IIB. Major Modifications

General Overview

Until 2002, all major mid-life overhauls of the orbiters, including both OMDP and OMM activities, were accomplished at Palmdale.[329] The last OMM at Palmdale, for OV-102, was performed during a 517-day period between September 26, 1999, and February 23, 2001. Starting with OV-103 in September 2002, NASA relocated the orbiter overhaul and upgrade activities from Palmdale to KSC, on the basis of both cost factors and program impacts. When OMDPs/OMMs were performed at Palmdale, USA subcontracted the work to Boeing. When modifications were done at KSC, USA performed the work.[330]

The SSP required an OMM every eight flights for each orbiter, or approximately every three years.[331] Work included the incorporation of new equipment or changes to existing equipment or structures, and both routine and special inspections. Inspections were to verify structural integrity and to identify and mitigate any corrosion or wear of components.[332] Maintenance procedures, deferred work, and correcting "stumble ons" also were performed during an OMDP. Of the twelve OMMs performed in the history of the SSP, eight were performed at the Palmdale facility, and four at KSC. Historically, the duration of each OMM has varied from 5.7 months to 19.5 months. The 1997-1998 OMM of *Atlantis* (OV-104), which included the first installation of the MEDS "glass cockpit," was "the most extensive orbiter modification and maintenance project in the program's history;" it entailed 443 structural inspections and 363 modifications.[333]

Typically, OMMs and upgrades served a number of purposes: to improve safety, to enhance performance, to improve ground turnaround processing, to add new technology, to cut operational costs, to add capability, and to combat obsolescence. In terms of level of importance when it comes to implementation, Bill Roberts believed that "Safety is number one, flight performance number two, and then ground turnaround processing."[334] In addition to the major changes in the aftermath of the *Challenger* (RTF-1) and *Columbia* (RTF-2) accidents, orbiter

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[329] An OMDP is defined by NASA as a period of time when one of the orbiters is taken out of service for detailed structural inspections and thorough testing of its systems before returning to operational status. These periods also provided opportunities for major modifications and upgrades. (NASA, "Human Space Flight Fiscal Year 1996 Estimate Budget Summary," http://www.hq.nasa.gov/office/budget/fy96/hsf_3.html). Given the variety of applications of the terms OMDP and OMM in the source literature, OMDP and OMM generally are used synonymously throughout this document.

[330] NASA Office of Inspector General, "Followup Audit on Orbiter Maintenance Down Periods at KSC," 1998, http://www.hq.nasa.gov/office/oig/hq/audits/reports/FY98/executive_summary/ig-98-016e.

[331] In actuality, this interval was exceeded because of scheduling complexities. For example, OV-102 had nine flights and four years between its J2 and J3 OMMs; OV-103 had nine flights and four and one-half years between its J2 and J3. CAIB, *Report, Volume II*, 415.

[332] Boeing, *OV-103, Volume II*, 52.

[333] Jay Levine, "Inside Atlantis Modifications and Maintenance near end in Palmdale," *X-Press*, September 18, 1998, 4, http://www.dfrc.nasa.gov/Newsroom/X-Press/1998/Sep18-TX/page4-TX.html.

[334] Roberts, interview, 37.

modifications were made to support specific mission goals, such as extending flight duration in support of the ISS. Other upgrades were part of programmatic weight reduction measures. Also, many changes were implemented during process flows between flights. As the last orbiter to join the fleet, *Endeavour* benefitted from lessons learned. Thus, it was originally built with a drag chute, improved nose wheel steering system, improved hydraulic power units, and upgraded avionics systems, all features which the other orbiters acquired during later, post-assembly modifications.[335] The following table provides the start and end dates, as well as duration, for each OMM performed during the SSP.

Schedule of Orbiter Major Modifications[336]

Orbiter Vehicle	OMM Designation	OMM Start Date	OMM End Date	Duration (in months)
OV-102	"AA"	January 25, 1984	September 11, 1985	18
OV-102	(non-OMDP) (J1)	August 15, 1991	February 7, 1992	5.7
OV-103*	OMDP-1 (J1)	February 17, 1992	August 17, 1992	7
OV-104	OMDP-1 (J1)	October 19, 1992	May 27, 1994	19.5
OV-102	OMDP-1 (J2)	October 13, 1994	April 10, 1995	6
OV-103	OMDP-2 (J2)	September 29, 1995	June 24, 1996	9
OV-105	OMDP-1 (J1)	July 30, 1996	March 24, 1997	8
OV-104	OMDP-2 (J2)	November 14, 1997	September 21, 1998	10.2
OV-102	OMDP-2 (J3)	September 26, 1999	February 23, 2001	17
OV-103*	OMDP-3 (J3)	September 1, 2002	April 1, 2004	19
OV-104*	RTF-2	June 2003	September 2006	28
OV-105*	OMDP-2	December 1, 2003	October 6, 2005	22

*Performed at KSC

Historically, during the first decade of the SSP, NASA undertook major upgrade programs to respond to problems and anomalies experienced during the initial flights. These initial upgrades included the replacement of several thousand insulation tiles with insulation blankets, and modifications to the wheel brakes and APUs.[337] During the approximate two-and-one-half year post-*Challenger* RTF period, more than 200 changes were made to the shuttle system, including the addition of a limited crew escape capacity, stronger landing gear, more powerful flight control computers, and updated inertial navigation equipment.[338] In the early 1990s, structural modifications enabled the shuttle to rendezvous and dock with the *Mir* space station and to support the ISS. Included was the development of a new airlock and docking system as well as weight reductions to allow for increased payload capacity. In the early 1990s, orbiter storage hardware was changed from aluminum to composite or fabric structure.[339] These modifications

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[335] USA Communications, "Orbiter Upgrades," *Shuttle Reference and Data*, April 6, 2000, http://www.shuttlepresskit.com/STS-101/REF125.htm.

[336] Boeing, *OV-103, Volume II*, 52; Boeing, *OV-104, Volume II*, 47; CAIB, *Report, Volume II*, 416.

[337] National Research Council, *Upgrading the Space Shuttle* (Washington, DC: National Academy Press, 1999), 9.

[338] NASA JSC, *The 21st Century Space Shuttle*, NASA Fact Sheet (Houston: Johnson Space Center, 2000), spaceflight.nasa.gov/spacenews/factsheets/pdfs/21stCenturyShuttle.pdf.

[339] NASA, *Space Shuttle Program 1999 Annual Report*, 23, http://www.spaceflight.nasa.gov/shuttle/reference/.

resulted in a total weight reduction of more than 600 pounds, as detailed in the table which follows below.

In FY 1997, NASA lifted a "design freeze," imposed the year before, and authorized the SSP to dedicate about $100 million each year to a new upgrade program. This funding went primarily to relatively minor modifications intended to "reduce obsolescence, support missions, improve safety, and reduce costs."[340] In the standdown following the 2003 *Columbia* accident, safety improvements included the expanded use of enhanced imaging equipment, such as the cameras and devices housed in the new OBSS.

Weight Reductions

Like the external tanks, a major evolutionary change for the five operational orbiters was a decrease in overall weight over time. Beginning with *Challenger*, each orbiter was lighter than her predecessor as knowledge was applied from prior construction and assembly. At rollout, *Columbia*, the heaviest orbiter, weighed 158,289 pounds. *Challenger* weighed 155,400 pounds; *Discovery* weighed 151,419 pounds; *Atlantis* weighed 151,315 pounds; and *Endeavour* weighed 151,205 pounds. *Endeavour*, in particular, benefited from the lessons learned from the older shuttles.[341]

Orbiter Storage Hardware Weight Reductions[342]

Part Description	**Old Weight**	**New Weight**	**Weight Reduction**
Lithium hydroxide rack assembly	97	27	70
Ceiling pallet	30	13	17
Floor pallet	27	14	13
External airlock pallet	47	26	21
Pallet assembly EMU (Extravehicular Mobility Unit) adapter	36	22	14
Locker trays (shipset)	164	75	89
Mid-deck lockers (shipset)	495	295	200
Mid-deck accommodations rack	220	100	120
Tool stowage assembly	150	75	75
Totals	1266	647	619

Beginning in 1995, crew seats were made with aluminum alloys, which cut their weight from 110 pounds to 49 pounds.[343] Since the mid-1990s, weight was decreased on the shuttles during OMDPs/OMMs, including the switchover from AFRSI to FRSI on the canopy and wing tip was

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[340] National Research Council, *Upgrading the Space Shuttle*, 1. Implementation of major upgrades was contingent upon whether the shuttle would be phased out by 2012.

[341] Jenkins, *Space Shuttle*, 242-243.

[342] NASA, *Space Shuttle Program 1999 Annual Report*, 23.

[343] Michael Klesius, "Evolution of the Space Shuttle," *Air & Space Magazine*, July 2010, http://www.airspacemag.com/space-exploration/Evolution-of-the-Space-Shuttle.html.

made during the second OMDP for both *Discovery* and *Atlantis*, and during the first OMDP for *Endeavour*. Similarly, the wheel well tape replacement and redesign of the flipper doors were made during *Discovery* and *Atlantis*' second OMDP, and *Endeavour's* first. Crew equipment hardware changes were effected during the first OMDP for both *Discovery* and *Atlantis*; this weight saving measure was incorporated into *Endeavour's* original build. The modifications resulted in 1,652 pounds of savings, in addition to the approximately 600 pounds that was removed from the orbiter's storage hardware in the early 1990s, as already noted.[344] These weight-saving modifications are provided in the following table.

Summary of Orbiter Weight Saving Modifications[345]

Modification	**Weight Savings (in pounds)**
TPS Modifications	
Payload bay doors and mid AFRSI to FRSI	490
Canopy and Wing Tip AFRSI to FRSI	137
Upper Wing AFRSI resizing	70
Aft fuselage sidewall AFRSI to FRSI	101
Wing and Elevon FRSI resizing	30
Payload bay doors FRSI resizing	126
Subtotal	**954**
Other Modifications	
Wheel Well Tape Replacement	39
Flipper Door Redesign	520
Delete OMS/RCS High Point Bleed Lines	30
Delete RCS Sniff Lines	60
Delete FRCS Heat Sink	49
Subtotal	**698**
Crew Equipment Hardware	500-600

Post- Challenger and Post-Columbia Major Modifications

Significant changes were made to the orbiter fleet in the aftermath of both the *Challenger* and *Columbia* accidents. In the aftermath of the *Challenger* accident, and following the recommendations of the Rogers Commission, the orbiters each received seventy-six modifications.[346] The most significant changes during this effort included a crew escape system, carbon brakes, a new drag chute, and improved nose wheel steering and brake controls.

Crew escape system: NASA initially believed a crew escape system was unnecessary on the shuttles.[347] However, in the aftermath of the *Challenger* accident, the Rogers Commission

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[344] Boeing, *OV-104, Volume II*, 64.

[345] Information derived from Boeing, *OV-104, Volume II*, 61-64.

[346] Jenkins, *Space Shuttle*, 278-282.

[347] On the first four shuttle missions, *Columbia* had ejection seats for two astronauts. On STS-5, with a crew of five, the seats were disabled. After STS-9 (November-December 1983), the seats were removed. Klesius, "Evolution of

recommended its implementation. After considering their options, NASA elected to install a telescopic slide pole in the orbiters. In an emergency, the side hatch on the shuttle would be jettisoned, the pole would be extended, and the astronaut(s) would slide down the pole and parachute to safety. As designed, the system was effective when the orbiter was below 30,000' and in a glide no faster than 230 miles per hour (mph).[348] *Discovery* was the first orbiter to undergo the modification, and work was completed on April 15, 1988, in time for RTF-1. Thereafter, the crew escape system was installed in *Atlantis* and *Columbia* and built into *Endeavour* at the time of original construction.[349]

Carbon brakes: Following the *Challenger* accident, the original beryllium brakes were replaced with carbon brakes. This design improvement increased the reuse and refurbishment capability while minimizing weight. Historically, the original brakes on each of the main landing gear wheels were designed for a lighter shuttle than was created, and brake damage occurred on the first twenty-four space shuttle landings. As a result, shuttle weight constraints were instituted, brake use was limited to speeds of 205 mph or less, and landings were restricted to Edwards AFB after *Discovery* blew a tire at KSC in 1985. During RTF-1 modifications, improved carbon-lined beryllium stator discs were installed on *Discovery* and *Atlantis* as a temporary solution, and a program was created to develop all-carbon brakes. Those brakes premiered in 1990 on *Discovery* for STS-31, and subsequently were installed on the other orbiters during OMDPs. The new brakes functioned at braking speeds of up to 260 mph and could stop quicker than the first two shuttle brake systems. They also were capable of reuse on up to twenty landings, as opposed to the one-time use for their predecessors.[350]

Orbiter Drag Chute: NASA originally intended the space shuttles to have a parachute braking system, but the idea was abandoned in 1974 because it was believed Edwards AFB's dry lake bed provided sufficient landing distance. As a result, without a drag chute system, orbiter landings in the early days of the SSP resulted in excess tire and brake wear. *Endeavour's* landing at Edwards AFB at the conclusion of STS-49 (May 1992) was the first use of a drag chute to reduce wear on the brakes and reduce rollout distance by up to 2,000 feet. The orbiter drag chute also increased vehicle stability when directional control input was required. *Endeavour* received its drag chute as part of her original build; the other orbiters were retrofitted with this feature during OMDPs in the early 1990s.[351] The new drag chute system, built by Rockwell at the Downey plant, consisted of a mortar-deployed pilot chute that extracted the deceleration drag chute. It was designed to stop the shuttle in 8,000' with a 10 knot tail wind and a temperature of 103 degrees F. The drag chute was manually deployed after touchdown at speeds of 230 knots or less, and was jettisoned at approximately 60 knots to prevent damage to the SSME bells.[352]

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the Space Shuttle."
[348] Klesius, "Evolution of the Space Shuttle."
[349] Jenkins, *Space Shuttle*, 370-371.
[350] Jenkins, *Space Shuttle*, 410-411.
[351] Boeing, *OV-103, Volume II*, 57.
[352] Jenkins, *Space Shuttle*, 411 and 437.

Development of the drag chute was preceded by tests of an experimental drag chute carried on NASA's NB-52B research aircraft. In 1990, researchers at DFRC conducted a series of eight chute deployment tests, landing at speeds ranging from 160 to 230 miles per hour. Landings were made at both the lakebed runways and concrete strip at Edwards AFB. The successful test series "helped validate the effectiveness of the chute in reducing the rollout distance and brake wear during shuttle landings."[353]

Improved Nose Wheel Steering System: Installation of this modification consisted of hydraulics and avionics upgrades which improved the systems' performance and reliability. Originally, the nose wheel steering system installed on *Columbia* was not effective at maneuvers conducted at high speeds, and it was deactivated on that shuttle. *Challenger* also had the system, but it was never activated; both *Atlantis* and *Discovery* had the capability for nose wheel steering installation, but it was never effected on either. Beginning in 1991, the nose wheel steering systems on *Columbia*, *Atlantis,* and *Discovery* were modified; *Endeavour*, which rolled out that year, was built with the new nose wheel steering system already in place. The improvement provided better control and was operable electro-hydraulically through either the general purpose computers or the rudder pedals.[354]

The **post-*Columbia* RTF modifications** included several changes to the orbiter wing, as well as the addition of the new OBSS to allow for the inspection of the shuttle TPS system while on-orbit. The heat shields on the wings were sent back to the manufacturers for thorough study, and the tail rudders and speed brakes were repaired.[355] On the wings, the front spar was reworked to counter sneak flow, gap fillers were implemented to impede hot gas intrusion, and impact sensors were added. Redesigned ET electrical and fuel umbilical doors were installed, as were redesigned payload bay door joint seals. Removable harnesses were added to the electrical connections that linked the ET and orbiter, and new FRCS rain covers were added.[356] Four "hardening" initiatives were implemented on all of the orbiters to increase the impact resistance and to reduce existing design vulnerabilities. These included front spar sneak flow protection for RCC panels 5 through 13; main landing gear corner void elimination; FRCS carrier panel redesign to eliminate bonded studs; and the replacement of side windows 1 and 6 with thicker outer thermal panes.[357] A description of selected changes follows.

Wing Leading Edge (WLE) Front Spar Protection for Sneak Flow: Materials were added to the exposed lower 2" of the wing leading edge front spar to protect against hot gas flow ("sneak

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[353] Peter W. Merlin, "Drag Chute Reduced Shuttles' Brake and Tire Wear," September 12, 2011, http://www.nasa.gov/mission_pages/shuttle/flyout/B-52_drag_chute_tests_prt.htm.

[354] Boeing, *OV-104, Volume II*, 51; Jenkins, *Space Shuttle*, 407, 408 and 437.

[355] Pat Duggins, *Final Countdown: NASA and the End of the Space Shuttle Program* (Gainesville, Florida: University Press of Florida, 2007), 193-200.

[356] Boeing, *OV-103, Volume II*, 54-92.

[357] NASA, *NASA's Implementation Plan*, 1-21.

flow") and convective heating conditions, in the event of a 0.25" hole in the lower RCC surface.[358]

WLE Horse Collar Gap Filler Redesign: The WLE horse collar gap fillers, located in the substructure behind the RCC panels, were redesigned with the addition of a 0.5" sleeve for redundancy to protect the lower access panel. The additional sleeving was to prevent hot gas intrusion into the WLE cavity in the event of a partial carrier tile loss.[359]

Wing sensors: Though it was not a recommendation by the CAIB, after January 2003, NASA installed eighty-eight sensors on each shuttle WLE behind the RCC panels during post-*Columbia* RTF modifications to monitor the condition of the wings. The eighty-eight sensors included sixty-six accelerometers to detect impacts and gauge their strength and location. Each made 20,000 readings per second to detect impacts.[360] In addition, twenty-two temperature sensors measured how heat was distributed across the wing spans. The data collected by the sensors during liftoff was collected by a laptop computer on the flight deck and then sent to the Mission Control Center once the ET was jettisoned.

Orbiter Boom Sensor System: The OBSS was created in the aftermath of the *Columbia* accident in response to the CAIB recommendation for on-orbit shuttle inspections. The Canadian Space Agency designed and constructed the OBSS as a 50' extension of the Remote Manipulator System (RMS).[361] This extension allowed the arm to reach around the spacecraft for the best possible views. The OBSS included a pair of sensor systems with cameras and lasers to inspect the TPS after each lift-off and before each landing.[362] The boom extension housed a laser camera system and a laser-powered measuring device, as well as a television camera and a digital camera. Installed on the starboard side of the payload bay, the OBSS was used to inspect the WLE RCC, and to measure the depth of damage sustained by the orbiter's TPS during launch. It also had the "capability to support an EVA crewmember in foot restraints for focused inspection and repair activities."[363] The OBSS debuted with STS-114 in July 2005.

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[358] Boeing, *OV-104, Volume II*, 73.

[359] Boeing, *OV-104, Volume II*, 74.

[360] Klesius, "Evolution of the Space Shuttle;" NASA KSC, "Shuttle in Shipshape: Part II," March 8, 2005, http://www.nasa.gov/returntoflight/system/rtfupgrades_partII.htm.

[361] The shuttle RMS consists of a 50'-long robot arm and hand with three joints, mounted on the port side of the payload bay. It was built by the Canadian Space Agency, and first used on STS-2 (November 1981). In 2000, all the joints were refurbished, the gear boxes and motor modules were replaced, and asbestos brakes were replaced with ceramic ones. Klesius, "Evolution of the Space Shuttle."

[362] Boeing, *OV-104, Volume II*, 75; NASA, *NASA's Implementation Plan*, 1-33.

[363] Klesius, "Evolution of the Space Shuttle."

Space Station Support Upgrades

Upgrades implemented in the 1990s were related to the support of missions to *Mir* and the ISS. These included Extended Duration Orbiter (EDO) upgrades, as well as a new payload bay airlock and docking system.

Extended Duration Orbiter: *Columbia* was the first orbiter to be modified for extended duration flight. A new suite of upgrades first flew on STS-50 (June 1992). These changes included an improved toilet; a regenerative system to remove carbon dioxide from the air; connections for a pallet of additional hydrogen and oxygen tanks to be mounted in the payload bay; and extra stowage room in the crew compartment.[364] A fifth set of cryogenic tanks were added to *Discovery* during OMDP-2. This was done so the orbiter could remain in space longer when it began to fly missions to the ISS later that decade.[365]

Orbiter Docking System and External Airlock: The orbiter docking system (ODS) was created so that the shuttle could link with the Russian space station *Mir* and the ISS and provide a secure external airlock. The original airlock, which measured 150 cubic feet, was located inside the middeck. It featured one hatch opening into the middeck and the other into the payload bay. To support missions to the space stations, the airlock was enlarged to 185 cubic feet and relocated to the payload bay. A third hatch was added on top for docking with *Mir* (1995-1998) and the ISS (starting with STS-88, December 1998). The new airlock provided an air tight tunnel between the shuttle and station.[366] The ODS initiative began in July 1992, and the prototype was installed on *Atlantis* two years later; the approximate project cost was $95.2 million. The external airlock was first flown on STS-71 (June 1995). The ODS later was installed on *Discovery* and *Endeavour*. After assembly of the ISS started, *Atlantis*' interim ODS was modified.[367] The success of the ODS was integral before construction of the ISS proceeded. It facilitated the exchange of crew members and cargo between the orbiters and *Mir* and demonstrated that the ISS was feasible.[368]

The ODS, placed on top of the external airlock, was a Russian-supplied piece of hardware basically designed to be compatible with *Mir*.[369] The ODS docking base was a metal structure on which the Russian-built docking mechanism was mounted. The four electrical connectors in which power, commands, and data were transferred between the orbiter and ISS were mounted on the docking base. The docking base housed supporting ODS wiring. The docking system was not put on the airlock at Palmdale, but rather installed at KSC.[370]

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[364] NASA JSC, "The 21st Century Space Shuttle."

[365] Bruce Buckingham, "Discovery Scheduled to Depart KSC for Orbiter Modifications in Palmdale, Calif.," NASA news release, September 25, 1995, http://www-pao.ksc.nasa.gov/kscpao/release/1995/94-95.htm.

[366] Boeing, *OV-104, Volume II,* 67.

[367] Jenkins, *Space Shuttle*, 326, 381-382.

[368] Duggins, *Final Countdown*, 124-125.

[369] Roberts, interview, 35.

[370] Roberts, interview, 35.

Other Significant Orbiter Modifications

Additional changes to the orbiter structure or systems were done to improve safety (e.g., improved main landing gear tire and wheel assembly), to upgrade technology (e.g., MEDS; Station to Shuttle Power Transfer System (SSPTS); 3-String GPS), to correct in-flight problems (e.g., fuel cell performance monitoring; forward reaction control system rain cover redesign), or to address post-flight anomalies (forward attach/ET fitting stud redesign). In a series of orbiter "Data Packs," Boeing described more than thirty "significant" orbiter modifications, and the respective time of implementation, for OV-103, OV-104, and OV-105. A brief description of these changes, and a summary table, follow.

Structural criteria (Loads database): *Enterprise*, *Challenger*, and *Columbia* were designed with structural design criteria (loads database) of 5.1; during construction it was realized that a 5.4 loads database was necessary. *Challenger* was modified during conversion from a test article to a flight orbiter in 1981, and *Columbia* was modified after STS-9 in 1983. *Discovery, Atlantis*, and *Endeavour* were built with the stronger load criteria. Wing strength criteria rose to a 6.0 loads database in 1992 in an effort to raise the orbiter landing weight to 250,000 pounds, and each space shuttle was modified during OMDPs.[371] After the orbiter structural criteria were increased, *Discovery* and *Atlantis* were built with lighter wings in order to save orbiter weight. However, data acquired during *Columbia's* first flights drew questions about the decreased wing strength, and the wings on *Discovery* and *Atlantis* were strengthened during OMDPs. *Endeavour* was built with the stronger wings.[372]

Improved Main Landing Gear Tire and Wheel Assembly: Early in the SSP, NASA set out to improve shuttle landings. The main landing gear wheel and tire assembly was redesigned to improve safety margins for higher touchdown speeds and vertical loads. A new larger size tire design incorporated two additional carcass plies, grooveless tread, and higher rated pressure. Two added nylon plies (eighteen plies total) increased tire structural strength. The removal of tire tread grooves improved wear.[373] The main landing gear's axle was thickened to provide more resistance, to reduce the chance of brake damage, and to decrease tire wear. Additionally, openings were cut in the main landing gear's hydraulic passages in the piston housing to stop pressure surges and damage when the brakes were pumped; the electronic brake control boxes were upgraded to equally distribute hydraulic brake pressure; and the anti-skid detector was removed. Finally, gauges were added to the nose and every main landing gear wheel to keep track of tire pressure before, during, and after each flight.[374]

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[371] Jenkins, *Space Shuttle*, 242.

[372] Jenkins, *Space Shuttle*, 242.

[373] Boeing, *OV-104, Volume II*, 71.

[374] NASA, *NSTS 1988 News Reference Manual* (Florida: Kennedy Space Center, 1988), http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/.

Significant Orbiter Modifications[375]

Modification	Implementation Period		
	OV-103	OV-104	OV-105
Improved Nose Wheel Steering System	OMM-1	OMM-1	Original Build
Five Rotor Structural Carbon Brake	Flt -10/Apr. ‘90	Flt-8/Apr. ‘91	Original Build
Orbiter Drag Chute	OMM-1	OMM-1	Original Build
Orbiter ET Umbilical Door Latch and Drive Actuators	OMM-3	OMM-2	OMM-1
Tire Pressure Monitoring Improvement	OMM-2	OMM-2	Original Build
ET Door Drive “C” Link Bolts	Flt-23/Aug. ‘97	Flt-20/Sept. ‘07	Flt-12/Jan. ‘90
Payload Bay Door Expansion Joint Dog-Bone Redesign	OMM-3	OMM-2	OMM-1
Main Propulsion System 17-inch Disconnect	OMM-2	OMM-2	OMM-1
Multifunction Electronic Display Subsystem (MEDS)	OMM-3	OMM-2	OMM-1
Orbiter Docking System (ODS) – External Airlock	OMM-2	OMM-2	OMM-1
ODS	OMM-2	OMM-2	OMM-1
Radiator Shield and Isolation Modification	OMM-3	OMM-2	Flt-14/ Feb.’00
Fuel Cell Performance Monitoring	Flt-24/June ‘98	OMM-2	Flt-12/Jan. ‘98
Improved Main Landing Gear Tire and Wheel Assembly	Flt-32/July ‘06	Flt-29/Feb. ‘07	Flt-20/Aug. ‘07
Monoball Production Break	OMM-3	Flt-25/Apr. ‘02	Flt-17/Dec. ‘01
Wing Leading Edge (WLE) Front Spar Protection for Sneak Flow	Flt-31/July ‘05	Flt-27/Feb. ‘07	Flt-20/Aug. ‘07
WLE Horse Collar Gap Filler Redesign	Flt-31/July ‘05	Flt-27/Feb. ‘07	Flt-20/Aug. ‘07
Orbiter Boom Sensor System (OBSS)	Flt-31/July ‘05	Flt-27/Feb. ‘07	Flt-20/Aug. ‘07
Forward Attach/ET Fitting Stud Redesign	Flt-32/July ‘06	Flt-28/June ‘07	Flt-20/Aug. ‘07
Orbiter Wiring Connector-Saver Redesign	OMM-1	OMM-1	OMM-2
ET Aft Attach Material Change	Flt-31/July ‘05	Flt-27/Feb. ‘07	Flt-20/Aug. ‘07
UHF Space Communication System	OMM-2	OMM-2	OMM-1
Orbiter/ET Separation Debris Containment	OMM-2	Flt-13/Nov. ‘94	Flt-8/March ‘95
FRCS Rain Cover Redesign	Flt-31/July ‘05	Flt-27/Feb. ‘07	Flt-20/Aug. ‘07
APU Heating Modification	Flt-37/Aug. ‘09	Flt-30/May ‘09	Flt-23/July ‘09
X_o1040 and X_o1090 Mid Fuselage/Boron Aluminum Strut Replacement	Flt-24/June ‘98	Flt-21/May ‘00	Flt-14/Feb. ‘00
Rudder Speed Brake Inconel Thermal Barrier Redesign	Flt-38/Apr. ‘10	Flt-31/Nov. ‘09	Flt-24/Feb. ‘10
Emergency Egress Slide Deployment Mechanism Improvement	OMM-2	OMM-2	Original Build
Orbiter Floor Reinforcement for 20G Seat Loads	OMM-2	OMM-2	OMM-1
Station to Shuttle Power Transfer System (SSPTS)	Flt-34/Oct. ‘07	N/A	Flt-20/Aug. ‘07
3-String Global Positioning System (GPS)	N/A	N/A	OMDP-1

Multifunction Electronic Display Subsystem: The Multifunction CRT (Cathode Ray Tube) Display System was state-of-the-art when it was installed in the space shuttle cockpits beginning in the late 1970s. However, by 1988, glass cockpits with multicolor displays and true graphics were common in commercial airplanes, and a study began to determine if they could be utilized by the space shuttle fleet. In 1992, NASA started a $209 million cockpit upgrade program, which included the MEDS. Installation began during OMDPs four years later. Initially, the plan called for the MEDS to be installed in two phases at KSC, but it was decided that the system could be

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[375] Boeing, *OV-103, Volume II*; Boeing, *OV-104, Volume II*; Boeing, *OV-105, Volume II*.

inaugurated at once.[376] Developed by Honeywell Space Systems in Phoenix, Arizona, the MEDS featured nine high-resolution, full-color, flat-panel, liquid crystal display units on the forward instrument panel. Two additional display units were located in the aft cockpit, with one on a side panel and another at the aft payload bay windows.[377] The new screens, which replaced thirty-two gauges and electromechanical displays and four CRT displays, provided easier pilot recognition of key functions. A secondary benefit was a reduction in orbiter weight (75 pounds) and in power consumption (90 watts).[378] Design changes included completely replacing the forward panel structure, modifying cockpit display and switch panels, and replacement of ducting for active cooling.[379] According to Robert Kahl, Boeing's site director (Palmdale) for the shuttle, the MEDS was a "huge" modification which entailed literally gutting the crew module.[380] The first flight of the MEDS "glass cockpit" was the *Atlantis* STS-101 mission, launched in May 2000.

Station to Shuttle Power Transfer System: The SSPTS allowed a docked shuttle to make use of power generated by the ISS's solar arrays. This reduced usage of the orbiter's onboard fuel cells, allowing the spacecraft to stay docked to the station for an additional four days (without an EDO pallet). The SSPTS was installed on OV-103 and OV-105 only. It permitted increased time for ISS assembly and maintenance, science experiments, crew handover time, and for orbiter TPS or other contingency repair.[381]

3-String Global Positioning System: Starting in 2000, the TACAN ground stations were scheduled for gradual phase-out in favor of GPS navigation. As a result, GPS systems were installed in the orbiters. Single-string GPS systems were initially installed to gain confidence. The 3-string system was installed only on OV-105. The upgrade was cancelled for OV-103 and OV-104, leaving them with single-string GPS systems and the TACAN units which worked with ground units that remained in service.[382]

Fuel Cell Performance Monitoring: After an in-flight anomaly, which resulted in a minimum duration flight, the fuel cell single-cell measurement system was developed to enhance the ability to fully assess the fuel cell performance. The fuel cell measurement system was used to provide additional fuel cell health data.[383]

FRCS Rain Cover Redesign: The FRCS rain covers were redesigned to change the material from a type of paper to Tyvek, and to add a pocket to catch the air. This was to prevent the

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[376] Jenkins, *Space Shuttle*, 373-374.
[377] Craig Covault, "MEDS Glass Cockpit To Enhance Shuttle Safety," *Aviation Week & Space Technology*, March 6, 2000, 54.
[378] Covault, "MEDS," 54.
[379] Boeing, *OV-104, Volume II*, 66.
[380] Kahl, interview, 6.
[381] Boeing, *OV-103, Volume II*, 80.
[382] Boeing, *OV-105, Volume II*, 87.
[383] Boeing, *OV-104, Volume II*, 70.

release of the covers at high velocities during ascent, which impacted windows and thermal seals, resulting in some damage/breach of the TPS.[384]

Forward Attach/ET Fitting Stud Redesign: Following flight STS-102, a crack was detected in the forward ET attach point fitting stud. The square shaft of the stud was redesigned to provide a larger bearing surface area to facilitate rotation.[385]

Orbiter ET Umbilical Door Latch and Drive Actuators: Two aft umbilical openings were located on the underside of the orbiter, through which electrical and propellant umbilical connections entered the orbiter from the ET. Two doors associated with the umbilical openings were in the open position during ground operations and through powered flight. They were then closed after ET separation to protect the umbilical cavities during entry and landing. Redesign to the door drive and latch torque limiters was required.[386]

Tire Pressure Monitoring Improvement: Monitoring capability was added to the nose and main landing gear assemblies to provide the crew with the ability to view in-flight tire pressure, and to quickly determine tire leak rate and temperature. Pressure and temperature measurement transducers were added to all the wheels.[387]

ET Door Drive “C” Link Bolts: The ET door bolts were replaced with those fabricated of a harder material. This upgrade was the result of bolt failure during turnaround processing prior to the launch on OV-103.[388]

Payload Bay Door Expansion Joint Dog-Bone Redesign: Dog-bone seal assemblies were located at each payload bay door expansion joint. They provided environmental sealing, grounding between door segments, and thermal barrier protection. The assembly tended to bind on either side of the joint seal cavities, which could have potentially caused structural damage. The redesign entailed the installation of extended angle brackets, eliminating the need for the existing retainer clips.[389]

Main Propulsion System 17-inch Disconnect: The 17” LO2 and LH2 umbilical disconnects located at the lower left and right aft fuselage provided the propellant feed interface from the ET to the orbiter main propulsion system and the three SSMEs. The disconnects also provided the capability for ET fill and drain of oxygen and hydrogen. Design changes included the latch system, two-piece follower-arm torsion bar bearing, and new linkage and seals in the valve actuator.[390]

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[384] Boeing, *OV-104, Volume II*, 81.
[385] Boeing, *OV-104, Volume II*, 76.
[386] Boeing, *OV-104, Volume II*, 54.
[387] Boeing, *OV-104, Volume II*, 55.
[388] Boeing, *OV-104, Volume II*, 56.
[389] Boeing, *OV-104, Volume II*, 57.
[390] Boeing, *OV-104, Volume II*, 58.

Radiator Shield and Isolation Modification: Eight radiator panels containing coolant loops with Freon were located inside the payload bay doors. These panels were vulnerable to strikes by micro-meteroid and orbital debris while on-orbit. This modification bonded 0.020" thick doublers to the panel face-sheet directly over the Freon tubes to provide additional impact protection.[391]

Monoball Production Break: Harnesses routed to the LH2 and LO2 electrical monoball established connections between the orbiter and the ET. These harnesses, located in a high traffic area in the aft fuselage, were vulnerable to damage during ground processing. Modification added a monoball wiring production break and removable harnesses, thus simplifying any subsequent repairs.[392]

Orbiter Wiring Connector-Saver Redesign: Connector-savers in four areas (monoball, T-0 Interface, OMS pod interface, and Ku-band assemblies) were redesigned to protect the receptacles from excessive wear during orbiter processing.[393]

ET Aft Attach Material Change: The ET/Orbiter aft attach interface shell material was changed from 6061-T651 aluminum plate to higher strength 7050-T7451 aluminum plate to eliminate potential local material damage. This reduced the potential for compression damage to the aft shell that could result in increased bending moments to the aft attach bolts during ascent.[394]

UHF Space Communication System: On-orbit ultra-high frequencies (UHF) were originally shared with the DoD. Later, because the DoD needed exclusive rights to those frequencies, new frequencies were obtained with new hardware that was compatible with ISS operations. Two new UHF communication systems were installed on the orbiter. One provided two-way communication with the ground, and the other provided communication with the orbiter and ISS during EVAs.[395]

Orbiter/ET Separation Debris Containment: During STS-41, the "hole-plugger" in one of OV-103's orbiter/ET aft attach fitting failed to seat properly. As a result, debris from the frangible nut escaped the container. More positive closure of the container was achieved by changing to a blade valve configuration.[396]

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[391] Boeing, *OV-104, Volume II*, 69.
[392] Boeing, *OV-104, Volume II*, 72.
[393] Boeing, *OV-104, Volume II*, 77.
[394] Boeing, *OV-104, Volume II*, 78.
[395] Boeing, *OV-104, Volume II*, 79.
[396] Boeing, *OV-104, Volume II*, 80.

APU Heating Modification: On-orbit, the APU fuel line temperatures had to be controlled to prevent freezing, rupture, or detonation. New thermostatically-controlled heaters, activated by switches, were added.[397]

X_O = 1040 and X_O = 1090 Mid Fuselage/Boron Aluminum Strut Replacement: A new design replaced four boron-aluminum struts with thicker walled aluminum struts at the X_O = 1040 and X_O = 1090 frames to increase the margin at these locations.[398]

Rudder Speed Brake Inconel Thermal Barrier Redesign: The rudder speed brake on the trailing edge of the vertical stabilizer contained sixty thermal spring clips which provided thermal protection from SRB/SSME plume heating during ascent. The Inconel thermal barrier taps which bridged the gap between the spring clip seals were redesigned to improve strength and durability.[399]

Emergency Egress Slide Deployment Mechanism Improvement: During crew training exercises, at times, the emergency egress slide deployment mechanism lanyard assembly released prematurely, resulting in the failure of the slide to inflate. The lanyard was shortened from 36” to 26” to eliminate the problem.[400]

Orbiter Floor Reinforcement for 20-g Seat Loads: Structural modification to the flight deck floor (commander and pilot seat locations) and middeck floor (mission specialist seat 5) was required to achieve 20-gravity (g) crash load structural capability.[401]

Discovery (OV-103) Major Modifications

NASA initially planned to modify orbiters during normal processing at KSC, but as the shuttle fleet aged, more time was necessary to adequately inspect, test, repair, upgrade, improve, and modify equipment. Most of the major modifications were executed during three OMDPs, as well as two major modification periods in the aftermath of the *Challenger* (RFT-1) and *Columbia* (RTF-2) accidents. More than 1600 modification records were completed. *Discovery’s* OMDP-1 was performed at KSC post-STS-42 after fourteen flights; she flew seven more missions before OMDP-2 was performed at Palmdale following STS-70. The third OMDP, at KSC, followed completion of STS-105, the ninth mission since the previous down period. *Discovery* underwent thousands of changes during her down periods.[402]

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[397] Boeing, *OV-104, Volume II*, 82.
[398] Boeing, *OV-104, Volume II*, 83.
[399] Boeing, *OV-104, Volume II*, 84.
[400] Boeing, *OV-104, Volume II*, 85.
[401] Boeing, *OV-104, Volume II*, 86.
[402] Boeing, *OV-103, Volume II*, 52.

According to Bill Roberts, the biggest challenge to the upgrade of OV-103 was working within existing limitations, particularly in regard to the capabilities of the old general purpose computers (GPCs) and the processors.

> *"As the vehicle got older, the program realized that we were limited. Sure, there's fast processing of data, but we couldn't do that because you couldn't gut the vehicle to the point where you changed out your GPCs. One of the mods did improve the GPCs, but it was a small improvement compared to what the capability of computers are today."*[403]

RTF-1

In January 1986, *Discovery* was in the VAB at KSC awaiting transport to Vandenberg AFB. However, that plan changed in the aftermath of the *Challenger* accident. Selected as the Return to Flight orbiter, *Discovery* was moved on October 30, 1986, from the VAB to OPF-1. NASA workers removed many of the major components and returned them to their manufacturers for refurbishment.[404] Subsequently, *Discovery* was powered down in February 1987. More than 200 modifications were made over the next six months. "Because 103 was the return to flight vehicle after the *Challenger* accident, all the best resources were put into that vehicle during that turnaround."[405] The majority of the post-*Challenger* modifications and upgrades were directed at eliminating as much risk as possible in the operating systems. Thus, Criticality 1 hardware was identified, and either modified or eliminated from the vehicle.[406] For example, check valves were eliminated, as well as plumbing items in the OMS/RCS area. At the component level, improvements either eliminated the Criticality 1 for that system or improved it.[407] Other upgrades included the installation of a crew escape system and reconfiguration of the landing system.

OMDP-1

In early 1992, *Discovery* was due for her first scheduled down period after completing her eighth flight since RTF-1 (STS-26) in 1988. OMDP-1 was performed at KSC between February 17 and August 17, 1992.[408] Seventy-eight modifications were completed, most notably the replacement of beryllium brakes with a carbon brake system, the addition of nose wheel steering, and the installation of a drag chute. Corrosion was repaired, the structural system was examined, and the TPS was improved.

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[403] Roberts, interview, 27.

[404] Jenkins, *Space Shuttle,* 291-292.

[405] Roberts, interview, 8.

[406] Criticality 1 hardware is defined as those hardware components that if they were to fail, would cause the loss of life or vehicle.

[407] Roberts, interview, 13-15.

[408] Boeing, *OV-103, Volume II,* 52.

OMDP-2

On September 27, 1995, three years after her last OMDP, *Discovery* left KSC for Palmdale. Over the next nine months, between September 29, 1995 and June 24, 1996, *Discovery* underwent ninety-six modifications and eighty-seven deferred maintenance items. "Basically it was the first time an orbiter was torn apart to the level it was since it was built," Bill Roberts related.[409] According to Roberts, the goal of OMDP-2 was to lighten the vehicle and gain performance in preparation for the flights to the ISS. This period "had more significant modifications and upgrades to an orbiter than ever before," and OV-103 was "the first vehicle to get all of those upgrades."[410] Improvements to the TPS included the replacement of tiles to make the system lighter, stronger, and more durable. AFRSI blankets were replaced with FRSI. A RCC panel between the nose cap and the nose wheel well door was added to provide improved insulation against the heat of reentry. The aluminum foil tape on the wheel wells was replaced with aluminized Kapton tape, and the Inconel and titanium flipper doors were changed to aluminum. Additionally, the whole crew module was rewired for the modular auxiliary data system.[411]

Other major modifications included the addition of a fifth cryogenic tank, the replacement of the internal airlock with an external airlock to support missions to the ISS, and the first installation of the permanent ODS for docking to the ISS. Improvements to the orbiter propellant supply system included a redesigned 17" disconnect valve. Also, a new crew escape system was added.

OMDP-3/RTF-2

OMDP-3 began on September 1, 2002, at KSC, nine flights and six years after OMDP-2; work was completed on April 1, 2004.[412] *Discovery*, the first orbiter to undergo an OMM at KSC, received ninety-nine scheduled upgrades and underwent eighty-eight special tests, including new RTF changes.[413] Safety modifications also were performed. Nearly all accessible parts were removed from the vehicle, exposing the orbiter's airframe, which was inspected for corrosion, and wear and tear. Examination included nearly 150 miles of wiring. Anticorrosive compound and paint were applied after the airframe was stripped. More than 1,400 of the 24,000 tiles were replaced. Many modifications were made to address the recommendations of the CAIB. Among the changes was the addition of new sensors in the leading edge of the wings, a new safety measure that monitored the orbiter's wings for debris impacts. Also, twenty-two temperature sensors and sixty-six accelerometers were added. The OBSS was added, and the orbiter was equipped with cameras and laser systems to inspect *Discovery's* TPS while in space. The front spar on the wings was retooled to counter sneak flow, and gap fillers were used to impede hot gas intrusion. The MEDS glass cockpit was installed, which improved graphic capabilities,

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[409] Roberts, interview, 8.
[410] Roberts, interview, 33, 34.
[411] Roberts, interview, 29.
[412] Boeing, *OV-103, Volume II,* 52.
[413] Anna Heiney, "My Shuttle's in the Shop," February 23, 2004, http://www.nasa.gov/missions/shuttle/f_omdp1.html.

reduced shuttle weight, and eased instrumentation use. Redesigned ET electrical and fuel umbilical doors were installed, as were redesigned payload door joint seals. The heat rejection panels on the radiator doors were insulated. Removable harnesses were introduced on the electrical connections that linked the ET and orbiter, and new FRCS rain covers were added.[414]

Other Modifications

Changes to *Discovery* were not limited to her OMDPs and RTF down periods. Hundreds of changes, large and small, were made during between-flight processing.

Discovery was one of two orbiters modified at KSC so that the Centaur upper stage could fit into the payload.[415] The rocket was built to deploy satellites while the shuttle was in orbit. The $5 million alterations to OV-103 included the addition of controls on the aft flight deck for loading and monitoring Centaur, and extra plumbing to load and vent the rocket's cryogenic propellants. However, no space shuttles carried the Centaur into space, and the idea of flying with a rocket full of liquid fuel in an orbiter's payload bay was deemed too risky after the *Challenger* accident on January 28, 1986.[416]

Between the *Challenger* and *Columbia* accidents, there were four major between-flight alterations to *Discovery*. The brakes were changed from the original beryllium to carbon after STS-33 in November 1989, and a single-string GPS was installed on the shuttle after STS-56 in April 1993.[417] The weakened ET door bolts were replaced after STS-82 in February 1997. Following STS-85 in August 1997, the fuel cell measurement system was implemented to provide better data, and stronger struts were added to the midfuselage.

Following the *Columbia* accident in 2003, there were four more major between-flight alterations to *Discovery*. Larger, stronger tires were added and the ET attachment was reconfigured after STS-114 ended in August 2005. The SSPTS was implemented in December 2006. After STS-119 in March 2009, the APU was converted so it could be controlled by a thermostat. After STS-128 in September 2009, the rudder speed brake was improved.[418]

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[414] Boeing, *OV-103, Volume II,* 54-92.

[415] *Challenger* was the other modified orbiter. *Atlantis* was originally built with a Centaur capability. Jenkins, *Space Shuttle,* 246.

[416] Jenkins, *Space Shuttle*, 246; NASA KSC, "Discovery (OV-103)."

[417] Gebhardt, "After 26 Years."

[418] Boeing, *OV-103, Volume II*, 54-92.