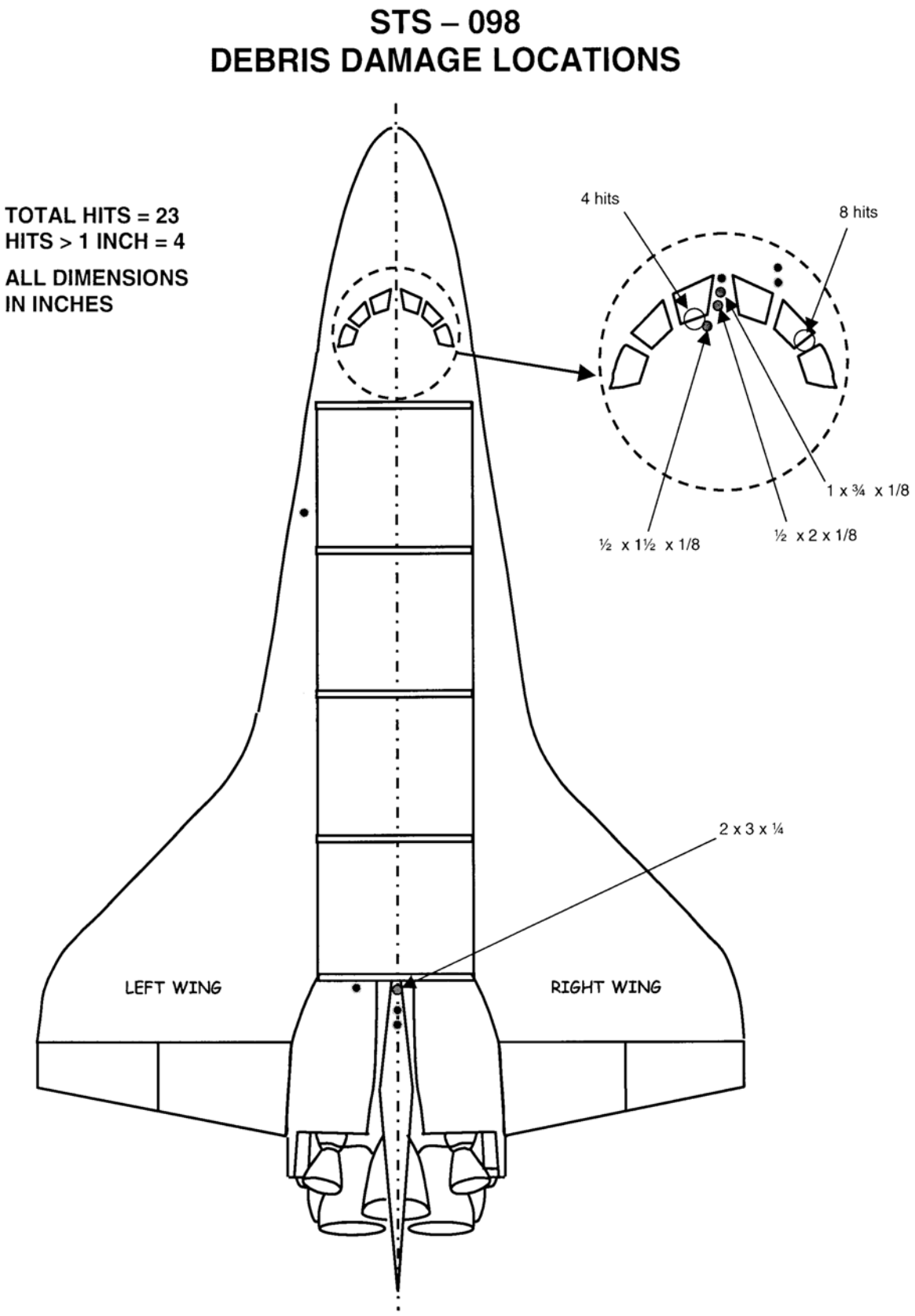
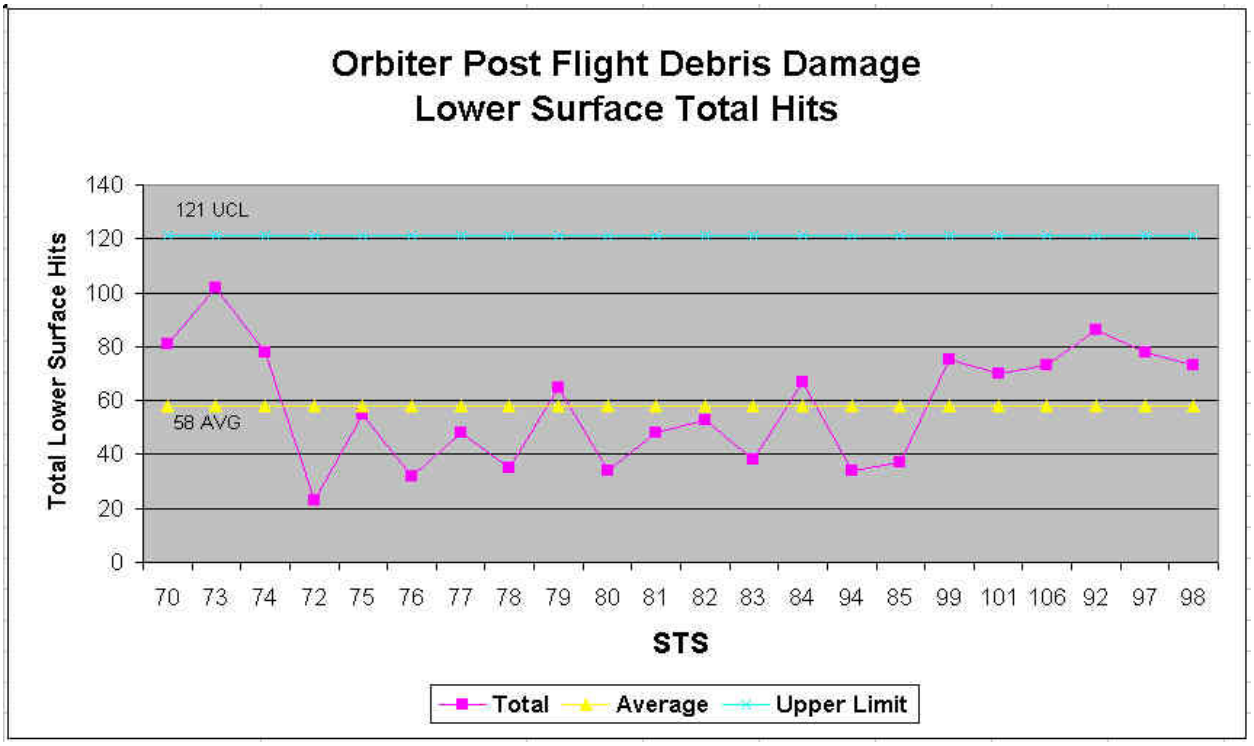


Figure 4: Orbiter Upper Surface Debris Damage Map

STS NUMBER	LOWER SURFACE		ENTIRE SURFACE	
	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS
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
STS-99	21	75	25	88
STS-101	19	70	27	113
STS-106	17	73	17	105
STS-92	14	86	24	127
STS-97	10	78	10	84
AVERAGE	11.6	63.0	16.2	103.0
SIGMA	5.8	32.8	6.4	29.3
STS-98	8	73	13	102

MISSIONS STS-86,87,89,90,91,95,88,96,93,103 ARE NOT INCLUDED SINCE THESE MISSIONS HAD SIGNIFICANT DAMAGE CAUSED BY KNOWN DEBRIS
SOURCES

Figure 5: Orbiter Post Flight Debris Damage Summary



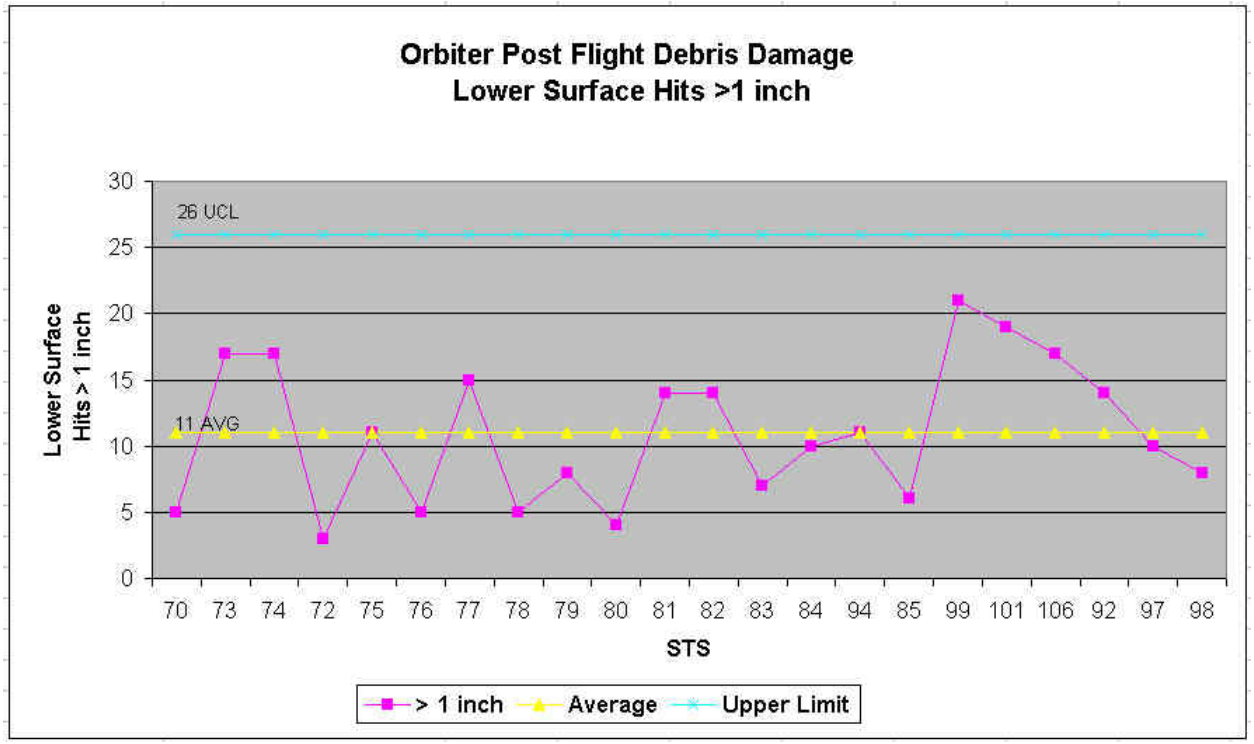
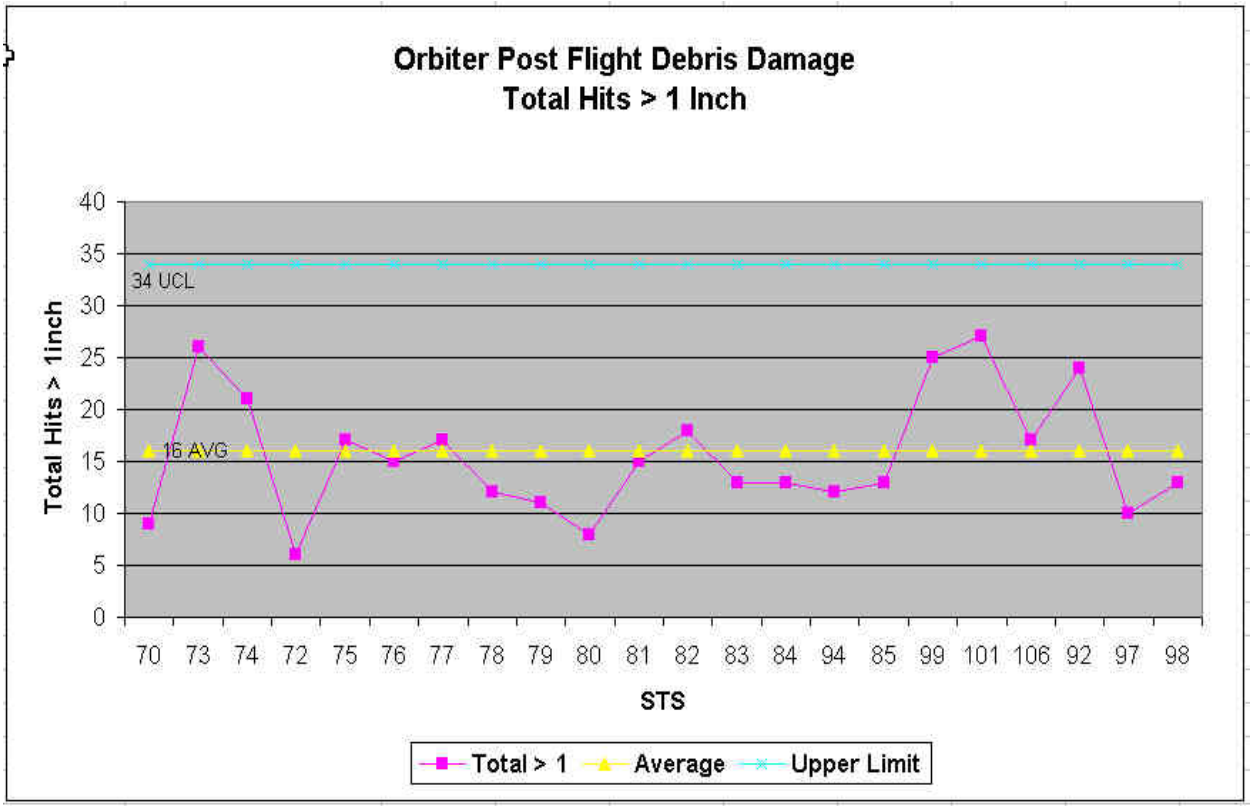


Figure 6: Control Limits for Lower Surface Hits



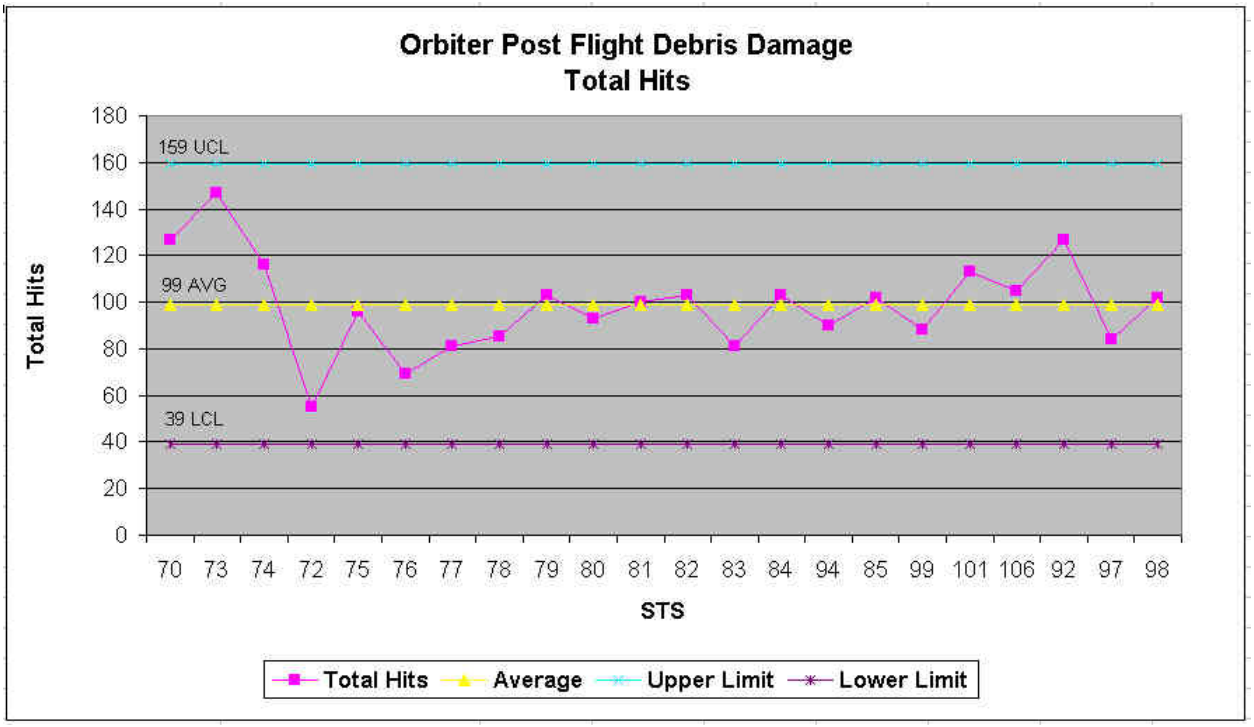


Figure 7: Control Limits for Total Hits

Photo 22 and 23: Overall View of Orbiter Sides

Photo 24: Damage to Lower Surface Tiles

This photo shows the largest damage site on the lower surface located just aft and outboard of the nose landing gear door measured 2.5 inches long by 2 inches wide by 0.25 deep. The cause of this damage has not been determined, an adjacent damage site had tile gap filler material embedded in it.

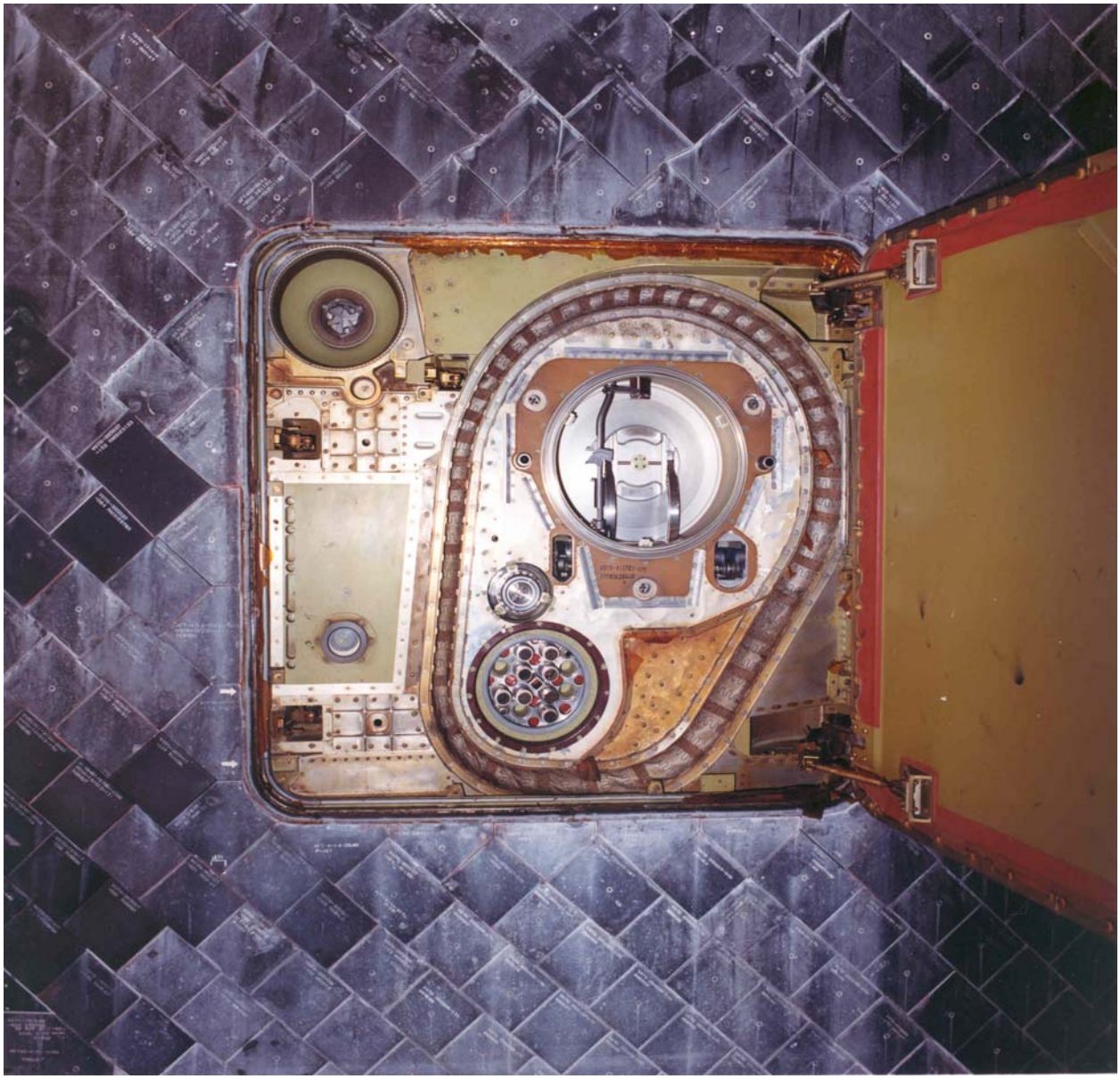


Photo 25: LO2 ET/ORB Umbilical

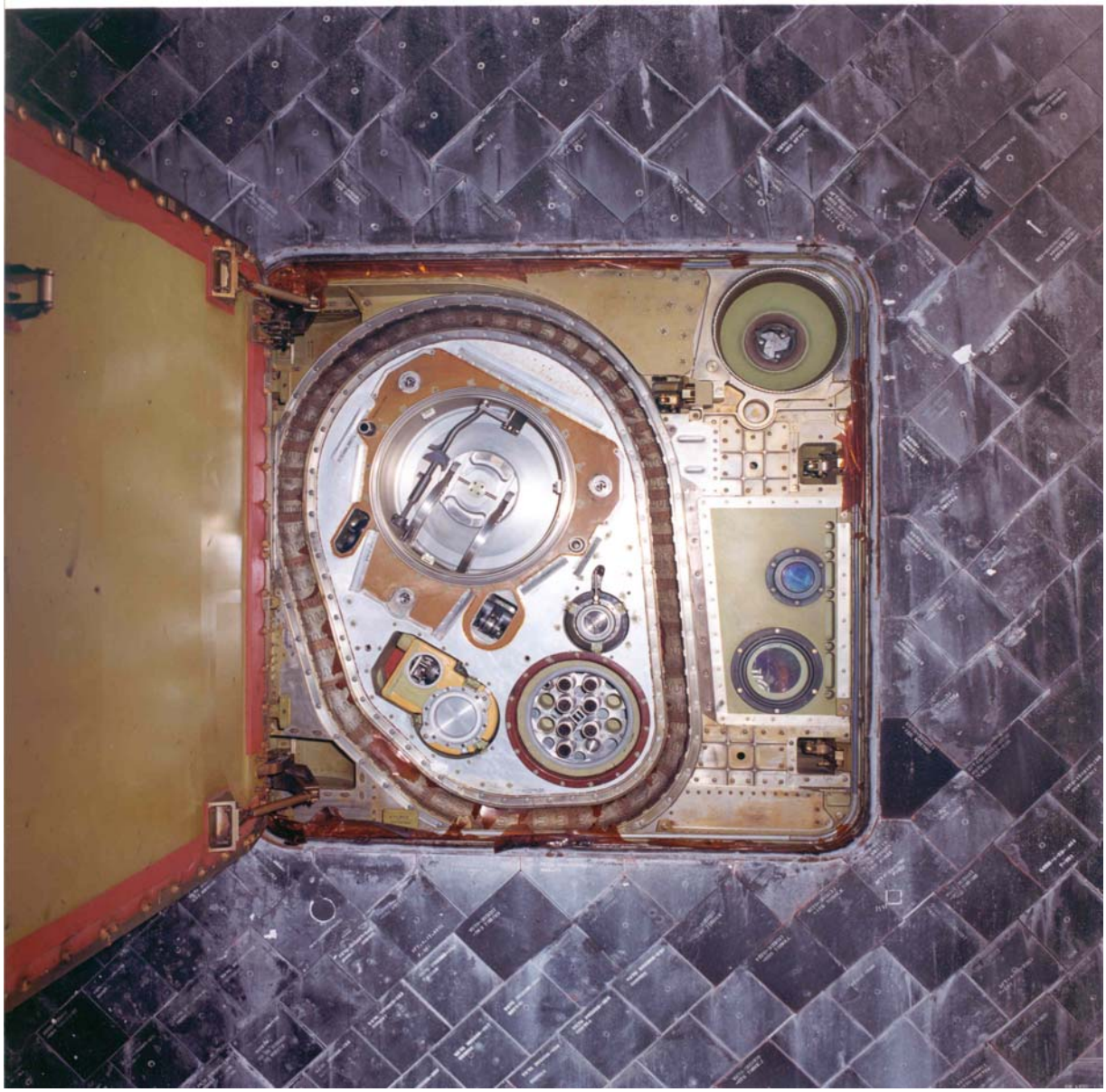


Photo 26: LH2 ET/ORB Umbilical

Photo 27: Windows

Damage sites on the window perimeter tiles were less than usual in quantity and size. Hazing and streaking of forward-facing Orbiter windows was less than average. The largest damage site, located between windows 3 and 4, was approximately 0.5-inches long by 2.0-inches wide. This damage may be attributed to impacts from FRCS thruster paper covers and RTV adhesive.

APPENDIX A. JSC PHOTOGRAPHIC ANALYSIS SUMMARY

Table of Contents

Tables and Figures

1 STS-98 (OV-104): Film/Video Screening and Timing Summary

1.1 Screening Activities

1.1.1 Launch

The STS-98 launch of Atlantis (OV-104) from Pad 39A occurred on Wednesday, February 7, 2001 at approximately 038:23:13:02.010 UTC as seen on camera E9. SRB separation occurred at approximately 23:15:07.46 UTC as seen on camera KTV4A.

On launch day, 23 of the 24 expected videos were received and screened. Camera ET213 was not received.

Twenty launch films were screened and a report was sent to the Shuttle Program distribution on February 12, 2001. Twenty-one additional films were received for contingency support and anomaly resolution. Films E208 and E12 were not received.

Two events were seen during the review of the STS-98 launch videos and films that were elevated to the in the Launch + 4 Day KSC, JSC, MSFC Film/Video Analysis Teams Consolidated Film Review Report:

CFVR-98-01 Unusual debris at 4.5 seconds before SRB separation

CFVR-98-02 Body flap motion during ascent.

(This report consolidates the multi-center post flight photo reviews into a single list of observations for engineering review. This integrates the photo review process into the IFA / PRACA process to ensure that the identified observations are assessed and dispositioned prior to the next flight per established problem reporting criteria.)

The 16mm umbilical well cameras did not fly on OV-104 during STS-98. The 35mm umbilical well TPS camera film was dark and not useable because of the nighttime conditions at the time of ET separation. Handheld still photography of the ET was not acquired following ET separation because of the nighttime conditions.

Video (acquired from cameras mounted on the SRB forward skirts) of the External Tank's +Y and –Y thrust panels was not acquired during ascent on STS-98.

1.1.2 On-Orbit

Figure 1.1.2 Vertical Stabilizer Tile Damage Seen On-orbit

No unplanned on-orbit Shuttle support tasks were requested. However, downlink video of tile damage to the Orbiter vertical stabilizer leading edge tiles and video of ice on the SSME nozzles was received.

Pre-planned real-time analysis support was provided to the ISS AF-5A Space Station photographic and television external survey. The Space Station image analysis support will be documented in the AF-5A Imagery Overview Report.

1.1.3 Landing

Atlantis made a day landing on runway 22 at Edwards Air Force Base (EAFB) on February 20, 2001 at 20:33:04.9 UTC. This was only the second time since March 1996 that an Orbiter has landed at EAFB (STS-92 landed at EAFB in October, 2000). Six public affairs landing videos with actual landing times were received. The engineering television replays were not received. Seven landing films were received. The long range Contraves tracking films were not received.

The landing touchdown appeared normal. The drag chute deploy sequence appeared normal on the landing imagery. No anomalous events were seen during the Orbiter approach, landing, and landing rollout.

Post landing, a sink rate analysis of the STS-98 main landing gear was performed for the main gear touchdown. See Section 2.5.

According to the pre-mission agreement, the STS-98 landing films were not screened due to budgetary constraints.

2 Summary of Significant Events

2.1 Findings Elevated to the Launch +4 Day KSC, JSC, MSFC Film / Video Analysis Teams Consolidated Film Review Report

CFVR-98-01: Unusual Debris at ~ 4.5 Seconds Prior to SRB Separation

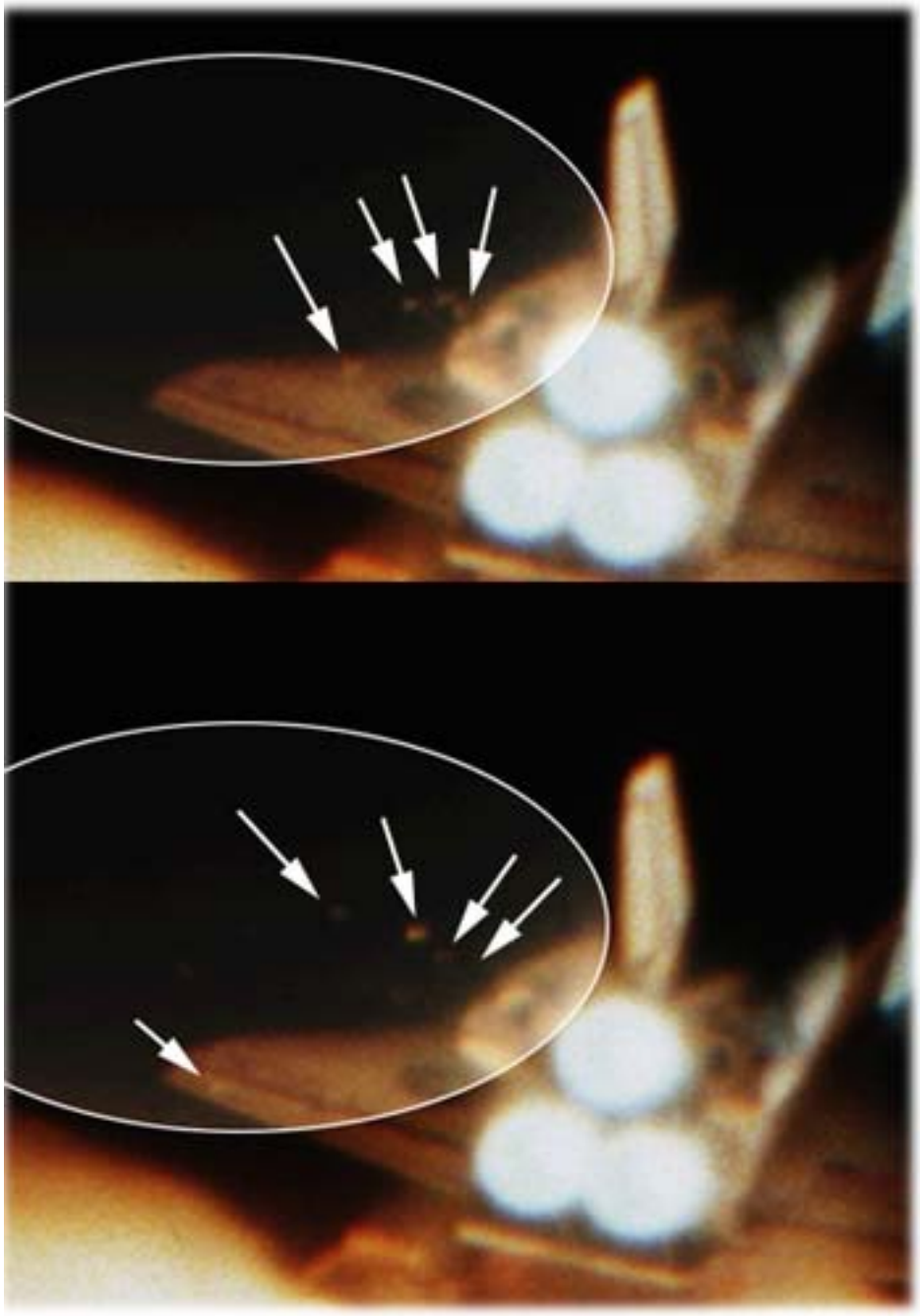


Figure 2.1 Debris Near Left OMS Pod (Camera E207)

Several pieces of light-colored debris (at least five or six) were seen near the Orbiter left wing and the port OMS pod approximately 4.6 seconds prior to SRB separation (23:15:02.924 UTC). At least two additional pieces of light-colored debris were also seen falling over the +Z side of the right wing near the Orbiter fuselage approximately 1.7 seconds prior to SRB separation on the films E207 and E212. On the E207 view, this debris appeared to have been moving outboard in a +Y direction across the top of the right wing. Post-landing, KSC reported that two minor hits were observed on the left OMS pod. However there were no missing tiles or blankets from the OMS pods that would coincide with the debris observed near the OMS pod on the E207 film. It is possible that this debris was mostly RCS paper. (Cameras ET207, E207, E212)

Two pieces of debris, one on the right side of the vertical stabilizer and one on the left side of the vertical stabilizer, were seen moving in an apparent +Y and –Y direction, respectively, away from the vehicle at 3.4 seconds prior to SRB separation. This debris may have been associated with the tile damage to the leading edge of the vertical stabilizer seen on the flight day one down link video. KSC reported that the vertical tail damage site seen on the on-orbit imagery appeared to have impact residue embedded in it.

A separate, probably normal and unrelated, debris event was seen at this same time period. Two large, solid-appearing pieces of probable SRB slag debris were seen exiting the SRB exhaust plume, one on the right side and one on the left side of the SRB exhaust plume, at 1.6 seconds and 0.4 seconds respectively prior to SRB separation on the E207 film.

CFVR-98-02: Body Flap Motion During Ascent

Similar to STS-97, body flap motion was very apparent during ascent (23:13:33.4 to 23:14:04 UTC). A side-by-side movie loop was constructed showing similar views of the body flap on STS-97 and STS-98 (Camera E207). The body flap motion seen on STS-98 appeared similar to that seen on STS-97. JSC Structures and Mechanics / ES did not request analytical measurements of the amplitude and frequency of the STS-98 body flap motion. (Cameras ET207, E207)

2.2 Other Launch Observations

2.2.1 Debris from SSME Ignition through Liftoff

Similar to previous missions, multiple pieces of ice debris were seen falling from the ET/Orbiter umbilicals and along the –Z side of the body flap during SSME ignition through liftoff. Umbilical ice debris was seen to contact the Orbiter LH2 umbilical well doorsill (23:12:59.2 UTC). This event has typically been seen on previous missions. No damage to the launch vehicle was detected. (Cameras OTV009, OTV054, OTV061, OTV063, E1, E4, E5, E18, E19, E31, E34, E52, E63, E76, E207)

A single piece of possible SRB throat plug debris, light-colored on one side and dark-colored on the other, was seen near the ET aft dome moving in an upward arc and falling aft along the body flap during liftoff (23:13:02.4 UTC). (Cameras OTV54, OTV063)

A light-colored piece of debris was seen just aft of the right RCS stinger after SSME ignition (23:13:01.1 UTC). This debris may have been RCS paper. Also, a piece of ice debris from the LO2 TSM disconnect was seen near the aft rim of SSME #3 during liftoff. (Camera OTV051)

Several light-colored pieces of debris were seen traveling from the area of both the right and left SRB flame ducts (probably SRB throat plug material or SRB aft skirt instafoam) in a northerly direction away from the launch vehicle after SRB ignition (23:13:03.723 UTC). Multiple pieces of debris from near the RSRB aft skirt were seen moving upward during and after liftoff. On OTV071, SRB throat plug debris was seen by the LSRB aft skirt. On camera E36, a single light-colored piece of unidentified debris was seen above the MLP deck near the Orbiter aft fuselage moving north toward the gap between the left and right SRB's (23:13:04.919 UTC). None of the debris was seen to contact the launch vehicle. (Cameras KTV4A, KTV7A, OTV071, E1, E4, E5, E36, E52, E222, E224)

Five or six pieces of light-colored debris were seen falling from near the Orbiter / ET attach bipod aft along the Orbiter fuselage tiles during liftoff. This debris was probably ice from the ET LO2 feedline bellows. Similar debris has been seen on previous missions. However, on STS-98 two of the debris pieces were seen to contact the Orbiter mid-level fuselage tiles (23:13:05.242 and 23:13:05.742 UTC). No damage to the Orbiter tiles was noted. (Camera OTV061)

Multiple pieces of debris, probably ice, were seen falling from the under side of the MLP after liftoff (23:13:06.5 UTC). (Camera KTV7A)

2.2.2 Debris During Ascent

Figure 2.2.2 Debris Near SSME Exhaust Plumes (Camera E207)

Multiple pieces of debris, too numerous to count (mostly umbilical ice and RCS paper debris), were seen falling aft of the launch vehicle during ascent. Examples are:

E224	Debris in SSME exhaust plume (23:13:19.835 UTC)
E224	Large spray of debris aft of the body flap in the SSME plume after the roll maneuver (23:13:19.959 UTC)
E207	RCS paper near the vertical stabilizer prior to the roll maneuver and near the left OMS pod after the roll maneuver.

As on previous missions, debris was seen exiting the SRB exhaust plumes. The pieces of debris exiting the SRB exhaust plumes during the majority of the ascent were probably instafoam from the aft end of the SRB's. The more dense appearing debris near the time of tail-off, just prior to SRB separation, were probably SRB slag debris Examples are:

KTV21A	23:13:32.6 UTC
KTV5	23:14:12.0 UTC
KTV5	23:14:12.4 UTC

KTV13 23:14:14.3 UTC
KTV5 23:14:14.5 UTC
KTV4A 23:14:18.8 UTC
KTV4A 23:14:18.9 UTC
KTV4A 23:14:23.9 UTC (three pieces)
KTV4A 23:14:28.2 UTC
KTV4A 23:14:33.1 UTC
KTV4A 23:14:51.0 UTC
KTV13 23:15:03.6 UTC
ET204 23:15:03.7 UTC
E207 Frames 7678, 7755
E212 Frames 7642, 7840, 7868, 7940, 7956, 8007
E223 Frames 7224, 7323, 7414, 7500, 758

A single piece of dark-colored unidentified debris was seen falling along the –Z side of the right wing and traveling toward the RSRB during ascent (23:13:25.8 UTC). (Camera ET207)

Several debris objects were seen near the SRB exhaust plume after liftoff that appeared to be birds in the foreground (23:13:23.1, 23:13:29.6, 23:13:32.2 UTC). On camera KTV5, a bird was seen close to the camera at 23:14:02.0 UTC. (Cameras KTV2, KTV5, KTV21A)

2.2.3 Mobile Launch Platform (MLP) Events

The SSME ignition appeared normal on the high-speed engineering films and the SSME Mach diamonds appeared to form in the expected sequence (3, 2, 1). The times for the Mach diamond formation given in Table 2.2.3 are from camera film E19. (Cameras E19, E20, E76, OTV070)

SSME	TIME (UTC)
SSME #3	23:12:58.668
SSME #2	23:12:58.873
SSME #1	23:12:58.925

Table 2.2.3 SSME Mach Diamond Formation Times

Orange vapor (possibly free burning hydrogen) was seen forward of the SSME rims and near the drag chute door during SSME ignition (23:12:56.867 UTC). Orange vapor forward of the SSME rims has been seen on previous mission films and videos, particularly under low light conditions. (Cameras OTV070, OTV071, E2, E5, E18, E19, E20, E52, E63, E222)

Typical of previous missions, small areas of tile surface coating material erosion were seen on the base heat shield outboard of SSME #3 (23:12:58.330 UTC) and on the base heat shield between the left OMS nozzle and the base of the vertical stabilizer (23:12:57.510 UTC) prior to liftoff. (Cameras E19, E20)

A single piece of light-brown-colored debris (possible tag) fell from the LO2 TSM T-0 umbilical lines prior to the umbilical disconnect (23:12:57.429 UTC). (Camera E17)

Summary of Significant Events

SRB ignition was at 23:13:02.010 UTC based on the observation of the PIC firing at RSRB holddown post M-1. (Camera E9)

A faint light-colored streak, typical of previous missions, was seen extending aft from the SSME #3 nozzle rim at liftoff (23:13:02.441 UTC). (Camera E19)

The center +Z RCS paper cover on the starboard stinger did not tear away during liftoff. This event has been seen on previous mission. (Camera OTV070, E19, E76)

The left and right SRB GN2 purge lines appeared wrapped, upright, and intact until they were obscured by exhaust plumes at 23:13:04.191 UTC (left purge line) and 23:13:04.405 UTC (right purge line). (Cameras E8, E13)

2.2.4 Ascent Events

The outgassing and vapors near the ET aft dome during early ascent appeared typical to that seen on previous mission films and videos. (Cameras ET207)

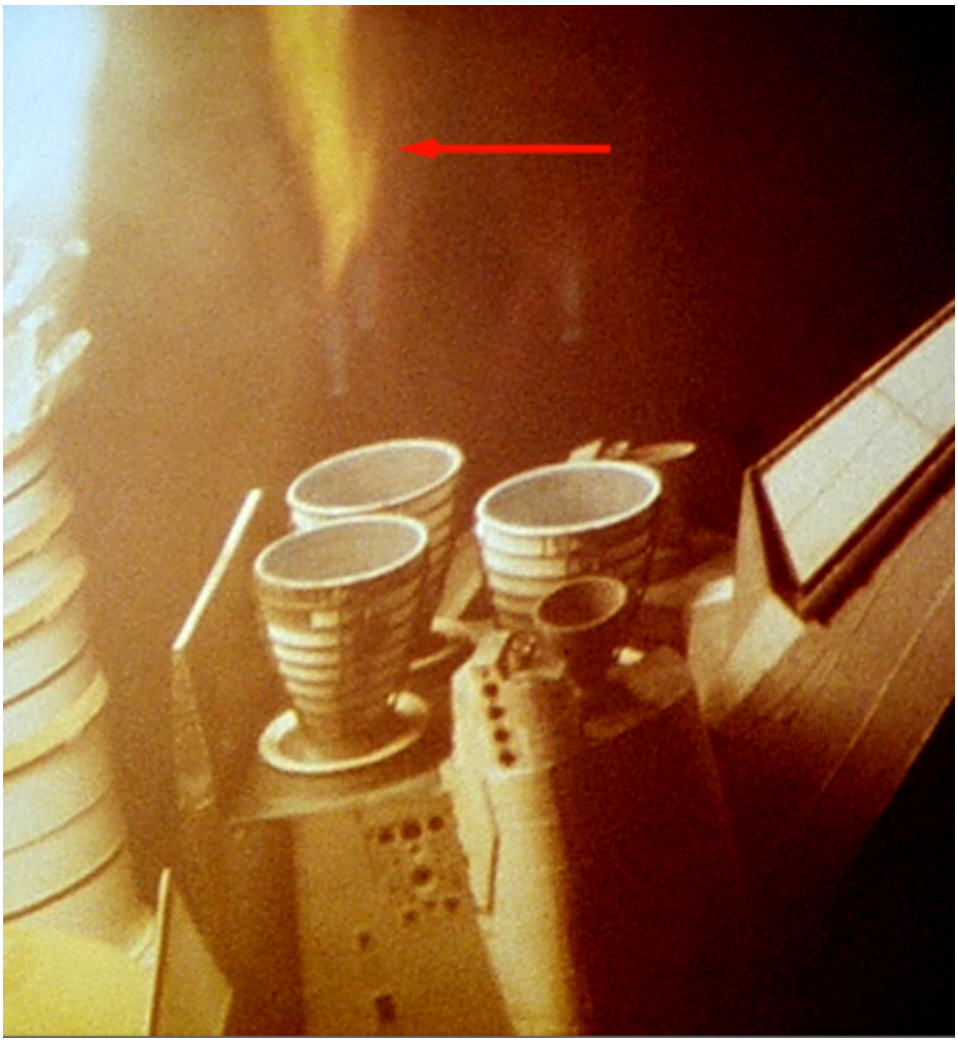


Figure 2.2.4 Flare in the SSME Exhaust Plume (Camera E222)

Light-colored flares (some seen to be debris induced) were seen in the SSME exhaust plumes during ascent on the intermediate and long range tracking camera films. Examples are:

E52	23:13:11.206, 23:13:17.595 UTC
E222	23:13:33.368, 23:13:37.753, 23:13:41.157 UTC
E224	23:13:33.357, 23:13:33.915, 23:13:41.178 UTC
ET207	23:13:28.8 UTC, 23:13:33.4 UTC, 23:13:37.2 UTC, 23:13:38.2 UTC, 23:13:38.3 UTC, 23:13:39.5 UTC, 23:13:42.8 UTC
E207	Frames 1872, 2049, 2147, 2359, 2462, 2704
E223	Frames 3950, 4272, 4426, 5300

Flares in the SSME exhaust plumes have been seen on previous missions films and videos. Often on previous mission imagery, debris has been seen contacting the SSME exhaust plume resulting in visible flares. Usually this debris appeared to be RCS paper. (On STS-26 and STS-101, debris that resulted in very large orange-colored flares was determined to have been tile material.)

A large piece of LO2 umbilical purge barrier material was seen partially detached and flapping against the Orbiter fuselage tiles during and after the roll maneuver (23:13:17.4 UTC). The flapping of this material against the tiles probably resulted in at least some of the tile damage near the Orbiter umbilical wells that was found during the post landing inspections. On camera E223, frame 5820, a single large orange-colored piece of probable umbilical purge barrier material was seen falling aft of the body flap and contacted the SSME exhaust plume resulting in a large orange-colored flare. Detached umbilical purge barrier material has been seen during ascent on previous missions. (Cameras ET207, E207, E212)

Two bright pulses or flashes were seen near the port side of the Orbiter approximately 3.3 and 4 seconds after SRB separation (23:15:10.818 and 23:15:11.519 UTC). These same flashes were observed on Camera ET204, but on this camera view the flashes appeared to be an optical effect rather than an actual event. Camera ET207 provided an excellent view of the aft end of the Orbiter at this same time period, however no flashes were detected. This event was not seen on the long range tracking camera films and it is, therefore, considered to have been an optical effect and not an anomaly. (Camera KTV13, ET204)

A new procedure was implemented by the Shuttle Program to fire the forward RCS thrusters during SRB separation in order to help keep the Orbiter windows free of hazing from the forward SRB separation motor exhaust. A light-colored, long, curved-shaped exhaust plume that appeared to be caused by the firing of the forward RCS thrusters during SRB separation was visible on the STS-98 E207 film. A comparison of images between the STS-98 SRB separation (where the RCS thrusters were used) with STS-97 imagery where the RCS thrusters were not used during SRB separation were placed on the sn-isag web page at the request of Boeing – Huntington Beach. (Camera E207)

Orange vapors from the early OMS-2 assist burn were visible approximately 10.1 seconds after SRB separation. (Camera E212)

2.3 Onboard Photography of the External Tank (ET-105)

2.3.1 Analysis of the Umbilical Well Camera Films

No External Tank or SRB separation photography was acquired on STS-98 with the umbilical well camera films.

2.3.2 16mm Umbilical Well Camera Films

The two 16mm umbilical well camera films were disabled preflight because of the investigation into an electric short problem.

2.3.3 35mm Umbilical Well Camera Film

The 35mm umbilical well TPS camera film was unusable due to the nighttime conditions at ET separation.

2.3.4 ET Handheld Photography

No handheld photography was acquired because of the nighttime conditions.

2.3.5 ET Handheld Video

No handheld video was acquired because of the nighttime conditions.

2.4 Landing Events Timing

The time codes from videos were used to identify specific events during the screening process. The landing event times are provided in Table 2.4.

STS-98 Landing and Drag Chute Event Times from Video:

Event Description	Time (UTC)	Camera
Main gear door opening	051:20:32:48.33	Dryden TV2
1st Left main gear tire touchdown	051:20:33:04.88	Dryden TV2
1st Right main gear tire touchdown	051:20:33:04.94	Dryden TV2
2nd Left main gear tire touchdown	051:20:33:06.18	Dryden TV2
2nd Right main gear tire touchdown	051:20:33:06.35	Dryden TV2
Drag chute initiation	051:20:33:08.21	Dryden TV2
Pilot chute at full inflation	051:20:33:09.35	NASA TV
Bag release	051:20:33:09.85	NASA TV
Drag chute inflation in reefed configuration	051:20:33:10.68	NASA TV
Drag chute inflation in disreefed configuration	051:20:33:14.45	NASA TV
Nose gear tire touchdown	051:20:33:17.32	NASA TV
Drag chute release	051:20:33:35.41	Dryden TV2
Wheel Stop	051:20:34:01.33	NASA TV

Table 2.4 Landing Event Times

Landing Sink Rate Analysis

Image data from the EL1017 35mm motion picture camera on runway 22 at Edwards Air Force Base was used to determine the landing sink rate for STS-98. This camera was fitted with a 100mm lens and was located on the side of the runway in the MD3 North position. (This view is considerably different from the nominal camera view used to determine sink rate for landings at Kennedy Space Center. The KSC view is aimed straight down the runway.) The sink rates of the Orbiter main gear, nose gear, and a point midway between these two gears were measured over the final second prior to touchdown of the right main gear. Data points defining the top and bottom of the right main gear tires were collected on every frame (100 frames for each of the main gear) along with points defining the bottom of the left main gear tires, the bottom of the nose gear tires, and a corresponding point on the runway directly below each gear. The distance from the top and bottom of the right main gear tire was used to determine a scaling factor. The height of each gear above the runway was calculated by the vertical difference between the bottom of the tires and the corresponding ground point. An assumption was made that the line of sight of the camera was parallel to the horizon and that the error in picking the ground points on the runway was small.

Straight lines were fit to the data for the final one-second, the final half-second, and the final quarter-second prior to touchdown of the right main gear. The slope of these lines defines the sink rate for each time interval, and they are listed in Table 2.5 along with the associated uncertainties based on the line fits. Included in the sink rate data are the values calculated for the main gear midpoint. All of the sink rates are based on touchdown of the right main gear since the right main gear touched down last and, therefore, defined the end of the Orbiter sink rate.

Time Prior to Touchdown	Main Gear Sink Rate	Estimated Error (1σ)
1.00 Sec.	2.4 ft/sec	± 0.1 ft/sec
0.50 Sec.	2.4 ft/sec	± 0.1 ft/sec
0.25 Sec.	2.9 ft/sec	± 0.3 ft/sec

Table 2.5 Main Gear Landing Sink Rate

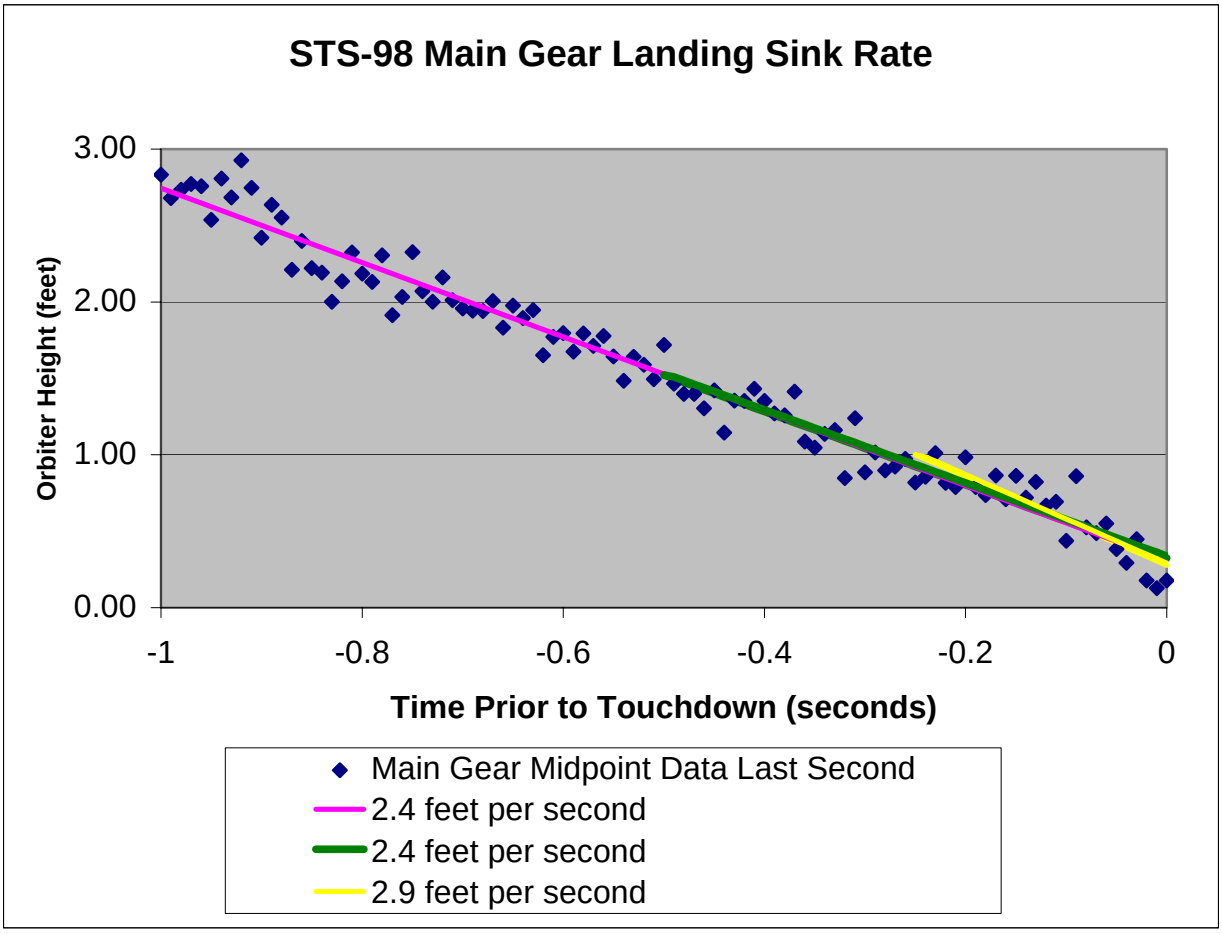


Figure 2.5. Main Gear Landing Sink Rate

The maximum allowable main gear sink rate values are 9.6 feet / second for a 212,000 lb. vehicle and 6.0 feet/second for a 240,000 lb. vehicle. The landing weight of the STS-98 vehicle was reported to be 197,581 lbs.

2.6 Other

2.6.1 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
- vapor off the SRB stiffener rings
- acoustic waves in the exhaust cloud during liftoff
- debris in the exhaust cloud (including water baffle material) after liftoff
- charring of the ET aft dome
- ET aft dome outgassing
- roll maneuver
- linear optical effects
- recirculation
- SRB plume brightening
- SRB slag debris before, during, and after SRB separation

2.6.2 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 disconnect and retraction
- LH2 and LO2 TSM door closures

APPENDIX B. MSFC PHOTOGRAPHIC ANALYSIS SUMMARY

Space Shuttle Mission STS-98

Engineering Photographic Analysis Summary Report
Marshall Space Flight Center

T. J. Rieckhoff (NASA/MSFC)
M. Covan (USA)
J.M. O'Farrell (USA)

February 16, 2001
Marshall Space Flight Center,
Huntsville, AL 35812

Contents

Figures

Engineering Photographic Analysis Summary Report for STS-98

Launch of the one-hundred-second space shuttle mission, STS-98, the twenty-third flight of the Orbiter Atlantis (OV-104), occurred February 7, 2001 at approximately 5:13 PM CST, from launch complex 39A, Kennedy Space Center (KSC), Florida. Launch time was reported as 01:038:23:13:01.990 Universal Coordinated Time (UTC) by the MSFC Flight Evaluation Team.

Photographic Analysis Website:

Further information concerning photographic analysis of this and previous space shuttle missions is available on the MSFC Engineering Photographic Analysis website at URL:

http://photo4.msfc.nasa.gov/STS/sts98/sts98.html.

Information available on the MSFC Engineering Photographic Analysis website includes:

- Photographic Acquisition Disposition Document (PADD),
- Individual camera status and assessments,
- Annotated images of notable observations,
- Movies of select events, and
- Photographic Analysis Mission Summary Report (PDF format).

Photographic Coverage:

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.

Sixty-two engineering photographic products consisting of launch video, ground-based engineering films and onboard film were received and reviewed at MSFC. Camera coverage received at MSFC for STS-98 is illustrated in the following table.

	16mm	35mm	Video
MLP	18	0	4
FSS	5	0	3
Perimeter	0	7	6
Tracking	0	9	10
Onboard	0	0	0
Other	0	0	0
Totals	23	16	23

Since the External Tank was in darkness at ET separation, there was no onboard ET (or SRB separation) photography on STS-98. Also, the ET crossed the sunrise terminator at approximately 43 minutes MET and no handheld ET imagery was available.

Film cameras E12 and E208 had no run for this mission. Videos OTV048 and OTV054 were overexposed at liftoff. Exposure was also too light on film from camera E222. Processing marks were noted on film from cameras E205, E220 and E212. The vehicle was imaged too low in the frame on film from camera E205. Film camera E213 experienced poor tracking for the last half of the vehicle ascent.

T-Zero Times :

T-Zero times are determined from MLP 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	Time (UTC)
M-1	E9	038:23:13:02.009
M-2	E8	038:23:13:02.008
M-5	E12	No Run
M-6	E13	038:23:13:02.008

SRB Separation Timing:

SRB separation time, as recorded by observations of the BSM combustion products from long-range film camera E207, occurred at 038:23:15:07.540 UTC.

Anomalies:

Film Camera E207: Anomalous Debris Just Prior to SRB Separation

Several trails of light-colored debris were observed, on film from camera E207, emanating from the vicinity of both the left, Fig. 1, and right, Fig. 2, sides of the aft portion of the Orbiter just prior to SRB separation. The first observance of this debris was at 038:23:15:02.470 UTC, approximately five seconds prior to SRB separation. The debris trails aft of the vehicle and some particles are noted to impinge onto the SSME plume. The debris appeared to change the reflectivity of the orbiter structure in the vicinity of the perceived ejection site.

This observation was listed on the STS-98 Consolidated Film/Video Report. A movie highlighting the debris as it travels away from the Orbiter is available on the website.

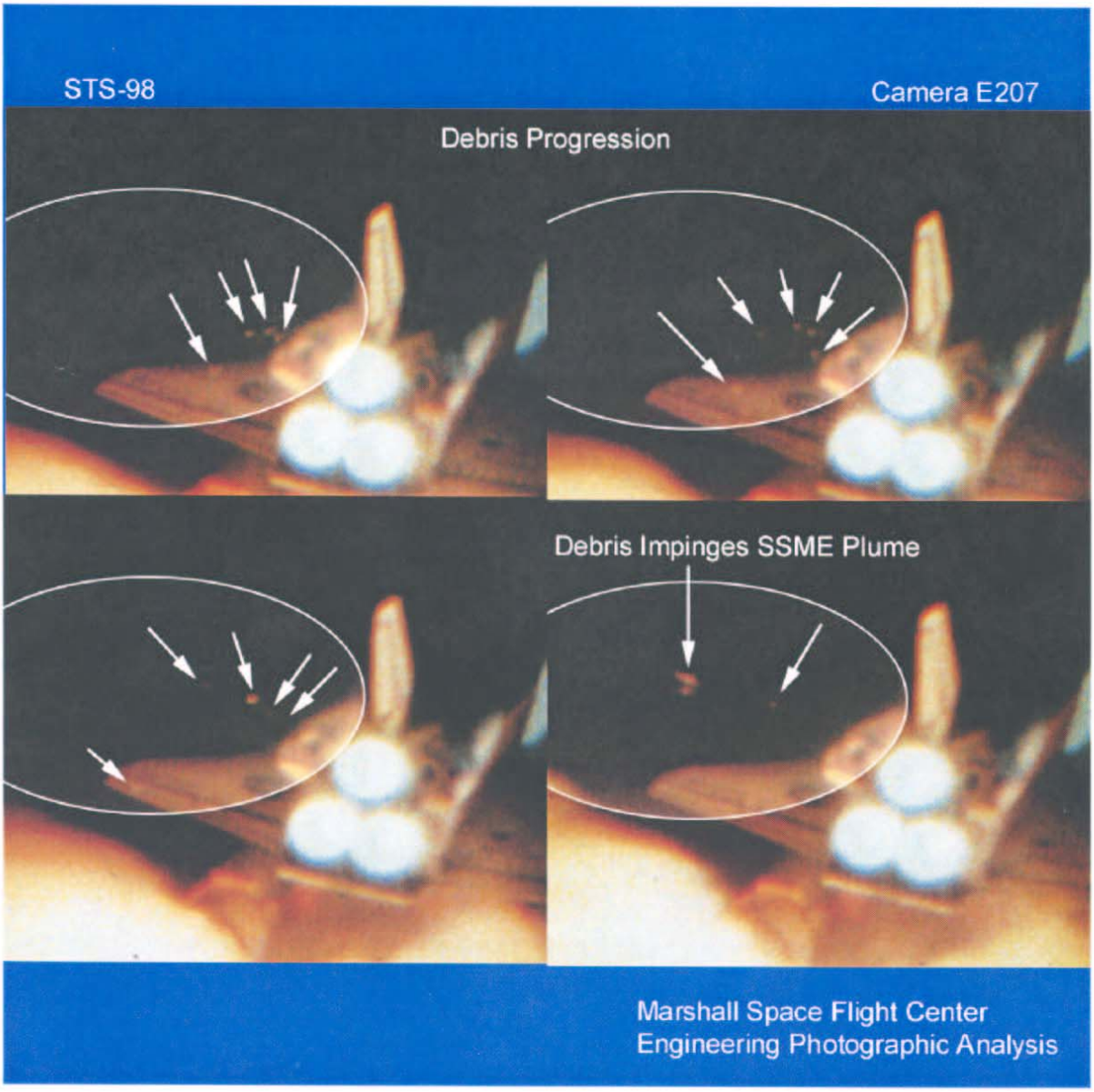


Figure 1. Debris Observed on Left Side of Orbiter

Debris emanated from the right side of the orbiter at approximately the same time as it became visible on the left. The following figure illustrates the direction of travel of the debris from the right side of the Orbiter.

While RCS cover paper provides a similar type debris profile, such debris is seldom observed from the vehicle at this time or later during flight.

A 2 inches by 3 inches by 0.25 inch, tile damage area at the base of the vertical stabilizer was observed during on-orbit operations.

Post-Landing Inspection of the Orbiter by the KSC Debris Team revealed no missing blankets or tiles from the OMS Pods. Tile damage to the Orbiter base heat shield was reported as typical with only the SSME number one closeout blanket torn at the seven o'clock position.

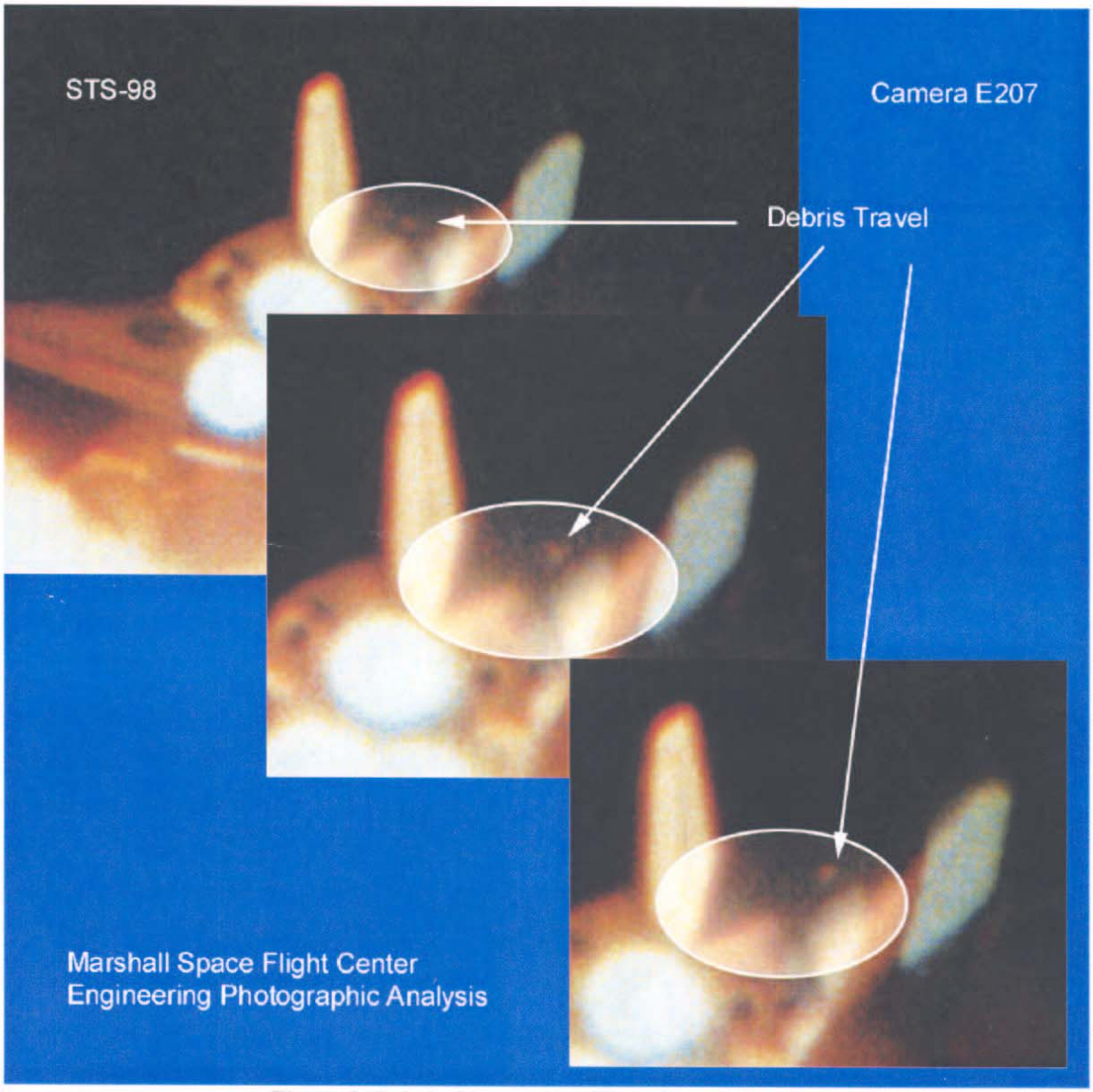


Figure 2 Debris Observed on Right Side of Orbiter

Observations:

Film Camera E207: Debris Induced Streak in SSME Plumes

Several large debris induced streaks were observed in the SSME plumes on this mission. These streaks are common occurrences on Shuttle missions. They are a result of normal debris (RCS paper, butcher paper, purge barrier material, etc…) falling aft during ascent.

Figure 3. Debris Induced Streak in SSME Plumes

Video Camera ET204: Linear Optical Distortion

A linear optical distortion was observed just after SRB separation. This distortion produced an optical flare as it moved away from the SSME plumes.

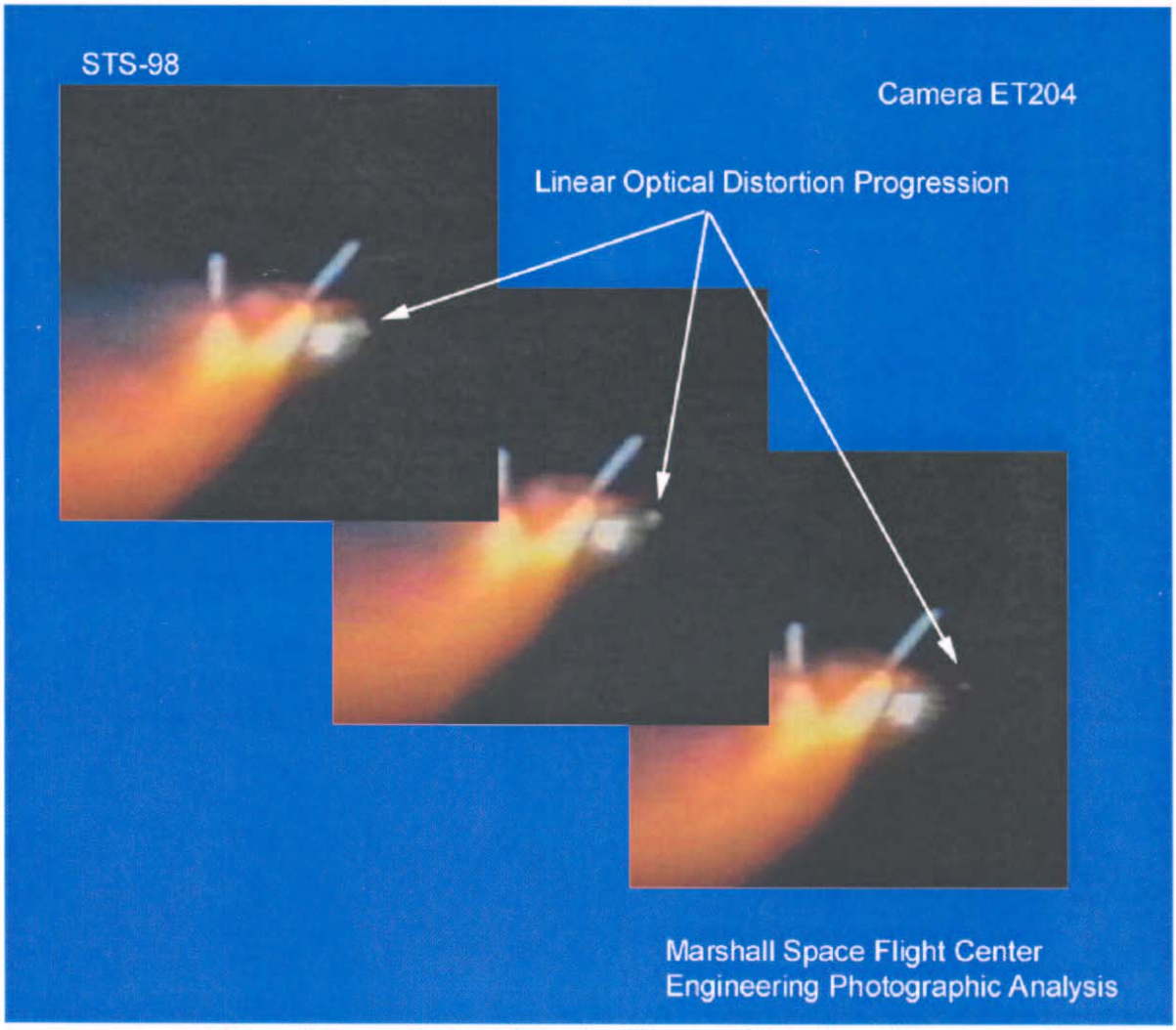


Figure 4. Linear Optical Distortion Observed After Separation

Film Camera E207: Linear Optical Distortion

Linear optical distortions are observed on most flights. An enlarged image from Film Camera E207 illustrates the distortion as it passes in front of SSME number two.

Figure 5. Linear Optical Distortion

Video Camera OTV063: Debris Near Aft Dome

A linear debris object, probably ice/frost was observed falling through the field of view by video camera OTV063 during launch.

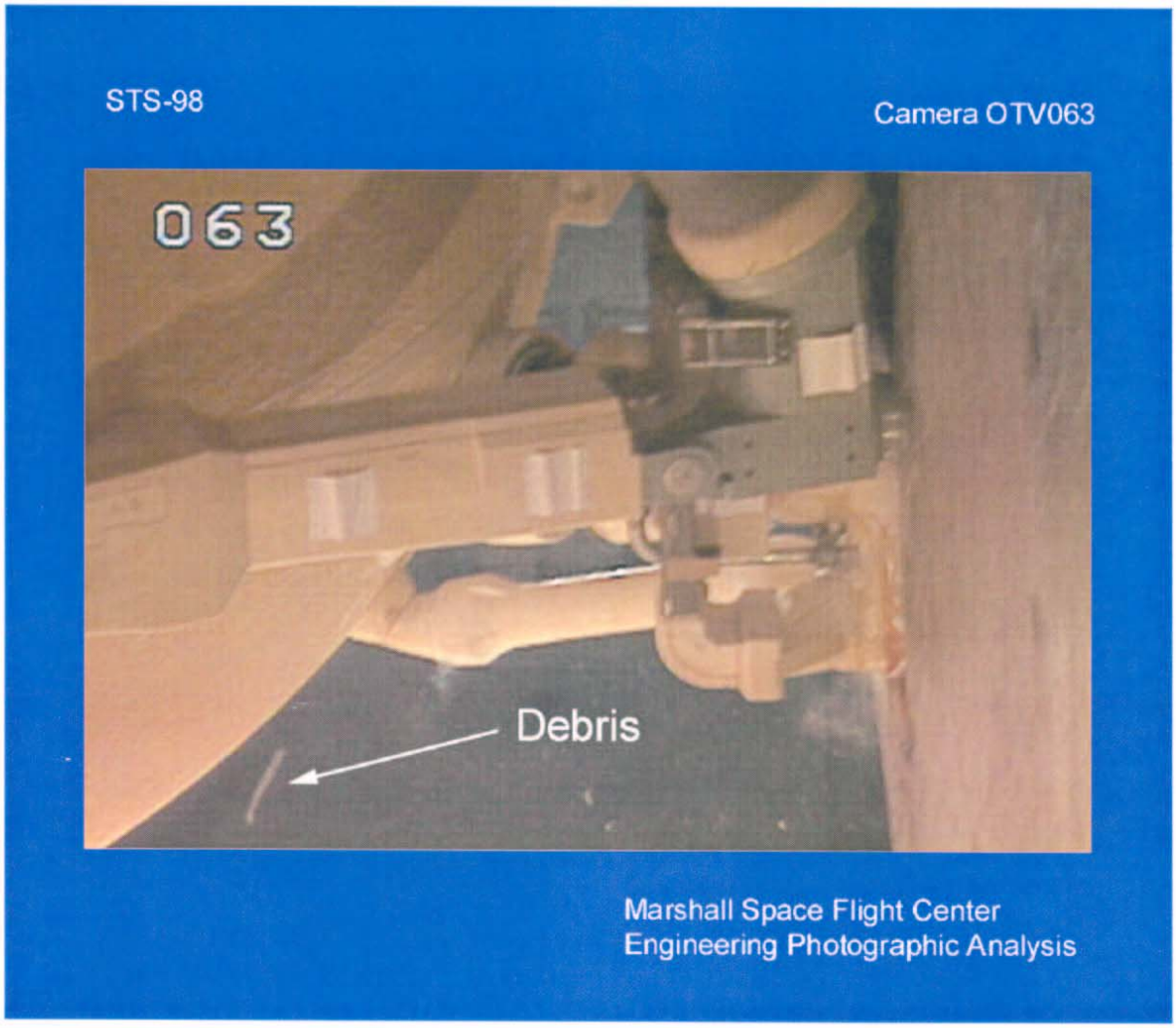


Figure 6. Debris Object Near Aft Dome

Video Camera OTV071: Pad Debris

Typical pad debris was observed to the left side of and moving away from the Orbiter at SRB ignition.

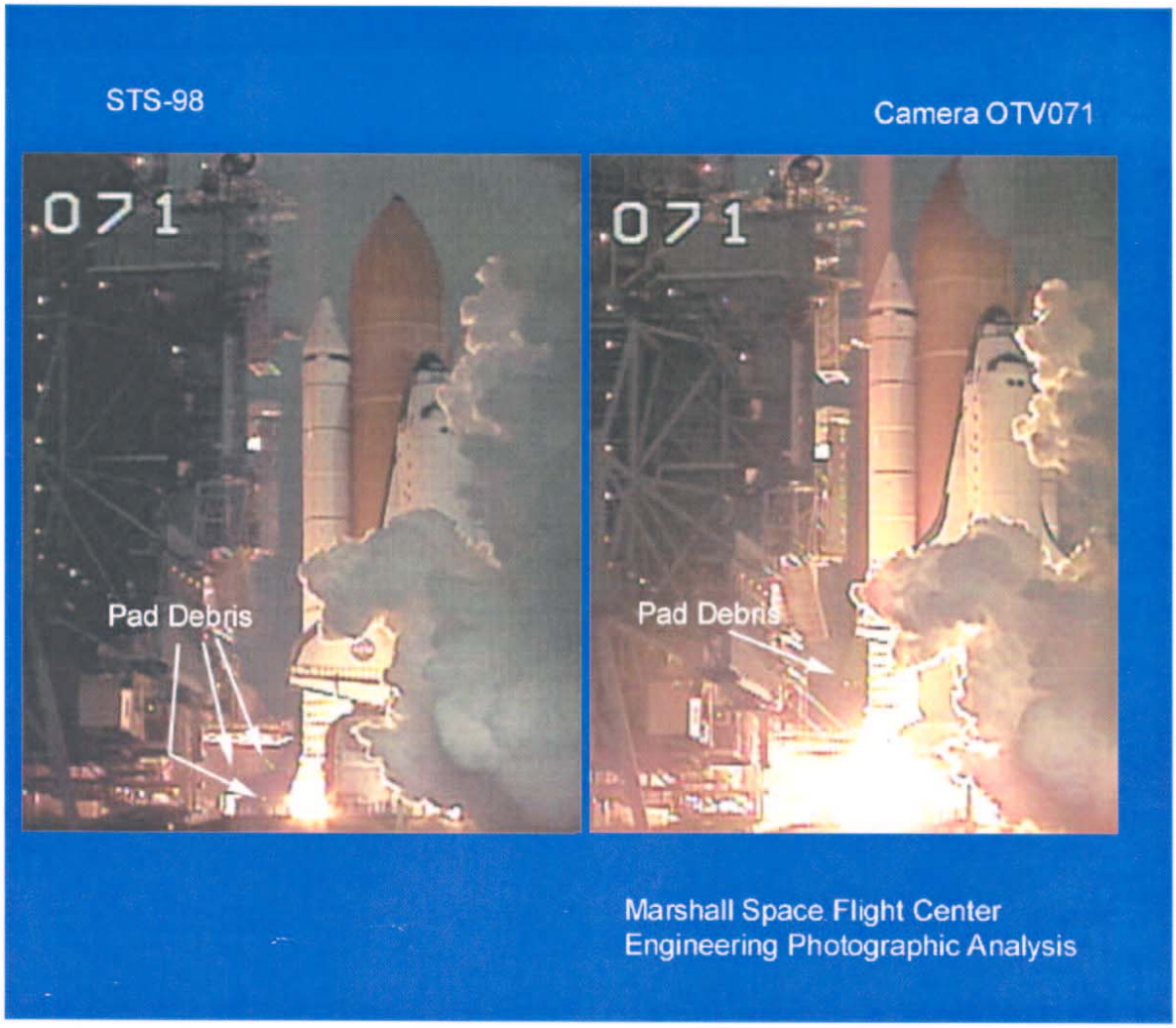


Figure 7. Pad Debris (OTV071)

Video Camera TV4A: Pad Debris

Typical pad debris observed to the right side of and moving away from the Orbiter at SRB ignition is highlighted in the following figure.

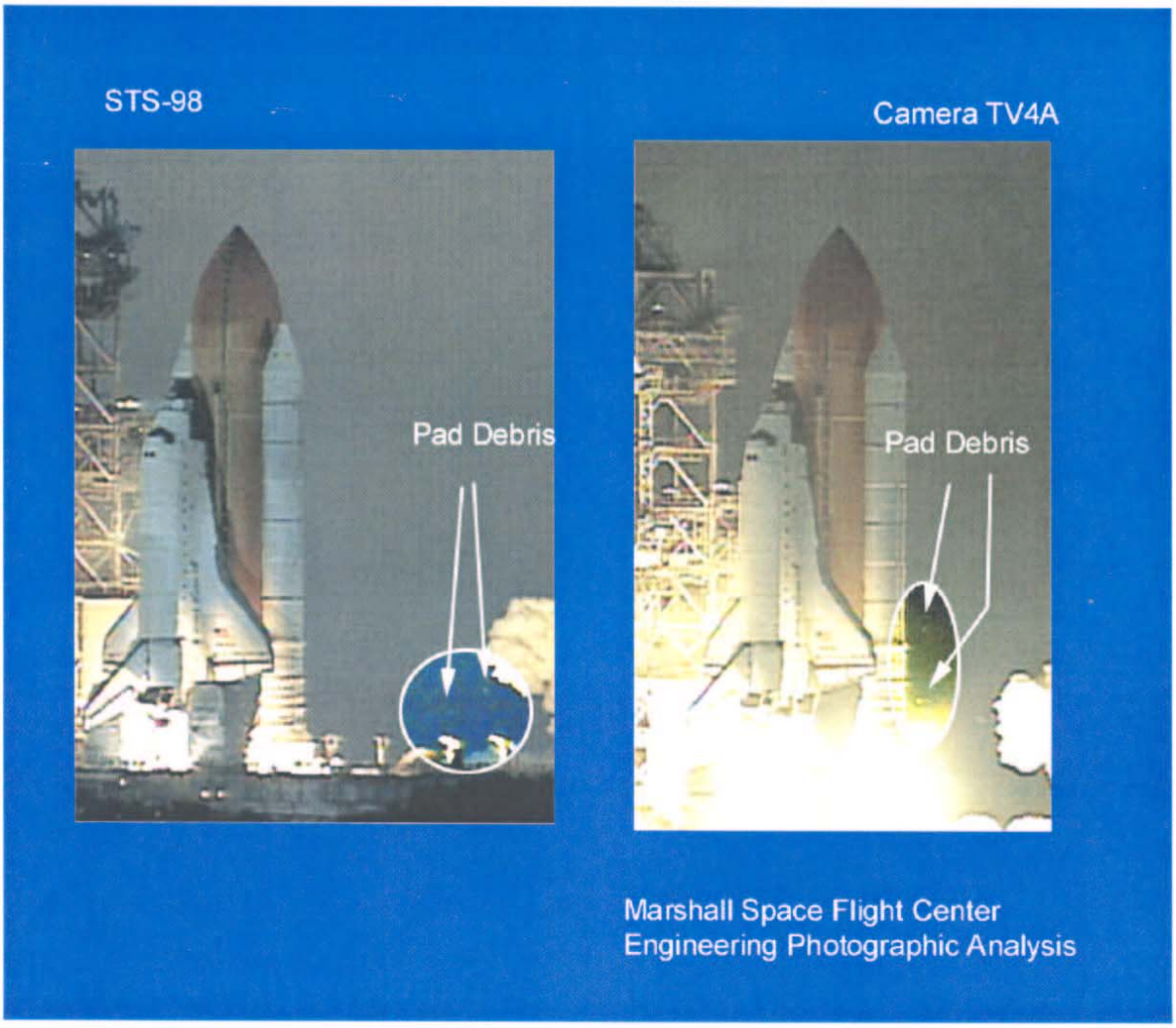


Figure 8. Pad Debris (TV4A)

Video Camera OTV061: Debris Falling Between ET and Orbiter

Debris from LOX Feedline, originating near the ET intertank, falls between the ET and the Orbiter. The debris was observed to impact the lower surface of the Orbiter. No damage was noted.

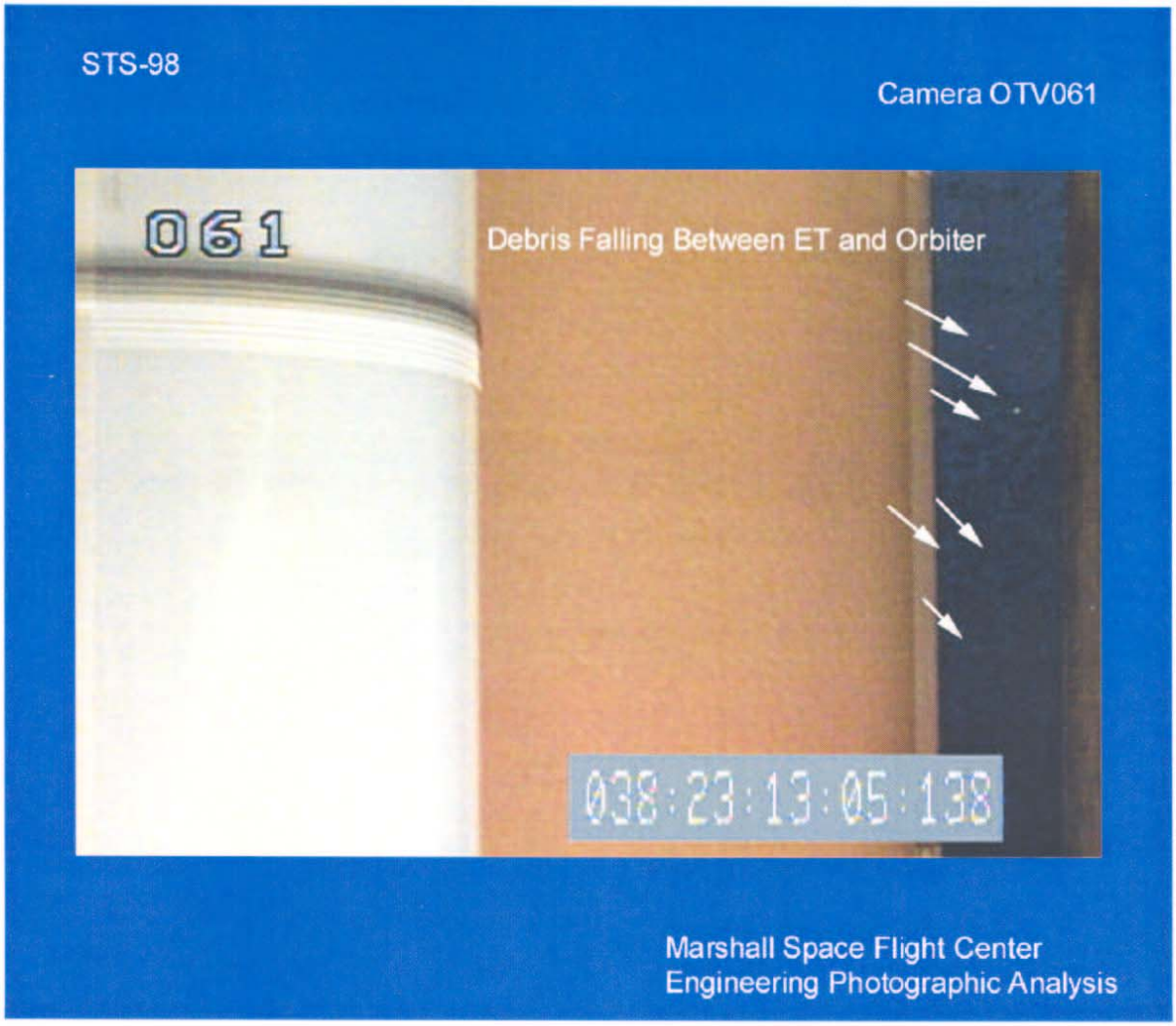


Figure 9. Debris Falling Between ET and Orbiter

Film Camera E33: Frost on ET Ground Carrier Assembly

Frost was observed around the lower perimeter of the ET Ground Carrier Assembly (ETCA).

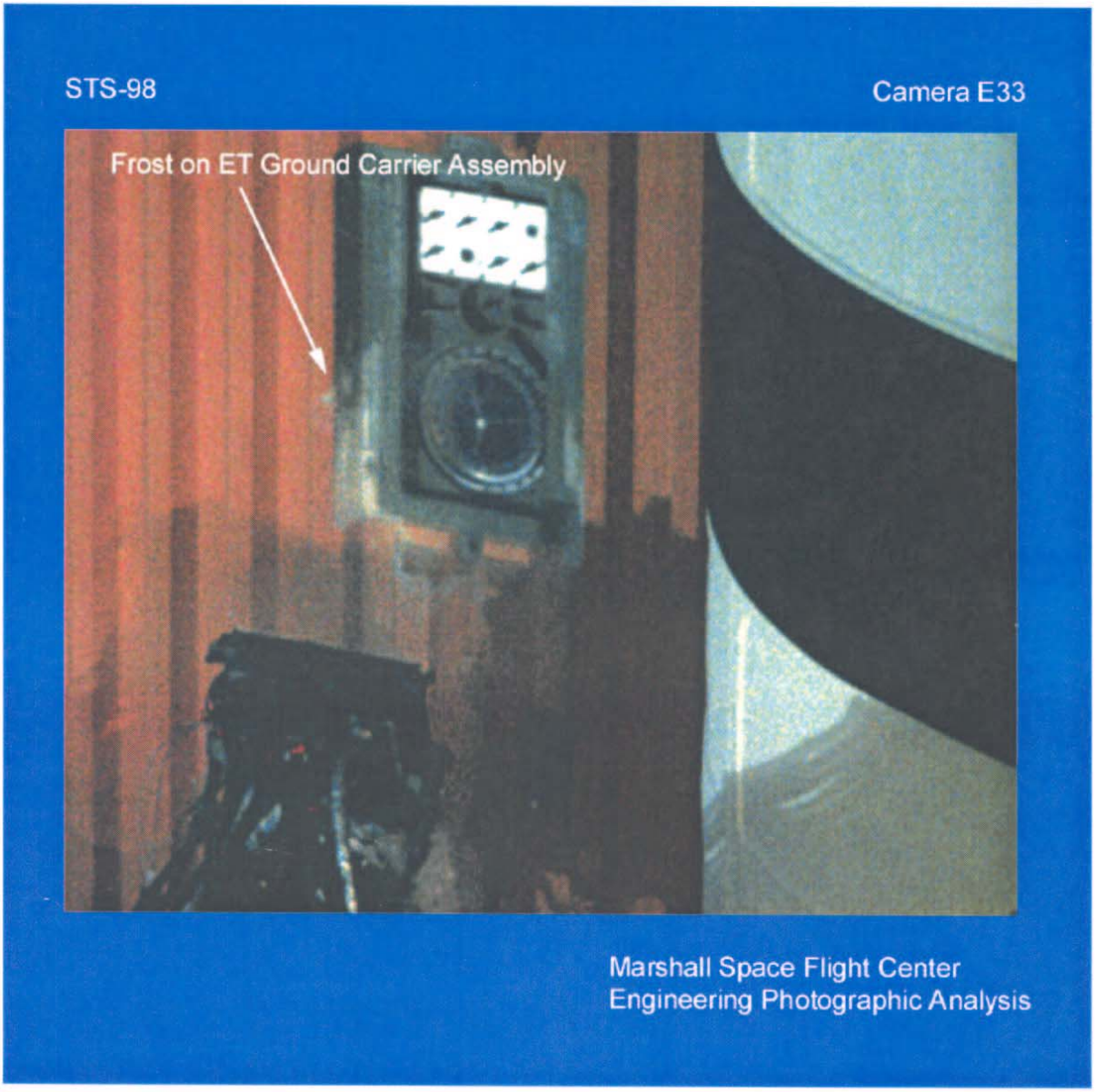


Figure 10. Frost on ET Ground Carrier Assembly

Film Camera E36: Debris from ET/Orbiter Vertical Attach Strut

Yellow-colored debris was observed falling from aft left ET/Orbiter attach strut at 038:23:13:04.902 UTC. The debris appeared to be detaching from the strut at the initial observation point. Through further analysis and consultation with the ET Project Office, this was determined to be Hydrogen fire detect paper fallen from above the first observable position in Figure 11.

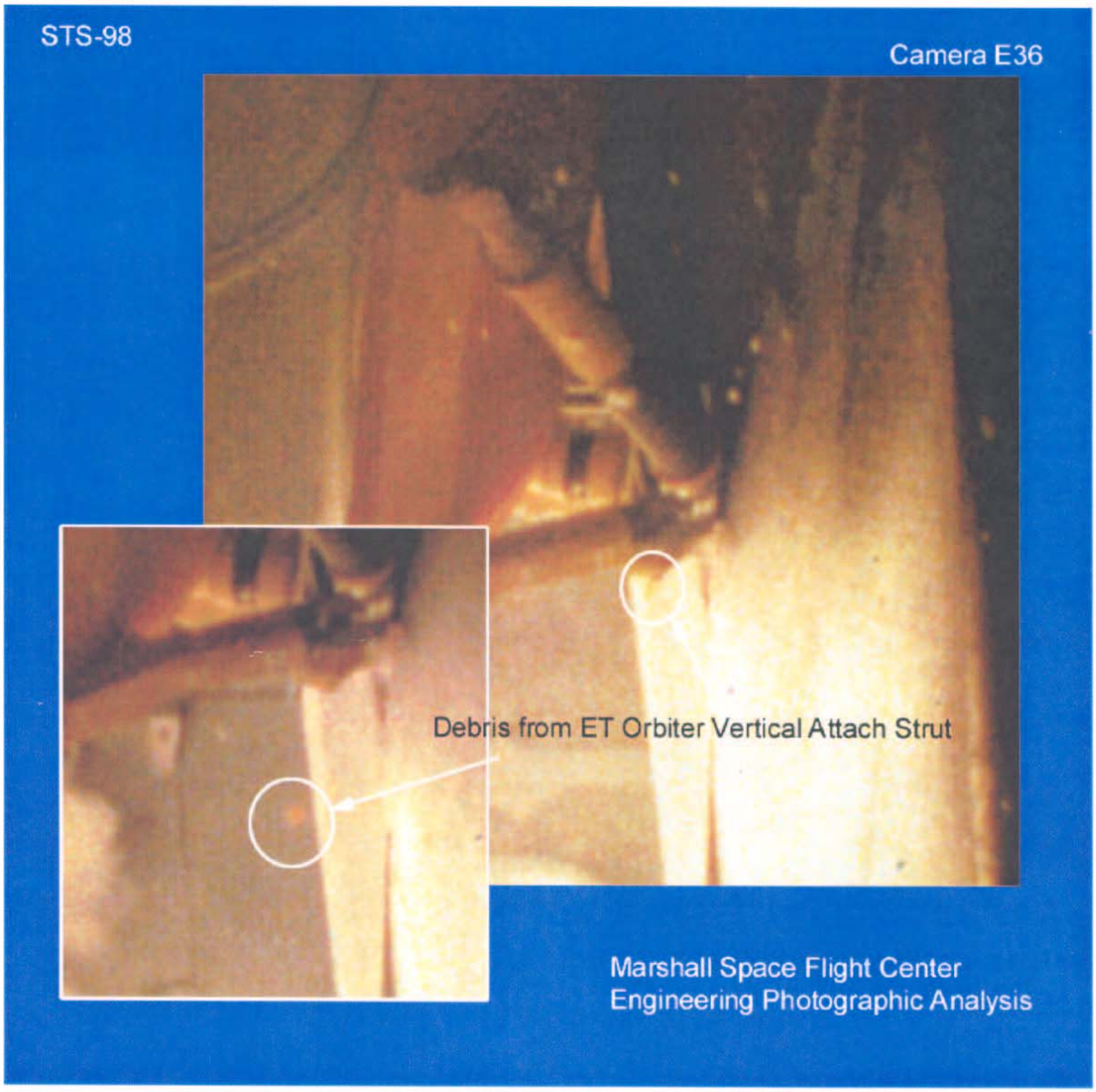


Figure 11. Debris from ET/Orbiter Vertical Attach Strut

Film Camera E57: Debris from Left SRB Plume

Debris was ejected intermittently from the left SRB plume starting at approximately 14.5 seconds MET and ranging for a period of about eight seconds. Figure 10 depicts a large shower of debris that was observed during this time period. Figure 10 was taken at approximately 038:23:13:16.46 UTC.

A movie of this debris being ejected from the left SRB plume is available on the website.

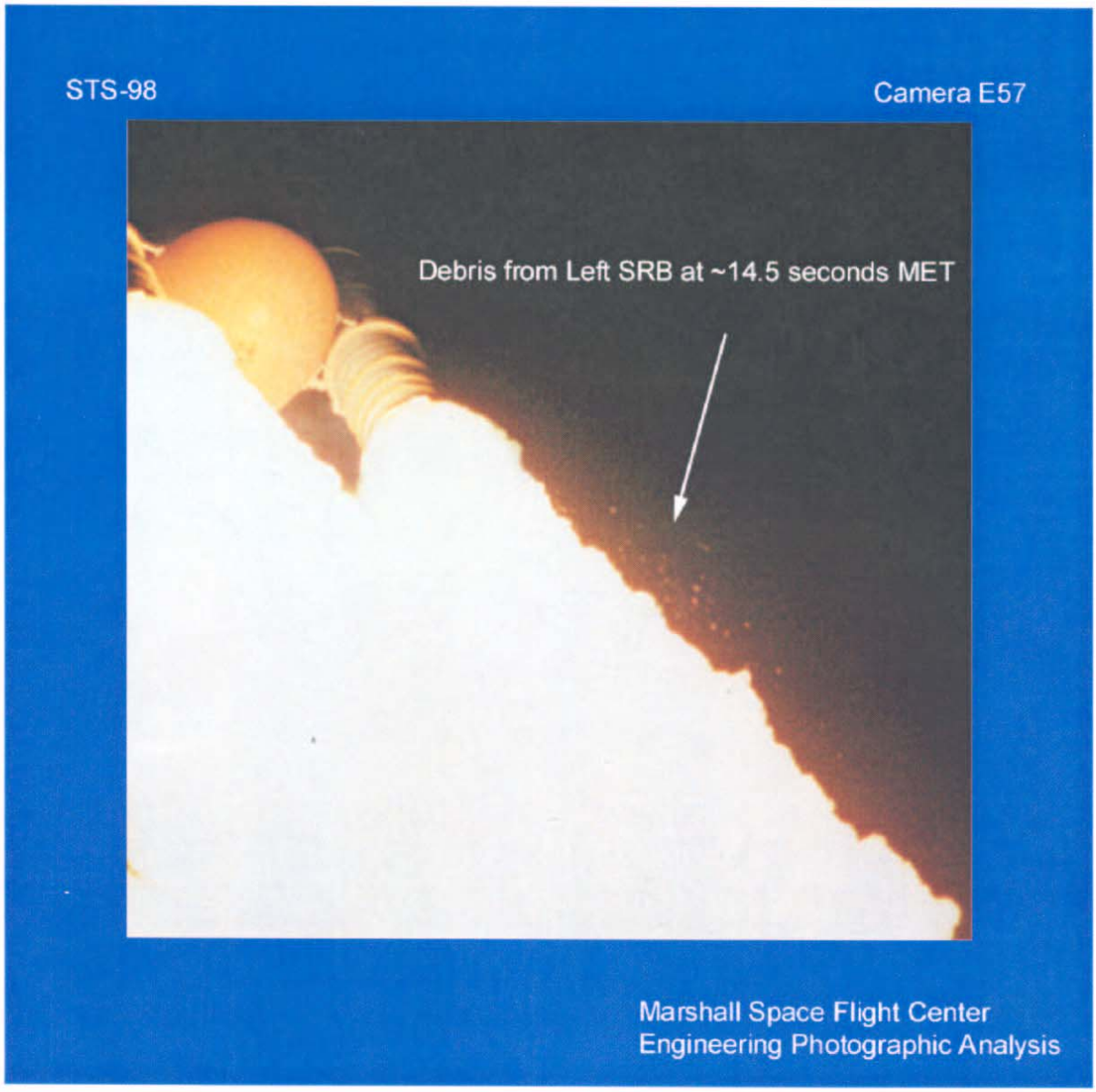


Figure 12. Debris from Left SRB Plume

Film Camera E207: RCS Motor Firing at SRB Separation

A procedure to fire the forward RCS thrusters during SRB separation in order to help keep the Orbiter windows free of exhaust particle hazing was initiated on this mission. RCS motor plumes were observed near the forward end of the Orbiter.

Figure 13. RCS Motor Firing at SRB Separation

Individual Camera Assessments:

Assessments for individual cameras are listed below. The assessments for all individual cameras for flight STS-98 may also be found on the website.

Video Camera Assessments

TV5 Debris ejected from SRB plumes prior to separation.

TV13 - Debris ejected from SRB plumes prior to separation.

TV4A Pad debris observed traveling north of pad, away from vehicle. Debris ejected from SRB plumes prior to separation.

TV7A Pad debris was noted rising and falling. Free burning Hydrogen impinges on vertical stabilizer.

ET204 SRB separation: 038:23:15:07.593 UTC. Debris ejected from SRB plume prior to separation at 038:23:15:03.722 UTC. Linear optical distortions noted after separation at 038:23:15:10.929 UTC and 038:23:15:11.630 UTC

ET207 Typical debris observed falling aft of vehicle. Glowing debris particles ejected from SRB plume prior to, during and after separation. Linear optical distortions noted. Flow recirculation noted. SRB separation: 038:23:15:07.578 UTC. Purge barrier material around LO2 disconnect flapping observed. Debris induced streaks in SSME plumes. Debris observed emanating from near OMS Pod area at 038:23:15:02.774 UTC.

ET208 Debris-induced streaks in SSME plume. SRB separation time: 038:23:15:07.609UTC.

ET212 SRB separation: 038:23:15:07.578 UTC.

TV21A Free burning Hydrogen observed. Debris induced streak in SSME plume observed at 038:23:13:17.596 UTC.

OTV009 Typical ice/frost from LH2 disconnect.

OTV048 Overexposed at liftoff.

OTV051 Free burning Hydrogen impinging on the drag chute door.

OTV054 Pad debris noted rising and falling. Typical ice/frost from 17-inch disconnects. Overexposed at liftoff.

OTV061 Frost from LOX Feedline originating near the intertank impacts Orbiter lower surface. No damage noted.

OTV063 Ice impacts umbilical well door sill. No damage noted.

OTV070 Free burning Hydrogen impacts drag chute door. Mach diamond formation in 3-2-1 order.

OTV071 Pad debris noted rising and falling. Free burning Hydrogen impacts vertical stabilizer.

Film Camera Assessments

E1 Pad debris noted rising and falling. Typical ice/frost from 17-inch disconnects.

E2 Free burning Hydrogen observed near drag chute door.

E3 Pad debris noted rising and falling. Free burning Hydrogen observed.

E4 Pad debris noted rising and falling. Typical ice/frost from 17-inch disconnects. Ice/frost falling from GUCP observed.

E6 Pad debris noted rising and falling. Typical ice/frost from LO2 disconnect.

E7 Pad debris noted rising and falling. Sound suppression system water pipe leaks, out of field of view. Thermal curtain motion at ignition with momentary separation at seams observed.

E8 Holddown Post M2 PIC firing time noted at 038:23:13:02.008 UTC.

E9 Holddown post M1 PIC firing time noted at 038:23:13:02.009 UTC.

E10 Debris particle, apparently emanating from Holddown Post M3 area, observed at 038:23:13:02.021 UTC. Leak observed in sound suppression system water pipe.

E11 Dark, thin, flat debris object falls through field of view before SRB ignition.

E13 Holddown Post M6 PIC firing time noted at 038:23:13:02.008 UTC. Large piece of foam pulled loose by shoe.

E14 Typical pad debris.

E15 Leak in sound suppression water system noted. Thermal curtain motion observed. Debris particle observed coming from behind Holddown Post M3 doghouse cover at 038:23:13:02.028 UTC.

E16 Thermal curtain motion noted.

E17 Notable amount of ice/frost from LO2 disconnect at SSME ignition. Tile chips on SSME Base Heat Shield noted.

E18 Typical ice/frost from 17-inch disconnects. Typical ice/frost from LH2 disconnect. Free burning Hydrogen observed. Ice on SSME#2 eyelid observed. Chips on SSME Base Heat shield observed.

E19 Free burning Hydrogen observed. Frost observed on SSME#2 eyelid. Several tile chips noted on Base Heat Shield.

E20 Free burning Hydrogen observed. Ice noted on SSME#2 eyelid. Several chips observed on Base Heat Shield.

E31 Typical ice/frost from LH2 disconnect. Typical wing motion at liftoff. Ice noted on SSME#2 eyelid.

E33 Typical frost falling from GUCP at SSME ignition. Frost observed around perimeter of ETCA after GUCP separation.

E34 Typical ice/frost from 17-inch disconnects. Frost from GUCP area observed falling prior to and after GUCP/ETCA separation.

E36 Typical ice/frost from 17-inch disconnects. Yellow-colored debris falls from aft left ET/Orbiter attach strut at 038:23:13:04.902 UTC. Frost noted falling from near GUCP prior to and after GUCP/ETCA separation.

E40 Typical ice/frost from 17-inch disconnects. Ice/frost from right side of ET forward of ET/Orbiter Forward Attach Bipod impacts Orbiter at 038:23:13:15.354 UTC. No damage observed.

E52 Pad debris noted rising and falling. Typical debris observed falling aft of vehicle. Debris-induced streak in SSME plume. Typical ice/frost from 17-inch disconnects. Free burning Hydrogen impinges on base of the vertical stabilizer. Purge barrier material noted falling aft of vehicle. Debris ejected from SRB plume.

E57 Typical debris observed falling aft of vehicle. Typical ice/frost from 17-inch disconnects. Foam debris from SRB plumes observed.

E62 Free burning Hydrogen observed.

E63 Pad debris noted rising and falling. Typical debris observed falling aft of vehicle. Free burning Hydrogen observed impinging on the base of the vertical stabilizer.

E204 Vehicle intermittently obscured by clouds. Linear optical distortions observed after SRB separation. Glowing debris particles ejected from SRB plumes prior to and after SRB separation.

E205 Glowing debris particles ejected from SRB plume prior to, during and after separation. Flow recirculation noted. Several large debris induced streaks in SSME plumes observed. OMS motor firing observed shortly after SRB separation. Vehicle imaged low in frame. Processing marks noted on film.

E207 Typical debris observed falling aft of vehicle. Glowing debris particles ejected from SRB plume prior to, during and after separation. Linear optical distortions noted. Flow recirculation noted. Debris induced streaks observed in SSME plumes. Purge barrier material observed flapping during early ascent. Numerous pieces of unknown debris, possibly Orbiter tiles, were observed coming from near left OMS pod area just prior to SRB separation. Additionally, during this time frame, a debris object was noted on the right side of the vertical stabilizer.

E212 Glowing debris particles ejected from SRB plume prior to, during and after separation. Debris observed over right wing (frame 7970) just prior to separation, as noted on E207. Processing marks noted on film.

E213 Butcher paper from forward RCS was observed falling along side of the orbiter at 038:23:13:26.759 (frame 2649) and at 038:23:13:31.629 (frame 3122). Butcher paper was also observed falling along the top of the orbiter at 038:23:13:32.403. This camera experienced poor tracking for the last half of vehicle ascent.

E220 Contrail noted off left wing early in ascent. Typical debris falling aft of vehicle. Several pieces of debris (>10) observed simultaneously coming from forward on the orbiter and flowing over

the right wing (frame 4096). Large debris induced streak (frame 4878) was observed. Film processing marks were observed.

E222 Pad debris noted rising and falling. Debris induced streaks in SSME plumes observed at 038:23:13:37:753 UTC and 038:23:13:41:157 UTC. Film exposure too light.

E223 Typical debris observed falling aft of vehicle. Glowing debris particles ejected from SRB plume prior to, during and after separation. Large debris induced streaks in SSME plumes (frames 3945, 4255, 4426, 5295).

E224 Pad debris noted rising and falling. A large debris induced streak in SSME plumes was observed at 038:23:13:25.305 UTC. Typical debris ejected from SRB plumes was observed.

For further information concerning this report contact Tom Rieckhoff/TD53 at 256-544-7677 or Michael O'Farrell at 256-544-2620.

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NASA, John F. Kennedy Space Center
Process Engineering, Mechanical Systems Division
ET/SRB Branch, Mail Code: PH-H
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14. ABSTRACT

A debris / ice / thermal protection system assessment and integrated photographic analysis was conducted for Shuttle Mission STS-98. 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 debris / ice / thermal protection system conditions and integrated photographic analysis of Space Shuttle mission STS-98 and the resulting effect on the Space Shuttle Program.

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5301 Bolsa Ave.
Huntington Beach, CA 92647

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