A HISTORY OF METEOROID AND ORBITAL DEBRIS IMPACTS ON THE SPACE SHUTTLE

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ABSTRACT

This paper describes observations and analyses of meteoroid and debris impact damage on the Space Shuttle Orbiter. NASA's Space Transportation System Orbiter has been in service since 1981. The reusable nature of the orbiter necessitates post-flight inspection and repair of exterior thermal protection system surfaces. Since 1992, post flight inspections have included an assessment of meteoroid/debris impacts in selected areas of the vehicle. Hypervelocity impact sites are identified post-flight on the crew module windows, payload bay door radiators, payload bay door exterior insulation and wing leading edge surfaces and subjected to sample collection and analysis. One product of the analyses is determination of impactor source (meteoroid or orbital debris) by scanning electron microscope (SEM) energy dispersive x-ray analysis (EDXA) of residual impactor materials recovered from the impact site.

1. HISTORY OF ORBITAL DEBRIS EFFECTS ON SHUTTLE DESIGN AND OPERATION

The first confirmed orbital debris impact to a Space Shuttle Orbiter Vehicle (OV) occurred on STS-7, by a piece of paint which left a 3.8mm diameter by 0.43mm deep pit in the right-side middle window (#5) of OV-099. In June 1992, STS-50 was the first extended duration orbiter (EDO) mission conducted over 13.8 days in a predominately payload bay forward attitude. After STS-50, 43 impact damage sites were found on the radiators, four of which perforated the outer thermal tape and underlying aluminum facesheet [1]. In addition, 6 impacts occurred to STS-50 windows, with 3 windows replaced. Orbital debris impacts, from paint and titanium metal, were responsible for the largest damages to STS-50 radiators and windows, respectively. The level of damage found after STS-50 represented about 10 missions worth of damage under typical flight conditions at the time. The long duration in a payload bay forward attitude was established as the single most likely reason for the increased damage sustained on this mission. Flight rule 2-77 was implemented in October 1992 to limit the amount of to baseline "preferred" Shuttle attitudes for debris protection, namely tail forward, payload bay toward Earth [7].

Other major events in the evolution of meteoroid/orbital debris protection for the Shuttle include:

- STS-73 in October 1995 was the first mission that used a partially closed payload bay door as a "bumper" shield. This 15.9 day mission flew in a predominately port wing forward, nose space attitude, with the port side payload bay door open only one-third of normal. The door in this position protected the radiator surfaces and the payload bay contents including the SpaceLab and cryogenic oxygen/hydrogen tanks in the EDO pallet. The largest confirmed orbital debris impact ever was found on this mission [2]. A 1mm diameter by 3mm long piece of lead-tin solder was recovered in a 17mm diameter cavity in the fibrous insulation material used on the exterior of the port side payload bay door (Table 1).
- Modifications to improve the survivability of the Orbiter in the meteoroid/debris environment are considered by the "Schneider Team" study conducted from 1995-1996. The Shuttle Program accepts recommendations to enhance the survivability of the Orbiter active thermal control system by adding "doublers" over the radiator panel coolant tubes and to include automatic shut-off valves in the coolant systems [8]. Another recommendation is accepted to enhance vehicle/crew safety by including Nextel ceramic fabric within insulators of the structural attachments of the wing leading-edge panels [8]. These design upgrades are implemented on all Orbiter Vehicles in the 1998-2000 time frame.
- After STS-86 in September 1997, an impact was found on an exterior radiator manifold that connects separate radiator panels on the Orbiter. Subsequent interior inspection of the radiator line showed a region of detached spall under the impact site [3]. This near perforation of the interconnect lines alerted the Shuttle Program to the

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vulnerability of the relatively lightly shielded interconnect lines.

Additional information on Shuttle debris protection can be found elsewhere [9-10].

2. METEOROID AND ORBITAL DEBRIS (M/OD) IMPACTS ON ORBITER VEHICLES

The Orbiter has since 1992 been visually inspected on a regular basis for meteoroid/debris damage during normal vehicle refurbishment following each Space Shuttle mission [1-6]. Samples of impact damage with identifiable hypervelocity impact features are returned to the laboratory for analysis. Of the 54 missions flown from STS-50 (June 1992) through STS-97 (November 2000), 43 have had post-flight inspections to identify meteoroid and debris impacts. Orbiter radiator and windows represent the majority of regularly sampled surfaces (~10% of the total surface area of the vehicle), as thermal tiles and other surfaces exposed to reentry heating are not as suitable for sampling (Fig.1). The samples are subjected to analysis by scanning electron microscope equipped with energy dispersive x-ray (SEM/EDX) spectrometers to determine elemental constituents of projectile residues. From this data, a determination is made as to type of impactor (meteoroid or debris) and category for the debris damage (e.g., paint, aluminum structure, solid rocket motor exhaust, electrical component, etc.) using standard procedures [4].

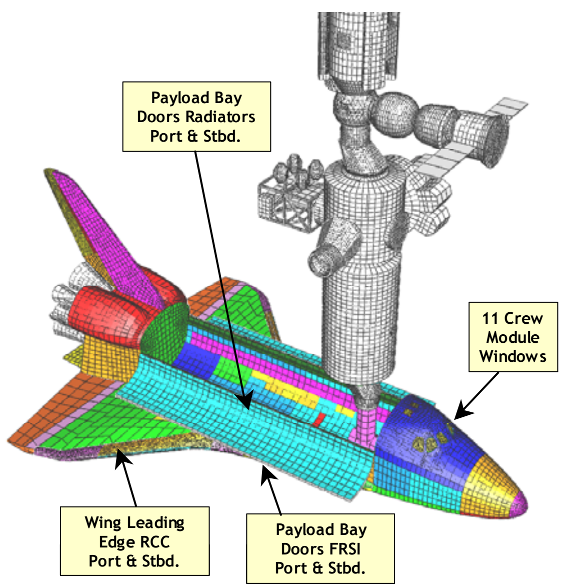

Fig. 1. Orbiter surfaces inspected for meteoroid/debris impact damage

2.1 Top 20 Meteoroid/Debris Impacts

Table 1 summarizes the data for the 20 most significant impacts that occurred to the Orbiter from STS-50 through STS-97. The impacts are presented by estimated impactor size and mission number for 3 different Orbiter areas: windows, radiators, and other surfaces.

Of the 20, orbital debris caused a clear majority of the total damage, and also resulted in the largest damage for each of the three location categories.

2.2 Window Damage

The largest impact to an Orbiter window occurred on STS-92, which was International Space Station (ISS) Flight 3A. A crater 10mm diameter by 1.9mm deep was found on the port-middle (#2) debris pane (Fig.2). SEM/EDX analysis indicated the cause of the damage was a piece of paint (orbital debris). The window was replaced. Based on average impact conditions for this mission (impact velocity of 9.3km/s and impact angle of 45^{o}), the crater geometry can be best explained by a 0.76mm diameter by 0.3mm thick paint chip that impacts the window in an edge-on orientation.

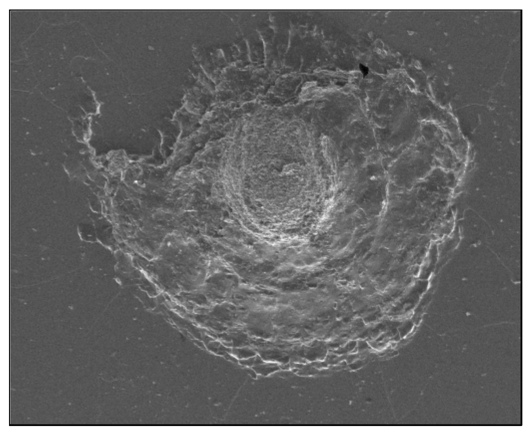

Fig. 2. STS-92 Left Hand (LH) #2 window crater caused by spacecraft paint debris impact (crater is 10mm diameter x 1.9mm deep)

Generally there are many small impacts found on the Shuttle windows that do not cause any concern. In some cases, the impacts are large enough to require the window to be replaced, because of the potential for flaw growth during subsequent launch/landing cycles. The replacement criteria vary for each window on the Orbiter and location of the flaw, because of the different stresses experienced by the windows during launch. Although 1385 impacts were recorded on the windows, only 76 were large enough to cause the window to be replaced due to hypervelocity impact damage over the

STS-50 through STS-97. Of the 76 impact replacements, SEM/EDXA revealed 32 were from orbital debris, 17 from meteoroids and 27 were unknown (no definitive SEM/EDXA results) or had no sample returned. Fig.3 illustrates the composition of orbital debris for the 32 debris impacts that caused a window replacement. Aluminum containing debris results in about half of the window replacements due to orbital debris impacts (which are ~1/2 of the total replacements). Paint, steel, titanium and copper cause the other large impacts.

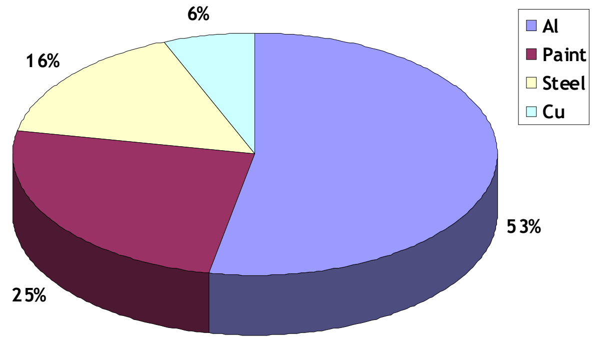

Fig. 3. Composition of orbital debris particles that caused 32 window replacements during the period from STS-50 (June 1992) through STS-97 (November 2000)

Table 1. Top Twenty Meteoroid/Debris Impacts Identified on Orbiter Windows, Radiators and other surfaces from STS-50 through STS-97

WINDOWS

Mission #	Duration (days)	Window Location	Flaw Dia. (mm)	Crater Depth (mm)	Particle Type (SEM/EDXA results)	Est. Particle Dia. (mm)
STS-92	12.9	#2, LH middle	10.0	1.9	orbital debris: paint	0.76 x 0.3
STS-94	15.7	#7, RH overhead	8.2	0.55	orbital debris: metallic Al	0.24
STS-59	11.2	#11, side hatch	12.0	0.57	orbital debris: paint	0.22
STS-50	13.8	#4, RH forward	7.2	0.57	orbital debris: Titanium metal	0.20

RADIATORS

Mission #	Duration (days)	Radiator Location	Tape Hole Dia. (mm)	Facesheet Hole Dia. (mm)	Particle Type (SEM/EDXA results)	Est. Particle Dia. (mm)
STS-80	17.7	RH #4	5.5	2.8	orbital debris: stainless steel	1.7
STS-103	8.0	LH #4	4.2	0.7	orbital debris: Na, K	1.1
STS-80	17.7	LH #4	3.2	2.0	orbital debris: stainless steel	1.0
STS-85	11.9	RH #4	5.0	1.3	meteoroid	0.7
STS-59	11.2	RH #1	5.3	perf	meteoroid	0.7
STS-73	15.9	LH #4	8.3	1.1	orbital debris: paint	0.6
STS-50	13.8	LH #1	3.8	1.1	orbital debris: paint	0.5
STS-86	10.8	ext.manifold-1	0.9 Dia.	0.5 Depth	orbital debris: stainless steel	0.4

OTHER ORBITER COMPONENTS AND PAYLOADS

Mission #	Duration (days)	Impact Location	Damaged Material	Hole Dia. (mm)	Particle Type (SEM/EDXA results)	Est. Particle Dia. (mm)
STS-73	15.9	Flexible Reusable Surface Insulation (FRSI) exterior PLB door LH #4	Nomex Felt	17	orbital debris: Pb/Sn solder, circuit board components	3 length x 1 dia.
STS-84	9.2	Flexible Reusable Surface Insulation (FRSI) exterior PLB door RH #2	Nomex Felt	12	orbital debris: metallic Al	2.1
STS-72	8.9	thermal spring seal of rudder speed brake	Inconel, RTV	3.4	orbital debris: metallic Al	1.3
STS-75	15.7	tethered satellite system pallet trunnion	Titanium	1.0	orbital debris: metallic Al	0.8
STS-56	9.3	reflector of Ku-band antenna	Graphite-Epoxy	1.4	meteoroid	0.6
STS-92	12.9	conical seal vertical stabilizer	Inconel	1.2	orbital debris: stainless steel	0.4
STS-94	15.7	conical seal of vertical stabilizer	Inconel	0.9	meteoroid	0.4
STS-55	10.0	DEA box of Ku-band	Ag-Teflon	4.1	orbital debris:	0.3

Radiator Damage

The Orbiter radiators consist of a silver-teflon thermal control coating over a honeycomb panel with aluminum facesheets. Under most circumstances, it is difficult to determine in SEM/EDX analysis of collected damage samples when a projectile contains aluminum as there is a strong aluminum signal from target materials.

Probably the severest impact to the Shuttle fleet as is it represents a "near miss" of a major problem is the impact found on a radiator line after STS-86 [3]. Post-flight inspection of OV-104 (*Atlantis*) radiator panels after mission STS-86 found a significant hypervelocity impact in the external manifold hard line that extends along the two forward panels (Fig. 4).

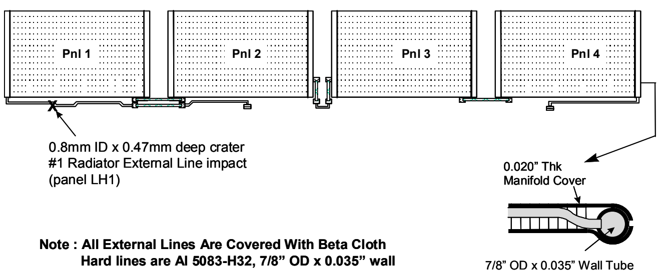

Fig. 4. External manifold impact location post STS-86

The impact penetrated through a beta cloth cover, crossed a 6.4mm (0.25 inch) gap, and left a 0.8 mm diameter by 0.47 mm deep crater in the manifold hard line (Fig. 5). The aluminum external hard lines are 0.9mm (0.035 inch) thick in the impacted region. From hypervelocity impact data, the crater depth to wall thickness ratio of 0.52 indicated spall effects were likely on the inside of the line at the point of impact [13]. A borescope inspection of the line interior was conducted to assess internal damage and a small area of detached spall was found on the inside of the tube under the impact site (Fig. 6). This indicates the impact very nearly put a hole in the external manifold that would have caused a leak of freon coolant, potentially shortening the mission. Mission rules dictate that a leak in one of the Orbiter's two radiator systems will result in a next primary landing site (PLS) abort. The Orbiter Project Office determined that an upgrade to the meteoroid/debris protection of the radiator external lines was needed, and additional two ply beta-cloth sleeves were installed on all external radiator lines.

Samples obtained for SEM/EDX analysis included the perforated beta cloth thermal cover and tape pull samples from the external line. Analysis found iron (Fe), chromium (Cr), and nickel (Ni) on the beta cloth (teflon-glass background) and in the external line samples, indicating the damage was caused by a stainless steel orbital debris particle (approximately 0.4mm diameter as indicated in Table 1).

Fig. 5. Crater (0.8mm dia. by 0.47mm deep) in the 0.9mm thick aluminum line. SEM/EDXA revealed the impactor was a steel debris particle

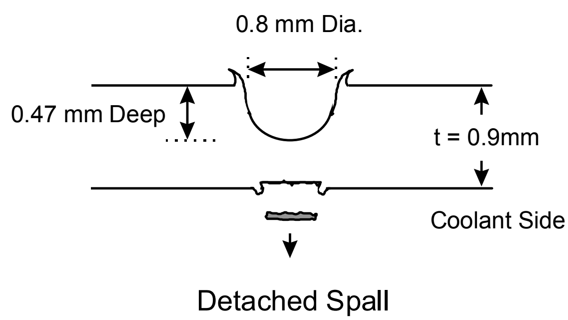

Fig. 6. Crater profile in external line. Detached spall found on inside of line in boroscope inspection. Small metal pieces were found in a coolant pump strainer post-flight.

3. PARTICLE SIZE ESTIMATES

An estimated projectile size for each impact is determined using results from hypervelocity impact tests and analysis [11-12]. The penetration equations that are used in this assessment are described in detail elsewhere [3, 13-15]. SEM/EDX analysis results were used to specify the density of the particle for the penetration equations used to estimate particle size. In addition, the projectile size estimates are based on the average impact velocity conditions for the meteoroid and debris environment. The calculations assume a 45^o average impact angle. Potential particle sizes causing the damage can be higher or lower depending on assumed velocity of impact.

A sensitivity analysis on estimated projectile size has been accomplished [3]. The sensitivity analysis indicates that the range of potential projectile sizes for a particular impact (within a 1-sigma velocity range centered on the mean) is influenced more by the low velocity component than the high end of the velocity range (Fig. 7). This analysis indicates average estimated particle size causing orbital debris damage given in Table 1 is biased toward the lower end of the potential size range.

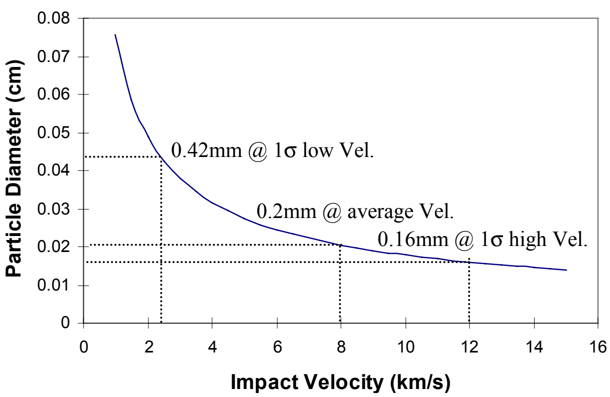

Fig. 7. Particle size sensitivity analysis considering 1-sigma variation in possible debris impact velocities for the STS-50 window #4 impact

4. COMPARISON OF ORBITER IMPACT DAMAGE TO BUMPER PREDICTIONS USING ORDEM96 DEBRIS ENVIRONMENT MODEL

The BUMPER code is the NASA standard meteoroid/debris analysis code [12]. BUMPER includes the meteoroid and debris environment models documented in [16-17]. Orbiter hypervelocity impact damage and penetration equations described in section 3 are implemented in BUMPER to predict Orbiter impact damage. The as-flown attitude time-line (ATL) is decomposed into typically 100-200 different attitude/duration combinations for each mission in the post-flight predictions of expected orbital debris damage using ORDEM96 [17]. The geometry models include shadowing effects from large structures such as ISS or MIR that are present during a portion of some missions (Fig. 1). Comparison of cumulative predicted to actual orbital debris damage over 21 shuttle missions assessed to-date is given in Fig. 8. As shown, actual radiator and window damage exceeds predicted using ORDEM96 by factors of 2 or more.

It should be noted that all "Unknowns" in the window impact database have been classified as "meteoroids", so that the on-orbit debris impact total shown in Fig.8 potentially undercounts debris impacts to the windows. More details on these assessments can be found elsewhere [6, 18-19].

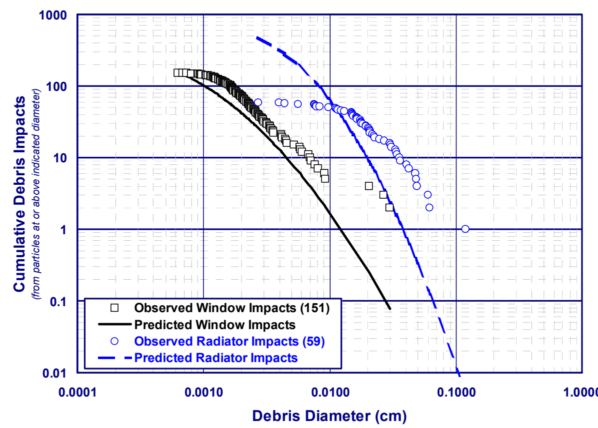

Fig. 8. Comparison of window and radiator damage (actual in circles/squares) to predicted (lines) Cumulative for 21 Flights: STS-50, 56, 71, 72, 73, 75, 76, 77, 79, 80, 81, 84, 85, 86, 87, 88, 89, 91, 94, 95, 96

5. CONCLUDING REMARKS

The Shuttle Program has implemented design and operational changes to reduce the risk from meteoroid/debris impact. To-date, meteoroid/debris damage has not resulted in significant effects to Shuttle missions; i.e., no mission has been terminated early and no damage has compromised crew safety. Meteoroid/orbital debris damage has resulted in replacement of windows, repair to radiator surfaces, and repair/refurbishment of other hardware.

Orbital debris represents the majority of the largest impacts to Orbiter surfaces (16 of the top 20 impacts to Orbiter windows, radiators and other surfaces).

Actual damage from orbital debris exceeds predicted values using BUMPER and the 1996 Orbital Debris Model (ORDEM96). Forward work includes updating the assessment for the 2000 Orbital Debris Model (ORDEM2000) and including the latest mission results.

6. REFERENCES

1. Christiansen E. L., Bernhard R.P., Hyde J.L., Kerr J.H., Edelstein K.S., Ortega J., Crews J.L., Assessment of High Velocity Impacts on Exposed

Space Shuttle Surfaces, *Proceedings of the First European Conference on Space Debris*, ESA SD-01, pp.447-452, 1993.

2. Christiansen E.L. and Bernhard R.P., STS-73 Meteoroid/Orbital Debris Impact Damage Assessment Report, JSC-27323, NASA Johnson Space Center, 1995.

3. Christiansen E.L., Bernhard R.P., Hartsough N., Orbiter Meteoroid/Orbital Debris Impacts: STS-50 (6/1992) through STS-86 (10/1997), NASA JSC-28033, 1998.

4. Bernhard R.P., Christiansen E.L., and Kessler D.J., Orbital Debris as Detected on Exposed Spacecraft, *Int. Journal Impact Engineering,* 20, pp.111-120, 1997.

5. Hyde J.L., *et al.*, STS-92 Orbiter Meteoroid/Orbital Debris Impact Damage Analysis, JSC-29318, 2001.

6. The NASA Johnson Space Center Hypervelocity Impact Technology Facility (HITF), web site, http://hitf.jsc.nasa.gov/hitfpub/main/index.html

7. Levin G. and Christiansen E.L., The Space Shuttle Program Pre-Flight Meteoroid and Orbital Debris Risk/Damage Predictions and Post-Flight Damage Assessments," ESA SP-393, *Proceedings of the Second European Conference on Space Debris*, pp. 633-636, 1997.

8. Loftus J.P., Christiansen E.L., Schneider W.C., and Hasselbeck M., Shuttle Modifications for Station Support, IAF-97-IAF.I.3.08, 48th International Astronautical Congress, October 6-10, 1997.

9. Jensen T.E., Loyd S.E., Whittle D.W., Christiansen E.L., Visible Effects of Space Debris on the Shuttle Program, IAA-97-IAA.6.4.02, 48th International Astronautical Congress, October 6-10, 1997.

10. National Research Council, Protecting the Space Shuttle from Meteoroids and Orbital Debris, National Academy Press, 1997.

11. Crews J.L. and Christiansen E.L., "The NASA JSC HITF," AIAA Paper No.92-1640, 1992.

12. Christiansen E.L., Design Practices for Spacecraft Meteoroid/Debris (M/D) Protection, *Hypervelocity Shielding Workshop Proceedings*, Institute of Advanced Technology Catalog Number IAT.MG-0004 (1999).

13. Christiansen E.L., "Design and Performance Equations for Advanced Meteoroid and Debris Shields," *Int. Journal Impact Engineering*, 14, pp. 145-156, 1993.

14. Christiansen E.L., Curry D.M., Kerr J.H., Cykowski E., and Crews J.L., Evaluation of the impact resistance of reinforced carbon-carbon, Proceedings of the ninth International Conference on Composite Materials (ICCM-9), Madrid Spain, 1993.

15. Christiansen E.L. and Friesen L., "Penetration Equations for Thermal Protection Materials," *Int. Journal Impact Engineering,* 20, pp.153-164, 1997.

16. NASA, Meteoroid and Debris Environment Model, "Space Station Program Natural Environment Definition for Design," SSP-30425, Rev.B, 1993. http://ts0101r.jsc.nasa.gov:8800/cgi-bin/docchk?27023

17. Kessler D.J., *et al.,* "A Computer-Based Orbital Debris Environment Model for Spacecraft Design and Observations in Low Earth Orbit," NASA TM 104825, 1996. Document available at: http://sn-callisto.jsc.nasa.gov/model/ordem96.html

18. Hyde J.L., *et al.* Shuttle Post-Flight Assessment Report, Part I Shuttle/MIR flights: STS-71, 76, 79, 81, 84, 86, 89, 91, NASA Johnson Space Center Report, JSC-28768, January 2000.

19. Hyde J.L., *et al.* Shuttle Post-Flight Assessment Report, Part II flights: STS-50, 56, 72, 73, 75, 77, 80, 85, 87, 88, 94, 95, 96, NASA Johnson Space Center Report, JSC-29070, September 2000.