PART II. *DISCOVERY* (OV-103)

Structurally and materially, the three extant orbiters in the STS fleet, *Discovery* (OV-103), *Atlantis* (OV-104), and *Endeavour* (OV-105), appeared very much alike. However, as Gerald Blackburn, former Rockwell manager and forty-year veteran in the aerospace industry expressed,

> *I think for the average person looking at it, an orbiter is an orbiter is an orbiter – they all look the same. But it's like a race car driver, he knows the difference between the cars and the way they handle.*[311]

As Blackburn noted, *Challenger* was the most significantly different, because it was originally built as a test article for structural testing. "Structurally and materials-wise," the differences between *Discovery*, *Atlantis*, and *Endeavour* were minor.[312]

William (Bill) Roberts, former *Discovery* project engineer at Downey (1988-2002), reflecting on the history of the vehicle, reported that because she was the RTF vehicle after the *Challenger* accident, "all the best resources were put into that vehicle during that turnaround." The second OMDP, done at Palmdale in 1994, was "a unique one for 103 and the program" because it was the first time an orbiter underwent a number of weight-saving modifications. "Basically it was the first time an orbiter was torn apart to the level it was since it was built."[313] *Discovery* has flown the most, and was the first vehicle "that came out of the initial upgrades." Designed to be much lighter, it was the first vehicle to become one of the "high performance" vehicles compared to the previously built orbiters, according to Roberts.[314]

Prior to the *Challenger* accident, when NASA was preparing to launch the space shuttle from Vandenberg AFB, OV-103 was the dedicated vehicle for the Air Force. Because of this, she had a different TPS design.

> *Reentries coming into Vandenberg . . . had a higher cross range requirement, meaning as you're descending you had to come off of your normal inclination and turn into Vandenberg at a much farther distance from your normal trajectory, which means you had to put it down steeper and you're getting higher heat loads. So it had a different TPS design on the underbelly of the vehicle.*[315]

Discovery was the third orbiter built for operational use, following *Columbia* (OV-102) and *Challenger* (OV-099), and it retired as the oldest and most traveled of the three remaining orbiters in the Space Shuttle fleet. *Discovery* completed its thirty-ninth and final mission on

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[311] Gerald Blackburn, interview by Rebecca Wright, *NASA STS Recordation Oral History Project*, August 24, 2010, http://www.jsc.nasa.gov/history/oral_histories/STS-R/BlackburnGA/BlackburnGA_8-24-10.htm.
[312] Blackburn, interview, 13.
[313] Roberts, interview, 8.
[314] Roberts, interview, 9.
[315] Roberts, interview, 10.

March 9, 2011. In twenty-seven years of service, beginning with its maiden launch on August 30, 1984, *Discovery* orbited the Earth 5,830 times, flew a total of 148,221,675 miles, carried 252 crewmembers to space, made thirteen missions to the ISS, and logged a total of 365 mission days – a year in space.[316]

NASA named *Discovery* after four British vessels: Henry Hudson's ship used in the 1610-11 voyage to find a Northwest passage between the Atlantic and Pacific oceans; *HMS Discovery* led by Captain James Cook, which was used to explore the South Pacific in the 1770s; a second *HMS Discovery* that was part of Captain George Nares' 1875-76 expedition to the North Pole; and the *RRS Discovery*, which carried Captain Robert Falcon Scott's crew during the 1901-04 *Discover Expedition* to Antarctica.

The following sections provide a description of *Discovery's* original assembly (Part IIA), and subsequent modifications (Part IIB), within the broader context of SSP-wide developments. Following the physical description of *Discovery's* systems (Part IIC), her missions and milestones are examined (Part IID). Part IIE concludes this section with a description of ground and ferry operations, which generally pertain to the entire orbiter fleet.

IIA. Manufacture and Assembly

Orbiter Manufacturers

The "production orbiter" OV-103 was built under Production Contract NAS9-14000, Schedule B, awarded to Rockwell International Corporation (now, The Boeing Company) on January 29, 1979.[317] The $1.9 billion contract also included the construction of OV-104 (*Atlantis*), the conversion of *Challenger* from a test vehicle (STA-099) into a flight orbiter, and major orbiter modifications. About 250 major subcontractors provided the approximately two million individual components, parts, and systems to Rockwell's Downey and Palmdale assembly facilities (see Figure Nos. B-1 through B-18 for representative photographs of individual components being manufactured).[318] Major structural components, including the upper and lower forward fuselage, the aft fuselage, the crew module, and the FRCS, were built and tested at Rockwell's Downey, California, facility. Other major structural modules were manufactured under subcontract to Rockwell's Space Transportation Systems Division. Rockwell selected McDonnell Douglas, St. Louis, Missouri, for the $50 million subcontract to build the OMS pods; Grumman Aerospace Corporation in Bethpage, New York, for $40 million, to build the orbiter wings (including the elevons); General Dynamics/ Convair Aerospace in San Diego, California,

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[316] NASA KSC, *Space Shuttle Era Facts*.
[317] Chris Gebhardt, "After 26 Years, Workhorse Discovery Stands Ready for Final Mission," February 22, 2011, http://www.nasaspaceflight.com/2011/02/workhorse-discovery-stands-ready-for-final-mission/.
[318] NASA, "Space Transportation System Contractors." In *NSTS Shuttle Reference Manual*, 1988, 971-990; NASA, "Orbiter Manufacturing and Assembly," April 7, 2002, http://spaceflight.nasa.gov/shuttle/reference/shutref/manu/.

to build the midfuselage for $40 million, and Fairchild Industries/Fairchild Republic in Farmingdale, New York, to build the vertical tail, including the rudder/speed brake, for $13 million. North American Rockwell divisions in Tulsa, Oklahoma, and Columbus, Ohio, provided the orbiter payload doors and body flap, respectively.

General Orbiter Flow and Build Sequence

> *The thing I think was most interesting is people at Palmdale had an unwritten agreement with the astronauts. That agreement was to do the best job they could, to give 100 percent, to make sure that it was the best orbiter vehicle that we could ever deliver because of their safety.*[319]

The shuttle parts manufactured by contractors across the US (see table on the following page) were transported to Building 150 at the US AFP 42, Site 1 North, in Palmdale, California, for assembly into the orbiter *Discovery*. The 5,800-acre government-owned, contractor-operated plant is located approximately 50 miles north of Los Angeles. NASA signed a memorandum of agreement with the USAF in 1973 to use Building 150 for the assembly, integration, testing, and checkout of the orbiters. The final assembly of all flight-ready orbiters, as well as the orbiter prototype *Enterprise*, occurred in the building's two high bays.[320]

The general orbiter build sequence, as outlined by Boeing, began with the delivery of the mid-fuselage from the General Dynamics facility in San Diego.[321] After being offloaded, this major component was checked out, then placed in a work station for the installation of systems. Following delivery from Downey, the lower forward fuselage was assembled, checked out, and mated with the midfuselage. The aft compartment was fabricated and assembled at Downey; the auxiliary power unit (APU) system also was installed and checked out here. This subassembly was transported to Palmdale, where it was mated to the midfuselage. The crew module followed a similar path. The structure was manufactured and assembled at Downey, where the systems, including the airlock, were installed. Following checkout, the crew module was transported to Palmdale for installation of the avionics crew system, followed by mating. The upper forward fuselage followed from Downey. The orbiter wings, fabricated, assembled, and checked out at Grumman's facility in Bethpage, New York, were transported by ship from New York, to Long Beach, California, via the Panama Canal, then transported overland to Palmdale and installed in

[319] Robert H. Kahl, interview by Rebecca Wright, *NASA STS Recordation Oral History Project*, August 25, 2010, 3, http://www.jsc.nasa.gov/history/oral_histories/STS-R/KahlRH/KahlRH_8-25-10.htm.
[320] Archaeological Consultants Inc., "Shuttle Orbiter Final Assembly Building/Building 150," (documentation package, NASA JSC, 2007), 7, 11-12.
[321] Boeing, *Orbiter Vehicle Data Pack Document: Orbiter Vehicle Discovery (OV-103), Volume I,* (Huntington Beach, California: The Boeing Company, 2011), 269-272.

Manufacturers of Major Orbiter Components and Subcomponents[322]

Major component	Subcomponent	Manufacturer	Location
Midfuselage		Convair Aerospace Division of General Dynamics Corporation	San Diego, CA
Aft fuselage		Columbus Aircraft Division of Rockwell International (tooling)	Columbus, OH
		Los Angeles Aircraft Division (upper truss thrust structure)	Los Angeles, CA
Forward fuselage		Space Transportation Systems Division of Rockwell International	Downey, CA
	Crew module	Los Angeles Aircraft Division (panels)	Los Angeles, CA
		Avco (bulkheads)	Nashville, TN
		Vought Corporation (skins and bulkheads)	Dallas, TX
		Marvin Engineering (skins and ejection panels)	Inglewood, CA
		Merco Manufacturing Co. (star tracker panels)	Anaheim, CA
	Airlock	Space Transportation Systems Division of Rockwell International	Downey, CA
Wings		Grumman Corporation	Bethpage, NY
	Elevons	Grumman Corporation	Bethpage, NY
	Landing gear doors	Grumman Corporation	Bethpage, NY
Payload bay doors		Tulsa Division of Rockwell	Tulsa, OK
	Actuation system	Curtiss Wright	Caldwell, NJ
	Latches	Ball Brothers Research Corp.	Boulder, CO
	Signal processor	TRW Systems, Electronic Systems Division	Redondo Beach, CA
	Data interleaver	Harris Corp., Electronics Systems Division	Melbourne, FL
Forward reaction control system		Space Transportation Systems Division of Rockwell International	Downey, CA
	Fuel and oxidizer tanks	Martin Marietta	Denver, CO
	Thrusters	Marquardt Co., CCI Corp.	Van Nuys, CA
Vertical stabilizer		Fairchild Republic	Farmingdale, NY
	Rudder/speed brake	Fairchild Republic	Farmingdale, NY
OMS/ RCS pods		McDonnell Douglass	St. Louis, MO
	OMS engines	Aerojet General	Sacramento, CA
	RCS thrusters	Marquardt Co., CCI Corp.	Van Nuys, CA
Body Flap		Columbus Aircraft Division of Rockwell International	Columbus, OH

the vehicle. The vertical tail, made by Fairchild Republic in Farmingdale, New York, was conveyed to Palmdale via truck. At Palmdale, it was checked out and prepared for installation.

[322] NASA, "Space Transportation System Contractors," 971-990; Boeing, *OV-104, Volume I,* 282-304.

The payload bay doors followed from their manufacture site in Tulsa, Oklahoma. Following mating of the payload bay doors, the FRCS, manufactured, assembled, and checked out at Downey, was shipped to Palmdale, where it was prepped and mated. The nose and main landing gear, followed by the body flap, arrived from their manufacturing sites, and were offloaded, checked out, prepared for placement, and installed at Palmdale. The aft orbiter maneuvering system/reaction control system (OMS/RCS) pods, manufactured by McDonnell Douglas in St. Louis, Missouri, were transported by aircraft to the Palmdale assembly facility for installation of the TPS materials. They were not installed on *Discovery* at Palmdale, but were transported separately by aircraft to KSC.[323] After final assembly was completed, the orbiter underwent acceptance testing and final checkout, before being prepared for delivery to KSC.

Historically, according to Gerald Blackburn, the actual build cycle for the orbiter fleet was from about 1972, when long lead items were purchased for *Enterprise* (OV-101), to about 1992. *Columbia* (OV-102) took the longest to build, about seven years, from first lead item on through. Most of the other vehicles had a three to four year build cycle. "A lot of the lessons learned were on *Columbia*, which later translated into the rest of the fleet." [324] The most intense period of orbiter construction at Palmdale was from 1979 to 1986. In 1986, there were four orbiters at KSC.[325]

OV-103 Assembly

Construction of OV-103 began in August 1979, with the long lead fabrication of the crew module. During the latter half of 1980, fabrication of the wings, lower fuselage, and midfuselage was started, and structural assembly of the wings, crew module, midfusleage and aft fuselage were begun. Fabrication and assembly of the payload bay doors and body flap were initiated in March and October 1982, respectively.

In March 1982, major components for the assembly of OV-103 began to arrive at the Palmdale assembly facility, starting with the midfuselage, and followed by the elevons later that month. The wings and lower forward fuselage were delivered to Palmdale at the end of April 1982; both were attached to the mid-fuselage in May. The upper forward fuselage arrived in July, the vertical stabilizer in August, the body flap in October, and the crew module in December. Also, installation of the TPS tiles was under way by October 1982. A pictorial representation of the final assembly of *Discovery* is provided in Figure Nos. B-19 through B-58.

The aft fuselage was delivered in January 1983 and installed that month. Also in January, the crew module and upper forward fuselage were installed. The OMS pods also arrived in January, and in February, the FRCS arrived. A fit-check was completed, and then the FRCS was set up

[323] Boeing, *OV-103, Volume I*, 261. The OMS/RCS pods could be interchanged between vehicles as required to accommodate maintenance and schedule requirements.
[324] Blackburn, interview, 11.
[325] Blackburn, interview, 14.

under a temporary clean room for inspections. In March 1983, the four sections of the payload bay doors were installed. First was the forward port door, then the forward starboard door, followed by the aft port and starboard doors, respectively. The FRCS and the body flap were installed in June.[326] Throughout this time, a number of smaller shuttle components were installed. Final assembly of *Discovery* concluded on August 12, 1983. Post-checkout was completed on September 9, 1983, and testing and other work continued on OV-103 over the next month.

Discovery was rolled out of Building 150 on October 16, 1983 (Figure No. B-59). It weighed 151,419 pounds without the SSMEs, about 6,870 pounds less than *Columbia*. From Palmdale, *Discovery* was transported overland to DFRC, mated to the SCA (Figure No. B-60), and flown to KSC, where it arrived on November 9, 1983.

Over the next six months, *Discovery* spent time in both the OPF for processing, and the VAB for storage. Beginning on May 12, 1984, the ET and SRBs were attached to *Discovery*, and all were moved to LC 39A one week later. On June 2, the SSMEs were tested for twenty seconds as part of a flight readiness firing of the main propulsion system. Deemed a success, *Discovery*'s first launch was scheduled for June 25.[327] The key events and dates for *Discovery's* build sequence are summarized in the following table.

[326] Archaeological Consultants Inc., "Shuttle Orbiter Final Assembly Building/Building 150," 16-17.
[327] Chris Gebhardt, "After 26 Years."

Key Events and Dates in the Construction of OV-103[328]

Date	Event
August 27, 1979	Long lead fabrication of the crew module starts
June 1, 1980	Fabrication and assembly of wings starts
June 20, 1980	Lower fuselage fabrication starts
September 29, 1980	Assembly of crew module starts
October 1, 1980	Assembly and fabrication of mid-fuselage starts
November 10, 1980	Structural assembly of aft fuselage starts
December 8, 1980	Initial installation of the aft fuselage starts
March 2, 1981	Fabrication and assembly of payload bay doors starts
October 19, 1981	Body flap detailed assembly and fabrication starts
October 26, 1981	Initial system installation into the crew module starts in Downey, Calif.
January 4, 1982	Initial system installation of the upper forward fuselage starts
March 16, 1982	Midfuselage delivered to Rockwell International's facility in Palmdale
March 30, 1982	Elevons delivered to Palmdale
April 30, 1982	Wings arrive at AFP 42 from the Grumman Corporation
April 30, 1982	Lower forward fuselage on dock in Palmdale
July 16, 1982	Upper forward fuselage on dock in Palmdale
August 5, 1982	Vertical stabilizer on dock in Palmdale
September 3, 1982	Final assembly starts
October 15, 1982	Body flap on dock in Palmdale
December 28, 1982	Crew module on dock in Palmdale
January 11, 1983	Aft fuselage on dock in Palmdale
February 25, 1983	Final assembly completed and closeout installation in Palmdale
February 28, 1983	Initial subsystems test starts and power-on in Palmdale
May 13, 1983	Initial subsystems testing completed
July 26, 1983	Subsystems testing completed
August 12, 1983	Final acceptance completed
September 9, 1983	Post-checkout completed in Palmdale
October 16, 1983	Rollout from Palmdale
October 28, 1983	First SSME on dock at KSC
November 5, 1983	Overland transport from Palmdale to DFRC
November 6, 1983	Flight from Edwards Air Force Base to Vandenberg Air Force Base
November 8, 1983	Flight from Vandenberg Air Force Base to Carswell Air Force Base in Texas
November 9, 1983	Flight from Carswell Air Force Base in Texas to KSC
November 15, 1983	Modification starts at the Orbiter Processing Facility
December 22, 1983	Second SSME on dock at KSC
January 5, 1984	Third SSME on dock at KSC
June 2, 1984	Flight Readiness Firing
August 30, 1984	First Flight (STS-41D)

[328] NASA KSC, "Space Shuttle Overview: *Discovery* (OV-103)," December 8, 2008, http://www-pao.ksc.nasa.gov/shuttle/resources/orbiters/discovery.html.

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

[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

[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]

[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

[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]

[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]

[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]

[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.

IIC. Physical Description[419]

Discovery was a double-delta winged reentry vehicle[420] that had the ability to carry both passengers and cargo into low-Earth orbit. It had approximate overall dimensions of 122'-2" in length (from nose to tail), 78' in width (from wing tip to wing tip), and 56'-8" in height, to the top of the vertical tail when the landing gear was deployed (Figure No. B-61). The height of the orbiter with the landing gear stowed was roughly 46'-4.5". It was primarily constructed of aluminum alloys, and covered with a reusable TPS. The original specifications for the vehicle required that the orbiter be capable of 100 flights; *Discovery* flew a total of thirty-nine missions.

The orbiter had its own coordinate reference system, which was separate from that for the entire Space Shuttle vehicle (Figure No. B-62). This reference system, similar to those used by most aircraft manufacturers, allowed engineers, technicians, and astronauts to locate specific points on and within the orbiter. The x-axis of this system extended along the length of the orbiter; the y-axis traveled through the width of the orbiter, and the z-axis extended through the height of the orbiter. The origin point of the orbiter's coordinate system was situated 236" forward of the tip of the nose (x-axis), along the centerline of the vehicle (y-axis), approximately 207" below the lowest point of the orbiter's belly, excluding the landing gear, when the payload bay doors were in the true horizontal position.[421]

Structurally, *Discovery* was divided into nine major sections (Figure No. B-63). These included the forward fuselage, which was comprised of the upper forward fuselage, the lower forward fuselage, and the crew module; the FRCS module; the midfuselage; the payload bay doors (two total); the wings (two total); the aft fuselage; the OMS/RCS module (two total); the vertical stabilizer; and the body flap.

Major Structural Sections

<u>Forward Fuselage</u>

The **forward fuselage** (Figure No. B-64) was comprised of a lower forward fuselage and an upper forward fuselage, which joined together to encase the crew module. All three components were manufactured by Rockwell International at their plant in Downey, California.[422] As a whole, the forward fuselage had a length of approximately 28.83', a width of 17' at its widest

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[419] This description focuses on *Discovery*, since she is the "shuttle of record." Any differences in *Atlantis* and *Endeavour* are noted throughout as appropriate.
[420] A delta wing is a wing that takes the form of a triangle; it derives its name from its similarity to the written form of the upper-case Greek letter Delta (∆). The "double-delta" indicates that the angle formed by the leading edge of the wing, or its sweepback, changes.
[421] For this description, the length of a component will always refer to its x-axis dimension; the width to its y-axis dimension; and height to its z-axis dimension.
[422] Jenkins, *Space Shuttle*, 367.

point (where it connected to the midfuselage), and a maximum height of 13’, excluding the nose landing gear.

The upper and lower forward fuselage segments were constructed of conventional 2024 aluminum alloy.[423] Their internal structural skeleton was formed by a series of frames, spaced 30” to 36” on center; the frames in each segment aligned with their counterparts in the other segment. Riveted to these frames were the skin-stringer panels, which were comprised of single curvature, stretch-formed skins braced by riveted stringers, spaced 3” to 5” on center.[424] There were two main bulkheads within the forward fuselage, one at the X_O = 378 mark and one at the X_O = 582 mark. The X_O = 582 bulkhead was manufactured of a machined upper frame and a built-up lower frame. It served as the attachment point between the forward fuselage and the midfuselage; the two components were separated by a flexible membrane. The X_O = 378 bulkhead contained an upper and a lower half. The upper portion was constructed of flat aluminum and formed sections, which were riveted and bolted together; this portion of the bulkhead was the forward end of the upper forward fuselage. The lower section, made of machined aluminum, was built into the lower forward fuselage and provided the interface fitting for the nose section. The nose section was constructed of aluminum machined sidewalls and fitted with machined beams and struts. Two truss supports connected it to the top of the upper half of the X_O = 378 bulkhead; two trunnion supports fastened it to the lower half of the X_O = 378 bulkhead.[425]

The forward fuselage was designed to carry the basic body-bending loads of the vehicle, and to provide a reaction to the nose landing gear loads.[426] Additionally, through the nose section, the forward fuselage supported the nose cap, the nose landing gear wheel well and doors, the nose landing gear, and the FRCS module.[427] The roughly 64”-diameter nose cap was formed by a single piece of RCC, and was attached to an interface on the lower forward fuselage. Thermal barriers protected the seal. Centered within the underside of the lower forward fuselage was the 8’-long, 3’-5”-wide wheel well; its aft end abutted the X_O = 378 bulkhead. The well consisted of two support beams, two upper closeout webs, drag-link support struts, a nose landing gear strut, actuator attachment fittings, and the nose landing gear door fittings. The two doors, which were made of aluminum alloy honeycomb, were attached to the nose section with hinges. Both doors were the same length, but the left was wider than the right, to provide an overlap when closed.

[423] “2084 Aluminum Alloy” is a type of aluminum alloy that uses copper and magnesium as the alloying elements. It has a high strength to weight ratio, and good fatigue resistance, which makes it ideal for use in aircraft construction.
[424] Riveted skin-and-stringer aluminum is sheet aluminum that is reinforced with aluminum ribs (stringers) that are riveted to the skin panels. The ribs are extruded, machined, or formed from sheet stock.
[425] United Space Alliance (USA), *Shuttle Crew Operations Manual* (Houston: United Space Alliance, 2004), 1.2-1; Boeing, *OV-103*, *Volume I*, 83-84.
[426] A body-bending load was a load that tended to change the radius of a curvature of the body.
[427] The nose gear is described further in the Deceleration and Landing Systems section (beginning on page 192); the FRCS module is described further later in this section (beginning on page 129).

Each door was also fitted with a pressure seal and a thermal barrier, and had an up-latch fitting at the forward and aft ends, which locked the door closed when the landing gear was retracted.[428]

The skin panels of the forward fuselage (Figure Nos. B-65 through B-68) were fitted with structural provisions that supported various pieces of flight equipment. For example, there were two air data sensors near the nose cone, one on each side of the vehicle, just below the FRCS module. Additionally, the top surface of the vehicle contained ten communications antennas. Just to the aft of the nose cone was a line of three Ku-band and microwave scanning beam landing system (MSBLS) antennas. Three TACAN antennas, placed in a triangular arrangement, were located between the FRCS module and the forward flight deck windows. Behind the forward flight deck windows, along the centerline of the vehicle, was one S-band, frequency modulation (FM) antenna, and centered between the overhead observation windows was one S-band payload antenna. In addition, one S-band phase modulation (PM) antenna was located to either side of the overhead windows. [429]

The bottom surface of the orbiter's forward fuselage (Figure No. B-68) was fitted with three TACAN antennas, one along the centerline of the vehicle, one near the starboard side, and one near the port side. One UHF antenna, fitted with an access door, was also situated along the centerline of the orbiter; directly behind it was one S-band FM antenna. Two S-band PM antennas were also located on the bottom surface of the forward fuselage. In addition, there were two radio alternate transmitters, and two radio alternate receivers, which formed a box around the UHF antenna. One last feature of the bottom surface of the forward fuselage was the forward orbiter/ET attach fitting, which was located at the Xo = 378 bulkhead, on the skin panel aft of the nose gear wheel well.[430]

In addition to structural provisions for flight equipment, the forward fuselage contained various external access panels to equipment or to different internal systems for flight processing activities. On the top surface (Figure No. B-65), there were two adjacent star tracker doors on the port side of the vehicle. The starboard side of the forward fuselage (Figure No. B-67) contained two vent doors just to the aft of the FRCS module. In addition, there was an access panel for the ground emergency egress window jettison T-handle. The port side of the forward fuselage (Figure No. B-66) had two vent doors, in the mirror location of those on the starboard side, as well as a water service panel and an opening for the main crew hatch.[431]

Discovery's **crew module** (Figure No. B-64) had approximate overall dimensions of 16.5' in length and 17.5' in height; it had a rough volume of 2,533 cubic feet. The module was constructed of 2219 aluminum alloy plate with integral stiffening stringers and internal framing,

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[428] USA, *Crew Operations*, 1.2-1, 1.2-2; Boeing, *OV-103, Volume I*, 84; Jenkins, *Space Shuttle*, 408.
[429] The antennas are discussed in more detail in the communications systems section, beginning on page 157.
[430] This fitting also served as the forward attachment point for the SCA.
[431] The crew hatch is described in more detail on page 126.

all of which were welded together to create a pressure-tight vessel.[432] Gold-coated, multilayer insulation blankets were attached to the outside surfaces.[433] There were roughly 300 penetrations within the module, all of which were sealed with plates and fittings.[434] Ten of these penetrations were the windows within the flight deck level. There were six windows at the forward end, surrounding the commander and pilot stations, two in the aft bulkhead, and two in the top surface of the vehicle.[435]

The crew module was connected to the forward fuselage at only four attachment points to limit thermal conductivity between the two components. The two main attachment points were situated at the aft end of the flight deck floor level. The third attachment point, which handled all vertical load reactions, was located on the centerline of the $X_O = 378$ bulkhead. The fourth attachment point, used to handle all lateral load reactions, was situated on the lower segment of the $X_O = 582$ bulkhead.[436]

The crew module contained three internal levels (Figure No. B-70): the flight deck at the top, the middeck in between, and the equipment bay at the bottom. Over these three levels, the crew module supported the vehicle's ECLSS, avionics equipment, guidance, navigation and control (GNC) equipment, inertial measurement units, displays and controls, star trackers, and crew accommodations for sleeping, waste management, seating, and eating. The module was accessed via the crew hatch, located on the port side of the orbiter, which was the only means of entry into and out of the orbiter (except in the case of emergency situations).[437] Two access openings in the flight deck floor, one on each side of the orbiter, allowed travel between the middeck and flight deck; both had approximate dimensions of 26" x 28".[438] A ladder was attached to the left opening for access between the levels at Earth atmospheric conditions. No provisions were available to allow the crew, or ground personnel, physical access into the equipment bay.

Flight Deck

The flight deck served as the location for flight controls and crew stations for launch, on-orbit operations, and landing (Figure Nos. B-71 through B-74). It was functionally divided into two areas: the forward flight deck and the aft flight deck. The forward flight deck generally included the commander and pilot stations; the aft flight deck consisted of the mission control station

[432] "2219 Aluminum Alloy" is a type of aluminum alloy that uses copper and nickel as the alloying elements. It has excellent resistance to corrosion, and has highly efficient thermal and electrical properties, making it an ideal use in extreme temperatures.
[433] *Enterprise* and *Columbia* had these blankets attached to the interior frames and skin of the forward fuselage; *Challenger*, *Atlantis*, and *Endeavour*, like OV-103, had them attached directly to the outside of the crew compartment. Jenkins, *Space Shuttle*, 367.
[434] During assembly procedures, there was a large removable panel in the aft bulkhead to provide access to the crew compartment. Boeing, *OV-103, Volume I*, 85.
[435] USA, *Crew Operations*, 1.2-3; Boeing, *OV-103, Volume I*, 85.
[436] USA, *Crew Operations*, 1.2-3, 1.2-4; Boeing, *OV-103, Volume I*, 86.
[437] A description of the crew escape systems begins on page 208.
[438] Typically, the right opening was closed and the left was open. USA, *Crew Operations*, 1.2-5.

(behind the pilot's seat), the payload control station (behind the commander's seat), and the on-orbit control station, mounted to the aft bulkhead. During launch and landing operations, the flight deck typically held four crewmembers, the commander in the front port seat and the pilot in the front starboard seat, with two mission specialists behind them.[439] The commander and pilot seats, which were used for all on-orbit propulsion activities, were left in place during the entire mission. The rear mission specialist seats, on the other hand, were typically removed and stowed while the vehicle was in orbit.[440]

All crew seats had approximate dimensions of 25.5" high, 15.5" wide, and 11" deep, and were primarily made of 7075 aluminum alloy.[441] The commander and pilot seats were fitted with two shoulder harnesses and a lap belt for restraint, and were capable of moving up to 5" backward and 10" upward, with the aid of a single electric motor; this assisted the commander and pilot in seeing and reaching controls during ascent and reentry. These seats also had stowage compartments for in-flight equipment, removable seat cushions, and provisions for oxygen and communications connections to the crew altitude protection system.[442] The mission specialist seats were also fitted with two shoulder harnesses and a lap belt. These seats could not move forward/backward or upward/downward, but they could be tilted a maximum of 10 degrees. Like the commander and pilot seats, these were also fitted with removable cushions and oxygen/communications connections; however, they did not contain any stowage compartments.[443]

Throughout the forward and aft flight deck areas, there were approximately 2,100 displays and controls. These displays and controls were divided among various panels, each of which had its own alphanumeric designation based on its location on the flight deck (Figure Nos. B-75, B-76). The designations for those panels on the forward wall of the flight deck began with an "F," while the labels for the panels on the aft wall began with an "A." The numeric designation for both forward and aft panels followed a sequential pattern that started at the top left corner (as facing the wall) and reading across in rows. A similar numbering pattern was used for the overhead

[439] USA, *Crew Operations*, 1.2-4.
[440] Jenkins, *Space Shuttle*, 369.
[441] "7075 Aluminum Alloy," is a type of aluminum alloy, which uses zinc as the primary alloying element. It has a strength comparable to many forms of steel and good fatigue strength; however, it has less resistance to corrosion than other aluminum alloys. This seat design was initiated in 1995, in preparation for ISS operations. The original seats were much heavier, and could not withstand the same loads as the new seats. At the same time, new floor fittings were designed to reduce loading at the attach points, a factor critical in relation to floor warping. The floor warping requirement was actually developed by the Federal Aviation Administration in response to common attach point failures that had been seen in commercial airline accidents. All of the seats were installed in the different orbiters as they went through their OMDP cycles. During the ALT and Orbital Flight Test (OFT) flights, the orbiter was fitted with only two seats, the commander and pilot seats, both of which were zero-zero ejection seats (seats designed to eject the crew from a grounded stationary position, or a low-altitude, low-velocity emergency). These were disabled after STS-4 and removed following STS-9. Jenkins, *Space Shuttle,* 369-370.
[442] There is also manual control over the movement of the seats, but that is available only during the on-orbit phase of the mission. Jenkins, *Space Shuttle,* 369.
[443] Jenkins, *Space Shuttle,* 369.

panels, which began with an "O," and the center console panels, which began with the letter "C." The panels along the right and left walls, denoted by "R" and "L," respectively, were numbered slightly differently. Those to the front of the bulkhead (i.e., within the forward flight deck) were numbered from top to bottom, forward to aft, whereas those behind the bulkhead (i.e., in the aft flight deck) were numbered from left to right, top to bottom.[444]

The forward flight deck was arranged in a standard pilot/copilot layout (Figure No. B-71), with the commander's seat on the port side of the vehicle and the pilot's seat on the starboard side. Both stations were capable of piloting the vehicle during all phases of flight; those panels that contained the appropriate controls were mirrored on each station. The forward flight deck had an area of approximately 24 square feet, including the center console; the side consoles added 3.5 square feet.[445]

A key feature of the forward flight deck was the MEDS (Figure No. B-77), commonly referred to as the "glass cockpit," which was designed in the early 1990s.[446] The MEDS extended across the three forward control panels, and contained nine identical, color, multifunction display units, four integrated display processors, and four analog-to-digital converters. The display units were similar to the flat panel displays developed for the Boeing 777, except modified to use a liquid crystal display produced in the U.S. The screen was 6.71" in height and width, with an allowable horizontal viewing angle of +/- 60 degrees and an allowable vertical viewing angle of +45/-10 degrees.[447] The integrated display processors performed all of the functions of the original display electronics units and display driver units, except for the operation of the rotational hand controllers. The processors controlled the operation of the MEDS, and provided the interface to the GPCs. The analog-to-digital converters converted roughly thirty-two analog flight instrument signals into digital transmissions that were usable by the MEDS.[448]

The dedicated displays were used to provide the flight crew with the data required to either fly the vehicle manually, or to monitor the automatic flight control system performance. The data were generated by the navigation or flight control system software, or more directly by the navigation sensors. There were eleven multifunction display units that made up the dedicated display system; they included the primary flight displays, the surface position indicator, the RCS activity lights, and the head-up displays. Nine displays were located among the commander and

[444] USA, *Crew Operations*, 1.1-8 through 1.1-10.
[445] USA, *Crew Operations*, 1.2-5; Boeing, *OV-103, Volume I*, 87.
[446] The original was referred to as the electro-mechanical cockpit.
[447] The display units replaced the original three cathode ray tube displays, and various dedicated displays, such as the altitude director indicators, the two horizontal situation indicators, and the altitude/vertical velocity indicators (Figure No. B-78). The MEDS was installed in each orbiter during one of its OMDPs. *Atlantis* was the first to receive it, during her 1998 OMDP; *Columbia* received hers during her late-2000 OMDP, *Discovery* got hers during her OMDP-3, and *Endeavour* got hers during her OMDP-2. Boeing, *OV-103, Volume II*, 70; Jenkins, *Space Shuttle*, 374-376.
[448] Jenkins, *Space Shuttle*, 375.

pilot stations, and two were on the aft flight deck panel near the aft-facing windows; all were considered part of the MEDS.[449]

The primary flight display, or the "flight instruments," was located between the commander's and pilot's stations in the forward flight deck. The visuals on the display changed with each phase of the mission to show the appropriate data. As the mission phase changed, data no longer needed were removed from the display, and the area was replaced with pertinent data to the new phase of flight, or left blank.[450] The various screens displayed the attitude director indicator, the horizontal situation indicator, and various flight instrument tapes and meters.

The attitude director indicator (Figure B-79) provided information relative to the vehicle's attitude, as well as attitude rates and errors; it was displayed as a software simulated enclosed ball that gimbaled to represent three degrees of freedom. A digital readout also showed the current pitch, yaw, and roll in degrees.[451] The horizontal situation indicator (Figure B-80) displayed a pictorial view of the vehicle's position with respect to various navigation points. It also showed a visual perspective of certain GNC parameters, such as direction, distance, and course/glide path deviation. It was typically displayed during ascent, abort, and entry.[452] Flight instrument tapes were only shown during ascent and entry, and consisted of several meters or digital displays that showed vehicle parameters, such as angle of attack, Mach/velocity, equivalent air speed, altitude, altitude rate, altitude acceleration, and a g-meter. With the exception of the altitude acceleration, the value of each parameter was read by a digital window centered on the moving tape.[453]

The surface position indicator was also a MEDS display; it was active only during the entry phase of flight (Figure B-81). This indicator displayed the actual position of the orbiter's elevons, body flap, rudder, aileron, and speedbrake, as well as the commanded speedbrake position. There was a separate indicator for each elevon; the indicators were in the order of appearance as viewed from the rear of the vehicle (i.e., left outboard, left inboard, right inboard, right outboard). The scales of each display typically ranged between the software limits for the particular component.[454]

The RCS activity lights were typically displayed on panel F6 in the forward flight deck; they were activated following main engine cut-off. The primary purpose of the lights was to indicate RCS jet commands by axis and direction during transitional and orbit phases. They were also used to indicate when more than two yaw jets were commanded, and when the elevon drive rate

[449] USA, *Crew Operations*, 2.7-1.
[450] USA, *Crew Operations*, 2.7-3.
[451] USA, *Crew Operations*, 2.7-3, 2.7-4.
[452] USA, *Crew Operations*, 2.7-8.
[453] USA, *Crew Operations*, 2.7-3, 2.7-14.
[454] USA, *Crew Operations*, 2.7-17, 2.7-18.

was saturated. There were three lights, one of which controlled vehicle roll (left to right), one controlled yaw (left to right), and one controlled pitch (up and down).[455]

A head-up display was located on the glare-shield in both the commander's and pilot's stations. The display served as an optical miniprocessor that cued the commander and pilot during the final phase of entry, in particular during the final approach to the runway. The display presented the same data that was shown on several other instruments, including the primary flight display and the surface position indicator. It superimposed flight commands and information on a transparent combiner in the window's field of view, requiring only minimal eye movement by the commander and pilot between the orbiter windows (head up) and the dedicated display instruments (head down).[456]

The commander and pilot stations were each also fitted with a rotational hand controller, which could control vehicle rotation along all three axes. These controllers allowed the crew to command different vehicle components depending on the phase of the mission. For ascent, they could gimbal the SSMEs and the SRBs; for orbital insertion and deorbit, they gimballed the OMS engines and commanded thrusting of the RCS engines; while on-orbit, they commanded the RCS thrusters; during reentry, they provided normal flight control-type inputs, commanding either the RCS thrusters or other aerodynamic surfaces as required. Each station was also fitted with a rudder pedal, which controlled the rudder during atmospheric flight, as well as the nose wheel steering system and the main wheel brakes during ground operations. The pedals also had a speedbrake/thrust controller, used to either vary the SSME thrust level during ascent or operate the speedbrake during descent.[457]

The aft flight deck (Figure No. B-74), which had an area of roughly 40 square feet, contained the displays and controls for executing attitude or translational maneuvers associated with rendezvous, stationkeeping, docking, payload deployment and retrieval, payload monitoring, RMS operations, payload bay door operations, and closed-circuit television operations. The aft flight deck was fitted with a rotational hand controller, similar to those in the commander and pilot stations, that was used to control the RMS; it also had a translational controller. In addition, the aft flight deck contained two dedicated displays that were considered part of the MEDS.[458]

In order to aid with piloting the vehicle, as well as on-orbit operations, the flight deck contained ten window sets, all of which were manufactured by the Corning Glass Company in Corning, New York.[459] There were six windows on the forward flight deck, with two above the aft flight deck, and two in the aft bulkhead, which looked out on the payload bay. The windows on the forward deck were surrounded with active cooling system loops to reduce heat loads during

[455] USA, *Crew Operations*, 2.7-19, 2.7-20.
[456] USA, *Crew Operations*, 2.7-21.
[457] Jenkins, *Space Shuttle*, 371-372.
[458] USA, *Crew Operations*, 1.2-4, 1.2-5; Boeing, *OV-103, Volume I*, 87.
[459] Jenkins, *Space Shuttle*, 369.

reentry. They were also the thickest pieces of glass ever produced in the optical quality for see-through viewing. The innermost pane was 0.625" thick, and was constructed of tempered aluminosilicate glass that was designed to withstand crew compartment pressure. The exterior face of this pane was coated with a red reflector coating, which reflected infrared rays (heat producing) while still transmitting the visible spectrum. The middle pane was constructed of 1.3"-thick, low-expansion, fused silica glass, and provided a thermal shock layer. The inner and outer surfaces were coated with a high-efficiency, anti-reflection coating to improve visible light transmission. The outer pane was of the same material as the middle pane, but was only 0.625" thick. It provided thermal and impact protection, and its inner surface was coated with the same high-efficiency, anti-reflection coating as the middle pane. The two inner panes measured 35" diagonally and were mounted to the crew cabin; the outer pane measured 42" diagonally and was attached to the forward fuselage. Redundant seals surrounded each window. The forward windows were used by the commander and pilot for entry and landing activities, as well as appropriate on-orbit operations.[460]

The two overhead windows were of the same construction as the forward windows, except for thickness. For these windows, the inner and center panes were 0.45" thick and the outer pane was 0.68" thick; their clear view area was 20" x 20". Like the forward windows, the two inner panes were attached to the crew cabin, while the outer pane was attached to the forward fuselage. The overhead port window was fitted with a pyrotechnic charge release for emergency exit purposes. The rear windows consisted of only two panes of glass, which were identical to the inner and middle panes of the forward windows, except for thickness and size. Each pane was 0.3" thick and measured 14.5" x 11"; both panes were attached to the crew compartment. The rear and overhead windows were used during rendezvous and docking procedures, as well as payload bay activities. All of the windows were provided with shades to control sun glare while the vehicle was in orbit. On the forward windows, these shades were rolled up and stored at the base of the windows. The overhead window shades were stored in the middeck and fitted to attachments on the windows. The rear window shades were held in place with Nomex Velcro around their perimeter.[461]

Middeck

Completely stripped of all equipment, the middeck was approximately 160 square feet in area; during a mission, its gross mobility area was nominally 100 square feet (Figure Nos. B-82, B-83). The middeck provided accommodations for the crew, such as a galley for food preparation, the waste management system (toilet, trash, etc.), and lockers for equipment and astronaut personal effects storage as well as experiment storage, and three avionics bays. During launch and landing procedures, the middeck was fitted with three seats, typically inhabited by mission

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[460] USA, *Crew Operations*, 1.2-6, 1.2-7; Jenkins, *Space Shuttle*, 367-368.
[461] USA, *Crew Operations*, 1.2-6; Jenkins, *Space Shuttle*, 368. Nomex is the trademark name for a rigid, heat resistant felt manufactured by DuPont.

specialists; these were stowed during on-orbit operations. If the sleep stations were not present, the middeck could accommodate an additional three seats.[462]

The crew hatch was located at the middeck level on the port side, and had an approximate diameter of 40" (Figure No. B-84). It was attached to the vehicle by hinges, a torque tube, and support fittings; it was also fitted with a pressure seal and an Inconel thermal barrier was situated between it and the TPS mounted to the forward fuselage.[463] The hatch could open to a 90-degree angle, and at its center was a 10" clear-view window that consisted of three panes of glass. The inner pane of glass was 11.4" in diameter and 0.25" thick, while the center pane was 11.4" in diameter and 0.5" thick. The outer pane was 15" in diameter and 0.3" thick. A window cover was permanently attached to the frame via a hinge, which allowed for easy opening and closing. The crew hatch could be operated from the interior or the exterior of the vehicle; following the *Challenger* accident, the hatch was modified to allow it to be explosively jettisoned in emergency situations.[464]

The middeck contained three of the orbiter's six avionics equipment bays.[465] Two of these, Avionics Bay No. 1 (port side) and Avionics Bay No. 2 (starboard side), were located along the forward bulkhead. Together, they extended across the entire width of the cabin; each was 39" in length and stood the full height of the middeck. The third bay, Avionics Bay No. 3A, was located on the starboard side of the aft bulkhead. It also had a length of 39" and stood the full height of the middeck; its width was roughly 46".[466] This avionics bay also had a built-in storage compartment, referred to as Volume 3B. This compartment typically held a cabin air cleaner and emergency breathing masks.[467]

The middeck had a stowage capacity of roughly 140 cubic feet. Crew, equipment, and experiment storage was provided by forty-four identical modular stowage lockers, each of which measured 11" x 18" x 21". The modular lockers were comprised of Kevlar-epoxy sandwich panels with a non-metallic core (Figure No. B-85).[468] The majority of the lockers were located along the forward wall of the middeck; typically, there were between six and eight rows of lockers, stacked in five columns. Modular stowage lockers were also installed on the forward side of the aft avionics bay. Usually, these were arranged in two columns with five or six rows.

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[462] USA, *Crew Operations*, 1.2-5; Boeing, *OV-103, Volume I*, 87-88. The seats were the same as the mission specialist seats used on the flight deck.
[463] Inconel is a registered trademark of Special Metals Corporation. It is a family of metallic, non-magnetic, nickel-chromium based superalloys that are oxidation and corrosion resistant, making them ideal for high temperature applications.
[464] USA, *Crew Operations*, 1.2-5; Boeing, *OV-103, Volume I*, 88.
[465] The space shuttle avionics system controlled, or assisted in controlling, most of the shuttle systems. The avionics system consisted of more than 300 major electronic black boxes located throughout the vehicle, and was designed to withstand multiple failures through redundant hardware and software.
[466] USA, *Crew Operations*, 1.2-5; Jenkins, *Space Shuttle*, 378.
[467] USA, *Crew Operations*, 2.24-4.
[468] Originally, the lockers were comprised of aluminum; the change in material provided a weight reduction of roughly 200 pounds in preparation for ISS activities. Jenkins, *Space Shuttle*, 378.

The lockers were interchangeable, and attached to the orbiter with spring-loaded captive bolts. They could be removed and installed during flight by the crewmembers. The modular lockers were fitted with insertable trays, which could be adapted to accommodate a wide variety of soft goods, loose equipment, and food.[469]

Aside from the modular stowage lockers, the forward wall of the middeck could be fitted with a work or dining table.[470] The aft wall of the middeck contained the opening for the airlock's access hatch. The access hatch opening was roughly situated along the centerline of the orbiter's y-axis; its center was approximately 24" above the middeck floor. To the upper port side of this opening was a control panel. On the port side of the aft middeck wall was the vehicle's waste management compartment, which included the toilet, as well as towel storage.

The starboard wall of the middeck had various attach points for crew sleeping bags (Figure No. B-86). In addition, this wall could be fitted with a four-tier bunk bed assembly for the astronauts to sleep in (see Figure No. B-82).[471] There was also a storage compartment, Volume B, along the starboard wall; it was typically used for dry trash, towels, or dirty laundry.[472] The port wall of the middeck contained the galley, the middeck accommodation rack, the crew hatch, and a few control panels. When installed, the galley/food system (Figure No. B-87) was situated near the forward end of the port wall. The galley was a multipurpose facility that provided a centralized location for handling all food preparation activities, stowage, and dining. It contained an oven, a rehydration station, hot and cold water, associated controls, and storage for utensils, condiments and other implements. The oven consisted of two principle compartments. The upper compartment was designed to heat up to fourteen rehydratable food containers inserted on tracks; the lower compartment could accommodate up to seven flexible packages. The rehydration station dispensing system interfaced directly with food and beverage packages to provide rehydration capability and drinking water for crewmembers.[473]

The galley was fitted with various switches and levers for different operations, such as dispensing hot water, selecting the amount of water, an oven/rehydration station on/off switch, two water heater on/off switches, and an oven fan switch. An auxiliary port water quick disconnect was also provided for dispensing water through a 12' flex line.[474] Next to the galley was a pantry, also referred to as Volume A, for the storage of snack food, beverages, condiments, and utensils. Only one set of utensils, which included a knife, a fork, a tablespoon, and a small pair of scissors, was provided for each crewmember for the entire flight.[475]

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[469] USA, *Crew Operations*, 2.24-1, 2.24-2.
[470] USA, *Crew Operations*, 2.24-2.
[471] See the discussion on crew systems, beginning on page 212.
[472] USA, *Crew Operations*, 2.24-2.
[473] USA, *Crew Operations*, 2.12-1.
[474] USA, *Crew Operations*, 2.12-2.
[475] USA, *Crew Operations*, 2.12-3.

The provided food supply was categorized as either menu food, pantry food, or fresh food; meals were individually tailored based on crewmember preference. Menu foods were the three typical daily meals (breakfast, lunch, dinner); pantry food was a two-day contingency food supply that also contained snacks and beverages; and fresh foods were perishable items such as fruits, vegetables and tortillas. In addition, reentry kits were provided for each crewmember, which contained either empty drink bags and salt tablets, chicken consommé packets, or Astroade packets. These were to provide the necessary water and salt for each crewmember for readjustment to 1-g atmospheric conditions.[476] The middeck accommodation rack (Figure No. B-88), which typically consisted of four compartments, was located to the aft of the galley. The middeck accommodation rack provided storage for small payloads and experiments in the middeck of the orbiter. It was installed just forward of the crew hatch in the aft area of the galley. If the middeck accommodation rack was not required, a lightweight version of the rack was installed, which could hold a maximum load of 390 pounds. It contained the same volumetric space as the standard rack.[477]

The ceiling of the middeck was fitted with various panels, light fixtures, and openings. Five compartments were located in the middeck floor for storage: they were labeled Volumes D, E, F, G, and H. Volume D was a floor compartment that was partially blocked by the forward lockers; it was used to store EVA tools, gravity suits, and miscellaneous items. Volume E was located next to Volume D and was used for official flight kits and personal preference kits; access to the compartment required the removal of two lockers. Volume F was the wet trash compartment, and was located in the floor near the starboard wall. Volume G was immediately to the aft of Volume F and contained contingency hygiene equipment and a spare odor bacteria filter; two lockers had to be removed for access to the compartment. Volume H, located at the base of the interdeck ladder on the port side of the middeck, was used to store EVA accessories.[478]

Equipment Bay

Aside from the compartments listed above, the *Discovery's* equipment bay (Figure No. B-89) contained components for various systems, such as fans for the avionics bays, water tanks (potable and wastewater), water pumps, air supply and return ducts, and heat exchangers.[479]

<u>Forward Reaction Control System Module</u>

The **FRCS module** (Figure No. B-90) was manufactured by Rockwell's Space Transportation System Division, located in Downey, California.[480] The module had rough overall dimensions of 84" in length, with a width of 72" and height of 28" at its forward end, and a width of 132" and

[476] USA, *Crew Operations*, 2.12-3, 2.12-4.
[477] USA, *Crew Operations*, 2.24-6.
[478] USA, *Crew Operations*, 2.24-2 through 2.24-4.
[479] Jenkins, *Space Shuttle*, 367.
[480] Jenkins, *Space Shuttle*, 367.

height of 64” at its aft end. While the top surface was rounded to correspond with the forward fuselage, the bottom surface was shaped to fit around the nose landing gear wheel well. Similar to the forward fuselage, it had conventional 2024 aluminum alloy, single-curvature, stretched form skin-stringer panels, which were riveted to a series of frames made of the same material. It was secured to the orbiter behind the nose cap (roughly at $X_O = 294$) and at the $X_O = 378$ bulkhead of the forward fuselage, with sixteen fasteners. This allowed the module to be removed for servicing, as required.[481]

The function of the module was to house the components associated with the FRCS.[482] This included fourteen primary engines, three near the forward end of the top surface, three at the aft end of the top surface, and four in the aft portion of each side surface, and two vernier engines, one near the center of each side. All of the engines were fitted with thermal barriers for protection. Attached to the inside of the module were the fuel (monomethylhydrazine [MMH]) and oxidizer (nitrogen tetroxide [N_2O_4]) tanks, on the left and right sides, respectively; two helium tanks, one per side; four heater panels; a fuel manifold; fluid piping; and several valves.[483]

Ground servicing access to the FRCS was provided by various panels around the module (see Figure Nos. B-65, B-66, B-67), which were protected during flight by TPS-clad, aluminum covers. On the port side of the module were the fuel purge/drain/checkout panel (forward) and the fuel servicing panel (aft), while the starboard side of the module was fitted with the oxidizer purge/drain/checkout panel (forward) and the oxidizer servicing panel (aft). In addition, two electrical panels were situated on the top surface of the module, an access panel to the port side, and a disconnect panel to the starboard. Each side of the module also had a relief vent, one for the MMH (port) and one for the N_2O_4 (starboard).

Midfuselage

The **midfuselage** (Figure No. B-91) was constructed by the Convair Aerospace Division of General Dynamics Corporation in San Diego, California.[484] It had approximate dimensions of 60’ in length, 17’ in width, and 13’ in height, and served as the structural backbone of the orbiter vehicle. On each side of the midfuselage, at the forward end, was a wing glove, which was used as an attachment point for the wing. To the aft of the wing glove, along the bottom of each side of the midfuselage, was the wing attachment interface. At the aft end of the midfuselage was the wing carry-through, just forward of which, on each side, was a main landing gear trunnion support structure, situated within the wing attachment interface.[485]

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[481] USA, *Crew Operations*, 1.2-3; Boeing, *OV-103, Volume I*, 91.
[482] The RCS is discussed in further detail beginning on page 205.
[483] USA, *Crew Operations*, 1.2-3; Boeing, *OV-103, Volume I*, 91.
[484] Jenkins, *Space Shuttle*, 382.
[485] USA, *Crew Operations*, 1.2-9.

The internal structure of the midfuselage was comprised of twelve main vertical frame assemblies, each of which was fitted with horizontal and vertical side strengthening elements. The horizontal strengthening elements, which sat below the payload bay area, were made from boron/aluminum tubes with bonded titanium end fittings; the vertical side strengthening elements were composed of machined aluminum. These frames divided the midfuselage into thirteen bays. The exterior of the midfuselage was faced with integrally-machined, reinforced aluminum skin panels. The skin panels located above the wing glove and wing attachment interface were reinforced by longitudinal T-stringers (forward eight bays) or aluminum honeycomb panels (aft five bays). The panels within the wing attachment interface had vertical aluminum stiffeners. The forward and aft ends of the midfuselage were open, and fitted with reinforced skin and longerons to provide an interface with the X_O = 582 bulkhead of the forward fuselage and the X_O = 1307 bulkhead of the aft fuselage.[486]

Discovery's midfuselage was strengthened following data collected from the earliest flights of the shuttle program, which showed higher than expected temperatures and stresses. To accomplish this, engineers attached torsional straps through the floor area (forward eleven bays only), which tied together all of the internal stringers, helping to eliminate potential torsional loads. In addition, vulcanized silicon rubber material was bonded to the lower midfuselage, from the fourth through the twelfth bays; this material helped to absorb heat and distribute it more evenly across the lower section.[487]

The midfuselage provided the main support for the payload bay doors, hinges, tie-down fittings, forward wing glove, and various orbiter systems, while forming the payload bay area and interfacing with the forward fuselage, the aft fuselage, and the wings. Supported by the twelve main vertical frame assemblies were the sill longerons, one per side, which with the door longerons, absorbed any bending loads on the vehicle. The sill longerons also supported payloads that were stowed in the payload bay, as well as the Ku-band antenna, the payload bay door actuation system, and, if installed, the RMS.[488] To support the various payloads, each longeron was fitted with 172 potential attach points, spaced at 3.933" on center.[489] These were augmented by eighty-nine attach points along the centerline keel at the bottom of the payload bay, seventy-five of which could support deployable payloads. Mounted above the sill longerons were the door longerons, one per side, which were supported by thirteen hinge fittings. Approximately halfway up each side of the midfuselage was an electrical wire tray, which contained all of the necessary wiring between the aft fuselage and the crew compartment.[490]

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[486] USA, *Crew Operations*, 1.2-9; Boeing, *OV-103, Volume I*, 95-96.
[487] This same modification was made to *Columbia*, *Challenger*, and *Atlantis*; *Endeavour's* midfuselage incorporated these features in its original construction. USA, *Crew Operations*, 1.2-10; Jenkins, *Space Shuttle,* 382.
[488] The Ku-band antenna, the payload bay door actuation system, and the RMS are further discussed in the communications system section, beginning on page 157.
[489] Forty-eight of these points were technically unusable because of their proximity to orbiter hardware.
[490] USA, *Crew Operations*, 1.2-9, 1.2-10; Boeing, *OV-103, Volume I*, 95-97.

Within the lower portion of the midfuselage was a variety of equipment associated with the orbiter's avionics, electrical power, environmental control and life support, hydraulics, and main propulsion systems. This equipment included such items as LH2 and LO2 tanks, fuel cells, hydraulic fluid lines, Freon pumps, purge circuits, nitrogen lines, power distribution boxes, and wire trays.[491]

Since 1996, *Discovery* contained an external airlock (Figure No. B-92), located within the forward end of the payload bay. The airlock assembly, constructed by Rockwell's Space Transportation Systems Division in Downey, California, provided a place where the astronauts could suit up and prepare for their EVA, without having to depressurize the entire crew compartment.[492] It had an approximate height of 83" and a rough diameter of 63", providing for an empty volume of about 228 cubic feet, and was constructed of aluminum and covered with thermal blankets.[493] The structural interface with the orbiter was via the X_O = 582 bulkhead, trunnion fittings at the payload bay centerline, and a beam-truss framework running across the payload bay.[494] A variety of utility panels and recharging stations were mounted to its internal walls to service and checkout the EVA equipment. The airlock also contained various handrails and foot restraints to assist crewmembers in maneuvering; all were sized for EMU gloves and boots as appropriate. Typically, an airlock stowed two EMUs, and was sized to hold two fully-suited crewmembers at the same time.[495]

The airlock was fitted with three, 40"-diameter, D-shaped openings (Figure No. B-93); the inner hatch, the EVA hatch, and the docking hatch. The inner hatch was mounted to the external surface on the forward side of the airlock, and opened into the middeck. The EVA hatch was mounted to the external surface on the aft side of the airlock, and permitted the crewmembers to exit the airlock into the payload bay. The docking hatch was situated in the top of the airlock and was used for docking operations. Each of the hatches was fitted with six interconnected latches and a gearbox/actuator, a hinge mechanism and hold-open device, a differential pressure gauge on each side, and two equalization valves. Each was also fitted with a 4"-diameter window at the center, the dual panes of which were comprised of polycarbonate plastic. Each hatch was fitted with dual pressure seals, one mounted to the hatch and the other to the airlock structure; a leak check quick disconnect was installed between the seals to verify hatch pressure integrity before flight. The gearbox with latches allowed the crew to open and close the hatch during transfers and EVA operations. The gearbox and latches were mounted to the low pressure side of the

[491] USA, *Crew Operations*, 1.2-10; Boeing, *OV-103, Volume I*, 98. These pieces of equipment will be discussed further in the appropriate system's section.
[492] Jenkins, *Space Shuttle*, 381.
[493] USA, *Crew Operations*, 2.11-9. Originally, all of the orbiters, with the exception of *Enterprise,* contained internal airlocks, located at the rear of the middeck. Jenkins, *Space Shuttle*, 379.
[494] Boeing, *OV-103, Volume I*, 101.
[495] A one-person EVA was not permitted by NASA. Additionally, experience has shown that three fully-suited crewmembers could fit in the airlock. Jenkins, *Space Shuttle*, 380.

hatch, but there was a gearbox handle on both sides. This enabled each hatch to be fully locked or unlocked from either side.[496]

The external airlock contained an air circulation system that provided conditioned air to the airlock during non-EVA periods. The duct for this system was installed once the inner hatch was opened, and needed to be removed before the hatch was closed for airlock depressurization. Depressurization was controllable only from inside the airlock. This operation was conducted immediately prior to the EVA, after all prebreathe sessions and suit checkouts. The airlock was not repressurized until the EVA was complete, and the participating crewmembers had returned; this operation could be controlled from either the middeck or inside the airlock.[497]

The external airlock was fitted with an orbiter docking system (Figure No. B-94) that was used to dock the shuttle to the ISS. It had approximate dimensions of 6.5' in length, 15' in width, and 13.5' in height.[498] The system consisted of three major components: the external airlock (described above), the truss assembly, and the androgynous peripheral docking system.[499] The truss assembly was physically attached to the payload bay, and provided a sound structural base to house the components of the docking system. It also held rendezvous and docking aids, such as camera/light assemblies and trajectory control systems.[500]

The androgynous peripheral docking system achieved the capture, dynamic attenuation, alignment, and hard docking of two spacecraft through identical mechanisms attached to each vehicle. The docking system was supported by a structural base ring that housed twelve pairs of structural hooks; attached to this was an extendible guide ring with three petals. Each guide petal contained a motor-driven capture latch. The docking system also contained three interconnected ball screw/nut mechanism pairs; six electromagnetic brakes (dampers); and five fixer mechanisms, which allowed for only z-axis movement of the active ring.[501]

Payload Bay Doors

The orbiter's **payload bay doors** (Figure No. B-95) were manufactured by Rockwell International's Tulsa, Oklahoma, Division.[502] Each door had a total length of 60', and was comprised of five segments, which were made of graphite epoxy/Nomex composite honeycomb panels; between each segment was a circumferential expansion joint to assist with the extreme temperature changes. The five segments were sized and arranged so that each door was divided into a forward section and an aft section, each of which had an approximate length of 30'. Each door roughly measured 8.75' along the y-axis and 6.7' along the z-axis, and had a mean chord of

[496] USA, *Crew Operations*, 2.11-10, 2.11-12.
[497] USA, *Crew Operations*, 2.11-8.
[498] Jenkins, *Space Shuttle*, 381.
[499] USA, *Crew Operations*, 2.19-1.
[500] USA, *Crew Operations*, 2.19-1.
[501] USA, *Crew Operations*, 2.19-2.
[502] Jenkins, *Space Shuttle*, 383.

approximately 10'. Each was capable of opening to a maximum angle of 175.5 degrees. Although the payload bay was not a pressurized area, thermal seals were fitted to the doors to provide an air-tight space when they were closed and latched.[503]

Each door was connected to its corresponding midfuselage longeron with thirteen Inconel-718 external hinges. Eight of these were "floating" hinges that allowed forward and aft movement of the door panels in response to thermal expansion and contraction of the materials. Each door was driven by a rotary actuator that powered a 55'-long torque shaft, which pushed the door open and pulled it closed; the right (starboard) door had to be opened first and closed last because it contained the structural/seal overlap and the centerline latching mechanism. This latching mechanism was comprised of sixteen latches, which were grouped into four latch gangs. Each of these gangs consisted of four latches, bellcranks, push rods, levers, rollers, and an electromechanical actuator. Additionally, the payload bay doors were further secured by eight positive position latches at each end (four per side), which hooked into the forward and aft fuselage bulkheads.[504]

The payload bay doors maintained a pressure seal for the payload bay during the ascent and descent phases of flight, and then provided crew access to the onboard payloads while in space. Since the doors remained open nearly the entire time the vehicle was in orbit, each was fitted with two to four radiator panels that were considered part of the orbiter's active thermal control system.[505]

<u>Wings</u>

The two orbiter **wings** (Figure No. B-96) were fabricated from conventional aluminum alloys by Grumman Aerospace of Bethpage, Long Island, New York.[506] Each wing had a length of roughly 67', a width that ranged from 1' to 29', and a maximum height (thickness) of approximately 5'. Each wing consisted of a wing glove/forward wing box, a leading edge spar, an intermediate section (within which was the main landing gear well), a torque box, the wing/elevon interface, the elevon seal panels, and two elevons along the trailing edge. The inner leading edge of the wing (i.e., the edge of the forward part of the wing) had an 81 degree sweep; the outer leading edge (i.e., the edge of the aft part of the wing) had a 45 degree sweep. The wings were attached to the wing interface sections of the midfuselage by a tension bolt splice along the upper surface, and a shear splice along the lower surface. Together, they provided the conventional lift and control for the orbiter when it was within the Earth's atmosphere.[507]

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[503] Boeing, *OV-103, Volume I*, 103-104; Jenkins, *Space Shuttle*, 383.
[504] Boeing, *OV-103, Volume I*, 104-105; Jenkins, *Space Shuttle*, 383.
[505] Boeing, *OV-103, Volume I*, 104; Jenkins, *Space Shuttle*, 383. The radiator panels, manufactured by LTV in Grand Prairie, Texas (now Lockheed Martin), are described in more detail beginning on page 182. Jenkins, *Space Shuttle*, 384.
[506] Jenkins, *Space Shuttle*, 387.
[507] USA, *Crew Operations*, 1.2-7; Boeing, *OV-103, Volume I*, 92; Jenkins, *Space Shuttle*, 387. A weight reduction program was initiated for the orbiters following construction of *Columbia* and *Challenger*, and before the

The forward wing box, which roughly extended from the X_O = 807 mark to the X_O = 1008 mark, had an internal structure that was comprised of aluminum ribs, aluminum tubes, and tubular struts; its skin panels were fabricated of stiffened aluminum. Its purpose was to aerodynamically blend the wing leading edge into the midfuselage wing glove. The leading edge spar of the forward wing box, situated along the outboard section of the wing, was constructed of corrugated aluminum, and served as the attachment point for the RCC wing leading edge panels.[508]

The intermediate section of each wing was approximately located between the X_O = 1008 and X_O = 1191 marks. Its internal structure was made of aluminum multiribs and tubes, while the skin was comprised of aluminum alloy honeycomb panels. It was within this section that the angle of the leading edge sweep changed. Along the inner face of the intermediate section of each wing, between the X_O = 1040 and the X_O = 1191 marks, was its corresponding main landing gear wheel well. The wheel well, which had approximate dimensions of 12.6' in length and 6' in width, was fitted with doors that were attached to the lower surface of the wing. The outboard door hinges, as well as the outboard main landing gear trunnion and drag link, were braced by a structural rib; the inboard counterparts were supported by the midfuselage. The doors were comprised of conventional aluminum honeycomb panels, with machined aluminum hinge beams and hinges. Each was fitted with pressure seals and thermal barriers.[509]

The torque box of each wing extended from approximately the X_O = 1191 mark to roughly the X_O = 1365 mark. It had an internal structure comprised of a conventional eleven, aluminum alloy rib truss arrangement with four graphite composite spars; its upper and lower surfaces were formed by stiffened aluminum panels.[510] As the primary structural portion of the wing, its purpose was to carry airloads into the midfuselage, as well as to resist bending and twisting loads. Immediately to the aft of the torque box was the wing/elevon interface area, which was roughly located between the X_O = 1365 and the X_O = 1397 marks. This area was comprised of a series of fifteen hinged panels, commonly referred to as flipper doors, which were attached to the trailing edge spar of the torque box; they were manufactured of aluminum and covered with FRSI.[511]

Each of *Discovery's* wings had a two-piece elevon (see Figure No. B-96), divided into an inboard segment and an outboard segment, which were physically connected to the trailing edge

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construction of *Discovery* and *Atlantis*, leading to a redesign of portions of the wings. As a result, additional doublers and stiffeners were inserted into the *Discovery* and *Atlantis*' wings to maintain positive margins of safety. USA, *Crew Operations*, 1.2-9; Jenkins, *Space Shuttle,* 388.

[508] USA, *Crew Operations*, 1.2-7, 1.2-8; Boeing, *OV-103, Volume I,* 92. *Columbia* and *Challenger's* leading edge spars were made of non-corrugated aluminum honeycomb sandwich construction. *Enterprise's* leading edge spar was made of fiberglass.

[509] USA, *Crew Operations*, 1.2-8; Boeing, *OV-103, Volume I,* 92-93.

[510] *Columbia* and *Challenger* had corrugated aluminum spars, which was later shown to be inadequate, leading to the installation of an additional rib.

[511] USA, *Crew Operations*, 1.2-8; Boeing, *OV-103*, *Volume I*, 94. Prior to 2000, the inner eight panels were made of titanium honeycomb sandwich construction, while the outer seven panels were comprised of Inconel honeycomb sandwich construction. Jenkins, *Space Shuttle,* 388.

spar of the torque box. The inboard elevon measured approximately 13.79' in width; the length at its inner face was roughly 8.72', while the length at its outer face was about 6.27'. The outboard elevon had a width of approximately 12.42', with an inner length of about 6.08' and an outer length of roughly 3.88'. The elevons were comprised of conventional aluminum multirib and beam construction, and faced with aluminum honeycomb skins. Their upper leading edge was fitted with a titanium rub strip that provided a sealing surface for the flipper doors. Protective thermal seals were located on the elevon lower cove area, while thermal spring seals were fitted on the upper rub strip. Each elevon segment was connected to the trailing edge spar by three hinges, which were attached to hydraulic actuators, which allowed for a maximum deflection of 33 degrees upward and 18 degrees downward.[512]

Aft Fuselage

The **aft fuselage** (Figure No. B-97), which was manufactured by Rockwell International in Downey, California, had approximate overall dimensions of 18' in length, 22' in width, and 20' in height.[513] At the forward end of the aft fuselage was the X_O = 1307 bulkhead, which was comprised of machined and beaded sheet aluminum segments and served as the interface with the midfuselage. It also provided the forward attachment point for the vertical stabilizer, through an aluminum support frame that extended for the entire length of the fuselage. At the rear of the aft fuselage was the heat shield (at roughly the X_O = 1293 mark), that closed off the fuselage and protected the SSMEs during ascent and reentry. This shield consisted of a machined aluminum base, to which were attached honeycomb domes that supported flexible and sliding seal assemblies. There were also three engine-mounted head shields, comprised of Inconel honeycomb material, which were removable for access to the SSME power heads. Below the heat shields was a small compartment that contained the four hinge points and actuators for the body flap.[514]

Aside from the X_O = 1307 bulkhead and the aft heat shield, the aft fuselage was comprised of an outer shell, a SSME thrust structure, and an internal secondary structure. The outer shell was composed of integral-machined aluminum, with numerous penetrations associated with the internal systems. On the top surface of the outer shell, there was one APU exhaust port, three water spray boiler vent, and one ammonia vent to the starboard side of the vertical stabilizer, and two APU exhaust ports and one LH2 feedline relief vent to the port side of the vertical stabilizer. The rear of the outer shell, or the heat shield, contained three openings for the SSMEs, one on top and two on the bottom, as well as one propellant crossfeed disconnect access panel to either side of the top engine. The starboard and port sides of the outer shell were mirror images of one another. Each contained an aft hoist attach access point, just below the forward end of the

[512] USA, *Crew Operations*, 1.2-8; Boeing, *OV-103, Volume I*, 93-94. The elevons are technically capable of deflecting 40 degrees upward and 20 degrees downward; however, the 33/18 limits were set to avoid over-stressing the airframe. USA, *Crew Operations*, 1.2-8; Jenkins, *Space Shuttle*, 388.
[513] USA, *Crew Operations*, 1.2-10; Boeing, *OV-103, Volume I*, 106; Jenkins, *Space Shuttle*, 385.
[514] USA, *Crew Operations*, 1.2-11; Boeing, *OV-103, Volume I*, 107.

OMS/RCS pod; an aft fuselage access door to the rear of the attach point; a T-0 umbilical panel below the aft end of the OMS/RCS pod; an APU servicing panel; and various vent holes.[515]

The bottom surface of the aft fuselage (see Figure No. B-68) featured the two ET attach/umbilical compartments, the compartment for the LO2 situated on the starboard side and the LH2 on the port side. The ET attach point in each compartment was situated at the outer forward corner, with a jack pad directly behind it.[516] The LO2 compartment also had a LO2 feedline disconnect at the inner forward corner with a gaseous oxygen (GO2) pressurization disconnect to its outer aft side, and an electrical umbilical in the aft center. Likewise, the LH2 compartment had a LH2 feedline disconnect at the inner forward corner with a gaseous hydrogen (GH2) pressure disconnect to its outer aft, an electrical umbilical in the aft center, and a LH2 tank recirculation disconnect towards the inner aft corner. Each of the compartments was fitted with a 48" x 48" beryllium door that electromechanically closed following ET separation. The two door hinges were located on the inner sides of the compartments.[517]

The internal thrust structure (see Figure No. B-97) was essentially a framework that was primarily comprised of twenty-eight machined, diffusion-bonded truss members; the bonds were formed with titanium strips.[518] In selected areas, the structure was reinforced with boron-epoxy tubular struts, which added stiffness to the component while minimizing the weight. The internal thrust structure was divisible into an upper thrust structure, which supported the top SSME, and a lower thrust structure that held the bottom two SSMEs. The upper thrust structure was composed of integral-machined aluminum construction with aluminum frames, with the exception of the vertical fin support frame, which was made of titanium. This structure also supported the OMS pods, the drag chute compartment, and the upper SSME.[519] In addition, the internal thrust structure included the SSME load reaction truss structure, engine interface fittings, and the SSME gimbal actuator support structure.[520]

The aft fuselage's internal secondary structure was made of conventional aluminum, with titanium and fiberglass used to thermally isolate the equipment within the component. The assembly contained various secondary brackets, buildup webs, trusses, and machined fittings for additional support where loads were higher, and included support provisions for the APUs, avionics, hydraulics, environmental control and life support systems, and electrical wiring trays. Some of these supports were shock-mounted to the structure.[521]

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[515] USA, *Crew Operations*, 1.2-11; Boeing, *OV-103, Volume I*, 108.
[516] The mount mechanism was considered part of the ET and is described in that section.
[517] USA, *Crew Operations*, 1.2-11; Boeing, *OV-103, Volume I*, 108.
[518] *Endeavour's*, however, is made of built-up titanium forgings. Jenkins, *Space Shuttle*, 386.
[519] The drag chute compartment was an add-on for *Columbia*, *Challenger*, *Discovery*, and *Atlantis*; it was a built-in production feature for *Endeavour*. Jenkins, *Space Shuttle*, 386.
[520] USA, *Crew Operations*, 1.2-11; Boeing, *OV-103, Volume I*, 107.
[521] USA, *Crew Operations*, 1.2-11; Boeing, *OV-103, Volume I*, 108.

The aft fuselage housed the main propulsion system of the orbiter (Figure No. B-98), including the three SSMEs and the propellant distribution manifold, as well as the APU and hydraulics systems, the flash evaporators, and the ammonia boiler. It supported and interfaced with the two OMS pods, the wing aft spar, the midfuselage, the orbiter/ET rear attachments, the SSMEs, the aft heat shield, the body flap, the vertical tail, and two T-0 launch umbilical panels. It also provided a load path to the midfuselage main longerons, main wing spar continuity across the forward bulkhead of the aft fuselage, structural support for the body flap, and structural housing around all internal systems for protection from operational environments and controlled internal pressures during flight.[522]

Orbital Maneuvering System/Reaction Control Subsystem Pods

Discovery was fitted with two rear **OMS/RCS pods** (Figure Nos. B-99, B-100), which were manufactured by the McDonnell Douglas Astronautics Company, St. Louis, Missouri.[523] Each pod had a length of 21.8', excluding the RCS housing, with a forward width of 8.41' and an aft width of 11.37', and a maximum height of 5'-9". The pods were comprised of a load-bearing thrust structure, made of 2124 aluminum alloy, with cross braces fabricated from aluminum tubing. Each pod also had a forward and aft support bulkhead, and a floor truss beam, comprised of 2124 aluminum alloy, and a centerline beam, made from 2024 aluminum sheeting with titanium stiffeners and graphite-epoxy frames. The curved skin panels were made from graphite epoxy composite honeycomb sandwich material. The RCS housing, with approximate overall dimensions of 64" in length and width, and 40" in height, was situated at the lower outside aft end of each pod. It was comprised of aluminum sheet metal (flat areas) and graphite epoxy honeycomb sandwich (curved panels). The RCS housing attached to the rear of the OMS section of the pod.[524]

Each pod was mounted to one of the outboard sides of the aft fuselage, right or left, by eleven bolts; pressure and thermal seals were located at the interface. Although each could be removed separately for maintenance, when they were attached to the orbiter, their internal propellant tanks were connected via crossfeed lines, which allowed a propellant exchange between the two pods. The pods were capable of withstanding acoustic levels up to 162 decibels, and heat levels between -170 degrees and +135 degrees Fahrenheit.[525]

The surface panels of each OMS/RCS pod held the engine interfaces, as well as removable panels that provided access to the internal systems and the attach points. The RCS housing carried twelve primary thrusters, three on the upper face, three on the lower face, four on the outer face, and two on the aft face, as well as two vernier thrusters, one on the lower face and one on the aft face. Thermal barriers were provided at each RCS thruster. The inner face of the

[522] USA, *Crew Operations*, 1.2-10, 1.2-11; Boeing, *OV-103, Volume I*, 106-107.
[523] Jenkins, *Space Shuttle*, 389.
[524] USA, *Crew Operations*, 1.2-11, 1.2-12; Boeing, *OV-103, Volume I*, 112-113.
[525] Jenkins, *Space Shuttle*, 389-390.

housing contained the RCS manifold drain/purge panel. To the inside of the RCS housing, in the aft face of each OMS section, was a single OMS engine. Adjacent to the engine was the ground service panel for both the OMS and RCS engines. The curved surface of the pod contained a pressurant checkout panel, an electrical/hydraulics access panel, and various relief valves.[526]

The interior of the RCS housing only contained the thrusters and the fuel and oxidizer piping. The actual fuel tanks were located in the forward portion of the main section of the pod; the MMH (fuel) tank to the upper side and the N_2O_4 (oxidizer) tank to the lower side. Two helium pressurization tanks for the RCS sat near the upper aft end of the pod. To the aft of the RCS fuel and oxidizer tanks were the respective tanks for the OMS engine; its helium pressurization tank was situated to the aft of the OMS oxidizer tank. Other components within the pod included fuel/oxidizer piping between the OMS engine and its associated tanks, piping between the helium pressurization tanks and their associated fuel tanks, and various relief valves.[527]

Vertical Stabilizer

The **vertical stabilizer** (Figure B-101) was fabricated by Fairchild Republic in Farmingdale, Long Island, New York.[528] It had a true horizontal length of approximately 32', a true vertical height of roughly 24', and a leading edge sweep of 45 degrees. It was attached to the top of the aft fuselage by two tension tie bolts at the front, and eight shear bolts at the rear; a thermal barrier was provided at the interface between the stabilizer and the aft compartment. The vertical stabilizer, which consisted of a structural fin surface, the rudder/speed brake surface, a tip and a lower trailing edge, was designed to handle an acoustical environment of up to 163 decibels, and a temperature of up to 350 degrees F.[529]

The fin structure was essentially a torque box that was manufactured of integral aluminum ribs, webs, stringers, and integral-machined aluminum spars.[530] It was through this subcomponent that the vertical stabilizer was attached to the vehicle. It was also primarily this subcomponent that provided the vertical stability for the orbiter. The tip of the vertical stabilizer was also made of aluminum, while the lower trailing edge, which housed the rudder/speed brake power drive unit, had aluminum honeycomb skin panels. While the fin structure is a common component on conventional aircraft, the split rudder/speed brake assembly was unique to the orbiter vehicle. The assembly, which had approximate dimensions of 16.6' in height, 7.5' in width at the bottom, and 4.18' in width at the top, was made of conventional aluminum ribs and spars, faced with aluminum honeycomb skin panels. It was attached to the vertical tail fin through rotating hinge

[526] Jenkins, *Space Shuttle*, 391.
[527] USA, *Crew Operations*, 1.2-12; Boeing, *OV-103, Volume I*, 113.
[528] The vertical tail for *Endeavour* was manufactured by Grumman Aerospace of Long Island, New York, who had taken over many of Fairchild Republic's contracts prior to the construction of this fifth orbiter. Jenkins, *Space Shuttle,* 388.
[529] USA, *Crew Operations*, 1.2-13, 1.2-14; Boeing, *OV-103, Volume I*, 109.
[530] *Enterprise's* vertical stabilizer was made of conventional aluminum alloy skin and stringer construction. Jenkins, *Space Shuttle*, 388.

parts; an Inconel honeycomb aerodynamic seal and a thermal barrier seal were situated between the two.[531]

The rudder/speed brake assembly was powered by the orbiter's hydraulic system. Each half of the split rudder was fitted with its own drive shaft, allowing the assembly to be operated solely as a rudder, solely as a speedbrake, or a combination of the two. When operated as a rudder, to provide yaw control for the vehicle within low supersonic and subsonic speeds, both drive shafts were turned in the same direction, to a maximum deflection of 27 degrees, with a maximum deflection rate of 14 degrees per second. When the assembly was operated as a speed brake, the shafts were turned in opposite directions for a maximum deflection of 49.3 degrees for each half, with a maximum deflection rate of 10 degrees per second. When combined, the assembly had a total maximum deflection of 61.5 degrees.[532]

Body Flap

The **body flap** (Figure No. B-102), which was manufactured by Rockwell International's Structures Division in Columbus, Ohio, was the wedge-shaped component that was mounted to the lower trailing edge of the aft fuselage.[533] It had an approximate total length of 7.24', with a width of 21.08' where it connected to the aft fuselage and a width of 18.25' at its trailing edge. It consisted of two main parts: a forward section and a trailing edge. The forward section was comprised of aluminum honeycomb skin panels, which were supported by aluminum ribs and spars. The forward end of its upper face contained five removable panels, which were attached to the internal ribs with quick-release fasteners. These panels provided access to the four integral-machined aluminum actuator ribs that were fitted with two self-aligning bearings for mechanical attachment to the four rotary actuators within the aft fuselage. The remaining skin panels on the forward section of the body flap were attached to the internal supports with structural fasteners. The lower surface was also fitted with an articulating pressure and thermal seal, which blocked heat and air from entering the aft fuselage, as well as protected the hinges and actuators from thermal damage. The trailing edge of the body flap, which had an approximate length of 2.33', was a full-depth aluminum honeycomb panel. It was attached to the forward section of the body flap by hinge pins connected to piano-hinge half cap angles mounted on the rear spar. Extending through the trailing edge were two moisture drain lines and one hydraulic fluid line.[534]

The main functions of the orbiter's body flap were to shield the three SSMEs from the heat of reentry, and to provide pitch control for the vehicle during atmospheric flight following its reentry into Earth's atmosphere. The body flap was capable of pivoting 15.7 degrees upward and 26.55 degrees downward.[535]

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[531] USA, *Crew Operations*, 1.2-13; Boeing, *OV-103, Volume I*, 109-110.
[532] USA, *Crew Operations*, 1.2-14. Limited rudder operations were also available when the assembly was at its full speedbrake position (total angle of 98.6 degrees).
[533] Jenkins, *Space Shuttle*, 386.
[534] USA, *Crew Operations*, 1.2-12, 1.2-13; Boeing, *OV-103, Volume I*, 114-115.
[535] USA, *Crew Operations*, 1.2-12; Jenkins, *Space Shuttle*, 386.

Orbiter Markings

Discovery had various markings applied to her outer surfaces. These markings typically served one of two purposes: to identify the vehicle or to provide instructions to ground technicians. On both the port and starboard sides of the forward fuselage, just below the flight deck windows and roughly in line with the payload bay door hinges, *Discovery's* name was painted in black lettering. Her name was also painted on the top surface of the starboard wing, just forward of the inboard elevon. Above her name on the starboard wing was a painted U.S. Flag; the NASA "meatball" logo was painted on the top surface of the port wing. In addition, towards the aft end of both the port and starboard sides of the midfuselage, was a painted U.S. Flag, the words "United States," and a NASA "meatball" logo.[536]

All of *Discovery's* instructional markings were located toward the forward end of the vehicle. On the port side of the vehicle, there were rescue instructions on the crew hatch, and locational data and instructions for a fuel cell purge port. The starboard side also contained instructions for an emergency rescue of the crew, as well as data regarding a fuel cell purge port. On top of the vehicle, to the port side of the overhead windows, was a triangular danger sign.

Thermal Protection System

Discovery's exterior was covered with a TPS (Figure Nos. B-103 through B-107) that kept the orbiter's structural skin from exceeding 350 degrees F, primarily during the reentry phase of a mission. Earlier spacecraft had used ablative heat shield materials, but these forms of thermal protection could only be used once because the materials were designed to burn away, carrying the excess thermal energy. Due to the reusable nature of the Space Shuttle orbiter, heat-sink materials were chosen to protect the vehicle's aluminum structure because they were reusable. In addition, the TPS was capable of handling the forces induced by deflections in the orbiter's airframe as the structure responded to different external environments (i.e., the wide range of temperatures experienced in the vacuum of space).[537] The materials also established the aerodynamics over the vehicle.[538]

Discovery's TPS was comprised of three principal components, which included RCC, insulation tiles, and insulation blankets. *Discovery* was fitted with fifty-seven RCC panels/segments,

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[536] The flag on the starboard side is painted in the reverse of how it is normally viewed, with the stars in the upper right corner. This portrayal of the flag is proper for the starboard side of a moving vehicle, as it gives the effect of the flag flying in the breeze as the wearer moves forward.

[537] David Baker, *Owners' Workshop Manual* (Minneapolis, Minnesota: Zenith Press, 2011), 72-74. A heat sink is a component that is used to conduct heat away from an object, in this case the orbiter's airframe, that would otherwise reach destructive temperatures.

[538] *Atlantis* and *Endeavour* had the same amount of RCC panels, and roughly the same quantities of tiles and blankets. *Columbia's* tile count was higher and its blanket count lower than *Discovery's*; the same was true of *Challenger*. USA, *Crew Operations*, 1.21-15. Aerodynamics refers to the study of the motion of air, particularly when it interacts with a moving object.

roughly 24,300 tiles, and about 3,300 blankets. The heat load experienced during reentry determined which component was used in a specific location. Gap fillers were used to supplement the principal TPS components.[539]

Reinforced Carbon-Carbon

RCC was used where reentry temperatures on the vehicle exceeded 2,300 degrees F. This included *Discovery's* wing leading edges, nose cone, chin panel, and the immediate area around the forward orbiter/ET attach point; these locations reached the highest temperatures during reentry.[540] The twenty-two leading edge panels on each wing were connected to the wing forward spar with metallic floating joints, which helped to reduce loading on the tiles caused by wing deflections. These metallic joints were protected by Incoflex insulation.[541] T-seals, also made of RCC, were placed between the panels to prevent the flow of hot gases into the leading edge cavity and to allow for lateral motion and thermal expansion. The nose cap was a single piece of RCC, which was secured to the lower forward fuselage by a pair of thermal seal strips, also made of RCC. The nose cone area was further insulated by a ceramic-fiber blanket filled with silica fibers.[542] The RCC chin panel, comprised of a single piece of RCC, was installed on *Discovery* in 1988.[543] Below the eleven RCC panels around the orbiter-ET attach point was a ceramic-fiber blanket filled with silica fibers, similar to the one below the nose cone.[544]

Discovery's RCC panels were manufactured by LTV (now Lockheed Martin) of Grand Prairie, Texas. RCC was a composite material comprised of pyrolyzed carbon fibers within a pyrolyzed carbon matrix, and coated with silicon carbide.[545] The carbon fibers/matrix provided rigidity and strength, while the silicon carbide coating provided high-temperature oxidation protection. The panels underwent densification with a hydrolyzed tetraethylorthosilane solution, and were sealed with sodium silicate for additional protection against oxidization.[546] The RCC panels were resistant to temperatures of up to 3,000 degrees F and were excellent thermal conductors.

[539] NASA, *Orbiter Thermal Protection System*, NASA Facts (Florida: Kennedy Space Center, 2008), 2, http://www.nasa.gov/centers/kennedy/pdf/167473main_TPS-08.pdf.
[540] The chin panel was the area on the lower surface, immediately aft of the nose cap.
[541] Jenkins, *Space Shuttle*, 398. In January 1999, Nextel 440 insulation was added to *Discovery*'s lower RCC wing leading edge panels to prevent plasma flow from entering the wings in case orbital debris punctured the RCC.
[542] Jenkins, *Space Shuttle*, 398-9.
[543] Initially, this area was fitted with high-temperature reusable surface insulation (HRSI) tiles. Due to constant damage by impacts during ascent and overheating during reentry, the decision was made to replace the tiles with RCC. Jenkins, *Space Shuttle*, 399.
[544] Jenkins, *Space Shuttle*, 399.
[545] Jenkins, *Space Shuttle*, 397. Pyrolysis is a thermochemical decomposition of organic compounds without the use of oxygen. The process generates gas and liquid products, while leaving a carbon-rich solid residue.
[546] NASA, *Orbiter Thermal Protection System*, 5. Densification is a process by which the density of a material is increased. The inner surface of all TPS tiles were densified to a depth of 0.125", which allowed for a more even distribution of applied loads.

Insulation Tiles

Five different types of insulation tiles were used on *Discovery*. These included high-temperature reusable surface insulation (HRSI), low-temperature reusable surface insulation (LRSI), fibrous refractory composite insulation (FRCI), toughened uni-piece fibrous insulation (TUFI),[547] and Boeing Rigid Insulation (BRI). To adhere the tile to the airframe, a strain isolation pad made of Nomex felt, which limited vibration-induced damage and compensated for thermal expansion and contraction, was bonded to the tile. The tile and pad combination was then bonded to the orbiter with a silicone adhesive, which remained flexible at low temperature and maintained bond strength at high temperatures.[548]

Like the RCC panels, **HRSI tiles** have been used on the orbiters since original assembly. These tiles covered the entire underside of *Discovery*, except the few places that used RCC. HRSI tiles were also located around the flight deck windows, on the FRCS module around the thrusters, on the sides of the forward fuselage immediately aft of the FRCS module, the wing glove areas, the interface between the wings and the wing leading edge panels, and the upper side of the elevon trailing edges. In addition, HRSI tiles were fitted on the forward and lower aft sides of the OMS/RCS pods, along the leading and trailing edges of the vertical stabilizer, on the SSME base heat shield, and on the upper body flap surface.[549] The tiles were available in two bulk densities, 9 pounds per cubic foot and 22 pounds per cubic foot. There were roughly 20,000 low-density tiles and 525 high-density tiles on *Discovery*.[550] The tiles were produced in 6” x 6” squares, cut to fit their specified location, and ranged in thickness from 1” to 6”. The thicker tiles were generally found toward the front of the orbiter, where more heat was encountered.[551]

Manufactured by Lockheed Missiles and Space Company[552] of Sunnyvale, California, HRSI tiles were made from a slurry composed of 99.8 percent silica glass fibers and water; only 10 percent of the total volume was solid material. After they were machined to the precise shape, a reaction-cured glass coating was applied to the top surface and sides, which turned a glossy black color after being baked in a kiln. The black coating allowed for maximum heat loss during reentry. In addition, the tiles received two applications of a waterproofing agent (dimethylethoxysilane) and one application of a silica powder densifier. HRSI tiles could withstand temperatures up to 2,300 degrees F.[553]

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[547] Jenkins, *Space Shuttle*, 395-401.
[548] NASA, *Orbiter Thermal Protection System*, 4.
[549] Jenkins, *Space Shuttle*, 397-398. HRSI tiles were located in the same places on *Columbia*, *Challenger*, *Atlantis*, and *Endeavour*. *Columbia* also had HRSI tiles on her rudder/speed brake and upper wing surfaces.
[550] NASA, *Orbiter Thermal Protection System*, 2. The higher density HRSI tiles were used around the windows and landing gear doors. NASA, *Orbiter Thermal Protection System*, 3.
[551] NASA, *NSTS Manual*.
[552] The Lockheed Missiles and Space Company is now known as the Lockheed Martin Corporation.
[553] Jenkins, *Space Shuttle*, 399; NASA, *Orbiter Thermal Protection System*, 3.

LRSI tiles were also original to the orbiters. On *Discovery*, these tiles were located on top of the forward fuselage, between the cockpit and overhead windows, and on the forward section of the OMS pods.[554] LRSI tiles came in two densities, 9 pounds per cubic foot and 12 pounds per cubic foot; there were approximately 725 and seventy-seven of each density on the orbiter, respectively. In contrast to the HRSI tiles, LRSI tiles ranged from 0.2" to 1.4" thick, and were produced in 8" x 8" squares; they were also cut to fit their designated location. LRSI tiles could withstand temperatures up to 1,200 degrees F.[555]

LRSI tiles were also manufactured by Lockheed Missiles and Space Company, and were very similar to HRSI tiles in composition. LRSI tiles also underwent the exact same waterproofing and densification processes. The main difference between the two was the applied coating, which for LRSI tiles turned white.[556] The white coating provided thermal control for the vehicle while it was in orbit.

FRCI tiles were developed after the SSP began. Approximately 2,950 FRCI tiles have replaced damaged HRSI tiles on *Discovery* since her maiden voyage in 1984; the FRCI tiles were not characteristic of any particular area of the vehicle. FRCI tiles had a bulk density of 12 pounds per cubic foot, and were comprised of 20 percent Nextel and 80 percent silica.[557] The tiles were produced in 6" x 6" squares, cut to fit their specified location, and ranged in thickness from 1" to 5". Like HRSI tiles, FRCI tiles were able to withstand temperatures up to 2,300 degrees F.[558]

FRCI tiles were developed by NASA's Ames Research Center ca. 1981, and manufactured by Lockheed Martin. The manufacturing process for FRCI tiles was similar to the process used to make HRSI tiles. As noted above, the slurry for the FRCI tiles contained 20 percent Nextel fiber, which resulted in a more durable and lighter tile. Additionally, the glass coating for the FRCI tiles was compressed as it was cured, to reduce the coating's sensitivity to cracking.[559]

TUFI tiles were also developed following the start of the SSP. Approximately 304 TUFI tiles were located on *Discovery's* base heat shield and lower body flap surface. TUFI tiles were essentially FRCI tiles that included small quantities of alumina fiber in the base slurry, which increased the thermal stability and conductivity of the material. TUFI tiles, also known as alumina-enhanced thermal barrier (AETB-8) tiles had a density of approximately 8.4 pounds per

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[554] LRSI tiles were located in the same places on *Columbia*, *Challenger*, *Atlantis*, and *Endeavour*. *Columbia* also had LRSI tiles on portions of her upper wing surfaces, the upper surface of the two outboard elevons, the top of the FRCS module (in areas where the HRSI tiles were not used), on portions of the vertical stabilizer, and on the rudder/speed brake.
[555] Jenkins, *Space Shuttle*, 400; NASA, *Orbiter Thermal Protection System*, 3.
[556] Jenkins, *Space Shuttle*, 400.
[557] Jenkins, *Space Shuttle*, 399-400; NASA, *Orbiter Thermal Protection System*, 2-3. Nextel is the trademark name for an alumino-boro-silicate fiber developed by the 3M Company.
[558] Jenkins, *Space Shuttle*, 400; NASA, *NSTS Manual*.
[559] NASA, *NSTS Manual*.

cubic foot.[560] The tiles were also more resilient to debris strikes because of the higher density exterior. TUFI tiles were developed in 1993 by NASA's Ames Research Center; they were fabricated by Rockwell International. Like HRSI and FRCI tiles, TUFI tiles were able to withstand temperatures up to 2,300 degrees F.[561]

BRI tiles were the fifth and last tiles used on the orbiter; the tiles were located on *Discovery*'s landing gear doors, wing leading edge, and external tank doors. They were developed by Boeing following the *Columbia* accident, and had a density of 18 pounds per cubic foot.[562] The tiles were made of a mixture of silica and alumina fibers and were processed so that the alumina fibers laid flat to conduct heat horizontally rather than vertically. BRI tiles were also five to ten times stronger and more durable than their predecessors and were capable of reaching higher reentry temperatures without warping. Like HRSI, FRCI and TUFI tiles, BRI tiles were able to withstand temperatures up to 2,300 degrees F.[563]

Insulation Blankets

There were two different styles of TPS insulation blankets: FRSI blankets and Fibrous Insulation Blankets (FIBs), which are also known as Advanced FRSI (AFRSI) blankets. Both types of insulation blankets were bonded directly to the orbiter by a room-temperature vulcanizing (RTV) silicon adhesive. The adhesive was applied at a thickness of roughly 0.20" to reduce weight and minimize thermal expansion during temperature changes. The direct application of the blankets also improved durability, reduced fabrication and installation costs, and reduced installation time.[564]

FRSI blankets have been used on the orbiters since original assembly. These blankets were located on the top surface of the forward three-quarters of *Discovery's* payload bay doors, on the upper surface of her wings, and on the upper surface of her two inboard elevons.[565] FRSI blankets were made of Nomex felt and coated with a white-pigmented silicone rubber paint, which waterproofed the felt and provided the required thermal and optical properties. FRSI blankets generally measured 3' x 4', and were between 0.16" and 0.32" thick. FRSI blankets could withstand temperatures up to 700 degrees F.[566]

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[560] Jenkins, *Space Shuttle,* 400; Richard W. Orloff, ed., *Space Shuttle Mission STS-59 Press Kit* (Washington, DC: NASA, 1994), 37, http://www.scribd.com/doc/19723409/NASA-Space-Shuttle-STS59-Press-Kit.
[561] NASA, STS-59 Press Kit, 37.
[562] NASA, *Orbiter Thermal Protection System*, 6. The tiles first flew on *Discovery's* nose landing gear doors during STS-121 in 2006. Bob Howard, "Beat the Heat: Boeing Team Develops Tiles to Make Shuttle Safer, Easier to Maintain," *Boeing Frontiers* June 2006, http://www.boeing.com/news/frontiers/archive/2006/june/i_ids2.html.
[563] Howard, "Beat the Heat."
[564] Jenkins, *Space Shuttle*, 401.
[565] FRSI blankets were located in the same places on *Challenger*, *Atlantis*, and *Endeavour*. *Columbia* had FRSI blankets on portions of her upper wing surfaces, around the overhead windows in the forward fuselage, on the entire top surface of her payload bay doors, on the aft sides of the payload bay doors, on large sections of her midfuselage, and on the upper surface of the two inboard elevons.
[566] Jenkins, *Space Shuttle*, 400-401; NASA, *Orbiter Thermal Protection System*, 3. The lighter FRSI blankets

AFRSI blankets were developed following the assembly of *Columbia*. These blankets covered the sides of *Discovery's* forward fuselage, midfuselage, and aft fuselage; the portions of the top surface of the forward fuselage not faced with HRSI and LRSI tiles; and the aft quarter of the top surface, and the sides of the payload bay doors. In addition, the blankets were fitted on the sides of the OMS/RCS pods, the sides of the vertical stabilizer, the rudder/speed brake, and the top surfaces of the two outboard elevons.[567] The blankets were made by placing a core of pure silica felt in between a layer of silica fabric (outer side) and a layer of glass fabric; they were sewn together with pure silica thread, in a 1" grid, producing a quilted pattern. They were then coated with ceramic colloidal silica and high-purity silica to provide extra strength and erosion resistance. The blankets were generally 3' x 3', although the size and shape could vary considerably, and ranged in thickness from 0.45" to 0.95". AFRSI blankets could withstand temperatures up to 1,200 degrees F.[568]

Gap fillers

Discovery's tiles were installed with gaps in between the individual tiles, allowing for expansion and contraction as the temperature fluctuated; the gaps ranged from 0.028" to 0.2". Gap fillers were used to prevent plasma from reaching the vehicle's airframe.[569] The fillers were made of Nomex felt, were typically 0.75" wide, and had a thickness of 0.09", 0.115", or 0.16". Horse collar-shaped gap fillers were located between the RCC wing leading edge panels; each had a small sleeve designed to prevent hot gas from passing into the wing leading edges in case a tile was punctured.[570]

Flight Critical Systems

The orbiter had a variety of systems that were required for operation of the vehicle. These included the APU/hydraulics system; the caution and warning system; the communications system; the data processing system; the dedicated display systems; the electrical power system; the environmental control and life support system; the guidance, navigation, and control system; the landing/deceleration system; the main propulsion system; different mechanical systems; the orbital maneuvering system; and the reaction control system.[571]

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replaced AFRSI blankets beginning with *Discovery*'s second OMDP from 1995 to 1996.
[567] AFRSI blankets were located in the same places on *Challenger*, *Atlantis*, and *Endeavour*. *Columbia* had limited AFRSI blankets, which were situated on most of the side surface of the payload bay doors, large sections of her midfuselage, on the OMS/RCS pods, and on the sides of her vertical stabilizer.
[568] Jenkins, *Space Shuttle*, 401; NASA, *Orbiter Thermal Protection System*, 5-6.
[569] NASA, *Orbiter Thermal Protection System*, 4.
[570] This was a modification made to the fillers in response to the *Columbia* accident. Boeing, *OV-103, Volume II*, 77-78.
[571] The main propulsion system, which primarily consists of the SSMEs and ET, will be discussed in Parts III and IV.

Auxiliary Power Unit/Hydraulic System

Discovery was designed to perform in a similar manner to a standard aircraft as it descended through the Earth's atmosphere for landing. The vehicle contained aerodynamic control surfaces, landing gear, and engines that required a hydraulic system in order to function properly. Power for the triple-redundant hydraulics system was provided by three APUs, as opposed to the orbiter's electrical power system. *Discovery's* APUs and hydraulics systems were similar to those found on large commercial aircraft.[572]

Functions and Operations

Discovery contained three functionally identical, but independent, APUs, which produced the power for one of the vehicle's three redundant hydraulic systems (Figure No. B-108).[573] In turn, the hydraulic systems provided hydraulic pressure to various hydraulic actuators throughout the vehicle (Figure B-109). These actuators were used for the following functions: gimbaling the three SSMEs to provide thrust vector control; actuating various control valves on the SSMEs; moving the orbiter aerosurfaces, such as the elevons, body flap, and the rudder/speed brake; retracting the ET/orbiter LO2 and LH2 disconnect umbilicals after the ET was jettisoned; deploying the main and nose landing gear systems; operating the main landing gear brakes and anti-skid features; and operating the nose wheel steering.[574]

Discovery's APU/hydraulic system operated during launch and landing procedures, in normal gravity and zero gravity atmospheres, and at varying temperatures. Prior to launch, the APU's fuel tank was loaded with roughly 333 pounds of anhydrous hydrazine, which provided about 90 minutes of operating time, and pressurized with gaseous nitrogen to 400 pounds per square inch (psi).[575] In addition, the tank for the water spray boiler was filled with around 138.5 pounds of water mixed with propylene glycol monomethyl ether in an azeotropic mixture (53 percent water/40 percent ether).[576] Other prelaunch preparations included pressurizing the gaseous nitrogen for the lube oil system to roughly 140 (pounds per square inch, absolute (psia); filling the tank in the APU injector water cooling system with around 9 pounds of water and pressurizing it to approximately 120 psi; and the water spray boiler pressure vessel was filled with roughly 0.77 pounds of nitrogen and pressurized to around 2,400 psi.[577]

At approximately 8 hours prior to launch, astronaut support personnel powered on the water spray boiler controllers, which in turn activated the water spray boiler system heaters to ensure

[572] Baker, *Manual*, 83-85.
[573] The APUs were considered "auxiliary" because they generated power separately from the fuel cells. USA, *APU/Hydraulic/Water Spray Boiler Systems Training Manual* (Houston: United Space Alliance, 2008), 2-1.
[574] USA, *APU*, 1-1; USA, *Crew Operations*, 2.1-1.
[575] Enough fuel was provided to support the nominal running time, and any defined launch abort mode. USA, APU, 2-5.
[576] USA, *APU*, 4-4.
[577] USA, *Crew Operations*, 2.1-5, 2.1-10, 2.1-13

that the boilers were ready to operate for launch. Roughly 30 minutes before liftoff, the pilot opened the boiler system's gaseous nitrogen supply valve to pressurize the storage tank. Approximately 6 minutes and 15 seconds before launch, the pilot began the prestart sequence for the APUs. This involved confirming that the water spray boiler system was operational, activating the APU controllers, and depressurizing the main hydraulic pump. Afterwards, the pilot opened the APU fuel tank valves and waited for the indication that the units were ready to start. The APUs were officially started at 5 minutes before launch, at which point the pressures of the main hydraulic pumps were monitored; if the pressure at each pump was not maintained greater than 2,800 psi after T-4:05, the launch was aborted.[578]

During launch, hydraulic fluid was fed to the main engine throttling valves, and the main engine thrust vector control actuators. Following main engine cutoff and ET jettison, fluid was fed to the ET umbilical plate retraction actuators.

The APUs and water spray boilers operated until roughly 13 minutes after launch, when the SSMEs were purged, dumped, and positioned for orbit operations, following which the fuel and water line heaters were activated to prevent freezing.[579] Approximately 2 hours after liftoff, the water spray boiler steam vent heaters were turned on for at least 1 ½ hours to remove any ice that accumulated in or around the vents. At the same time, the crew placed the hydraulic circulation pump switches into the automatic mode; this allowed the GPCs to maintain system temperatures and pressures. Roughly 6 hours after launch, the APU gas generator and fuel pump heaters were activated. The APU/hydraulics system then remained inactive until the day before the deorbit burn.[580]

While the vehicle was on orbit, the circulation pump was used to maintain accumulator pressure and for hydraulic thermal conditioning. The systems management software activated the pump if the hydraulic lines were cold and needed thermal conditioning, or if the hydraulic accumulator pressure had decayed and needed to be repressurized.[581] The circulation pump motor and inverter provided the primary source of heat to warm the hydraulic fluid, which flowed through and cooled the motor/inverter assembly. Additionally, a temperature-controlled bypass valve could direct the hydraulic fluid through a Freon/hydraulic heat exchanger to pick up the heat from the vehicle's Freon coolant loops, if the temperature at the heat exchanger inlet was less than 105 degrees F.[582] The valve directed the fluid around the exchanger if the temperature at the inlet was greater than 115 degrees F. In the case of pressurizing the accumulator, the flow from the high pressure pump was redirected through the accumulator until its pressure was above 2,563 psia, at

[578] USA, *Crew Operations*, 2.1-21; USA, APU, 5-2.
[579] USA, *Crew Operations*, 2.1-21, 5.2-4; USA, APU, 5-3.
[580] USA, *APU*, 5-3, 5-4; USA, *Crew Operations*, 2.1-21.
[581] USA, *APU*, 3-4.
[582] The Freon coolant loops were part of the ECLSS. They removed heat from other parts of the orbiter, and transferred it to the hydraulic fluid.

which point the flow was then combined with the low pressure output prior to being sent through the hydraulic lines.[583]

The redundant APU heaters were set to maintain temperatures between 55 and 65 degrees F. There was also a system of heaters for the fuel pump, gas generator valve module, and gas generator bed heater; these were also redundant. The temperatures for the fuel pump and gas generator valve module were maintained at 100 degrees F, while the temperature for the gas generator bed heater was maintained between 360 and 425 degrees F. The temperature of the gas generator ensured efficient APU startup through efficient catalytic reaction; the heaters were automatically deactivated at APU start. Each APU also had a heater system for the lube oil system lines; like the others, this system had a redundancy. The lube oil lines were maintained at a temperature between 55 and 65 degrees F.[584]

Each water boiler, water tank and steam vent was equipped with redundant electrical heaters to prevent freeze-up while on orbit. The boiler and tank heaters automatically cycled from on at 50 degrees F to off at 55 degrees F, while the steam vent heaters were activated approximately two hours before APU startup. They then cycled on at 150 degrees F and off at 175 degrees F.

On the day prior to reentry, one of the APUs was started to supply hydraulic pressure throughout the vehicle for the flight control system checkout; its associated water spray boiler was also activated. The checkout operation required approximately five minutes, after which the system was again shut down. Approximately 3 hours and 30 minutes before the deorbit burn, the water spray boiler steam vent heaters were activated and the hydraulic circulation pumps were shut down. Roughly 45 minutes before the deorbit burn, the crew pressurized the water spray boiler tanks, activated the APU controllers, and set the hydraulic pumps to low pressure. One of the APUs was started five minutes prior to the deorbit burn; the remaining two APUs were started roughly 30 minutes later, at 13 minutes before the entry interface. At the same time, all three hydraulic systems were pressurized to normal. If necessary, an automatic cycle sequence was performed to ensure warm hydraulic fluid was reaching the vehicle's aerosurface drive units.[585]

The APU/hydraulic system continued to operate until after the orbiter landed. Hydraulic fluid was sent to the elevons, the rudder/speed brake, the body flap, the landing gear deploy mechanism, the nose wheel steering, and the brakes. A hydraulic load test was sometimes performed after touchdown to test the response of the APU catalyst bed under high load conditions. Data from this test were used to extend the installed life of the APU (generally set at five flights) before an overhaul. After this test was finished, the SSME hydraulic isolation valves were opened in order to set the engines to their transport position. The APUs, hydraulic systems, and water spray boilers were then completely shut down.[586]

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[583] USA, *APU*, 3-4, 3-6.
[584] USA, *APU*, 2-19.
[585] USA, *Crew Operations*, 2.1-22, 5.4-1, 5.4-3, 5.4-4; USA, *APU*, 5-5.
[586] USA, *Crew Operations*, 2.1-22, 5.5-1; USA, *APU*, 5-5.

System Description

Auxiliary Power Unit: The APU was a hydrazine-fueled, gas turbine-driven power unit that was fueled by liquid anhydrous hydrazine, which was different from the monomethyl hydrazine in the RCS. The three units were located behind the X_O = 1307 bulkhead, within the aft compartment and beneath the OMS pods (Figure Nos. B-108, B-110). Each unit consisted of a fuel tank, fuel tank valves, a fuel pump, fuel control valves, a gas generator bed and turbine, a digital controller, a lubricating oil system, an injector cooling system, heaters, an exhaust duct, a lube oil cooling system, and fuel/lube oil vents and drains. In addition, each was fitted with insulation and redundant electrical heater systems to prevent the fuel from freezing and to maintain the required lubricating oil viscosity.[587]

Each APU had its own 28”-diameter, spherical hydrazine fuel tank, with a 350 pound capacity. All three fuel tanks were mounted on supports, which were cantilevered from the interior surface of the aft fuselage; two on the port side and one on the starboard side. Each tank was fitted with a diaphragm, which separated the hydrazine from the gaseous nitrogen that was used to pressurize the fuel. In addition, each had hydrazine fill and drain service connections, as well as a gaseous nitrogen servicing connection. Pressurized gaseous nitrogen was used to expel the hydrazine fuel from the tank and into the fuel distribution system. At the tank outlet, the fuel traveled through a filter that removed any particulates. After the filter, the fuel was fed through two isolation valves in parallel before being routed to the APU fuel pump. These redundant valves allowed fuel to flow to the APU, or isolated the APU from the supply tank.[588]

The APU fuel pump was a fixed-displacement, gear-type pump that discharged fuel at approximately 1,400 to 1,500 psi, delivering hydrazine at a rate of 14 pounds per minute to the titanium gas generator bed. The fuel pump was mated to the gearbox; both were suspended partly inside a cavity that was designed to contain fuel and oil leaks. The cavity was divided into two sections to separate the fuel and the oil. A filter was located at the outlet of the pump, and a relief valve was included in the event that the filter became clogged. The pump was driven by the turbine, located downstream, by a shaft from the reduction gearbox.[589] Past the fuel pump were the primary and secondary fuel control valves, installed in series, which controlled the operating speed of the APU.[590] There were two speed control selections: normal and high. When operating normally, the primary valve pulsed to maintain a speed of roughly 74,000 revolutions per minute (rpm), while the secondary valve was set at full-open and attempted to control at 81,000 rpm. If the high speed mode was selected, the primary valve was set at full-open and attempted to control the speed at 83,000 rpm, and the secondary valve pulsed to control the speed at about 81,000 rpm. When the valve controlling the turbine speed was closed, the fuel was routed

[587] USA, *APU*, 1-1, 2-1, 2-3, 2-5; USA, *Crew Operations*, 2.1-1, 2.1-2.
[588] USA, *APU*, 2-5; USA, *Crew Operations*, 2.1-2. Since the turbine was not spinning at startup, the fuel bypassed the fuel pump by way of a startup bypass line and went directly into the gas generator. USA, *APU*, 2-7.
[589] USA, *Crew Operations*, 2.1-4.
[590] The valves were controlled by four identical speed control channels within the APU digital controller. At the unpowered state, the primary valve was open while the secondary valve was closed. USA, *APU*, 2-8.

through a bypass line back to the inlet of the pump. An automatic shutdown feature turned off the pump if the speed fell below 57,600 rpm or rose above 92,880 rpm.[591]

Downstream of the flow control valves, the hydrazine fuel was fed into a gas generator, at a rate of roughly 14 pounds per minute. The gas generator, which consisted of an injector and a bed of Shell 405 catalyst in a pressure chamber, was mounted within the APU exhaust chamber, allowing exhaust gas to cool the generator. The gas generator converted all incoming liquid fuel into a spray, which was then directed onto the catalyst bed. Upon contact with the Shell 405 catalyst, the hydrazine underwent an exothermic reaction, causing the fuel to decompose into a hot gas. The gas rapidly expanded and passed through the single-stage turbine that produced the power for the APU's associated hydraulic main pump; it also drove the APU fuel pump and lubrication oil pump. The turbine was a 5.5"-diameter, two-pass, impulse pressure-driven unit with a typical operating speed of 74,160 rpm. It had an exhaust system comprised of three 2.5" ducts, located near the root of the orbiter's vertical tail, two to the left and one to the right. Between the turbine and the hydraulic main pump was a speed reduction box used to reduce the shaft speed and increase the torque from the turbine prior to directing it to the hydraulic pump. Each APU was fitted with its own digital controller, which operated the APU within a controlled speed range and provided automatic shutdown protection for overspeed and underspeed situations.[592]

Each APU had a scavenger-type lubricant oil system with a fixed-displacement pump, which was necessary to lubricate the gearbox and fuel pump. The oil system pump was driven at about 12,215 rpm by the APU gearbox, with gaseous nitrogen used to pressurize the system. The gaseous nitrogen was kept in its own tank that held enough to repressurize the gearbox six or seven times.[593] A distribution line exited the lube pump and carried the oil through a water spray boiler for cooling, from which it was directed to the accumulators and gearbox. There were two accumulators used to maintain the pressure within the system, by allowing for thermal expansion of the oil and accommodating any gas initially trapped within the lube circuit.[594]

Each APU was also fitted with a gas generator injector water cooling system, which was only used when the normal cool-down period (180 minutes) was unavailable. A single, 9.4"-diameter, water tank served all three APUs; the tank held 8.5-9.5 pounds of water, sufficient for approximately six cooldowns, and was pressurized with gaseous nitrogen. Three supply lines extended from the tank, one for each APU; all spent water (in the form of steam) was exhausted into the aft fuselage. In addition, each APU was provided with a set of redundant heaters for the fuel tank, the fuel line, and the water line; they were set to maintain system temperatures

[591] USA, *Crew Operations*, 2.1-5; USA, *APU*, 2-8. Due to valve cycling, the actual fuel consumption of an operating APU was in the range of 1 to 4 pounds per minute.
[592] USA, *Crew Operations*, 2.1-5; USA, *APU*, 2-10, 2-11. The digital controller first flew in 1993, and was designed to provide increased fault tolerance so that no single component failure would cause a shutdown of the APU. USA, *APU*, 2-12.
[593] USA, *APU*, 2-12. Gearbox repressurizations were not uncommon, with certain APUs requiring more than others.
[594] USA, *Crew Operations*, 2.1-6.

between 55 and 65 degrees F. There was also a system of heaters for the fuel pump, gas generator valve module, and gas generator bed heater, which were maintained at a temperature of 100 degrees F (fuel pump and gas generator valve module) and between 360 and 425 degrees F (gas generator bed heater). There was also a heater system for the lube oil system lines; they were maintained between 55 and 65 degrees F.[595]

Hydraulic System: *Discovery* had three independent hydraulic systems for redundancy (Figure Nos. B-109, B-110). The systems were functionally identical, but differed in volume, routing, and subsystem support. Each system consisted of a main hydraulic pump, a hydraulic reservoir, a hydraulic bootstrap accumulator, an electrical circulation pump, a hydraulic/Freon heat exchanger, and electrical heaters. The pumps for all three systems were located in the vehicle's aft compartment, behind the X_O = 1307 bulkhead.[596] Hydraulic lines extended throughout the orbiter, typically within the equipment bay of the crew compartment, below the payload bay in the midfuselage, and at the bottom of the aft compartment.

The main hydraulic pump for each hydraulic system was a variable displacement type, which operated at roughly 3,900 rpm, providing up to 63 gallons of fluid per minute at 3,000 psia at normal speed, or up to 69.6 gallons per minute at 3,000 psia at high speed.[597] It was fitted with an electrically-operated depressurization valve to reduce both the pump outlet pressure and the torque at startup.[598] Just downstream of the pump was a filter module, which also contained a high-pressure relief valve and a pressure sensor.[599]

Each hydraulic system also contained a hydraulic reservoir, which had a capacity of 8 gallons and provided for thermal expansion and contraction of the fluid. In addition, the reservoir helped maintain positive head pressure at the main pump and the circulation pump inlets, as well as maintain leaks, if necessary. The pressure of the reservoir was maintained by an accumulator bootstrap mechanism, which was of a bellows type and was precharged with gaseous nitrogen. The accumulator was fitted with a 40:1 differential area piston that dampened pressure surges. It also provided pressure on the main pump inlet so that the system could be restarted in zero gravity.[600]

The circulation pump was comprised of two fixed-displacement, gear-type pumps arranged in parallel and driven by a single motor. One pump was a high pressure (2,500 psia)/low volume, and the other was low pressure (200 psia)/high volume. The former was used to maintain

[595] USA, *APU*, 2-17, 2-18, 2-19; USA, *Crew Operations*, 2.1-10, 2.1-11.
[596] USA, *APU*, 3-1, 3-2.
[597] USA, *Crew Operations*, 2.1-16, 2.1-17. This pump was similar to those on high performance aircraft. USA, *APU*, 3-2.
[598] USA, *APU*, 3-2; USA, *Crew Operations*, 2.1-16. A failure of this valve while the APU was not running would prevent the APU from being started, but a failure of the valve while the pump was running under normal pressure would go unnoticed.
[599] USA, *Crew Operations*, 2.1-17.
[600] USA, *APU*, 3-3; USA, *Crew Operations*, 2.1-19.

accumulator pressure while the hydraulic system was inactive on orbit, and the latter was used to circulate hydraulic fluid through the orbiter's hydraulic lines while the system was inactive in order to warm cold spots. A temperature-controlled bypass valve was included in the system to direct the hydraulic fluid through or around the Freon/hydraulic heat exchanger depending on its temperature. In addition, heaters were provided for those portions of the hydraulic lines that could not be warmed by fluid circulation while the system was inactive on orbit. The heaters were automatically controlled by thermostats, to maintain temperatures within a specified range.[601]

Water Spray Boiler: There were three identical, independent water spray boiler systems (Figure No. B-111) in *Discovery*, each of which corresponded to one of the APUs and was located within the aft fuselage. This system was used to cool both the lube oil system and the hydraulic system. Each water spray boiler had approximate dimensions of 45" in length, 31" in height, and 19" in width, and was comprised of electronic controllers, a water tank, and a boiler. The boilers helped to maintain the temperature of the lube oil at roughly 250 degrees F; the temperature of the hydraulic fluid was maintained between 210 and 220 degrees F. In addition, each system was equipped with redundant electrical heaters to prevent freeze-up while on orbit.[602]

Each boiler had two identical electronic controllers, which were powered by different buses; only one was used at a time. They were used to control the water spray and the hydraulic fluid bypass valve. In addition, they powered sensors used to compute the quantity of water remaining in their respective tank. The water supply tank was a positive-displacement, bellows-type, aluminum tank with a capacity of 142 pounds. The welded metal bellows separated the water, typically mixed with an antifreeze additive of propylene glycol monomethyl ether, from the gaseous nitrogen used to pressurize the tank. A separate gaseous nitrogen pressure vessel, with a 6"-diameter, stored the nitrogen until use. The feed line extended from the tank and split into two parallel lines prior to reaching the boiler; one of the lines was used to spray the hydraulic fluid line, through three spray bars, and the other to spray the lube oil line, through two spray bars.[603] The spray bars were flush with the internal surface of the boiler, which itself encased the loops for the hydraulic fluid and the oil lubricant.

As the water boiled off, the lube oil and hydraulic fluid were cooled. The steam produced by each boiler was vented out of an exhaust duct located on the top surface of the vehicle, on the starboard side of the vertical stabilizer. There were two controllers, powered by different buses; only one was used at a time. Each controlled the water spray and the hydraulic fluid bypass valve; they were identical.[604] The hydraulic fluid was passed through the water spray boiler three times, while the lube oil passed through only twice. As the hydraulic fluid and lube oil passed through the boiler, they were sprayed with water from three spray bars and two spray bars,

[601] USA, *APU*, 3-4, 3-6, 3-7; USA, *Crew Operations*, 2.1-19, 2.1-21.
[602] USA, *APU*, 4-1, 4-8; USA, *Crew Operations*, 2.1-12, 2.1-16.
[603] USA, *APU*, 4-3, 4-4; USA, *Crew Operations*, 2.1-12, 2.1-13.
[604] USA, *APU*, 4-4, 4-7.

respectively. The bars for each were controlled independently through their own valve. The water spray boiler helped to maintain the temperature of the hydraulic fluid between 210 and 220 degrees F; the temperature of the lube oil was maintained at roughly 250 degrees F.[605]

Caution and Warning System

Discovery was fitted with a caution and warning system (CWS), which alerted the crew of any hazardous conditions, or to situations that required time-critical procedures (under 5 minutes) to correct. The system interfaced with nearly every other vehicle system, including the APU/hydraulics, data processing, ECLSS, electrical power system, flight control, guidance and navigation, main propulsion system (MPS), RCS, OMS, and the mission payloads. Four alarm classes constituted the CWS: Class 1 (emergency), Class 2 (caution and warning), Class 3 (alert), and Class 0 (limit-sensing).[606] The system consisted of software and electronics that provided the crew with visual and/or aural cues, dependent upon the class of the malfunction.

There were five types of visual cues associated with the CWS. Most were incorporated within the control panels on the flight deck. There was a red master alarm light on the F2 and F4 panels in the forward flight deck, and the A7 panel on the flight aft deck (see Figure Nos. B-75 and B-76 for flight deck panel locations). The forward flight deck also contained a forty-light array on panel F7 (Figure No. B-112) and a blue systems management light; fault messages generated by the GPCs appeared on the dedicated displays. In addition, a 120-light array was situated on panel R13U in the mission station on the flight deck. On the middeck, there was a red master alarm light on panel MO52J. Aural cues were sent to the communications system for distribution to flight crew headsets or speaker boxes.[607]

Class 1 consisted only of the most severe emergencies: smoke detection/fire suppression and rapid cabin depressurization. Class 1 was strictly a hardware system that included hard-wired sensors, which monitored the designated parameters and issued all alarms.[608] Both smoke detection and fire suppression capabilities were provided within the crew cabin avionics bays, and within the crew cabin proper. The smoke detection subsystem was comprised of ionization detection elements, which sensed the levels of smoke concentration or the rate of concentration change. The normal parameters for the smoke detection system were 300 to 400 micrograms per cubic meter. If a detection element sensed an out-of-parameter condition, the subsystem would

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605 USA, *Crew Operations*, 2.1-12.
606 USA, *Crew Operations*, 2.2-1, 2.2-2, 2.2-5; Jeffrey W. McCandless, Robert S. McCann and Bruce R. Hilty, "Upgrades to the Caution and Warning System of the Space Shuttle," Paper presented at the Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting, Santa Monica, CA, October 13, 2003, 17-18, http://human-factors.arc.nasa.gov/publications/20051025103849_McCandless_HFES_2003%202.pdf.
607 USA, *Crew Operations*, 2.2-1.
608 A hardware only system was one in which input was not processed by the vehicle's multiplexers/demultiplexers or other software systems. USA, *Crew Operations*, 2.2-2.

illuminate the applicable lights on different panels, and a siren, similar to those on typical emergency vehicles, was activated.[609]

The fire suppression subsystem contained equipment specifically for the crew cabin avionics bays, as well as the cabin's habitable areas. Each of the three avionics bays had one permanently-mounted Halon 1301 extinguisher bottle, which measured roughly 8" in length and 4.25" in diameter, and contained approximately 3.8 pounds of Halon.[610] Each had a switch to arm the bottle, and a pushbutton to discharge the Halon. The discharge created a Halon concentration of 7.5 to 9.5 percent that provided protection for roughly seventy-two hours. The habitable area of the crew cabin was fitted with three Halon 1301, hand-held fire extinguishers; two were located on the middeck, one above the airlock hatch and the other above the main crew hatch, and the third was on the flight deck, within the pilot's station. These hand-held extinguishers were operated by inserting their tapered nozzle into the fire hole port located on the affected display/control panel, and then depressing the actuating mechanism for 15 seconds. They could also be used as a backup for the extinguishers in the avionics bays.[611]

Rapid cabin depressurization was the second Class 1 alarm situation. This subsystem consisted of a cabin pressurization rate detector that sensed the rate at which the atmospheric pressure within the crew compartment was changing. If air was leaking from the cabin at a rate much higher than normal (rapid depressurization), the klaxon, a short, repeating tone that was readily distinguishable from other CWS tones, sounded. At the same time, the four Master Alarm pushbuttons were lit. In addition to rapid cabin depressurization, if there was a decrease in pressure greater than or equal to 0.12 pounds per square inch per minute, a Class 3 alert sounded; if the change in pressure versus the change in time decreased at a rate of -0.08 pounds per square inch per minute or greater, an alarm was issued.[612]

Class 2 incorporated the largest set of malfunctions, which were considered not as critical as Class 1, but still potentially life-threatening.[613] Class 2 consisted of two subclasses, the primary CWS, which was comprised of a hardware system, and a backup CWS, which was comprised of a software system. The primary CWS monitored up to 120 parameters through sensors located throughout the orbiter's critical systems, and had three modes of operation: ascent, normal, and acknowledge. Under the normal setting, the CWS received its input from transducers through either signal conditioners or flight forward multiplexer/demultiplexers; all baseline limit values

[609] USA, *Crew Operations*, 2.2-2, 2.2-5, 2.2-6. An out-of-parameter condition was defined as a concentration of 2,000 (+/- 200) micrograms per cubic meter for at least 5 seconds, and/or a rate of smoke increase of 22 micrograms per cubic meter per second for eight consecutive counts in 20 seconds.
[610] Halon 1301, or bromotrifluoromethane, is an organic halide introduced in the 1960s as a gaseous fire suppression agent for use around valuable materials, such as aircraft and computer mainframes. "Bromotrifluoromethane," *wikipedia.org*, last modified April 3, 2011.
[611] USA, *Crew Operations*, 2.2-6, 2.2-7, 2.2-9.
[612] USA, *Crew Operations*, 2.2-11. The normal change in pressure versus change in time rate was 0 psi per minute.
[613] McCandless, et. al., "Caution and Warning System," 17-18.

were stored within the CWS electronics unit, which was located within Avionics Bay 3.[614] When a primary CWS warning was issued, the appropriate light on the panel F7 array and all four Master Alarm indicators were illuminated, and a tone sounded. During the ascent mode of operation, the system operated the same as it did in the normal mode, except that the Master Alarm indicator on panel F2 (commander's area of the flight deck) did not illuminate. Similarly, in the acknowledge mode of operation, the annunciator matrix on panel F7 did not illuminate, unless the Master Alarm pushbutton on panel F2 (commander's area) or panel F4 (pilot's area) was depressed.[615]

The backup CWS was part of the orbiter's systems management fault detection and annunciation, GNC, and backup flight system software programs. If the backup CWS sensed an out-of-tolerance condition, it caused the four Master Alarm lights and the Backup C/W Alarm, on panel F7 on the flight deck, to illuminate, and displayed a message on the fault message line and fault summary page. It also activated the aural master alarm for Class 2.[616]

Class 3, the Alert system, was a purely software system that was operated by the orbiter's systems management software; these alerts were generally of lower priority than Class 1 or Class 2 alarms. The primary purpose of the Class 3 system was to inform the crew of a situation that could lead to a Class 2 alarm, or a condition that required a long procedure (more than 5 minutes) to correct. If the system detected that a specific parameter exceeded its limits, the blue systems management light was illuminated, and an alert tone, typically a steady tone of a predefined duration, was sounded. In addition, a fault message was displayed on both the fault message line and the fault summary page. The out-of-limits conditions were sensed by both the GNC system and the systems management software.[617]

The CWS also contained a Class 0, or Limit Sensing system, which provided visual cues only. These cues appeared on the data processing system display, and consisted of up and down arrows next to the monitored parameter(s). The up arrow indicated than the upper limit for a particular parameter had been exceeded, while the down arrow indicated that the lower limit for a parameter had been met or exceeded. The down arrow was also used to indicate a state that did not agree with the nominal state (for example: when a fan that was normally on, was off).[618]

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[614] Nearly all of the baseline limit values were set to be identical to those programmed into the backup CWS, but were changeable through switches on panel R13U on the flight deck. If power was lost and recovered, the limits returned to their original values. USA, *Crew Operations,* 2.2-3, 2.2-12.
[615] USA, *Crew Operations*, 2.2-12.
[616] USA, *Crew Operations*, 2.2-3, 2.2-4.
[617] USA, *Crew Operations*, 2.2-5.
[618] USA, *Crew Operations*, 2.2-5.

Communications System

Functions and Operations

The orbiter's communications system provided a variety of data paths between the orbiter and Mission Control. These included two-way internal and extravehicular voice and data links, and two-way audio, telemetry, and video communications. In addition, the system provided two-way data links between the vehicle and the ISS. The communications system could handle six different types of data: telemetry (operating conditions and configurations; systems, payloads and crew biotelemetry measurements); command (functional or configuration changes); rendezvous and tracking (onboard radar/communications system for tracking/performing rendezvous with orbiting satellites/spacecraft); video; voice; and documentation (printed data from the thermal impulse printer system). The information was passed directly between onboard equipment through wires, or between the vehicle and the ground by radio frequency links. All commands that were sent to the orbiter from the ground were routed to the onboard GPCs through the network signal processor and associated flight forward multiplexer/demultiplexer (MDM).[619]

Radio frequency communication took place directly with the ground sites, through the space flight tracking and data network (STDN) ground stations, or indirectly, through a TDRS system (TDRSS).[620] For direct communications, transmissions from the ground to the orbiter were referred to as uplinks, while signals from the orbiter to the ground were called downlinks. For indirect communications, signals from the ground to the orbiter were referred to as forward links and transmissions from the orbiter to the ground were called return links.[621] The TDRSS network provided most of the communications relays between the orbiter and Mission Control. It was comprised of nine satellites, which were located approximately 130 degrees apart, in geosynchronous orbit. The satellites were supported by the White Sands Ground Terminal and the Second TDRS Ground Terminal (both near White Sands, New Mexico).

System Description

The communications system was divided into several smaller systems, which included the S-band PM, the S-band FM, the Ku-band, the UHF simplex, the space-to-space orbiter radio, the payload communications, the audio, and the closed-circuit television.[622] The first four systems were used to transfer information between the orbiter and the ground. They provided near-

[619] USA, *Crew Operations*, 2.4-1, 2.4-2.
[620] For all military (DoD) missions, direct communications took place through the Air Force Satellite Control Facility remote tracking station sites, also known as space-ground link system ground stations. USA, *Crew Operations*, 2.4-1.
[621] This indirect terminology was also used to describe the communication links between a detached payload and the orbiter. Those from the orbiter to the payload were forward links, and those from the payload to the orbiter were return links. USA, *DPS Overview Workbook* (Houston: United Space Alliance, 2006), 1-1.
[622] A description of the closed circuit television system begins on page 210.

continuous communication, except for the zone of exclusion and the reentry phase of the mission.[623] The space-to-space orbiter radio was used to provide communications between the orbiter and the ISS, or the orbiter and the EMU, and the payload communication system provided data transfer between the orbiter and the payloads. The audio system was used to provide analog voice connection between the orbiter and Mission Control (or the Payload Operations Control Center).[624]

The **S-band PM system** (see Figure Nos. B-65 through B-68 for antenna locations) provided two-way communication between the vehicle and the ground, through either the STDN stations or TDRSS satellites. This system relied solely on radio frequency signals, which required a “line-of-sight” between the transmitting and receiving antennas. The TDRSS network allowed for about 80 percent coverage. If necessary (i.e., during a critical phase, such as the deorbit burn), a TDRS Z satellite could be scheduled to provide 100 percent communication coverage. It provided channels for commands from the ground to the orbiter; two-way voice communications between the ground and the orbiter; real-time orbiter/payload telemetry data from the vehicle to the ground; turnaround tone ranging that aided in tracking the orbiter; and two-way Doppler tracking, also used to track the orbiter.[625]

The S-band PM system contained four antennas, two of which were situated on the top of the forward fuselage and two on the bottom of the forward fuselage. Each antenna was a dual-beam unit that could look forward or aft without any physical movement. All four were capable of transmitting information to a STDN ground station or a TDRS; the specific antenna used was based on the computed line-of-sight. A dual S-band preamplifier was used to strengthen transmission signals. There was also a power amplifier to further strengthen the signals, if required.[626] The S-band PM system also contained redundant transponders, which functioned as multipurpose, multimode transmitters and receivers. The transponders could transmit signals, receive signals, or do both simultaneously. The transponders sent all forward link commands to the network signal processor, and received return link data from the network signal processor. The transponders also handled two-way Doppler and two-way tone ranging signals, both of which were used by the ground stations to track the orbiter.[627]

The transponders worked with one of two redundant network signal processors, which either received commands from the transponder or transmitted data to the transponder. For the transmission of data, the processor received one or two analog voice channels from the orbiter’s systems, and converted them to digital signals. The processor then multiplexed them with telemetry data from the pulse code modulation master unit, and sent the composite signal to the transponder, which sent the signal to the ground. For forward links, this process was reversed.

[623] The zone of exclusion was an area where the orbiter was not within the line of site of either TDRSS satellite; geographically the zone was over the Indian Ocean region. USA, *Crew Operations*, 2.4-2.
[624] USA, *Crew Operations*, 2.4-1.
[625] USA, *Crew Operations*, 2.4-2, 2.4-4.
[626] There were two preamplifiers and two power amplifiers for redundancy.
[627] USA, *Crew Operations*, 2.4-7, 2.4-8.

All S-band phase modulation communications were capable of being encrypted (and decrypted) as a means of security for operational data.[628]

The **S-band FM system** (see Figure Nos. B-65 through B-68 for antenna locations) was used exclusively to downlink telemetry data from as many as seven different sources, although only one source could be downloaded at a time. The seven sources of data were as follows: real-time SSME data from the engine interface units during launch; real-time video; solid state recorder dumps of high- or low-data-rate telemetry; payload analog data; payload digital data; real time or playback DoD data. In addition, these activities were only available when there was a line of sight between the orbiter and a STDN or USAF ground station. There were two redundant S-band FM transmitters on the orbiter, both of which were tuned to 2,250-Megahertz (MHz); only one could be used at a time. There were two S-band FM antennas on the outer skin of the vehicle's forward fuselage: one on the top surface and one on the bottom surface. Each was hemispherical, and covered with reusable TPS. Either antenna was selected for use based on the computed line of sight between the orbiter and the ground stations.[629]

The **Ku-band system** could be used as a communications system or a tracking/rendezvous radar system (both functions could not occur simultaneously); it was operated through the TDRSS. The Ku-band antenna for this system was located within the orbiter's payload bay (Figure No. B-113); thus, it was not operational until the vehicle was in orbit and the payload bay doors were opened. The antenna was stored on the starboard sill longeron; when deployed, it was angled 113 degrees counterclockwise from its stowage position. Once the antenna was deployed and activated, the vehicle's network signal processor directed the return link data stream to both the Ku-band signal processor and the S-band PM transponder, both of which transmitted data to the TDRS within the orbiter's line-of-sight.[630]

The Ku-band system was capable of handling more data than the S-band systems; it could transmit three channels of data at a time, either as forward or return links. There were two communications modes for forward and return links, each consisting of three channels. In all cases, the three channels of data were sent to the Ku-band signal processor, where they were layered with the return link. The signal was then sent to the deployed electronics assembly (which contained the transmitter), from which it was transmitted through the Ku-band antenna to the appropriate TDRS.[631]

Ku-band system interfacing between the orbiter and the TDRS was through the Ku-band deployed assembly, which consisted of a two-axis, gimbal-mounted, high-gain antenna; an integral gyro assembly; and a radio frequency electronics box. The assembly was mounted to the starboard sill longeron within the payload bay; gimbal motors were used to position the antenna

[628] USA, *Crew Operations*, 2.4-9.
[629] USA, *Crew Operations*, 2.4-10, 2.4-11.
[630] USA, *Crew Operations*, 2.4-13.
[631] USA, *Crew Operations*, 2.4-13, 2.4-15.

and rate sensors were used to determine how fast the antenna was moving. When stowed in the payload bay, the assembly was 7’ long and 1’ wide; the graphite epoxy parabolic antenna dish had a diameter of 3’. The dish was edge-mounted on a two-axis gimbal, which provided roll and pitch movements; it could be steered manually or automatically. Ground controllers sometimes “masked” the antenna, by inhibiting the RF carrier, to provide protection from Ku radiation for payloads, EVAs, and the ISS. This was accomplished by either inhibiting the transmitter when a certain beta gimbal angle was exceeded, or by inhibiting the transmitter in a specialized zone, defined by elevation and azimuth angles relative to the orbiter’s axes.[632]

The **payload communication system** was used to transfer information between the orbiter and the payloads. It supported both cabled and radio frequency communications, and was used to activate, check out, and deactivate attached and detached payloads. Its basic components were the payload interrogator, the payload signal processor, the payload data interleaver, and the pulse code modulation master unit; all of which were located in the forward avionics bays. Commands to the system were routed through the ground control interface logic controller from the payload MDMs.[633]

The payload interrogator was a transmitter/receiver/transponder unit through which the orbiter and a detached payload communicated with one another. The interrogator transmitted commands to, and received telemetry from, NASA payloads through the payload antenna, and then routed the telemetry directly to the Ku-band system for transmission to the ground and to the payload signal processor. The payload signal processor served as the interface between the flight crew and the payload, or between the ground and the payload. Attached payloads were connected to the payload data interleaver through interfaces on the payload patch panel. The payload data interleaver allowed the payload communication system to interface with the rest of the orbiter communication systems and computers. It was capable of receiving up to six inputs from attached or detached payloads, as well as one ground support equipment input. The interleaver sent the payload telemetry to the pulse code modulation master unit so it could be accessed by the GPCs for display, or combined with other orbiter telemetry for transmission to ground control.[634]

The **UHF system** (see Figure Nos. B-65 through B-68 for antenna locations) was typically used as a back-up for the S-band PM during ascent and entry operations for voice communications between the crew and the ground. It also served as the primary system for EVA communications. In addition, the UHF system could be used with the TACAN system on approach and landing operations, as well as with the Shuttle Training Aircraft during launch/landing. The UHF signals were routed through one antenna located on the bottom of the forward fuselage; a second antenna was located within the airlock.[635]

[632] USA, *Crew Operations*, 2.4-15 through 2.4-17.
[633] USA, *Crew Operations*, 2.4-21, 2.4-22.
[634] USA, *Crew Operations*, 2.4-22, 2.4-23.
[635] USA, *Crew Operations*, 2.4-23.

Also a part of the communications system was the **audio distribution system**, which was used to route all audio signals throughout the orbiter. It also provided the means for the crew members to communicate with each other and with external locations (such as Mission Control). The major components of this system were the audio central control unit, the audio terminal unit, the speaker units, the audio center panel, loose communications equipment, and crew communications umbilical jacks. The audio system had eight loops for routing the communications signals; different loops were designated for specific communications types (such as vehicle to Mission Control, or crew member to crew member).

There were two, redundant audio central control units located in the forward avionics bay of the middeck; only one was used at a given time. The control unit gathered and routed audio signals throughout the orbiter. Its circuitry could also activate signals from the launch umbilical connections to communicate with the Launch Control Center at KSC. There were six audio terminal units positioned throughout the crew compartment, four on the flight deck, one in the middeck, and one in the airlock. Each terminal unit had a control panel, which was used to select and control the volume of each audio loop. The audio terminal units were also connected to a paging system, which allowed one unit to transmit audio signals to all other audio terminal units, the space-to-space orbiter radio, and the ISS.[636]

There were two speaker units on the orbiter, one in the flight deck and one in the middeck. Each speaker unit was fitted with two speakers; the top speaker was for audio signals, while the bottom speaker was dedicated to caution and warning tones. There was one audio center panel, located on the aft flight deck. The panel was fitted with switches that sent digital impulses to the audio central control unit, enabling communications.[637] Loose communications equipment included small, stowable items, such as headsets, cables, and microphones. It also included the launch and entry helmet, which each crewmember wore during launch and entry procedures.[638] Crew communications umbilical jacks were headset plugs located on various control panels throughout the crew cabin.

Another aspect of the communications system was the **operational instrumentation system**, which monitored more than 3,000 parameters. This system consisted of transducers, fourteen dedicated signal conditioners, seven MDMs, two pulse code modulation master units, two recorders, master timing equipment, and onboard checkout equipment. These components worked together to sense, acquire, condition, digitize, format, and distribute data for display, telemetry, recording, and checkout. With the exception of sensors and dedicated signal conditioners, which were positioned throughout the orbiter as required, the operational instrumentation system was located within the forward and aft avionics bays.[639]

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636 USA, *Crew Operations*, 2.4-28, 2.4-30, 2.4-33.
637 USA, *Crew Operations*, 2.4-34.
638 USA, *Crew Operations*, 2.4-35 through 2.4-37.
639 USA, *Crew Operations*, 2.4-38-2.4-40.

Data Processing System

Discovery's data processing system (DPS) was considered "the heart of the space shuttle orbiter." This system directly or indirectly controlled the majority of the vehicle's systems (Figure No. B-114). The DPS was operated through five GPCs; four of the computers were loaded with the primary avionics software system (PASS), whereas the fifth contained the backup flight system (BFS).[640] The software accommodated nearly all phases of a mission, including orbiter checkout, prelaunch and final countdown operations, turnaround activities, control/monitoring during launch, ascent, on-orbit, entry and landing activities, and aborts or other contingency operations. It performed various GNC tasks, which were necessary to fly the vehicle, and provided the entire shuttle vehicle with computerized monitoring and control. In addition, the system managed and filtered orbiter system data (also known as telemetry) for transmission to Mission Control, and allowed Mission Control to remotely command many of the orbiter's systems.[641]

Functions and Operations

The DPS had a variety of functions that expanded across all phases of a mission, as follows:

- Supporting the guidance, navigation, and control of the vehicle, including calculation of trajectories, SSME burn data, and vehicle attitude control data;
- Monitoring and controlling the vehicle subsystems, such as the electrical power system and the environmental control and life support system;
- Processing vehicle data for use by the flight crew and for transmission to the ground controllers, as well as allowing remote control of some of the vehicle's systems;
- Checking data transmission errors and crew control input errors, and supporting the annunciation of vehicle system failures and out-of-tolerance system conditions;
- Supporting payloads with flight crew or software interface for activation, deployment, deactivation, and retrieval; and
- Processing rendezvous, tracking, and data transmissions between payloads and ground controllers.[642]

During the ascent phase of the mission, the four GPCs running the PASS were responsible for flying the vehicle; they performed all GNC functions simultaneously and redundantly. The fifth GPC, loaded with the BFS, "listened" to the other four computers so that in the event of a failure in the PASS, the BFS computer could continue to control the vehicle from where the PASS left off. In addition, the BFS computer performed all systems management functions during ascent, while the PASS computers were "preoccupied" with GNC operations.[643]

[640] USA, *Crew Operations*, 2.6-2.
[641] USA, *DPS Overview*, 1-1.
[642] USA, *Crew Operations*, 2.6-1.
[643] USA, *Crew Operations*, 2.6-22; USA, *DPS Overview*, 2-1, 2-2.

Once *Discovery* reached orbit, the PASS GPCs, which handled all on-orbit activities, were loaded with new software. During this phase of the mission, any failure of the PASS was considered non-life threatening; therefore, the BFS was no longer required and the computer was put into sleep mode. Throughout the orbit phase of the mission, different operational sequence software was loaded into the GPC from the modular memory unit as required. The typical on-orbit configuration assigned one to three PASS GPCs the responsibility of flying the orbiter, and one PASS GPC the task of performing all systems management tasks, as well as some payload activities. Any PASS GPC not being used for GNC was also loaded with orbit GNC software, but kept in sleep mode, until their use was required.[644]

Approximately 2 hours prior to the deorbit burn, the BFS computer was restarted, and all five GPCs were configured with the operational sequence for reentry and landing. As with launch and ascent procedures, the four computers with PASS conducted all GNC operations, while the BFS computer performed all systems management functions and monitored the status of the PASS.[645]

System Description

The vehicle contained five identical **GPCs** that allowed for redundant data processing and transfer; all five computers were IBM AP-101S with semiconductor memories. Four of the computers were loaded with the PASS, which was developed by IBM. These computers were used throughout the entire mission to fly the vehicle; provide life support, thermal control, and communications; and to assist with payload activities.[646] The fifth computer was loaded with the BFS software, which was developed by Rockwell International. This computer and software system was designed to take control of the vehicle if the PASS failed, or if other multiple failures caused a loss of vehicle control; the BFS was only capable of controlling basic flight and operation functions.[647] Each computer had an alphanumeric designation, GPC 1, GPC 2, GPC 3, GPC 4, or GPC 5. GPCs 1 and 4 were located in Avionics Bay 1 (forward middeck), GPCs 2 and 5 were located in Avionics Bay 2 (forward middeck), and GPC 3 was located in Avionics Bay 3 (aft middeck). GPC 5 was typically the computer provided with the BFS software, although any of the five computers could be loaded with the software.[648] Each computer was stored in a 19.55”-long, 10.2”-wide, and 7.62”-high avionics box.

Each GPC had a central processing unit and an input/output processor. The central processing unit controlled access to the computer’s main memory for data storage and software execution. It was also used to execute instructions to control vehicle systems and manipulate data. The input/output processor was used to format and transmit commands to vehicle systems, receive and validate response data from the vehicle systems, maintain the status of interfaces with the

[644] USA, *Crew Operations*, 2.6-20.
[645] USA, *Crew Operations*, 2.6-20, 5.4-2; USA, *DPS Overview*, 2-2.
[646] USA, *Crew Operations*, 2.6-2. 2.6-20; USA, *DPS Overview*, 2-1.
[647] USA, *Crew Operations*, 2.6-2; USA, *DPS Overview*, 2-1. NASA purposefully had the BFS designed by a different company to protect against a generic software flaw in the PASS.
[648] USA, *Crew Operations*, 2.6-3, 2.6-22.

associated central processing unit and the other GPCs, and interface with the twenty-four data buses and their processors. Each GPC also contained a timing oscillator that regulated operations between the computer's internal components, and kept track of Greenwich Mean Time and/or Mission Elapsed Time (MET) (as a backup to the master timing unit). The computer with the BFS also had a watchdog timer, which ensured that the computer was functioning properly.[649]

There were three modes of operation for the GPCs: redundant set, common set, and simplex. During redundant set operations, two or more of the GPCs concurrently received the same inputs, executed the same GNC software, and produced the same outputs. During common set operations, two or more GPCs communicated with one another while they performed their individual tasks, although the tasks could be the same. The simplex mode was used primarily for systems management and major payload functions. In addition, each of the four GPCs with the PASS software operated in synchronized steps and cross-checked their results with one another hundreds of times per second. If any of them failed to meet a synchronization point, the other computers voted it out of the redundant set, and initiated a fault message on the GPC status matrix and illuminated the master alarm.[650]

Aside from the five GPCs, the DPS contained two modular mass memory units, twenty-four serial digital data buses, twenty-four MDMs, three SSME interface units, the MEDS, two data bus isolation amplifiers, two master event controllers, and one master timing unit (Figure No. B-114).

The two **modular memory units** contained all of the software for the GPCs. Each consisted of a solid state recorder and a solid state mass memory storage device for GPC software and orbiter systems data. Each had approximate dimensions of 20" in length, 12" in width, and 7.7" in height, used 83 watts of power, and was located in the forward avionics bays on the middeck. Each unit was connected to all five GPCs, but was connected to only one mass memory data bus through a multiplexer interface adapter. The modular memory units contained eight memory configurations that corresponded to different phases of a mission; each memory configuration contained the functional data for the activities executed during that specific phase.[651] Critical programs and data were loaded into both memory units and protected from erasure. Besides storing the basic flight software, the modular memory units stored background formats and codes for some of the dedicated displays, and periodically saved select data in case of a GPC failure.[652]

Discovery's DPS contained twenty-eight **data buses** that supported the transfer of serial data commands and data between the five GPCs and the vehicle's systems. The data buses were

[649] USA, *Crew Operations*, 2.6-3. The four GPCs with the PASS did not need to use this function because they were synchronized with one another.
[650] USA, *Crew Operations*, 2.6-5, 2.6-6.
[651] This arrangement was necessary because the GPCs had limited memory space. All of the software was therefore stored in the modular memory units and transferred to the GPCs at specified times in the mission. USA, *Crew Operations*, 2.6-13; USA, *DPS Overview*, 2-2.
[652] USA, *Crew Operations*, 2.6-13.

divided into seven functional groups: flight-critical data buses, payload data buses, launch data buses, mass memory data buses, display/keyboard data buses, instrumentation/pulse code modulation master unit buses, and the intercomputer communication data buses. The eight flight-critical data buses connected the GPCs to the flight-critical MDMs, integrated display processors, head-up displays, engine interface units, and master events controllers. There were two payload data buses that interfaced the GPCs to the two payload MDMs. The MDMs, in turn, were connected to the orbiter systems and payloads, and sometimes with other payload equipment. The two launch data buses were used to interconnect the GPCs, the ground support equipment, the launch processing system, the three launch MDMs, and the two left and two right SRB MDMs. One of the launch data buses was also interfaced with the RMS while on orbit.[653]

There were two **mass memory data buses** used to connect the GPCs to the modular memory units. Each bus was connected to all five GPCs but only one of the memory units. The four display/keyboard data buses were used to interface the integrated display processors with the GPCs. Similar to the mass memory data buses, each display/keyboard data bus was connected to one integrated display processor and all five computers. There were five instrumentation/pulse code modulation master unit buses, each of which was connected to one GPC and two pulse code modulation master units. The five intercomputer communication data buses allowed the PASS computers to exchange information with each other. The exchanged data included input/output errors, fault messages, GPC status matrix data, integrated display processor major function switch settings, GPC/CRT keyboard entries, resident GPC memory configuration, memory configuration table, operational sequences, master timing unit data, time, internal GPC time, system-level display information, uplink data, and state vectors.[654]

The twenty-four **MDMs** converted and formatted serial digital GPC commands into separate and parallel digital and analog commands for the different vehicle hardware systems (demultiplex), and vice versa (multiplex). Each MDM was 13” x 11” x 7”, weighed about 38.5 pounds, and was redundantly powered by two main buses. Each MDM was fitted with two redundant multiplexer interface adapters; each adapter was connected to a separate data bus. Each MDM was also hardwired to a specific vehicle system. Four of the MDMs were connected to the SRBs, two per booster; twenty of the MDMs were onboard the orbiter. Thirteen of the orbiter’s MDMs were considered part of the DPS and were connected to the GPCs. There were four flight-critical forward MDMs, two payload MDMs, one launch forward MDM, and one launch mid MDM, which were in the forward avionics bays, and four flight-critical aft MDMs, and one launch aft MDM, located within the aft avionics bays. Seven of the orbiter’s MDMs were considered part of the vehicle instrumentation system; these MDMs sent vehicle instrumentation data to the pulse code modulation master units. Four of the vehicle instrumentation MDMs were located in the forward avionics bays, and three were in the aft avionics bays.[655]

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[653] USA, *Crew Operations*, 2.6-8, 2.6-9.
[654] USA, *Crew Operations*, 2.6-9, 2.6-10, 2.6-11.
[655] USA, *Crew Operations*, 2.6-11.

The **MEDS** allowed onboard monitoring of orbiter systems, computer software processing, and manual control for flight crew data and software manipulation.[656] The crewmembers could use the MEDS to control vehicle system operations, alter system configurations, change data or instructions in the GPC main memory, change memory configurations corresponding to different mission phases, respond to error messages and alarms, request special programs to perform specific tasks, run through operational sequences for each mission phase, and request specific displays. The system consisted of four different types of hardware: integrated display processors, multifunction display units, analog-to-digital converters, and keyboard units. These components communicated with the GPCs through the display/keyboard data buses.[657]

The four integrated display processors served as the interface between the MEDS and the GPCs. The processors formatted data from the computers and the analog-to-digital converters, for display on the MEDS display units. They could also accept operator inputs from switches, edgekeys, and keyboards, as well as monitor their own status and the status of other MEDS line replaceable units. The processors were located in the forward cockpit; two beneath panels to the left of the commander and two beneath panels to the right of the pilot; they were able to be swapped during a flight, if necessary. Each had its own dedicated data bus that connected it to the display units and to the two analog-to-digital converters.[658]

There were eleven multifunction display units, each of which was a full color, flat panel, 6.7"-square, active matrix liquid crystal display. The unit's primary function was to drive the various color displays on the multifunction display units (MDUs), which were designed to ensure readability in the harsh lighting conditions. Each display was fitted with six edgekeys below the screen, which were used to navigate the MEDS menu system, and to perform MEDS-specific activities. On either side of the edgekeys were a brightness control knob and an on/off switch. Nine of the multifunction display units were located on the forward cockpit; one was located on the mission station, and one was located on the aft station. All but three of the MDUs were connected to two integrated display processors, although only one of the processors controlled the display at a given time.[659] Within the forward cockpit, the left five display units were operated by switches on the commander's side (specifically, panel F6), while the right four display units were operated by switches on the pilot's side (specifically, panel F8).[660]

The four analog-to-digital converters were used to convert the analog data from the main propulsion system, the APU/hydraulics system, the OMS, and the surface position indicator subsystem data into digital data. The digital data was used by the integrated display processors to generate the images on the display units. Two of the analog-to-digital converters covered the main propulsion system, the OMS, and the surface position indicator subsystem; the other two

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[656] The physical description of the MEDS begins on page 122.
[657] USA, *Crew Operations*, 2.6-13, 2.6-14.
[658] USA, *Crew Operations*, 2.6-14.
[659] The three forward MDUs were only connected to one integrated display processor.
[660] USA, *Crew Operations*, 2.6-15.

processed the APU and hydraulics system data. Each converter simultaneously communicated with two integrated display processors.[661]

Three identical keyboards on the flight deck provided the means to command the MEDS. Two were on the center console, one for the commander and one for the pilot, and the third was on the aft mission station. The commander and pilot keyboards contained thirty-two momentary double-contact pushbutton keys; the double contact allowed communication on separate signal paths to two integrated display processors. They used a select switch to select which integrated display processor they wanted to use. The mission station keyboard also had thirty-two keys, but only used one set of contacts, because it was only wired to the aft processor. Through the ten numeral keys, six letter keys, two algebraic keys, and thirteen special function keys, the crew could ask the GPCs over 1,000 questions about the mission and condition of the vehicle. Individual keys or entire keyboards could be changed out while on orbit in the event of a failure.[662]

The **master timing unit** provided precise frequency outputs for various timing and synchronization purposes for the GPCs, as well as many of the orbiter's subsystems. It had three time accumulators that provided both Greenwich Mean Time and MET, in days, hours, minutes, seconds, and milliseconds for up to one year. It was a stable, crystal-controlled frequency time source that contained two oscillators for redundancy; the signals from the oscillators were passed through signal shapers and frequency drivers to three accumulators. From the accumulators, the serial digital time data was provided on demand to the GPCs, which used the data for reference time and time-tagging systems management processing. The master timing unit also provided digital timing outputs to drive four digital timers in the flight deck (two mission timers, two event timers); it was located in the aft avionics bay on the middeck of the crew compartment.[663]

The DPS contained three **SSME interface units**, which were used to command the SSMEs. The system also had two **data bus isolation amplifiers** that interfaced with ground support equipment, the launch processing system, and the SRBs.[664] In addition, there were two **master events controllers**, one in the forward avionics bays and one in the aft avionics bays. These controllers provided all synchronization of control and measurement data between the GPCs and the orbiter, SRB, and ET pyrotechnic and control devices.[665]

Software

The **PASS** was the principal software used to operate the orbiter during a mission. The PASS software was divided into two main groups, system software and applications software; data from the two groups was combined to form a memory configuration for a specific mission phase.

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[661] USA, *Crew Operations*, 2.6-15.
[662] USA, *Crew Operations*, 2.6-15, 2.6-16.
[663] USA, *Crew Operations*, 2.6-16, 2.6-17.
[664] USA, *Crew Operations*, 2.6-2.
[665] The Boeing Company, "Vehicle Engineering," (presentation during STS-106 Flight Readiness Review, August 29, 2000), 109.

The programs were written in HAL/S (high-order assembly language/shuttle), a computer language developed specifically for real-time space flight applications. System software controlled the interfaces between the GPCs and the other components of the DPS. The system software consisted of three different programs. The flight computer operating system controlled key vehicle system parameters, allocated computer resources, interrupted programs for higher priority activities, and updated computer memory. User interface programs provided the instructions for processing crewmember commands and requests. The system control program initialized each GPC and coordinated the multi-computer operations during critical mission phases.[666]

The applications software performed the functions required to fly and operate the vehicle. The software was divided into three major functions: GNC, systems management, and payload. GNC software was used during launch, ascent, maneuvering on orbit, entry, and landing; it was the only function that allowed for redundant set synchronization. Systems management programs monitored the various vehicle systems, and only one GPC could process a memory configuration at a given time. Payload functions were typically only used during vehicle preparation activities at KSC; on-orbit payload operations were covered by systems management programs. These major functions were divided into mission phase oriented blocks called operational sequences. Each operational sequence was loaded into the GPCs from the mass memory units, as specified by the flight plan.[667]

The GNC portion of the **BFS** was intended for use only in a contingency situation; it was capable of controlling the vehicle and performing systems management functions. Although the BFS was simpler than the PASS, it was also divided into system software and applications software. The BFS system software performed basically the same functions as the PASS system software. The applications software had two major functions, GNC and systems management. The GNC programs supported ascent and deorbit/entry activities, as well as limited on-orbit operations. The systems management applications supported only the ascent and entry phases.[668]

<u>Electrical Power System</u>

Functions and Operations

The electrical power system (EPS; Figure No. B-115) served as the main source of power for the orbiter during all phases of flight. The system, consisting of equipment and reactants, produced electrical power for distribution throughout the orbiter, as well as for the ET, SRBs, and payloads, when the vehicle was not connected to ground support equipment. The electrical power system was functionally divided into three subsystems: the power reactants storage and

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[666] USA, *Crew Operations*, 2.6-20.
[667] USA, *Crew Operations*, 2.6-21, 2.6-22.
[668] USA, *Crew Operations*, 2.6-23.

distribution subsystem, the fuel cell power plant subsystem, and the electrical power distribution and control subsystem.[669]

During prelaunch operations, ground support equipment filled the power reactant storage tanks with LH2 and LO2, approximately 2 days before launch. In addition, ground support equipment provided GH2 and GO2 to the power reactants storage and distribution system manifold to minimize use out of the tanks prior to liftoff. This supply operation was terminated roughly 2 minutes, 35 seconds before launch[670]. The fuel cells were activated prior to the crew entering the vehicle; nevertheless, until 50 seconds before liftoff, power to the orbiter was provided by both the fuel cells and ground support equipment.[671]

The EPS continued to operate through all phases of the mission, requiring minimal flight crew interaction for nominal operations. The entire system could, however, be actively monitored by both the crew and ground controllers.[672]

System Description

Power Reactants Storage and Distribution Subsystem: The power reactants storage and distribution system stored the reactants (cryogenic hydrogen [H2] and oxygen [O2]) and supplied them via three isolatable reactant manifolds to the three fuel cells; it also supplied O2 to the ECLSS for crew cabin pressurization. The major components of the system were the storage tanks for the H2 and O2, tank heaters, and the reactants distribution system. All of the components were located in the midfuselage, underneath the payload bay liner. The storage tanks were grouped into sets of one H2 and one O2 tank; up to five sets were installed in the vehicle depending upon the mission requirements.[673] Both reactants were stored in double-walled, thermally insulated spherical tanks at cryogenic temperatures (-420 degrees F for the H2 and -285 degrees F for the O2); the temperatures of the fuel and oxidizer increased as each reactant was used. The reactants were maintained at supercritical pressures, over 188 psia for the H2 and over 731 psia for the O2. The tanks were fitted with sensors to measure remaining quantities.[674]

The H2 tanks were comprised of a 41.51”-diameter inner pressure vessel and a 45.5”-diameter outer shell; both were made of aluminum 2219. Each had an internal volume of 21.39 cubic feet and could store up to 92 pounds of H2. The O2 tanks consisted of a 33.435”-diameter inner pressure vessel made of Inconel 718 and a 36.8”-diameter outer shell made of aluminum 2219. Each had an internal volume of 11.2 cubic feet and stored up to 781 pounds of O2. The inner pressure vessels of both the H2 and O2 tanks were kept supercold by minimizing conductive,

[669] USA, *Crew Operations*, 2.8-1.
[670] The LH2 and LO2 were later pressurized, resulting in cryogenic H2 and O2, which was neither liquid nor gas, but rather had properties of both.
[671] USA, *Crew Operations*, 2.8-32, 2.8-33.
[672] USA, *Crew Operations*, 2.8-1.
[673] An extended duration orbiter pallet, which held additional tank sets, could be installed in the vehicle.
[674] USA, *Crew Operations*, 2.8-1.

convective, and radiant heat transfer. Conductive heat was minimized by suspending the inner vessel within the outer shell through the use of twelve low-conductive supports; convective heat transfer was limited by maintaining a vacuum between the inner vessel and the outer shell. Radiant heat transfer was reduced by inserting a shield between the vessel and the shell; this was provided only for the H2 tanks. In addition, each H2 tank was fitted with one heater probe, and each O2 tank was fitted with two heater probes. The purpose of the heaters was to add heat energy to the tank, in order to maintain a constant pressure as the reactant was depleted.[675]

From the storage tanks, the reactants flowed through a relief valve/filter package module. Every tank contained a tank pressure relief valve, and a filter; tank sets 1 and 2 also included a manifold pressure relief valve. Each reactant then flowed through a valve panel, which provided an isolation capability for the three reactant manifolds, as well as an isolation capability between a fuel cell and its associated manifold. The O2 valve panels also had the capability to provide O2 to the ECLSS pressure control system. In addition, each module had a check valve to prevent reactants from flowing from one tank to another if there was a tank leak.[676]

Fuel Cell Power Plant Subsystem: *Discovery* contained three fuel cells, all were located in the forward portion of the midfuselage. Each fuel cell had a length of 40", a width of 15", and a height of 14", and was reusable and restartable. Each fuel cell was individually coupled to the power reactant storage and distribution system, the active thermal control system, the supply water storage subsystem, and the electrical power distribution and control subsystem. The fuel cells produced heat and water as they generated electrical power; the heat was directed to the fuel cell heat exchanger to be redirected to the Freon coolant loops, whereas the water was sent to the supply water storage subsystem for use by the ECLSS.[677] Each of *Discovery's* three fuel cells operated as an independent electrical power source, supplying up to 10 kilowatts (kW) of maximum continuous power in nominal situations, 12 kW continuously in off-nominal situations, or 16 kW for a maximum of 10 minutes.[678] The average on-orbit power consumption of the vehicle itself was roughly 14 kW, which left additional capability for payloads. Each fuel cell was serviced in between flights, and could be reused until it accumulated up to 2,500 hours of on-line service.[679]

Each fuel cell consisted of two distinct parts: a power section and an accessory section. The power section was where the H2 and O2 reacted to produce electrical power, water, and heat. This section contained ninety-six individual cells, which were grouped into three substacks of thirty-two cells. Manifolds extended over the length of each substack to distribute H2, O2, and coolant to the individual cells. Each cell contained an oxygen electrode (cathode) and a hydrogen electrode (anode) separated by a porous matrix with potassium hydroxide electrolyte.[680] The

[675] USA, *Crew Operations*, 2.8-3.
[676] USA, *Crew Operations*, 2.8-7, 2.8-8.
[677] USA, *Crew Operations*, 2.8-9.
[678] An example of an off-nominal situation would be if one or more of the fuel cells failed during the mission.
[679] USA, *Crew Operations*, 2.8-10.
[680] An electrolyte is a substance with extra ions, which makes the substance electrically conductive. A pH sensor,

accessory section of the fuel cell served several functions. It monitored fuel cell performance and health, and provided the optimal operating conditions for the fuel cell by removing water from the fuel cell, regulating its temperature, purging contaminants from the fuel cell, providing electrical control, and regulating fuel cell pressure.[681]

The fuel cells generated power through an electrochemical reaction of H2 and O2. The reactants entered the cell manifold through a preheater, which heated them to around 40 degrees F. The reactants then passed through a 6-micron filter and a dual gas regulator module; the latter reduced the pressure of the reactants, returning them to a gaseous state. The regulated GO2 lines were connected to an accumulator, which maintained an equalized pressure between the oxygen and the fuel cell coolant. The fuel cell's coolant system circulated a liquid fluorinated hydrocarbon through the cell stack and carried the waste heat to the fuel cell heat exchanger, where it was transferred to the Freon coolant loop system. This maintained the cell stack at an approximate operating temperature of 200 degrees F.[682]

After passing through the regulator module, the GH2 was first mixed with recirculated water vapor and hydrogen gas exhaust from the cell stack. It was then routed through a condenser where the saturated water vapor was cooled to form liquid water droplets, which were separated from the mixture and pressure-fed to the potable water tanks in the crew compartment's equipment bay.[683] The GH2 and water vapor mix was routed back to the cell stack, where some of it was consumed in the reaction. The remainder flowed through the stack, removing the product water vapor formed at the anode. In the meantime, GO2 from the dual gas regulator module flowed directly through two ports into a closed-end manifold within the fuel cell stack. All of the GO2 that flowed into the stack was consumed, except during purge operations.[684]

In order to maintain efficiency, the fuel cells were periodically purged to cleanse them of inert gases or contaminants that accumulated around the electrodes during operation; the sequence could be controlled manually by the crew, or automatically by the flight software (after being initiated by the crew or by a ground command sent by Mission Control). The operation began by activating the purge line heaters, to ensure that the reactants did not freeze within the lines. The purge valves were later opened to increase the flow of the GO2 through the cell stacks and to allow contaminants to be dumped overboard with the purged gas.[685]

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which measures how acidic or basic a substance is, was located downstream of the hydrogen pump/water separator to detect if any of the potassium hydroxide electrolyte had entered the product water. USA, *Crew Operations*, 2.8-14.

[681] USA, *Crew Operations*, 2.8-10.

[682] USA, *Crew Operations*, 2.8-11.

[683] This water could then be used for crew consumption and for cooling the Freon loops by feeding the flash evaporator system. If the tanks were full, excess water was dumped overboard. USA, *Crew Operations*, 2.8-11, 2.8-14. The discussion of the ECLSS begins on page 174.

[684] USA, *Crew Operations*, 2.8-11.

[685] USA, *Crew Operations*, 2.8-15, 2.8-16.

Electrical Power Distribution and Control Subsystem: The electrical power distribution and control subsystem controlled and distributed all electrical power (both alternating current [ac] and direct current [dc]) to the orbiter's systems and subsystems, the SRBs, the ET, and all payloads (Figure No. B-116). The subsystem consisted of three main power buses, three primary ac buses, three essential buses, nine control buses, and two preflight buses.[686] In general, the power created by each fuel cell was distributed to one of three main dc buses, as well as one of three essential buses.[687] The essential buses provided power to switches that were necessary to restore power to a failed main dc or ac bus, and to some essential electrical loads or switches.[688] Each main bus also supplied power to three solid-state, single-phase inverters. The three inverters were phase sequenced with each other to provide 117 volt, 400-Hertz (Hz) ac power to one of three ac buses that powered all of the vehicle's ac loads.[689]

Direct current electrical power for the orbiter was routed through three distribution assemblies, each of which was nominally powered by one of the fuel cells, and contained fuses, relays, and remotely controlled motor-driven switches. Each assembly further distributed power to one forward power controller assembly, one mid power controller assembly, and one aft power controller assembly.[690] Each forward power controller assembly supplied power to one forward motor controller assembly and one forward load controller assembly; it also provided dc power to three ac inverters associated with a single ac bus. Two of the mid power controller assemblies supplied power to two of four mid motor controller assemblies, while the third mid power controller assembly distributed power to all four mid motor controller assemblies. Each aft power controller assembly supplied power to a smaller aft power controller assembly, one aft load controller assembly, and one aft motor controller assembly. In addition, the aft power controller assemblies contained power contactors, which controlled and distributed ground-supplied power to the orbiter prior to startup of the fuel cells. Further, each aft load controller assembly provided power to the ET, and each aft power controller assembly supplied power to the SRBs.[691]

The load controller assemblies contained hybrid drivers, which were solid-state switching devices, and thus, had no mechanical parts. These devices were either used as logic switches, for turning on a specific load, or as low-power electrical loads. The function of each motor controller assembly was to supply ac power to noncontinuous ac loads, such as the motors used to open and close vent doors, star tracker doors, payload bay doors and latches, ET doors, RMS

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[686] A bus is a distribution point of electrical power.
[687] In the event of a failure, any main bus could be connected to another main bus.
[688] Examples of essential switches were those that powered the general purpose computer switches, the TACAN and MSBLS power switches, the caution and warning system, and the master timing unit. USA, *Crew Operations*, 2.8-24.
[689] USA, *Crew Operations*, 2.8-20.
[690] As the designations infer, the forward power controller assembly was for the forward section of the vehicle, the mid power controller assembly was for the midsection of the orbiter, and the aft power controller assembly was for the aft section of the vehicle.
[691] USA, *Crew Operations*, 2.8-23, 2.8-28.

deploy motors and latches, and RCS/OMS motor-actuated valves. Each assembly contained main dc buses, ac buses, and hybrid relays that were remotely controlled. The hybrid relays permitted major electrical power distribution buses to be located close to the major electrical loads, which minimized use of heavy electrical feeders to and from the pressurized crew compartment display and control panels. This reduced the amount of wiring, thus limiting the weight and permitting more flexible electrical load management. The dc buses were used only to supply control or power to the hybrid relays so that the ac power could be started or terminated.[692]

The ac power generated by the electrical power distribution and control system was distributed to system loads through three independent ac buses. This ac power system included ac inverters, which converted dc power to ac power, and inverter distribution and control assemblies, which contained the ac buses and ac bus sensors. The ac power was distributed from the inverter distribution and control assemblies to the three-phase motor loads throughout the vehicle, as well as some single phase loads (mostly lighting).[693]

The power controller assemblies, load controller assemblies, motor controller assemblies, and inverters within the forward avionics bays were mounted on cold plates and cooled by the water coolant loops. The inverter distribution and control assemblies in the forward avionics bays were air-cooled. All of the electrical components in the midfuselage were mounted on cold plates and cooled by the Freon coolant loops. The load controller assemblies, power controller assemblies, and motor controller assemblies that were located in the aft avionics bays were mounted on cold plates and cooled by the Freon coolant loops.[694]

Environmental Control and Life Support System

While on orbit, *Discovery's* crewmembers required a habitable environment, similar to that on Earth. This was provided by the ECLSS (Figure No. B-117), which regulated the temperature and pressure of the crew cabin, as well as the external airlock. The system also managed the storage and disposal of water and crew waste. Although by the end of the SSP a typical mission lasted approximately fourteen days, the ECLSS was capable of supporting eight crewmembers for a period of up to twenty-one days.[695]

The ECLSS was functionally divided into four systems: the pressure control system, the atmospheric revitalization system, the active thermal control system, and the supply and wastewater system. Each of these systems is discussed separately.

[692] USA, *Crew Operations*, 2.8-28, 2.8-29.
[693] USA, *Crew Operations*, 2.8-26.
[694] USA, *Crew Operations*, 2.8-30.
[695] Baker, *Manual*, 78-79; USA, *Environmental Control and Life Support System* (Houston: United Space Alliance, 2006), 1-1.

Pressure Control System

Function and Operations

The pressure control system maintained a pressure of roughly 14.7 psi within the crew cabin and provided the proper atmosphere to cool all cabin-air-cooled equipment. It also provided an air mixture of approximately 80 percent nitrogen and 20 percent oxygen, which closely matches the Earth's atmospheric conditions at sea level. There were two identical, redundant systems, known as PCS 1 and PCS 2, each of which was individually capable of maintaining the proper pressure and atmosphere within the crew cabin.[696]

Approximately 90 minutes before lift-off, the cabin was pressurized to approximately 16.7 psi to check for leaks; it was left at that pressure for roughly 35 minutes.[697] During ascent, both of the cabin regulator inlet valves were closed to isolate the regulators, in case a cabin leak developed.[698] In addition, the oxygen regulator inlet valves were closed to direct all oxygen to the crossover manifold to supply the crew's advanced crew escape suit helmets.[699] The oxygen/nitrogen control valve on PCS 1 was open to allow nitrogen to pressurize the oxygen/nitrogen manifold; the oxygen/nitrogen control valve on PCS system 2 was closed. The pressure control system remained in this ascent configuration until early in the flight plan.

Typically, on the first flight day, the cabin regulator inlet valve on the selected pressure control system (usually PCS 1) was opened, enabling the cabin regulator to automatically maintain the cabin pressure at 14.7 psia. In addition, the oxygen regulator inlet valve was opened, and the selected system oxygen/nitrogen control valve was set to automatic, enabling the controller to control whether oxygen or nitrogen flowed into the oxygen/nitrogen manifold based on cabin partial pressure of oxygen level. The system was reconfigured to PCS 2 halfway through the mission.[700]

During the SSP, flight surgeons developed a "10.2-psia cabin protocol" to minimize the risk of decompression sickness for the crewmembers preparing for an EVA.[701] In order to minimize the in-suit prebreathe just prior to the EVA, the entire crew cabin was depressurized to 10.2 psia using the airlock depressurization valve located in the airlock. During this operation, the cabin pressure and the partial pressure of oxygen levels had to be manually managed, because there

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[696] USA, *Environmental Control*, 2-1. Throughout this section, the acronym PCS (pressure control system) will only be used when distinguishing between the two redundant systems.
[697] USA, *Crew Operations*, 2.9-11.
[698] This configuration conserved nitrogen by not allowing any makeup flow into the cabin until the cabin pressure dropped below 8 psia. USA, *Crew Operations*, 2.9-44.
[699] The crew closed their helmet visor shortly before lift-off and breathed 100 percent oxygen until shortly after Solid Rocket Booster Separation. USA, *Crew Operations*, 2.9-44.
[700] USA, *Crew Operations*, 2.9-44.
[701] The EVA crewmembers must prebreathe pure oxygen before they go EVA to help flush the nitrogen out of their body tissue. USA, *Crew Operations*, 2.9-44.

was no automatic regulator. Typically, the cabin remained at this reduced pressure for twelve or twenty-four hours prior to the EVA, dependent upon the length of the final crewmember prebreathe in the EVA suit.[702]

The pressure control system configuration was set the same for entry as it was for ascent.[703]

System Description

The pressure control system contained four cabin pressure relief valves, which protected the structural integrity of the crew cabin. Two of the valves were positive pressure relief valves; they were arranged in a parallel configuration and provided overpressurization protection. The other two were negative pressure relief valves, which were also arranged in parallel and protected the crew cabin from underpressurization. One of two systems, PCS 1 or PCS 2, each of which consisted of a liquid oxygen storage system, a gaseous nitrogen storage system, and an oxygen/nitrogen manifold, maintained the crew cabin atmosphere.[704]

The orbiter's power reactant and distribution system, part of the EPS, supplied the pressure control system with oxygen from the cryogenic tanks used to feed the power fuel cells; they were located below the payload bay in the midfuselage. Supply valves controlled the flow of oxygen into the pressure control system, which was then routed through a restrictor, which regulated the flow. In addition, the restrictor served as a heat exchanger, to warm the oxygen with Freon before it flowed into the cabin.[705] Prior to entering the cabin, the oxygen flowed through a restrictor, which protected the fuel cell from being depleted by the pressure control system. The restrictor in PCS 1 was a single, 25 pound per hour flow restrictor; PCS 2 contained two 12.5 pounds per hour flow restrictors in a parallel formation. From the restrictor, the oxygen flowed through its piping system, which penetrated the X_o = 576 bulkhead and entered into the crew compartment; check valves prevented the reverse flow of oxygen. Downstream of the check valve, a crossover valve connected the two oxygen systems, allowing both to supply the oxygen crossover manifold, which provided oxygen to the launch/entry suit helmet regulators, the direct oxygen valve, and the airlock's EMU oxygen supply lines. An oxygen regulator inlet valve, located downstream of the oxygen crossover line, reduced the oxygen supply pressure to roughly 100 psia. The regulated oxygen then passed through another check valve and into the oxygen/nitrogen manifold; the oxygen could only enter the manifold when the nitrogen supply line was closed.[706]

The gaseous nitrogen system included four permanently installed storage tanks; all orbiters could carry up to four additional tanks if required. The two storage tanks designated for PCS 1 were

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[702] USA, *Crew Operations*, 2.9-44.
[703] USA, *Crew Operations*, 2.9-45.
[704] USA, *Crew Operations*, 2.9-3, 2.9-4; USA, *Environmental Control*, 2-1.
[705] Freon loop 1 warms the PCS 1 oxygen, and Freon loop 2 warms the PCS 2 oxygen. USA, *Environmental Control*, 2-1.
[706] USA, *Environmental Control*, 2-1, 2-3.

located at the aft end of the midfuselage, below the payload bay, while the two tanks designated for PCS 2 sat at the forward right side of the midfuselage.[707] The nitrogen tanks were constructed of filament-wound Kevlar fiber with a titanium liner, and had a volume of 8,181 cubic inches. Gaseous nitrogen left the tanks at an approximate pressure of 3,300 psia, flowed through the supply valves, and entered the nitrogen manifold. The system then directed the nitrogen through a regulator, which reduced the pressure to roughly 200 pounds per square inch, gauge (psig), before the gas was routed into supply lines that passed through the $X_o = 576$ bulkhead and into the crew compartment; a check valve prevented the reverse flow of nitrogen. The system then directed the nitrogen through the water tank regulator, which pressurized the supply and wastewater tanks. Downstream of the water tank regulator was the nitrogen crossover valve, allowing the PCS 1 and PCS 2 nitrogen systems to be connected. Afterward, the nitrogen entered the oxygen/nitrogen manifold.[708]

A cabin regulator maintained the cabin pressure at 14.7 psia when the regulator inlet valve was open; an emergency regulator maintained the cabin pressure at 8 psia in the event of a large cabin leak. The oxygen/nitrogen control valve controlled the flow of either the oxygen or the nitrogen into the oxygen/nitrogen manifold. The position of the control valve could be set manually by the crew, or automatically by the oxygen/nitrogen controller. When the valve was manually open, nitrogen flowed into the manifold and forced the oxygen check valve to close. When the valve was manually closed, nitrogen was unavailable, so any remaining gas in the manifold entered the cabin, and once the manifold's pressure dropped below 100 psi, the oxygen check valve opened and oxygen entered the manifold. While the vehicle was on orbit, the control valve was primarily set to automatic control. In this mode, the control valve opened or closed, depending on the partial pressure of oxygen within the crew cabin. If the partial pressure of oxygen was below 2.95 psia, the valve closed and oxygen entered the manifold. On the other hand, if the partial pressure of oxygen was greater than 3.45 psia, then the valve opened and nitrogen entered the manifold. If the partial pressure was between 2.95 and 3.45 psia, whatever gas was within the manifold flowed into the cabin until one of the limits was reached.[709]

Other features of the pressure control system included a cabin vent isolation valve, a cabin vent valve, and an airlock equalization valve. The cabin vent isolation valve and a cabin vent valve were arranged in series to vent the crew cabin to ambient pressure while the vehicle was on the ground or to vent the cabin on orbit in an extreme emergency. An airlock equalization valve maintained equal pressure between the airlock and the crew cabin; the airlock depressurization valve was used to depressurize the crew cabin to 10.2 psia, in preparation for an EVA, and to further depressurize the airlock for an EVA.[710]

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[707] USA, *Environmental Control*, 2-4. The tanks were moved to these positions to provide the vehicle with a more favorable center of gravity.
[708] USA, *Environmental Control*, 2-5.
[709] USA, *Environmental Control*, 2-8, 2-9.
[710] USA, *Crew Operations*, 2.9-11, 2.9-12.

Atmospheric Revitalization System

Functions and Operations

The atmospheric revitalization system controlled ambient heat, relative humidity, carbon dioxide levels, and carbon monoxide levels within the crew cabin; it also provided cooling for cabin avionics (Figure Nos. B-118, B-119, B-120). The system maintained a crew cabin air temperature between 65 and 80 degrees F, with a relative humidity between 30 and 65 percent.

The atmospheric revitalization system was configured for ascent prior to the crew entering the orbiter at the launch pad. For the air subsystem, one cabin fan, one humidity separator, one inertial measurement unit fan, and one fan in each avionics bay were operating. Once the proper cabin temperature was reached, the controller was unpowered. In addition, the signal conditioners for the humidity separator and the inertial measurement unit fan were unpowered to prevent against a potential electrical short that could cause a loss of the SSME controller. For the water subsystem, the primary water loop was operational.[711]

Assuming there were no failures within the air subsystem during launch and ascent, the only action required to manage the system while on orbit was the periodic replacement of the lithium hydroxide canisters. Up to thirty spare canisters were stored under the middeck floor. The controls for the water subsystem were set to automatically cycle the inactive secondary water loop every four hours in order to prevent freezing.[712]

System Description

The atmospheric revitalization system was divisible into two subsystems, the air subsystem and the water subsystem. The air subsystem consisted of a network of fans that circulated air through the cabin, the avionics bays, and the inertial measurement units to remove heat, humidity, carbon dioxide, odors, dust, debris, and particles. The water subsystem was comprised of a series of water coolant loops, which collected heat from the various heat exchangers and transferred it to the Freon/water heat exchanger.[713]

The **air subsystem** was functionally divisible into three circulation systems: the cabin fan system that circulated air throughout the crew cabin, the avionics fan system, which circulated air throughout the three forward avionics bays, and the inertial measurement unit fan system that cooled the inertial measurement units. A separate system provided air to the vehicle's airlock. With the exception of the ductwork, all air subsystem components were located under the middeck floor.

[711] USA, *Crew Operations*, 2.9-45; USA, *Environmental Control*, 3-29.
[712] USA, *Crew Operations*, 2.9-45; USA, *Environmental Control*, 3-29.
[713] USA, *Environmental Control*, 3-1. The Freon/water heat exchanger was considered part of the active thermal control system; it is described in further detail beginning on page 180.

The cabin fan system was comprised of two cabin fans, each of which was powered by a three-phase 115-volt ac motor. Only one of the fans was used at a given time to circulate air throughout the crew cabin at a nominal flow rate of 1,400 pounds per hour. The fan drew air into the cabin ductwork where a 70-micron filter removed any particles suspended in the air. A check valve was located at the outlet of each fan to prevent the air from backflowing through the non-operating fan. The cabin air was then directed through two lithium hydroxide canisters, in a parallel arrangement, for carbon dioxide removal; activated charcoal within the canisters removed odors and trace contaminants.[714]

Downstream of the lithium hydroxide canisters was the cabin temperature control valve, a variable position valve that regulated the air temperature by proportioning the volume of air that bypassed the cabin heat exchanger. The valve was controlled manually or automatically by one of two cabin temperature controllers, which were motor-driven actuators that adjusted the cabin temperature control valve to achieve the selected temperature.[715] Depending upon the setting of the temperature control valve, part of the air volume was directed to the crew cabin heat exchanger, where heat was transferred to the air revitalization system's water coolant loop.[716] Humidity condensation that formed in the heat exchanger was pushed by the airflow to the two humidity separators, which separated the water from the air; the water was routed to the wastewater tank, while the air was returned to the cabin. A small portion of the revitalized and conditioned air from the heat exchanger was sent to the carbon monoxide removal unit, which converted the carbon monoxide into carbon dioxide.[717]

The portion of the air volume that was not routed through the heat exchanger was directed through a bypass duct. This duct carried the warm cabin air around and downstream of the heat exchanger, where the warm air was mixed with the revitalized and conditioned air, thereby bringing the air to the designated temperature. The air was then routed through the supply air duct and exhausted into the crew cabin through various station duct outlets.[718]

Each of the three avionics bays within the crew compartment had its own fan system, which functioned as an enclosed system although it was not airtight. Similar to the cabin fan system, each avionics bay circulation system contained two fans, only one of which was used at a given time. Each fan was powered by a three-phase 115-volt ac motor, and circulated air at a rate of

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[714] USA, *Crew Operations*, 2.9-12, 2.9-13; USA, *Environmental Control*, 3-2, 3-3. Both *Discovery* and *Atlantis* were configured for this lithium hydroxide system; *Endeavour* was upgraded to use a regenerable carbon dioxide removal system while on orbit. This system involved passing the cabin air through one of two identical solid amine resin beds, which consisted of a polyethylenimine sorbent coating on a porous polymeric substrate. This process was only available while on-orbit; the lithium hydroxide system was used for launch and landing. USA, *Crew Operations*, 2.9-13, 2.9-14.
[715] USA, *Crew Operations*, 2.9-17; USA, *Environmental Control*, 3-3.
[716] In support of ISS missions, the orbiters were modified to redirect the water from the humidity separator to a contingency water container while on orbit. This container allowed dumping to be minimized while the orbiter was docked to the ISS. USA, *Crew Operations*, 2.9-18; USA, *Environmental Control*, 3-8.
[717] USA, *Crew Operations*, 2.9-17.
[718] USA, *Crew Operations*, 2.9-17.

875 pounds per hour. The fan drew air through the bay and across the avionics equipment to pick up heat. The air was pulled through a 300-micron filter, and into the fan, which then directed the heated air to that avionics bay's heat exchanger, located beneath the middeck floor. Here, the heat was transferred to the air revitalization system's water coolant loop, and then the cooled air was returned to the avionics bay. A check valve was located in the outlet of each fan to prevent a reverse flow through the non-operating fan.[719]

The inertial measurement unit fan system contained three identical fans for a triple redundancy. Each fan was powered by a three-phase 115-volt ac motor that circulated air at a rate of 144 pounds per hour. Nominally, only one fan was used at a given time; it drew cabin air through a 300-micron filter and across the three units. The heated air was then directed into the inertial measurement unit heat exchanger, where the heat was transferred to the air revitalization system's water coolant loop. The cooled air was then returned to the cabin. Each fan was fitted with a check valve to prevent reverse airflow through the non-operating fans.[720]

The **water subsystem** contained two complete, independent water coolant loops, the primary loop and the secondary loop, that flowed side-by-side through the crew compartment to collect excess heat. The two loops could operate simultaneously, although only one was typically used at a given time. The only difference between the two water loops was that the primary loop had only one water pump, while the secondary loop contained two water pumps.[721]

The water pumps for both loops were each powered by a three-phase, 115-volt ac motor and were located in the equipment bay of the crew compartment. Downstream of each loop's water pump(s), the water flow was split into three parallel paths. One path went through the Avionics Bay No. 1 heat exchanger and cold plates.[722] The second travelled through the Avionics Bay No. 2 heat exchanger and cold plates, and also provided thermal conditioning of the crew cabin window seals. The third path was routed through the crew cabin MDM cold plates, the Avionics Bay No. 3A heat exchanger and cold plates, and the Avionics Bay No. 3B cold plates. In each avionics bay, the heat generated by the electronic equipment was transferred through its cold plate to the water coolant loop.[723]

After passing through their respective avionics bay, the three water loop paths rejoined upstream of the Freon/water heat interchanger. Just prior to entering the heat interchanger, the water line split into two paths. One path flowed through the Freon/water interchanger, where the water loop was cooled. The cooled water was then directed through the liquid-cooled garment heat exchanger, the potable water chiller, the cabin heat exchanger, and the inertial measurement unit heat exchanger. The second path bypassed the Freon/water interchanger and liquid-cooled

[719] USA, *Crew Operations*, 2.9-19; USA, *Environmental Control*, 3-9.
[720] USA, *Crew Operations*, 2.9-19; USA, *Environmental Control*, 3-10.
[721] USA, *Crew Operations*, 2.9-19, 2.9-20; USA, *Environmental Control*, 3-10.
[722] A cold plate was essentially a metal base, to which a piece of equipment was mounted. Water flowed through the plate, providing a means of cooling the equipment.
[723] USA, *Crew Operations*, 2.9-20, 2.9-21; USA, *Environmental Control*, 3-12.

garment heat exchanger. A bypass valve regulated the amount of water that went through the coolant loop and that bypassed the Freon/water interchanger and heat exchangers. Like the air subsystem, this division of the path provided temperature control of the water that exited the pump package.[724]

Active Thermal Control System

Functions and Operations

The active thermal control system had three basic functions. First, it transferred heat from the vehicle's various heat sources to a collection of heat sinks, through the Freon coolant loops. The system's second function was to cool or heat the orbiter's subsystems through cold plates and heat exchangers. Its third function was to provide heat rejection during all phases of a mission, following SRB separation.[725]

Prior to launch, the active thermal control system was connected to the T-0 umbilicals on the mobile launcher platforms through its ground support equipment system heat exchanger. Approximately 6 seconds before liftoff, the ground servicing coolant flow was terminated; all umbilicals were disconnected by T-0.[726] Following liftoff, the orbiter had no active means of cooling until after SRB separation, at which time the flash evaporator system was activated. This system served as the primary cooling system through ascent and into post-insertion of the vehicle in orbit. The radiator system was activated on orbit, just prior to the opening of the payload bay doors. Once the doors were opened, the radiator system became the primary means of cooling the orbiter; the flash evaporator system was used for supplemental cooling as required.[727]

During deorbit preparations, before the doors were closed, the Freon in the radiators was coldsoaked for use as a heat sink during the latter stages of entry. This entailed storing cooled Freon within the panels by activating the flash evaporator system to cool the Freon loops to a temperature of 39 degrees F. After the panels were coldsoaked for a little over an hour, the radiators were bypassed and the flash evaporator system became the primary cooling source. The flash evaporator system cooled the vehicle until it reached an altitude of approximately 175,000'; at this point the system was deactivated and the radiators were reactivated using the coldsoaked panels for cooling until after the orbiter came to a stop following landing, or until the radiator coldsoak was depleted. Once either of these events occurred, the ammonia boiler system became the primary cooling source until the vehicle was connected to ground support equipment at the runway.[728]

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[724] USA, *Crew Operations*, 2.9-20, 2.9-21; USA, *Environmental Control*, 3-12, 3-13.
[725] USA, *Crew Operations*, 2.9-23; USA, *Environmental Control*, 4-1.
[726] USA, *Environmental Control*, 4-6.
[727] USA, *Crew Operations*, 2.9-46; USA, *Environmental Control*, 4-27.
[728] USA, *Crew Operations*, 2.9-46; USA, *Environmental Control*, 4-27.

System Description

The active thermal control system (Figure No. B-121) consisted of two complete, identical Freon coolant loops, various cold plate networks for cooling avionics equipment, liquid/liquid heat exchangers, and three types of heat sinks: radiators, flash evaporators, and ammonia boilers. Each of the two Freon loops had a pump assembly, which was located in the midfuselage, below the payload bay liner. The assembly consisted of two pumps and an accumulator; one of the pumps was active at all times. The accumulator provided a positive pressure on the pumps and permitted thermal expansion in the loop. A check valve downstream of the pumps prevented a reverse flow through the non-operating pump.[729]

When a pump was operating, Freon was directed through two paths, one that went through the fuel cell heat exchanger and one that traveled through the midfuselage cold plate network;[730] the Freon absorbed the excess heat from the heat exchanger and the cold plates. The Freon then converged into one flow path before entering the hydraulic fluid heat exchanger, which absorbed some of the heat from the Freon to keep the vehicle's idle hydraulic systems warm.[731] From the hydraulic fluid heat exchanger, the Freon flowed to the radiator system, the ground support equipment heat exchanger system, the ammonia boiler system, and the flash evaporator system. Dependant upon the mission phase, one of these four systems further cooled the Freon.[732]

The **radiator system** consisted of eight radiator panels, with four panels mounted on the inside of each payload bay door; it was typically used while the vehicle was on orbit (Figure No. B-122). The radiator panels were made of an aluminum honeycomb face sheet that was 126" wide and 320" long. The two forward panels on each door were double-sided and had a core thickness of 0.9"; each panel contained sixty-eight, 0.131"-inside diameter, tubes spaced 1.9" apart. These panels were secured to the insides of the payload bay doors by six motor-operated latches, and were deployable when the doors were opened on orbit. The deployment of the radiator panels provided a greater surface area for heat rejection. The two aft radiator panels on each door were one-sided, with cores that measured 0.5" thick, and twenty-six, 0.18"-inside diameter, longitudinal tubes spaced 4.96" apart. The radiator panels on the aft payload bay doors were not deployable. They were attached to the payload bay doors by a ball joint arrangement at twelve locations, which compensated for any movement of the door and radiator panel caused by thermal expansion and contraction. A radiator flow control valve assembly was located in each Freon coolant loop; it controlled the temperature of the Freon by mixing the cold Freon coolant from the radiators with hot Freon that had bypassed the radiators. Freon radiator isolation valves were included in the system to isolate one of the radiators in the event that it was damaged by space debris.[733]

[729] USA, *Crew Operations*, 2.9-23; USA, *Environmental Control*, 4-3.
[730] The fuel cells were part of the electrical power system; see description beginning on page 170.
[731] USA, *Environmental Control*, 4-8.
[732] USA, *Crew Operations*, 2.9-46; USA, *Environmental Control*, 4-2.
[733] USA, *Crew Operations*, 2.9-26 through 2.9-29; USA, *Environmental Control*, 4-11, 4-12.

The **ground support equipment heat exchanger system** was only used prelaunch and postlanding. Prior to launch, the heat exchanger interfaced with the T-0 umbilical panels; it was connected to a portable cooling cart within 30 minutes of landing.[734]

The **ammonia boiler system** was used to cool the Freon coolant loops when the orbiter was below 400,000' during entry, if the radiators were not cold-soaked, or on the ground after landing before the vehicle was connected to the ground service equipment. The system consisted of one common boiler, which was fed by two complete, individual ammonia storage and control systems. Each storage and control system consisted of a storage tank, an isolation valve, an overboard relief valve, two control valves, a controller, three temperature sensors, a pressure sensor, and a feedline; all components were located within the aft fuselage. The ammonia boiler was a shell-and-tube system, divided into an ammonia side and a boiler side. The ammonia flowed into the boiler via tubes, where it was sprayed onto the Freon coolant loops; the ammonia immediately vaporized cooling the Freon. The steam carried the heat away from the loops, and all exhaust was vented overboard, next to the bottom right side of the orbiter's vertical stabilizer. Each of the two ammonia storage tanks contained a total of 49 pounds of ammonia, which provided approximately 30 minutes of cooling; the tanks were pressurized with gaseous helium. A relief valve was also included in each storage system to provide overpressurization protection for the storage tank.[735]

Between each tank and the boiler were three control valves: an isolation valve (typically closed), a primary control valve (normally open), and a secondary control valve (normally open). The controller energized the ammonia system isolation valve, which permitted the ammonia to flow to two motor-operated controller valves. The controller also commanded the primary control valve to regulate the flow to the ammonia boiler. Three temperature sensors were located on each Freon coolant loop, one was associated with the primary controller and its valve to regulate the ammonia system; the second was associated with the controller fault detection logic; and the third was associated with the secondary controller and secondary motor-operated valve.[736]

The **flash evaporator system** was used during the ascent phase of the mission, once the vehicle was above 140,000' and during deorbit and entry, until the orbiter reached an altitude of 100,000'; it could also be used on orbit to supplement the radiators. The system was situated in the aft fuselage of the orbiter, and contained two evaporators, one high-load evaporator and one topping evaporator; three logic controllers; two water feedlines; and two overboard steam ducts.[737] Each of the two evaporators were cylindrical shells with dual water spray nozzles at one end, and a steam exhaust duct at the other end; the shell was composed of two separate finned packages, one for each Freon loop. The difference between the two evaporators was that the

[734] USA, *Environmental Control*, 4-6.
[735] USA, *Crew Operations*, 2.9-33; USA, *Environmental Control*, 4-18.
[736] USA, *Crew Operations*, 2.9-33 through 2.9-35.
[737] USA, *Environmental Control*, 4-22. The high-load evaporator was used in conjunction with the topping evaporator during ascent and entry when higher Freon coolant loop temperatures imposed a greater heat load, which required a higher heat rejection.

high-load evaporator had larger spray nozzles, and thus a higher cooling capacity.[738] The heated Freon in the coolant loops flowed around its designated finned shell, on which water was sprayed by the nozzles from either evaporator; the water was supplied by the vehicle's potable water storage tanks. Upon contact with the fins, the water vaporized into steam, which was vented overboard, carrying the heat away from the Freon coolant loops. The flash evaporator system had two primary controllers and one secondary controller. Each of the primary controllers controlled water flow to the flash evaporator from one of the water feedlines. The secondary controller modulated the water spray from the evaporators. The steam generated in the evaporators was ejected through two overboard steam ducts on opposing sides of the orbiter's aft fuselage. Electrical heaters were employed on the topping and high-load flash evaporators' steam ducts to prevent freezing.[739]

After the Freon was cooled by one of these four systems, the coolant loop split into two parallel paths. One of the paths flowed in series through aft avionics bays 4, 5, and 6 to cool electronic avionics equipment and the four rate gyro assemblies. The second path flowed through the cargo heat exchanger (located on the port side of the midfuselage, roughly in the center), and continued through the ECLSS oxygen restrictor to warm the cryogenic oxygen to 40 degrees F. Afterwards, the flow split into parallel paths, one of which travelled through the payload heat exchanger and the other through the atmospheric revitalization system interchanger. The three loops were then reunited and returned in series to the Freon coolant pump within that coolant loop.[740]

Supply and Wastewater System

Functions

The supply water system provided water for crew consumption, hygiene, and flash evaporator system cooling; the wastewater system stored waste from the crew cabin humidity separator and from the flight crew.[741] The system was operational throughout the entire mission.

System Description

The supply water system stored water generated by the three EPS fuel cells in four water tanks, which were pressurized with nitrogen. Each tank had a usable capacity of 168 pounds, and had a length of 35.5" and a diameter of 15.5". There were redundant product water line paths from the fuel cells to two of the storage tanks, in the event that a blockage occurred in the primary water path. Temperature, pressure, and pH sensors were installed in each of the redundant paths. The water that exited the fuel cells was hydrogen-enriched, therefore it was directed through the single water relief panel through two hydrogen separators before reaching the storage tank. The

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[738] USA, *Environmental Control*, 4-23.
[739] USA, *Crew Operations*, 2.9-31, 2.9-32; USA, *Environmental Control*, 4-22, 4-24, 4-25.
[740] USA, *Crew Operations*, 2.9-24; USA, *Environmental Control*, 4-2.
[741] USA, *Crew Operations*, 2.9-35; USA, *Environmental Control*, 5-1.

separator removed roughly 85 percent of the excess hydrogen, which was then dumped overboard through a vacuum vent.[742] As the water entered "tank A," it passed through a microbial filter that added approximately one-half parts per million of iodine to the water to prevent microbial growth; this tank was typically used for flight crew consumption. The other three tanks, labeled B, C and D, were generally used to supply the flash evaporator system and were filled after tank A. The water from the tanks could be dumped overboard, if necessary. The supply water line and the supply water dump nozzle were fitted with heaters to prevent the water from freezing.[743]

A single wastewater tank collected wastewater from both the humidity separator and the waste management system. The tank was located beneath the crew compartment middeck floor, next to the potable water tanks. It was capable of holding 168 pounds, was 35.5" in length and 15.5" in diameter. A wastewater dump isolation valve and a wastewater dump valve allowed the wastewater to be dumped overboard, through the wastewater dump line. Like the potable water supply lines, the wastewater dump line, which was upstream of the waste dump nozzle, had electrical heaters to prevent the wastewater from freezing. The wastewater tank was typically dumped when it reached 80 percent full.[744]

Guidance, Navigation, and Control

The GNC system was a combination of sensor and manual inputs, vehicle control components, and data management. The orbiter's GNC software commanded the system to effect vehicle control, and to provide sensors and controllers with the data needed to compute these commands. The overall process included three steps. First, the navigation subsystem tracked and/or measured the current position and velocity of the spacecraft with respect to a reference frame. The guidance subsystem then used this information to compute the required orbiter location needed to satisfy mission requirements. Finally, the flight control subsystems transported the vehicle to the required locations.[745]

Functions and Operations

The principle function of *Discovery's* **navigation subsystem** was to maintain an accurate estimate of the vehicle's state vector, its inertial position and velocity, with respect to time. The system tracked the orbiter's position and velocity using six parameters: X, Y, Z, Vx, Vy, and Vz. The X, Y, and Z components specified the orbiter's position in the Mean of 1950 coordinate system.[746] The Vx, Vy, and Vz components measured the velocity in feet per second, using the Mean of 1950 for distance and Greenwich Mean Time for time. To predict the components of the

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[742] The redundant path did not pass through the hydrogen separator. USA, *Crew Operations,* 2.9-35.
[743] USA, *Crew Operations*, 2.9-35 through 2.9-42; USA, *Environmental Control,* 5-1 through 5-4.
[744] USA, *Crew Operations*, 2.9-42 through 2.9-44; USA, *Environmental Control*, 5-6.
[745] USA, *Crew Operations*, 2.13-5.
[746] The Mean of 1950 coordinate system measured the X, Y, and Z distances in feet from the center of the Earth.

state vector at each time value, the navigation system used the standard equations of motion, as well as information received from the inertial measurement units, the navigation sensors, and the software models of the forces acting on the orbiter. To reduce errors, Mission Control periodically uplinked new state vector data, based on ground radar tracking data. This was the typical method used to establish and maintain the inertial position and velocity of the orbiter during all flight phases.[747]

At certain times during a mission, for example when landing the orbiter, the Mean of 1950 coordinate system significantly complicated calculations. Thus, different coordinate systems were used to simplify the inputs, outputs, and computations required. All of the systems used were right-handed Cartesian systems, with three mutually perpendicular axes (x-axis, y-axis, and z-axis). The body axis coordinate system, which maintained its origin at the orbiter's center of mass, was used for pitch, roll, and yaw activities.[748] The local vertical/local horizontal system was also an orbiter-centered system, but the positive z-axis pointed toward the center of the Earth along the geocentric radial vector of the vehicle. This system was used to allow the crew to see the attitude of the orbiter in relation to the Earth's surface. The runway coordinate system was an Earth-fixed reference frame used during the ascent, entry, and landing phases of a flight. The origin of this system was at the runway center, at the approach threshold.[749]

The state vector data were used by the **guidance subsystem** to compute the actions necessary to move the orbiter from its navigation-determined position to the required position, per mission specifications. The guidance subsystem then commanded the **control subsystem** to perform the actions. These actions could be completed either through the digital autopilot, which was part of the PASS, or by the crewmembers.[750]

Beginning approximately 20 minutes before launch, the appropriate GNC software was loaded into the GPCs. Roughly 8 seconds before liftoff, the navigational software was initialized; first-stage guidance software was not activated until SRB ignition (liftoff). During launch and ascent, most of the GNC commands were directed to gimbal the SSMEs and SRBs to obtain proper attitudes and throttle the engines. The guidance subsystem also attempted to relieve the vehicle of aerodynamic loads based on system measurements of acceleration. Typically, all commands were issued by the programmed software, as opposed to the commander or pilot. Although the crew could select to perform the commands themselves, there were no planned crew actions during this first stage of flight unless a failure occurred.[751]

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[747] USA, *Crew Operations*, 2.13-1, 2.13-3.
[748] USA, *Crew Operations*, 2.13-3; USA, *Navigation Overview Workbook* (Houston: United Space Alliance, 2006), 1-2.
[749] USA, *Crew Operations*, 2.13-3, 2.13-4.
[750] USA, *Crew Operations*, 2-13.5. In control stick steering mode, the flight crew's commands were still passed through and issued by the GPCs.
[751] USA, *Crew Operations*, 2.13-56.

During the second-stage ascent, between SRB separation and main engine cutoff (MECO), *Discovery's* crew monitored the onboard systems to ensure that the major GNC events, such as throttling, MECO, and ET separation, occurred correctly. The guidance subsystem continued to issue throttling commands to the SSMEs. Once the ET was jettisoned, about 20 seconds after MECO, the digital autopilot commanded the RCS thrusters to move the orbiter in the –z direction. The next function of the GNC system was to accomplish orbit insertion of the vehicle. Although this was typically performed through the digital autopilot, the crew could issue commands through the translational hand controller or rotational hand controller.[752]

While *Discovery* was on orbit, the main function of the GNC system was to achieve the proper position, velocity, and attitude required to accomplish all mission objectives. Associated activities included maintaining an accurate state vector, maneuvering to specified attitudes and positions, and pointing a specific orbiter body vector at a selected target (rendezvous). As appropriate, the GNC software or the crew provided commands to the OMS engines or RCS thrusters to reposition the vehicle. During rendezvous activities, the system also maintained an estimate of the target's position and velocity, which the guidance subsystem used to compute the commands required to transfer the vehicle from one position and velocity to another.[753]

During the deorbit phase of the mission, the navigation subsystem used the vehicle's three inertial measurement units to calculate the orbiter's state vector. The guidance subsystem was used to calculate altitude, position, velocity, and flight path necessary to conduct the deorbit burn. Flight control at this time was typically performed by the digital autopilot.[754]

The entry phase of a shuttle mission was subdivided into three subphases because of the different guidance software requirements; also at this time, the crew took on an active role in the management of the vehicle's state vector. During the entry subphase, the guidance subsystem attempted to keep the vehicle on a trajectory that would limit temperature, dynamic pressure, and acceleration effects on the vehicle. The guidance software issued commands to the control subsystem detailing how to guide the vehicle during flight. The crew used data provided on the various MEDS displays to determine how to use the rotational hand controllers and speed brake thrust controllers to help maintain the vehicle's trajectory. The entry subphase continued until the orbiter reached an altitude of around 83,000', when the terminal area energy management subphase began. During this period, the guidance software computed the commands that would enable the vehicle to achieve proper approach and landing conditions. Again, the crew could use the various controls to maintain these conditions. When *Discovery* reached an altitude of around 10,000', the third subphase software, approach/landing, took control of the vehicle. At this time, the guidance software commanded the vehicle to track the runway centerline and remain on a steep glide slope until an altitude of 2,000', when the pre-flare maneuver was performed to place the orbiter on a shallow guide slope. The software commanded the final flare between a height of

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[752] USA, *Crew Operations*, 2.13-57, 2.13-58.
[753] USA, *Crew Operations*, 2.13-58.
[754] USA, *Crew Operations*, 2.13-60, 2.13-61.

30' and 80', during which the sink rate was reduced to 3 feet-per-second; it then directed the vehicle to the runway centerline. Throughout this phase of the mission, the navigation subsystem performed similar to the deorbit phase, except additional sensor data was incorporated to provide the accuracy needed to bring the orbiter to a pinpoint landing.[755]

System Description

Navigation Hardware: There was a variety of sensors on the orbiter that were used to gather physical data. These included the inertial measurement units, the star trackers, the crew optical alignment sight, the TACAN system, the air data system, the microwave landing system, the radar altimeters, and the GPS. Each individual element was hard-wired to one of eight flight-critical MDMs, which were connected to the GPCs. Many of the parameters could be monitored on the display system.[756]

There were three redundant inertial measurement units (Figure No. B-123) on the orbiter to provide inertial attitude and velocity data to calculate the state vector; only one was needed at a given time. The units were mounted within the crew compartment, forward of the flight deck control and display panels. The three inertial measurement units had skewed orientations to ensure that no more than one unit had an orientation problem and to allow resolution of a single-axis failure on one unit by multiple axes on another. Each unit contained three accelerometers, one each for the x-, y-, and z-axes. The accelerometers measured acceleration through two two-axis gyros. One gyro was aligned with the x- and y-axes to provide pitch and roll stabilization, and the other gyro was oriented between the z-axis and the x-y plane for yaw stabilization. Each inertial measurement unit also contained four resolvers that were used to measure the vehicle's attitude. Attitude information was used by the crew for turn coordination and steering command guidance. Each unit also contained temperature sensors and heaters to maintain thermal control in order to meet performance requirements.[757]

The two star trackers (Figure No. B-123, see Figure No. B-66 for location on vehicle) were located just forward, and to the left of, the commander's windows, within a well outside of the crew compartment. Each star tracker well had a door to protect the tracker during ascent and entry; the doors were opened once the vehicle was on orbit. The trackers consisted of a -y-axis tracker and a negative z-axis tracker. The -y tracker was oriented so that its optical axis pointed approximately along the negative y-axis of the orbiter, while the optical axis of the -z tracker pointed roughly along the negative z-axis of the orbiter. The star trackers were used to align the inertial measurement units onboard the orbiter, by searching for, acquiring, and tracking stars. They were also used to track targets and provide line-of-sight vectors for rendezvous

[755] USA, *Crew Operations*, 2.13-61, 2.13-62.
[756] USA, *Crew Operations*, 2.13-5, 2.13-6.
[757] USA, *Crew Operations*, 2.13-7, 2.13-8.

calculations. Their output consisted of the horizontal and vertical position within the field of view of the object being tracked, and its intensity.[758]

The crew optical alignment sight was an optical device that contained a reticle focused at infinity that was projected on a combining glass.[759] It was typically used if there was a significant error in the alignment of the inertial measurement units, which rendered the star trackers incapable of performing their job. The device could be mounted at either the commander's station to view along the positive x-axis, or next to the aft flight deck overhead starboard window to view along the negative z-axis.[760]

The GNC system's TACAN units were used to determine slant range and magnetic bearing of the orbiter in relation to a ground station (Figure No. B-125; see Figure Nos. B-65 through B-68 for antenna locations). There were three TACAN units on *Discovery*, each of which included a transmitter, a receiver, and a data processor; the latter decoded the selected channel and sent the frequency to the receiver.[761] The units were located within the middeck avionics bays, and were used to obtain orbiter position data from an external source and update the state vector position components during entry. Each TACAN unit had two antennas, one of which was on the bottom and the other on the top of the vehicle. Their maximum range was 400 nautical miles. Each of the ten TACAN ground stations used by the orbiter had an assigned frequency and a three-letter Morse code identification. Its omnidirectional ground beacon continuously transmitted pulse pairs on its assigned frequency, which the orbiter's receivers picked up and routed to the data processors to decode in order to compute bearing. The onboard units detected the phase angle between magnetic north and the position of the orbiter with respect to the ground station. Slant range was computed by measuring the elapsed time from when the onboard units emitted an interrogation pulse to a selected ground station and when the station responded with distance-measuring equipment pulses.[762]

The air data system provided information on the movement of the orbiter in the air mass, or flight environment. The orbiter was equipped with two air data probes, one on the left side and one on the right side of the vehicle (Figure No. B-126; see Figure Nos. B-65, B-66, B-67 for location on vehicle); both were within the lower forward fuselage. Each probe was fitted with four pressure-port sensors and two-temperature sensors. The pressure sensors sensed static

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[758] USA, *Crew Operations*, 2.13-11 through 2.13-13.
[759] A reticle was a grouping of fine lines or fibers within the eyepiece of a sighting device.
[760] USA, *Crew Operations*, 2.13-14.
[761] *Endeavour* was upgraded to a three-string global positioning system. USA, *Crew Operations*, 2.13-2. The system was a space-based radio positioning navigation system. It provided three-dimensional position, velocity and time information to equipment on or near the surface of the Earth. The orbiter was fitted with three receivers for redundancy; each had two antennas. The antennas received the signals, which were then amplified through a preamplifier, and then routed through a combiner that merged the signals from both antennas into one data stream. This stream was then transmitted to the associated receiver for processing. USA, *Crew Operations*, 2.13-19, 2.13-20.
[762] USA, *Crew Operations*, 2.13-16, 2.13-17.

pressure and angle-of-attack upper, center, and lower pressures. The probes were stowed inside the fuselage during ascent, on-orbit, deorbit, and for the initial entry phases; they were deployed upon reentry when the vehicle's speed reached Mach 5 (five times the speed of sound). The system sensed air pressures related to the spacecraft's movement through the atmosphere in order to update the state vector in altitude, provide guidance in calculating steering and speed brake commands, and to provide display data for the commander's and pilot's flight instruments.[763]

The microwave landing system consisted of three onboard units, which were airborne navigation and landing aids with decoding and computational capabilities (Figure No. B-127; see Figure Nos. B-65 through B-68 for antenna locations). The system was used to determine slant range, azimuth, and elevation during the approach and landing phases of flight through the two ground stations alongside the landing runway. The onboard units received elevation data from the glide slope ground station, and azimuth and slant range from the azimuth/distance-measuring equipment ground station. Each microwave landing system unit was comprised of a Ku-band receiver, transmitter, and decoder. The three Ku-band antennas were located on the orbiter's upper forward fuselage; the transmitters and decoders were situated within the avionics bays.

Discovery contained two radar altimeters, which measured absolute altitude from the orbiter to the nearest terrain within the beam width of the vehicle's antennas. The two altimeters could operate simultaneously without adversely affecting each other. Each altimeter consisted of a transmitter antenna, a receiver antenna, and a receiver/transmitter. The four antennas were located on the lower forward fuselage, while the two receiver/transmitters were situated within the forward avionics bays. The data from these components were processed by the GPCs for display on the commander's and pilot's altitude flight tape and head-up displays.[764]

Guidance Hardware: The guidance subsystem of the orbiter consisted of software modules, which transformed crew commands and/or computed vector changes into steering commands, which then operated the thrust vector control, OMS/RCS, or aerosurfaces, as appropriate.

Flight Control System Hardware: The flight control system ascent and entry hardware provided manual guidance commands to GNC software, and responded to commands from the GNC software to effect vehicle and trajectory control. The system included three types of hardware: sensors responsible for flight control data, hardware to provide manual guidance commands, and hardware that responded to software commands. Sensors included the accelerometer assemblies, the orbiter rate gyro assemblies, and the SRB rate gyro assemblies. Manual guidance hardware included the rotational hand controllers, the translational hand controllers, the rudder pedal transducer assemblies, and the speed brake/thrust controllers. The

[763] USA, *Crew Operations*, 2.13-22, 2.13-23.
[764] USA, *Crew Operations*, 2.13-27.

hardware that responded to software commands included the ascent thrust vector control units and the aerosurface servoamplifiers.[765]

The orbiter contained four accelerometer assemblies, each of which had two identical single-axis accelerometers. One sensed the vehicle's acceleration along the lateral y-axis and the other sensed the vehicle's acceleration along the vertical z-axis. The four accelerometers were located within the forward avionics bays on the middeck. They provided acceleration feedback to the flight control system, which was used to augment stability during first-stage ascent, aborts, and entry, to relieve vehicle load during first-stage ascent, and to compute steering errors for display on the commander's and pilot's attitude director indicators. The y-axis readings enabled the control system to null any side forces during ascent and entry, while the z-axis readings augmented pitch control and indicated the need to relieve normal loads.[766]

Discovery also contained four rate gyro assemblies, each of which was fitted with three identical single-degree-of-freedom rate gyros. One of the gyros sensed roll rate (x-axis), one gyro sensed pitch rate (y-axis), and one gyro sensed yaw rate (z-axis). These rates were the primary feedback to the flight control system during ascent, entry, insertion, and deorbit; good feedback was required to maintain control of the vehicle. All four of the rate gyro assemblies were located on the vehicle's aft bulkhead, below the floor of the payload bay.[767]

There were three rotational hand controllers on the orbiter's flight deck: one at the commander's station, one at the pilot's station, and one at the aft flight deck station. Each was capable of controlling vehicle rotation about the roll, pitch, and yaw axes. The controllers at the commander's and pilot's stations were used during ascent to gimbal the SSMEs and the SRBs. During insertion, orbit, and deorbit, these controllers were used to gimbal the OMS engines or command the RCS thrusters. During the early part of entry, they could command the RCS jets; during the latter portion of entry, they controlled the orbiter's aerosurfaces. The controller on the aft flight deck could only be used while the vehicle was on orbit; it could gimbal the OMS engines and command the RCS jets.[768]

The translational hand controllers were used to command the RCS jets while the vehicle was on orbit. There were two translational hand controllers, one at the commander's station and one at the aft flight deck station. The controller at the commander's station was active during orbit insertion, on orbit, and during deorbit; the one in the aft flight deck station was only active on orbit. Each controller was capable of manually commanding the vehicle to move in the plus and minus directions for each of the orbiter's three axes. The aft controller was typically only used when the crewmember was looking out of the rear or overhead windows.[769]

[765] USA, *Crew Operations*, 2.13-27.
[766] USA, *Crew Operations*, 2.13-28.
[767] USA, *Crew Operations*, 2.13-30.
[768] USA, *Crew Operations*, 2.13-31, 2.13-32.
[769] USA, *Crew Operations*, 2.13-34.

The orbiter was equipped with two pairs of rudder pedals, one pair in the commander's station and one pair in the pilot's station; the two were mechanically linked so that movement on one pair moved the other pair. These pedals moved a mechanical input arm inside the rudder pedal transducer assembly, which contained three tranducers that generated an electrical signal proportional to the rudder pedal deflection. The rudder pedals were capable of commanding orbiter acceleration within the yaw direction by positioning the vehicle's rudder during atmospheric flight; however, because the flight control software automatically performed turn coordination during banking maneuvers, they were typically not used until after touchdown when the crew used them for nose wheel steering.[770]

There were two speed brake/thrust controllers on the orbiter, one in the commander's station and one in the pilot's station. These served two different functions. During ascent, the pilot's controller could be used to throttle the SSMEs; during entry, either could be used to control aerodynamic drag by opening or closing the speed brake. Each was located within the left-hand side of the stations. Each contained three transducers that produced a voltage proportional to the deflection.[771]

The ascent thrust vector control portion of the flight control system controlled the attitude and trajectory of the orbiter by directing the thrust of the SSMEs and the SRBs during lift off and first-stage ascent, and of the SSMEs during second-stage ascent. Ascent thrust vector control was provided by four avionics hardware packages that supplied gimbal commands and fault detection for each of the vehicle's hydraulic gimbal actuators. All four hardware packages were located within the aft avionics bays, and were connected to one of the aft MDMs.[772]

Discovery contained seven aerosurfaces that were used to control the vehicle during atmospheric flight (Figure No. B-128). Each aerosurface was driven by a hydraulic actuator, which was controlled by redundant sets of electrically driven servovalves, four per aerosurface.[773] These servovalves were controlled by electronic devices known as aerosurface servoamplifiers. There were four of these servoamplifiers, all located within the aft avionics bays. Each commanded one of the servovalves for each aerosurface, with the exception of the body flap, which only used three servoamplifiers. They also received feedback from the actuators, which included position and pressure signals. These paths between the servoamplifiers and the servovalves were called flight control channels. Each of the aerosurface servoamplifiers was hardwired to one of the aft MDMs.[774]

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770 USA, *Crew Operations*, 2.13-37.
771 USA, *Crew Operations*, 2.13-38.
772 USA, *Crew Operations*, 2.13-45, 2.13-46.
773 The only exception to this was the body flap, which had three actuators that were hard-assigned to the three hydraulic systems. USA, *Crew Operations*, 2.13-42.
774 USA, *Crew Operations*, 2.13-42, 2.13-45.

Landing/Deceleration System

Functions and Operations

Discovery's landing and deceleration system provided the crew with the capability to safely land the orbiter, and perform braking and steering operations. The system contained three landing gear, four brake assemblies, a nose wheel steering system, and a drag chute. The three landing gear were arranged in a tricycle configuration. There was one nose landing gear, located within the lower forward fuselage (Figure Nos. B-129, B-130), and two main landing gear, one each within the lower left and right wings adjacent to the midfuselage (Figure Nos. B-131, B-132). All three landing gear retracted forward and upward into their respective wheel well; each was held in the retracted position by an uplock hook.[775]

Discovery's landing and deceleration system was essentially dormant throughout a mission. At approximately 12 minutes prior to landing, the orbiter's speedbrake was opened to 81 percent. Roughly 11 minutes prior to landing, *Discovery's* onboard software repositioned the SSMEs to 10 degrees below nominal position, for drag chute deployment.[776] At approximately 4 minutes prior to touchdown, the speedbrake position was verified, and at 3 minutes prior to landing, the pilot verified that the landing gear extend isolation valve was open; at an altitude of 2,000' (about 33 seconds before landing), the commander or pilot armed the landing gear. This was accomplished by depressing a button on control panel F6 (commander) or control panel F8 (pilot), which energized the latching relays, and armed the pyrotechnic initiator controllers.

At an altitude of 300' (roughly 20 seconds before landing), when the air speed of the vehicle was below 312 knots, the commander or pilot deployed the landing gear, through a second pushbutton on their respective control panels (F6 or F8). At this point, hydraulic actuators released the uplock hooks, and the landing gear fell backwards, with the assistance of the strut actuators and aerodynamic loads, to their extended position, where they were locked in place by spring-loaded downlock bungees. The landing gear doors, which were connected to the gear by mechanical linkages, automatically opened as the gears fell. A bungee assembly exerted an additional force on the inside of the door over the first 2" of travel. The pyrotechnic actuator on the nose landing gear fired approximately 2 seconds after the uplock hook was released to ensure the doors opened in the event of high aerodynamic loads and a high angle of attack.[777] Each gear also had redundantly activated pyrotechnic systems for deploy in the event the hydraulics failed.[778] The pyrotechnic actuator accomplished the same action as the hydraulics with regard to

[775] USA, *Mechanical Systems*, 6-1.
[776] USA, *Crew Operations*, 2.14-12. The general purpose computers would alert the crew if repositioning efforts failed. Failure to reposition the SSMEs did not preclude drag chute deployment, but there was a possibility of the chute risers contacting and damaging the center engine bell. Therefore, for a repositioning failure, the drag chute would only deploy in a contingency situation. USA, *Crew Operations*, 5.4-6.
[777] USA, *Mechanical Systems*, 6-1.
[778] If a gear indicated it was still in the retracted position one second after the command to deploy was received, the dual pyrotechnic initiators would fire.

opening the uplocks and allowing the gear to deploy. Gear deploy, from initiation to the gear reaching the down and locked position, required roughly 5-6 seconds.[779]

At touchdown, the main landing gear tires made contact with the runway. When weight was sensed on the main landing gear, the brake/skid control boxes were enabled and the brake isolation valves opened to enable the brakes to become operational; this occurred roughly 1.9 seconds after weight on the main gear was sensed. The drag chute was deployed roughly 1 second later, after the orbiter's speed was reduced to around 195 knots (Figure No. B-133).[780] Drag chute deploy was performed so that full inflation of the chute occurred just prior to nose gear touchdown. Upon simultaneous arm and fire commands from the commander or the pilot, the pilot chute was deployed first, which in turn, extracted the main chute within 1 second. At this time, the main chute deployed to its roughly 40 percent reefed diameter. After approximately 3.5 seconds, the reefing ribbon was severed and the main chute inflated to its full 40' diameter. The drag chute was then jettisoned after the orbiter's speed was reduced to 60 (+/- 20) knots ground speed to prevent damage to the SSMEs.[781]

Roughly 10 seconds after touchdown, the nose landing gear made contact with the runway. The commander or pilot applied the brakes when either the orbiter had decreased to a speed of 140 knots, or when only 5,000' of runway remained, whichever occurred first. At roughly 32 seconds after touchdown, the pilot jettisoned the drag chute at the commander's call. Beginning at approximately 36 seconds after touchdown, the commander reduced pressure on the brakes until wheelstop, at which point, the speed brake was closed. The vehicle's nose wheel steering system became operational after three preconditions were met: weight on the main wheels was sensed, the vehicle had a pitch angle of less than 0 degrees; and weight on the nose gear was sensed. The anti-skid function was disabled once the speed of the orbiter dropped below 10-15 knots to prevent a loss of braking for maneuvering and/or coming to a complete stop.[782]

System Description

Each landing gear included a shock strut and two wheel and tire assemblies. The shock strut was constructed of stress- and corrosion-resistant, high strength steel and aluminum alloys, stainless steel, and aluminum bronze; urethane paint and cadmium-titanium plating were applied to all exposed steel surfaces. In addition, all exposed aluminum surfaces were covered with conventional anodizing and urethane paint.[783] The shock strut served as the primary source of shock attenuation at landing impact, and was fitted with conventional pneumatic-hydraulic shock

[779] USA, *Crew Operations*, 2.14-1 through 2.14-4. The landing gear would not be retracted until the orbiter was within its designated Orbiter Processing Facility, if it landed at KSC, or when it was being suspended by the Mate-Demate Device for attachment to the SCA, if it landed at Edwards AFB.
[780] USA, *Crew Operations*, 2.14-14, 5.4-7.
[781] USA, *Crew Operations*, 2.14-13. If the speed of the orbiter fell below 40 knots, the chute was retained until the orbiter came to a complete stop to minimize damage to the SSME nozzles.
[782] USA, *Crew Operations*, 2.14-7, 2.14-9.
[783] USA, *Crew Operations*, 2.14-2, 2.14-3; Jenkins, *Space Shuttle*, 408.

absorbers containing gaseous nitrogen and hydraulic fluid. However, these shock absorbers were unique in that the gaseous nitrogen and hydraulic fluid were separated by a floating piston to maintain absorption integrity and to assure proper performance.[784] Each strut had a strut actuator, which assisted in the deployment of the landing gear through hydraulic pressure; the actuator also served to retract the landing gear. The actuators included an oil snubber to control the rate of gear extension and prevent damage to the gear.[785] The nose landing gear was also fitted with a pyrotechnic boost system to ensure deployment in the event of high aerodynamic forces on the doors.[786]

Each landing gear had two wheels, which were constructed of forged aluminum and divided into two halves. The nose gear wheels co-rotated through a common axle; the main gear wheels rotated independently. The two nose landing gear wheels were fitted with 32” x 8.8” tires that each had a maximum allowable load of 45,000 pounds. These tires were rated for a 217-knot maximum landing speed, and could be reused once.[787] Each main landing gear wheel, two per gear, was fitted with a 46.25” x 16.8” to 21” tire that was comprised of sixteen cord layers in a cross-ply design. These tires had a maximum allowable load of 171,000 pounds per tire, or 220,000 pounds per strut. These tires were rated at a 225-knot maximum landing speed and could be used only one time.[788]

Each of *Discovery’s* four main landing gear wheels was fitted with an electrohydraulic, carbon disc brake assembly, with an associated anti-skid system.[789] Included in each disc brake assembly were nine discs, five rotors, four stators, a backplate, a pressure plate, and eight hydraulic pistons. The carbon-lined rotors were splined to the inside of the wheel and rotated with the wheel; the carbon-lined stators were splined to the outside of the axle assembly and did not rotate with the wheel. The pistons were divided into two groups of four; each group received hydraulic pressure from a different hydraulic system. The brakes had a life-expectancy of twenty missions, assuming normal operating conditions.[790]

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[784] The shock absorbers controlled the rate of compression and extension, as well as load application rates and peak values, to prevent damage to the vehicle. USA, *Crew Operations*, 2.14-2; Jenkins, *Space Shuttle*, 408; NASA, *Space Shuttle News Reference* (Washington, DC: U.S. Printing Office, 1981), 3-24.
[785] USA, *Mechanical Systems*, 6-1.
[786] Jenkins, *Space Shuttle*, 409.
[787] USA, *Crew Operations*, 2.14-3, 2.14-17; Jenkins, *Space Shuttle*, 409. Initially, the nose landing gear tires were manufactured by B.F. Goodrich and had a maximum load of 22,300 pounds, which was based on early vehicle specifications. As more data were obtained during the early Space Shuttle missions, Michelin won a contract to develop new tires. Jenkins, *Space Shuttle*, 409.
[788] USA, *Crew Operations*, 2.14-3; Jenkins, *Space Shuttle*, 410.
[789] The original four operational orbiters were originally fitted with beryllium brakes, with four rotors and three stators, that were designed based on the original predicted weight of the orbiter; the “as-built” weight was greater. During missions STS-5, STS-23, and STS-32, *Columbia* (STS-5/STS-32) and *Discovery* (STS-23) suffered severe stator damage; all missions prior to the *Challenger* accident experienced some brake damage. This prompted a redesign of the brakes, which were first installed on *Discovery* and flown on STS-35 (April 1990). Jenkins, *Space Shuttle*, 410-411.
[790] Jenkins, *Space Shuttle*, 410; USA, *Mechanical Systems*, 6-5. The description of the hydraulics system begins on page 146.

Each brake assembly was fitted with an anti-skid system that monitored the wheel velocity and controlled the brake pressure to prevent wheel lock and tire skidding. Speed sensors, two per wheel, supplied wheel rotational velocity information to the skid control circuits in the brake/skid control boxes. Here, the velocity of each wheel was continuously compared to the average velocity of all four main wheels, and adjustments were made as appropriate.[791]

Discovery's nose landing gear was fitted with a nose wheel steering system, which provided the crew with vehicle steering capability following nose wheel touchdown to supplement the directional control provided by aerodynamic forces on the rudder or by differential braking.[792] The system consisted of a steering actuator that responded to electronic commands from either the commander's or the pilot's rudder pedals, and was powered by the vehicle's hydraulic system. The system provided positive lateral directional control of the orbiter during post-landing rollout, even in the presence of high crosswinds and blown tires. Steering operations were conducted by applying heel pressure to the rudder pedal assembly.[793]

Discovery was fitted with a drag chute to assist the deceleration system in safely stopping the vehicle on the runway at either end of mission or abort weights. Design requirements specified that the chute be able to stop a 248,000 pound orbiter within 8,000' in atmospheric conditions of up to 103 degrees F and a 10 knot tailwind.[794] The drag chute was housed at the base of the vertical stabilizer and consisted of two individual chutes. The first was a 9'-diameter pilot chute, and the second was a 40'-diameter, partially reefed, main chute. The main chute was connected to the vehicle by a 41'-6" riser, and trailed the vehicle by approximately 89'-6". The drag chute was typically used on both lake bed and concrete runways, except when crosswinds exceeded 15 knots or if there was a SSME repositioning problem.[795]

Mechanical Systems

Discovery's mechanical systems were considered those components that had to be deployed, stowed, opened, or closed.[796] There were two types of mechanical systems: electromechanical and electrohydraulic; the former were driven by electrical actuators, the latter by hydraulic

[791] USA, *Crew Operations*, 2.14-7.
[792] NASA, *Shuttle News Reference*, 3-24. Originally, *Columbia* and *Challenger* had a nose wheel steering system that was ineffective at controlling the orbiter during rapid maneuvers at high speeds. The system was subsequently deactivated in each of these orbiters, and only the "plumbing, wiring, and fittings" for a steering system were installed in *Discovery* and *Atlantis*, while NASA investigated a solution. An improved steering system was first installed on *Columbia* for flight STS-32; it was later installed in *Discovery* (OMM-1, 1992) and *Atlantis* (OMM-1, 1994). The improved system was installed in *Endeavour* during its original build (1987-1991); *Challenger* was lost before the system could be installed. Jenkins, *Space Shuttle*, 409-410; Boeing, *OV-103, Volume II*, 54-55.
[793] Jenkins, *Space Shuttle*, 408; USA, *Mechanical Systems*, 6-6.
[794] Jenkins, *Space Shuttle*, 411.
[795] The drag chute could still be employed without repositioning the SSMEs if there were landing/rollout control problems. USA, *Crew Operations*, 2.14-4.
[796] Not all systems that used mechanical actuators were considered mechanical systems, for example, the Ku-band antenna, the star tracker doors, and the air data probes. USA, *Crew Operations*, 2.17-1.

actuators.[797] Major electromechanical systems included the active vent system, the external tank umbilical doors, the payload bay doors, the deployable radiator system, and the landing and deceleration system.

The common element for each electromechanical system was the electromechanical actuator, also known as the power drive unit. The vehicle's motor control assemblies, considered part of the EPS, directed the power to the actuator motors. Though each power drive was unique to its application, they shared a number of common characteristics, including two three-phase ac motors, motor brakes, a differential assembly, one or two torque limiters, a gearbox, and in most cases, various microswitches. The power drive units differed in arrangement of these items; some had separate torque limiters for each motor (e.g., radiator latches), while others utilized a single torque limiter downstream of the differential (e.g., payload bay door latches). The ET door centerline latches did not include torque limiters at all.[798] The ac motors provided the rotational shaft power that drove a piece of equipment to a particular position; typically, both motors ran at the same time.[799] Each motor was reversible to allow the component to be driven in both directions, either opened or closed, deployed or stowed, or latched or released. The brake in each motor prevented the output shaft from turning when the motor was unpowered. When power was removed from a motor, the brake locked the motor output shaft in a fixed position; once power was applied, the brake disengaged to allow the shaft to rotate.[800]

The differential assembly combined the two ac motor shaft outputs into one shaft input to the gearbox, allowing the system to continue to operate if one of the motors failed, or if one of the power sources to the motors was lost.[801] The torque limiter(s) protected the motor(s) from mechanical or structural damage in the event that a mechanism jammed by not allowing torque to be transmitted to the mechanism if the torque limit was exceeded. The gearbox provided the link between the differential assembly and the mechanism that was being driven. It included a series of reduction gears that transferred the low torque and high-speed output produced by the motors to a high torque and low speed input to the mechanism. The microswitches, also referred to as limit switches, were used to indicate the state of a mechanism (open/closed, stowed/deployed, or latched/released) and to turn off the motors once the mechanism was in the

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[797] USA, *Mechanical Systems*, preface. With electromechanical systems, electrical energy was converted to mechanical energy through electrically powered motors. For the electrohydraulic systems, electrical signals commanded the hydraulic actuators; the APUs drove the hydraulic pumps by converting chemical energy to shaft power. The electrohydraulic systems are described within the APU/Hydraulics section of this report, beginning on page 146.

[798] USA, *Crew Operations*, 2.17-1; USA, *Mechanical Systems*, 1-1 through 1-3.

[799] If only one motor is operating, it is referred to as single motor drive. If both motors are operating, it is referred to as dual motor drive. The time required to drive equipment with a single motor is twice as long as with two motors. USA, *Crew Operations* 2.17-1; USA, *Mechanical Systems*, 1-3.

[800] USA, *Crew Operations*, 2.17-1; USA, *Mechanical Systems*, 1-2.

[801] USA, *Crew Operations*, 2.17-1; USA, *Mechanical Systems*, 1-2. The differentials were speed-summing (as opposed to torque-summing), so using a single motor took twice the amount of time to complete an operation, compared to the use of both motors.

desired position. Typically, there were two microswitches for each state, each associated with one of the two motors.[802]

Active Vent System

Discovery's active vent system equalized the orbiter's unpressurized compartments to the ambient environment during launch, ascent, orbit, entry, and landing. The system originally consisted of eighteen vents along the port and starboard sides of the orbiter, nine per side, each with a numeric designation from forward to aft (Figure No. B-134). Each vent was sized according to the volume to be vented; it took roughly five seconds for the vent doors to open or close (using both motors in a vent actuator).[803] Vents 1 and 2 were operated by the same power drive unit and vented the FRCS module and forward fuselage, respectively. Vents 3, 5, and 6 were used to vent the midfuselage and wings; each had their own power drive unit. Vents 8 and 9 were operated by the same power drive unit, and vented the OMS pods and aft fuselage, respectively.[804]

During prelaunch activities, Vents 1, 2, 8, and 9, and sometimes Vent 6 depending on payload requirements, were partially opened to allow purging of the associated compartments with dry air or nitrogen; all other vents were closed. The vents remained in this position until T-28 seconds, when the opening sequence began, and all of the doors were opened in a staggered sequence. All of the vents remained open while on-orbit until 20 minutes prior to "time of ignition" for the orbiter's deorbit burn, when all were closed. Immediately after closing, Vents 1, 2, 8, and 9 (on the port side only) reopened to vent hazardous gases in the event of a leak during the deorbit burn.[805] Approximately 5 minutes prior to entry interface (an altitude of roughly 400,000'), all of the vents were closed to protect the vehicle from ingesting hot plasmas during reentry. The vents were left closed until the vehicle reached a relative velocity of 2,400 feet per second (an altitude of about 80,000'), when all vents were opened. After the orbiter landed and came to a complete stop, the vents were reset to their prelaunch purge positions.[806]

External Tank Umbilical Doors

Discovery contained two external tank umbilical doors (Figure No. B-135), each of which sealed off one ET/orbiter umbilical cavity post-ET separation to prevent entry heating damage to the aft compartment. The doors were located on the underside of the orbiter at the forward end of the aft

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[802] USA, *Crew Operations*, 2.17-1; USA, *Mechanical Systems*, 1-3.
[803] USA, *Crew Operations*, 2.17-2; USA, *Mechanical Systems*, 2-3.
[804] In the 1980s, Doors 4 and 7 on each side of the midfuselage were permanently capped shut and their associated actuators and mechanical linkages were removed. It was discovered through an engineering analysis that six of the ten vents within the midfuselage provided sufficient venting for that portion of the orbiter. *Atlantis'* were also removed; *Endeavour* never had the equipment installed. USA, *Crew Operations*, 2.17-3; USA, *Mechanical Systems*, 2-3, 2-4, 2-5.
[805] USA, *Mechanical Systems*, 2-5, 2-6.
[806] USA, *Crew Operations*, 2.17-1; USA, *Mechanical Systems*, 1-3, 2-7.

fuselage. Each door measured approximately 50" x 50", and was covered with reusable TPS tiles and fitted with an aerothermal barrier. Each door contained a hinge assembly on its inboard side, and three uplock latch rollers near its outboard side. In addition, the outboard edge of each door contained two fittings, one for each of the two centerline latches.[807]

Prior to mating the ET to the orbiter in the VAB, the ET umbilical doors were opened and held in place with the two centerline latches. At approximately 8 minutes and 30 seconds after liftoff, MECO occurred and the ET was jettisoned from the orbiter. Once this was performed, the two centerline latches were stowed. This was completed by the pilot using controls located on panel R2 on the flight deck. The centerline latches rotated roughly 45 degrees to release the umbilical doors, and were then retracted into the underside of the orbiter. Then, a power drive unit in each door was activated to drive the doors closed, an operation that took roughly 24 seconds. Once the rollers were in range of the uplock latches, which were located within the umbilical cavity, they were captured by the latches to secure the doors after they were closed.[808]

Payload Bay Door System

The payload bay door system consisted of the two payload bay doors, twenty-six hinges (thirteen per door), sixteen centerline latches, sixteen bulkhead latches, and the payload bay door drive system. Payload bay door operations were controlled from switches on panel R13L in the aft flight deck in conjunction with the flight software.[809] Of the thirteen hinges that connected each payload bay door to the midfuselage, five were shear hinges and eight were floating hinges (Figure No. B-136).[810] Beneath the sill longeron of each payload bay door was a 55'-long torque shaft that was driven by a single power drive unit in order to open and close the door (Figure No. B-137). The torque shaft turned six rotary actuators, which transferred the motion via push rods and bellcranks that pushed the door open or pulled it closed; it took roughly 55 seconds to open or close each door. Each push rod extended from a rotary actuator through the sill longeron to its bellcrank, and was color-coded with silver and gold bands at intervals along its length that assisted the crew in determining how far the door was open. Each band represented approximately 17.5 degrees of rotation of the door about its hinges.[811] The door actuator is an exception in that it did not contain any limit microswitches. Instead, the limit switches for indicating that the door was closed were in four modules, two mounted on both the forward and

[807] The cavities contained the electrical and fuel umbilicals between the ET and the orbiter; the left contained those associated with the LH2, the right had those associated with the LO2. Each umbilical area contained a closeout curtain to prevent hazardous gases from entering the orbiter's aft fuselage. USA, *Crew Operations*, 2.17-5; USA, *Mechanical Systems*, 3-3, 3-5.
[808] USA, *Mechanical Systems*, 3-5 through 3-7.
[809] USA, *Mechanical Systems*, 4-2, 4-9.
[810] Fixed hinges held the attach point on the payload bay door to a constant location relative to the midfuselage and only allowed rotation about the axis of the hinge pin. Floating hinges allowed translation along and rotation about the axis of the hinge pin. Since these hinges allowed translational movement, orbiter shape changes due to thermal expansion and contraction did not apply loads to the doors. USA, *Mechanical Systems*, 4-2.
[811] USA, *Mechanical Systems*, 4-2, 4-6. This information could also be used to determine if the door was warped or jammed. USA, *Crew Operations*, 2.17-13.

aft bulkheads of the payload bay, each near a door hingeline. The open microswitches were contained within the forward- and aft-most rotary actuators. Locating the end-of-travel microswitches at the extreme ends of the door provided a better indication that the door was in the correct position (i.e., not warped).

The payload bay doors were held closed by thirty-two latches: sixteen centerline latches, eight forward bulkhead latches, and eight aft bulkhead latches (Figure No. B-138). The centerline latch actuators, and structural and seal overlap, were fitted on the starboard door, therefore it was always opened first and closed last. The centerline latches, numbered 1 through 16 from forward to aft, were grouped into four sets, or "gangs," of four latches, each group driven by its own common actuator. The starboard door contained the latch hooks, while the port door contained the latch rollers; the hooks were the active portion of the centerline latch system that rotated to grasp the latch rollers. Each gang was driven by a single power drive unit, and it required approximately 20 seconds to open or close a gang of latches.[812] Like the centerline latches, the bulkhead latches were also grouped into four gangs of four latches, two at the forward bulkhead and two at the aft bulkhead, one gang on the starboard door and one gang on the port door. The latches in each gang were numbered 1 through 4, starting with the latch closest to the hinge line. The latch hooks for each gang were on the forward and aft edges of the doors, while the latch rollers were situated on the forward and aft bulkheads. Each gang was driven by one power drive unit; the operation required roughly 25 seconds. The motion of the latches in each gang was in a slightly staggered sequence: they latched in ascending order and unlatched in descending order.[813]

The payload bay doors were opened once the vehicle was in orbit, approximately 1 hour and 25 minutes after liftoff. First, a check for any failures, in components such as OMS engines, communications, or the ECLSS that would require first day landing, was conducted. If there were no failures of this nature, the payload bay doors were unlatched and opened in a specific sequence to accommodate any thermal expansion/contraction, bending, or twisting of the doors. Nominally, all latches were opened two gangs at a time, beginning with centerline latches 5 to 8 and 9 to 12. Opening the middle sets of latches relieved any tension on the doors. Next, centerline latches 1 to 4 and 13 to 16 were opened to relieve any tension on the bulkhead latches. After the centerline latches were opened, the starboard forward and aft bulkhead latches were opened together, allowing the starboard door to be driven open. Following this operation, the port forward and aft bulkhead latches were opened. Finally, the port door was opened.[814]

The payload bay doors were closed approximately 2 hours and 40 minutes prior to the deorbit burn. The closing sequence was the reverse of the opening sequence. First, the port door was closed, followed by the port forward and aft bulkhead latches. Next, the starboard door was commanded closed. The door was stopped just before it reached the port door, which allowed the

[812] USA, *Mechanical Systems*, 4-4.
[813] USA, *Mechanical Systems*, 4-5.
[814] USA, *Mechanical Systems*, 4-12, 4-13.

crewmembers to check the centerline latch trajectory and verify that an overlap condition did not exist. Once cleared, the starboard door was driven closed, followed by the starboard forward and aft bulkhead latches. Then, the centerline latching sequence began with latches 1 to 4 and 13 to 16. In the event that the payload bay doors became slightly warped, these gangs were easier to latch than the middle gangs because the bulkhead latches had already been latched. Finally, latches 5 to 8 and 9 to 12 were closed.[815]

Orbital Maneuvering System

Function and Operations

Once *Discovery* reached orbit, the vehicle did not require any form of propulsion to keep it circling around the Earth. However, the main propulsion system was designed to cut off prior to the vehicle reaching its specified orbit.[816] Therefore, *Discovery* was fitted with an OMS, which provided the required thrust for the vehicle to achieve orbit (referred to as orbit insertion). In addition, the OMS provided the necessary propulsion for on-orbit operations, such as orbit circularization, orbit transfer, and rendezvous; and for the vehicle's deorbit burn.[817]

The OMS system was controlled either through the digital autopilot or by manual operation. Typically, the system was first activated roughly 35 minutes into the flight, when the commander or pilot loaded the targets for the OMS 2 burn into the software system.[818] Approximately 37 minutes after liftoff, both OMS engines were fired to insert the vehicle into the designated orbit. The burn duration varied greatly, but usually lasted about two minutes. Afterwards, the engines were shut down, the thrust control vector gimbals were checked, and the OMS valves were reconfigured for on-orbit operations.[819]

The OMS engines operated in the following manner. First, pressurized helium was directed through supply lines to the fuel and oxidizer storage tanks, which forced the propellants into their respective feed lines.[820] Just prior to reaching the engine, the propellants were directed into the bipropellant valve assembly; each fuel/oxidizer valve pair was mechanically linked to open and

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[815] USA, *Mechanical Systems*, 4-14.
[816] Baker, *Manual*, 124.
[817] USA, *Crew Operations*, 2.18-1. Orbit circularization was a maneuver to change the vehicle's orbit from an elliptical path to a circular path. A "burn" was essentially a firing of the engine.
[818] If a mission was deemed "performance-critical," an OMS assist burn was conducted during the nominal ascent. This burn lasted roughly 1 minute, 42 seconds and provided 250 additional pounds of thrust. USA, *Crew Operations*, 5.2-1, 5.2-2. A post-main engine cutoff OMS burn, referred to as OMS 1, could be conducted about 10 minutes, 30 seconds into the flight, if the proper altitude was not reached with the SSMEs. During many early missions, an OMS 1 burn was performed as part of nominal operations, but later missions phased out the use of this burn in favor of completing a "direct insertion," with the SSMEs powering the vehicle to a higher orbit. USA, *Crew Operations*, 5.2-3.
[819] USA, *Crew Operations*, 5.2-4, 5.2-5.
[820] The single helium tank in each OMS pod pressurized both the fuel and the oxidizer tanks, a design that helped ensure the tanks were at the same pressure, thus avoiding incorrect mixture ratios. USA, *Crew Operations*, 2.18-9.

close together through a control valve. These control valves were operated by pressurized nitrogen, fed from the tank near the engine's thrust chamber.[821]

After passing through the bipropellant valve assembly, the oxidizer was fed directly to the injection plate within the thrust chamber. The fuel, however, was first routed through cooling lines within the chamber wall to cool the engine. Once the propellants exited their respective feed lines onto the thrust chamber injection plate, they atomized and ignited on contact. This reaction created a hot gas that exited the thrust chamber and expanded through the engine's nozzle, creating roughly 6,087 pounds of thrust.[822]

Following an OMS burn, the nitrogen system was used to purge the engine's fuel lines. This operation, which lasted about two seconds, cleared the lines of any residual fuel by forcing it through the inlet lines, cooling lines, and out through the engine. This prevented the propellants from freezing in lines in the event that an immediate restart of the engines was required.[823]

While the vehicle was on orbit, the OMS was used to modify the orbit for rendezvous, payload deployment, or transfer to another orbit; these burns could use either both or only one engine. Typically, critical maneuvers, or maneuvers that required large velocity changes, were conducted using both engines. In such an instance, the thrust vector of both engines was directed parallel to the orbiter's x-axis. However, burns that required a velocity of just over 6 feet per second could be accomplished with a single engine; its thrust vector was directed through the vehicle's center of gravity. The use of a single OMS engine required the use of the RCS system to control roll movement.[824]

The OMS engines were both used for the final time to perform the vehicle's deorbit burn. About 40 minutes prior to the burn, the OMS thrust vector control gimbals were checked and the OMS valve switches were placed in the pre-burn configuration. Roughly 2 minutes before the burn, the OMS engine switches on the control panels were set to their "armed position;" ignition was triggered approximately 15 second before the burn. The deorbit burn lasted two to three minutes, dependent mostly on the vehicle's orbital altitude. Afterwards, the OMS valves were closed and the engine gimbals were powered down.[825]

System Description

The OMS was comprised of two engines, two N_2O_4 (oxidizer) tanks, two MMH (fuel) tanks, a propellant pressurization subsystem, a pressurized nitrogen valve subsystem, associated plumbing and control components, and a thrust vector control system (Figure No. B-139). The

[821] USA, *Crew Operations*, 2.18-3, 2.18-7.
[822] USA, *Crew Operations*, 2.18-4, 2.18-5.
[823] USA, *Crew Operations*, 2.18-9.
[824] USA, *Crew Operations*, 2.18-7, 2.18-9. For velocity changes less than 6 feet per second, the RCS system was used. This system is described in further detail beginning on page 205.
[825] USA, *Crew Operations*, 5.4-3, 5.4-4.

OMS was housed within two independent pods on each side of the orbiter's aft fuselage, which also held the aft RCS. The pods were designed to be reused for up to 100 missions, with only minor repair, refurbishment, and maintenance; they were removable to facilitate orbiter turnaround.[826]

Each OMS pod contained one engine and all of the hardware needed to pressurize, store, and distribute the propellants to operate that engine. The engine was installed in the aft end of the pod, had a size of 77" x 46", and was capable of producing roughly 6,087 pounds of thrust. The engine was fitted in a gimbal mount, which allowed it to pivot left and right (yaw), and up and down (pitch). The main components of the engine were the bipropellant valve assembly, the injector plate, the thrust chamber, and the nozzle.[827]

The bipropellant valve assembly regulated the flow of the propellants to the engine. It consisted of two fuel valves in series and two oxidizer valves in series; each fuel valve was mechanically linked to an oxidizer valve so that they opened and closed at the same time. The dual valves provided redundant protection against leakage, and also required that both valves be open for the propellant to reach the engine. The fuel and oxidizer were mixed at the injector plate; which was located within the engine's thrust chamber. The chamber walls contained 120 cooling channels through which the fuel was routed to cool the engine prior to reaching the injector plate; the oxidizer line went directly to the plate. The nozzle was bolted to the aft flange of the thrust chamber, and served as an expansion area for the hot gas produced by the reaction between the fuel and oxidizer.[828]

The movement of the engine was controlled either from the digital autopilot or from the manual controls through the thrust vector control system, which consisted of a gimbal ring assembly, two gimbal actuator assemblies, and two gimbal actuator controllers. The gimbal ring assembly contained two mounting pads to attach the engine to the gimbal ring, and two pads to attach the gimbal ring to the orbiter. There was one gimbal actuator assembly for pitch and one for yaw control. Each actuator contained a primary and secondary motor and drive gears. The primary and secondary drive systems were isolated and never operated concurrently. The gimbal assembly provided control angles of +/- 6 degrees for pitch and +/-7 degree for yaw.[829]

Adjacent to the thrust chamber in the engine was a spherical gaseous nitrogen storage tank. Gaseous nitrogen was used to operate the engine control valves and to purge the fuel lines at the end of each burn. Aside from the tank, the engine's nitrogen system contained an engine pressure isolation valve, a regulator, a relief valve, a check valve, an accumulator, engine purge valves, bipropellant solenoid control valves, and actuators to control the bipropellant ball valves. The dual-coil, solenoid-operated engine pressure isolation valve permitted the flow of nitrogen from

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[826] USA, *Crew Operations*, 2.18-1.
[827] USA, *Crew Operations*, 2.18-1, 2.18-3.
[828] USA, *Crew Operations*, 2.18-3 through 2.18-6.
[829] USA, *Crew Operations*, 2.18-20, 2.18-21.

the tank into a regulator. The regulator, located between the engine pressure isolation valve and the bipropellant control valves, reduced the nitrogen pressure from its tank pressure (as high as 3,000 psig) to the desired working pressure (315-360 psig). A pressure relief valve was located downstream of the regulator to limit the pressure to the engine bipropellant control valves and the actuators in the case of a regulator malfunction. The check valve was also located downstream of the regulator; it was closed in the event that gaseous nitrogen pressure was lost on the upstream side of the check valve. The accumulator, which had a volume of roughly 19 cubic inches, provided pressure to operate the engine bipropellant control valves at least one time with the engine pressure isolation valve closed. The solenoid-operated control valves allowed the nitrogen to control the bipropellant control valve actuators and bipropellant ball valves. The actuator contained a rack-and-pinion gear that converted the linear motion of its connecting arm into rotary motion, which drove the bipropellant ball valves, allowing the propellants to enter the thrust chamber.[830]

Each OMS pod had a helium pressurization system that consisted of one high-pressure gaseous helium storage tank, two helium pressure isolation valves, two pressure regulator assemblies, parallel vapor isolation valves on the regulated helium pressure lines to the oxidizer tank only, dual series-parallel check valve assemblies, and pressure relief valves. The helium tank pressurized both the fuel and oxidizer tanks. An advantage to this was that it helped ensure each propellant tank remained at the same pressure, thus avoiding incorrect mixture ratios. The two helium pressure valves, arranged in parallel, isolated the helium tank from the propellant tanks and provided redundant paths to the tanks. Below each pressure valve was a pressure regulator to reduce the helium source pressure (often as high as 4,800 psia) to a working pressure of roughly 250 psig. The vapor isolation valves were located in the helium line to the oxidizer tank to prevent oxidizer vapor from migrating into the fuel system and causing a premature hypergolic reaction. The check valve assembly contained four independent check valves comprised of two series of two valves in a parallel configuration. The parallel path permitted path redundancy, while the series arrangement provided redundant backflow protection. The pressure relief valves were located downstream of the check valves; they protected the propellant tanks from overpressurization.[831]

Each engine had its own MMH and N_2O_4 tank, which stored the propellants in liquid form. The tanks were components of the overall OMS propellant storage and distribution system, which also contained the required propellant feed lines to each engine, as well as the crossfeed lines, isolation valves, and crossfeed valves between the two OMS pods. The fuel and oxidizer were each stored in a domed cylindrical titanium tank. The tanks, which were pressurized by the helium system, were divided into forward and aft compartments. In the aft compartment was the propellant acquisition and retention assembly. This consisted of a mesh screen that divided the two compartments, and an acquisition system. Pumps were not used to feed the propellants to the engines. Instead, the propellant tanks were pressurized with helium to maintain the flow.

[830] USA, *Crew Operations*, 2.18-6 through 2.18-9.
[831] USA, *Crew Operations*, 2.18-9 through 2.18-11.

Propellants from one pod could be passed to the other through crossfeed lines; the propellants could also be shared with the aft RCS engines by completing what was referred to as an "interconnect."[832]

The OMS propellant storage and distribution system contained tank isolation valves that were arranged in parallel, and were located in each pod between the propellant tanks and the engine and the crossfeed valves; they permitted propellant to be isolated from the rest of the downstream systems. The valves were driven open and closed by ac motors. The crossfeed lines were used to send propellant from one pod to the other to either balance the propellant weight in each pod or in the event of an engine failure.[833] The crossfeed lines connected the left and right propellant lines at a point between the tank isolation valves and the bipropellant valves. Each crossfeed line had two crossfeed valves, arranged in parallel to provide redundant paths for propellant flow.[834]

Although the propellants remained in liquid form within the temperatures normally experienced during a mission, heaters were provided to prevent freezing during long periods in orbit when the system was not in use. This system consisted of strip heaters and insulation on the interior surface of the pod, and wraparound heaters and insulation on the crossfeed lines. The OMS heaters were divided into three segments: left pod, right pod, and crossfeed lines. Each pod was divided into eight heater areas; the crossfeed lines were divided into eleven heater areas.[835]

<u>Reaction Control System</u>

Functions and Operations

While the OMS was used for major velocity changes, the RCS thrusters were generally used for small (less than 6 feet per second) velocity changes.[836] In addition, the RCS provided thrust for attitude control and rotational maneuvers. Each jet was permanently fixed to fire in a specific direction: up, down, left, right, forward, or aft. The selective firing of individual thrusters or specific combinations provided thrust for attitude control, rotational maneuvers along all three axes (roll, pitch, and yaw), and small velocity changes along the orbiter's axes. The thrusters were used to correct OMS burns, augment aerodynamic flight during reentry, conduct small rotational and translational maneuvers for rendezvous and docking, provide changes to orbital parameters, and trim reentry burn.[837]

The RCS thrusters were first used to maintain attitude hold between MECO and ET separation. Once the ET was released, the thrusters provided a translation maneuver in the negative z

[832] USA, *Crew Operations*, 2.18-12.
[833] They could also be used to feed the RCS, but through different valves. USA, *Crew Operations*, 2.18-16.
[834] USA, *Crew Operations*, 2.18-15, 2.18-16.
[835] USA, *Crew Operations*, 2.18-19, 2.18-20.
[836] Baker, *Manual*, 126.
[837] USA, *Crew Operations*, 2.22-1.

direction to move the orbiter away from the tank. The RCS then continued to hold the vehicle's attitude until the time of the OMS 2 burn.[838] While the vehicle was on orbit, either the RCS primary or vernier thrusters could be used for attitude control or hold, as required.[839]

Prior to the deorbit burn, *Discovery's* crew used the RCS thrusters to maneuver the vehicle to the desired attitude. Following the burn, the thrusters were used to null any residual velocities, as necessary. The RCS was also then used to orient the orbiter to the proper entry interface attitude. Once the vehicle reached an altitude of 400,000', only the aft RCS thrusters were used to control its roll, pitch, and yaw (the forward RCS thrusters were automatically deactivated); the aft thrusters were deactivated when the orbiter reached an altitude of roughly 45,000'.[840]

System Description

The RCS was distributed among three components of the orbiter: the FRCS module, which was located in the nose area of the orbiter, and the left and right OMS pods, mounted to the vehicle's aft fuselage.[841] The system, as a whole, contained forty-four RCS thrusters, thirty-eight of which were considered primary thrusters and six of which were considered vernier thrusters (Figure No. B-140). There were sixteen thrusters (fourteen primary and two vernier) in the forward module, and twenty-eight between the two rear modules (twelve primary and two vernier in each pod). All thrusters used MMH and N_2O_4 as their fuel and oxidizer, respectively.[842] Each module also contained its own propellant storage tanks, and propellant distribution network.

The primary thrusters each had a thrust of 870 pounds and a chamber pressure of 152 psia. A primary thruster had a nominal lifetime of 100 missions, with 20,000 starts and 12,800 seconds of accumulated time. It could operate for 150 continuous seconds, or a minimum pulse burn of 0.08 seconds, and had a maximum single-mission contingency of 300 seconds (forward thrusters) and 800 seconds (aft thrusters). The multiple primary thrusters provided redundancy to the system. Each vernier thruster had a thrust of 24 pounds and a chamber pressure of 110 psia, with a nominal lifetime of 330,000 starts and 125,000 seconds of accumulated time. Each thruster could run for up to 275 seconds of continuous operation in any two-hour period, or a minimum pulse burn of 0.08 seconds. The vernier thrusters were not redundant.[843]

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[838] The system could also be used to complete the "OMS 2" burn if one of the OMS engines failed. USA, *Crew Operations*, 5.2-4. During an OMS burn, the RCS was typically inactive, unless they OMS gimbal rates or limits were exceeded, requiring RCS roll control, or if only one OMS engine was being used. USA, *Crew Operations*, 2.22-17.
[839] USA, *Crew Operations*, 2.22-17, 5.3-4.
[840] USA, *Crew Operations*, 2.22-17. The system could also be used to complete the deorbit burn if one of the OMS engines failed.
[841] See the description of the FRCS module beginning on page 129, and the description of the OMS pods beginning on page 137.
[842] USA, *Crew Operations*, 2.22-2.
[843] USA, *Crew Operations*, 2.22-3; Jenkins, *Space Shuttle*, 391.

The major components of each RCS thruster were the reaction jet driver, the fuel and oxidizer valves, the injector head assembly, the combustion chamber, the nozzle, and the electrical junction box. The reaction jet driver converted commands from the GPCs into the required voltage for opening the bipropellant valves. This allowed the fuel and oxidizer to flow into the injector head assembly, which directed the propellants into the combustion chamber. The injector head assembly for each primary thruster had eighty-four injector hole pairs; each pair contained one hole for the fuel and one hole for the oxidizer. Additional fuel holes were provided near the outer edge of the injector for cooling the combustion chamber walls. The injector head assembly for each vernier thruster had only a single pair of injector holes.[844]

The combustion chamber of each RCS thruster was constructed of columbium, and had a columbium disilicide coating to prevent oxidation. At the combustion chamber, the fuel and oxidizer were combined to produce hypergolic combustion, or hot gas thrust; the hot gas expanded through the nozzle. The nozzle of each thruster was tailored to match the external contour of the FRCS module, or the left and right aft RCS pods; therefore, the thrusters were generally not interchangeable. Each thruster nozzle was radiation-cooled; insulation was provided around the combustion chamber and nozzle to prevent excessive heat from reaching the orbiter's structure. The electrical junction box in each thruster contained electrical connections for a heater, a chamber pressure transducer, oxidizer and fuel injector temperature transducers, and the propellant valves.[845]

Each group of RCS thrusters, one forward and two aft, had its own propellant system that distributed the fuel and oxidizer to the various thrusters. Each system consisted of a fuel and oxidizer tank, tank isolation valves, manifold isolation valves, crossfeed valves, distribution lines, and filling and draining service connections.[846] Each propellant tank was spherical in shape; the fuel tank held roughly 923 pounds of MMH, and the oxidizer tank held about 1,464 pounds of N_2O_4. The tanks were pressurized with gaseous helium, which expelled the propellant from an internally mounted, propellant acquisition device.[847] This device, necessitated by the various orientations of the orbiter throughout a mission, acquired and delivered the propellant to the RCS thrusters. The acquisition devices in the FRCS propellant tanks were designed to operate primarily in low-gravity environments, while those in the aft propellant tanks could operate in both high- and low-gravity environments.[848] The tank isolation valves isolated the propellant tanks from the remainder of the distribution system. They were located between the tanks and the manifold isolation valves, and consisted of a ball flow control device and an actuator assembly. The manifold isolation valves for each manifold of thrusters were positioned

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[844] USA, *Crew Operations*, 2.22-3.
[845] USA, *Crew Operations*, 2.22-3.
[846] The tanks for the forward structures were mounted directly within the FRCS module; the tanks for each set of aft thrusters were situated within the main section of the OMS pod, instead of the RCS housing.
[847] Each RCS module had two gaseous helium tanks, one to pressurize the fuel tank and the other to pressurize the oxidizer tank. USA, *Crew Operations*, 2.22-9.
[848] USA, *Crew Operations*, 2.22-4. The propellant tanks in the aft pods also incorporated an entry collector, sumps, and gas traps to ensure proper operation during abort and entry mission phases.

between the tank isolation valves and the thruster. The two aft RCS modules were also connected by crossfeed lines, which allowed the transfer of propellant between the modules.[849]

Electrical heaters were provided in the FRCS and the OMS/RCS pods to maintain the propellants at safe operating temperatures, and to maintain safe operating temperatures for the injector of each primary and vernier RCS jet. The FRCS contained six heaters mounted on radiation panels in six locations; each OMS/RCS pod was divided into nine heater zones, each of which was controlled by redundant heater systems.[850]

Additional Systems

Discovery also contained a variety of systems that helped ensure the safety of the crew, and maintained the living and working environment of the vehicle while on orbit. Such systems included the closed circuit television system, various crew systems, the lighting system, the payload deployment and retrieval system, the payload and general support computer, the waste management system, and the extravehicular activities systems.

Escape Systems

Escape systems, in general, referred to equipment and systems that were intended to facilitate emergency and contingency egress of the flight crew from the vehicle. The systems included equipment worn by the crewmembers, hardware built into the orbiter, and external systems located on the launch pad. The types of escape or emergency egress from the orbiter depended upon the phase of the mission: prelaunch, in-flight, or post-landing. Prelaunch emergency egress occurred while the orbiter was still positioned on the launch pad. For prelaunch emergency egress, the crew opened the side hatch and exited the vehicle into the white room on the launch pad.[851] In-flight emergency egress required the vehicle to be in a controlled glide, at an altitude of 30,000’ or below; post-landing emergency egress followed an emergency landing or a landing at a contingency location. There were three methods of escape from the orbiter, one of which was for in-flight escape and the other two were typically for stationary escapes.

The in-flight bailout procedure was usable when the orbiter was in a controlled, gliding descent. This procedure could be used during the ascent or entry phase of flight, if the orbiter was unable to reach a suitable landing site. In such an event, cabin depressurization was begun at an altitude of roughly 40,000’; then at approximately 30,000’, the side hatch was jettisoned with pyrotechnic charges. An extendable crew escape pole, mounted within the middeck, was used to

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[849] USA, *Crew Operations*, 2.22-6, 2.22-7. The aft RCS thrusters could also be fed from the OMS engine fuel and oxidizer tanks.
[850] USA, *Crew Operations*, 2.22-11.
[851] USA, *Crew Operations*, 2.10-1. For a description of the launch pad egress systems, see Patricia Slovinac. “Cape Canaveral Air Force Station, Launch Complex 39, Pad A (John F. Kennedy Space Center,” HAER No. FL-8-11-F, Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, August 2010.

guide the crewmembers through the hatch, and down a trajectory that cleared the vehicle's left wing, beneath and away from the vehicle. The pole consisted primarily of a curved, spring-loaded, telescoping steel and aluminum cylinder with an aluminum housing. It was fitted with a magazine near the port end of the pole that held eight lanyards, which guided crewmembers down the pole (Figure B-141).[852]

Post-landing, there were two exit options. The first was to open the side hatch and release an emergency egress slide, which provided a means of descent for the crew (Figure B-142). This equipment consisted of an inflatable slide, a pressurized Argon bottle, an aspirator, a girt bracket, and a slide cover, all of which were attached as an assembly below the side hatch. The slide could be deployed by attaching it to the hatch (if still in place) or by rotating it into the hatch opening (if the hatch had been jettisoned). The slide was inflated by pulling a lanyard that activated the pressurized Argon bottle.[853]

The secondary option was through the port side overhead window on the flight deck, which was jettisoned with pyrotechnic charges; it was used in the event that egress through the side hatch was not possible. The jettison system consisted primarily of expanding tube assemblies, mild detonating fuses, frangible bolts, and associated initiators. A ring handle on the center console activated the system; the system could also be activated by ground rescue personnel via a T-handle on the starboard side of the vehicle. The outer window pane (there were three total) was jettisoned first; the inner window frame (containing two pressure panes) was released 0.3 seconds later and rotated into the crew compartment, via hinges. Seat No. 4, one of the mission specialist seats on the flight deck, was used by the crewmembers to climb through the window. As each crewmember exited the vehicle, he or she connected themselves to the descent device, essentially a controlled tether called a "Sky Genie," which enabled him or her to reach the ground over the starboard side of the orbiter (Figure B-143).[854]

During launch and landing, each crewmember wore an advanced crew escape suit, which was designed to protect the crewmember in the event of a loss of cabin pressure, extreme environmental conditions, and a contaminated atmosphere (Figure B-144). The suit consisted of numerous components, each with a specific function. There was an inner pressure bladder, fabricated of Gore-Tex, that was capable of wicking moisture and vapor away from the body when unpressurized. An outer covering, made of an orange Nomex material, protected the crewmember from flames, and provided a highly visible target if search and rescue operations were necessary. On the upper right leg of the suit was a bioinstrumentation pass-thru, which provided an opening for medical lines and water cooling lines; the water was cooled in an individual cooling unit mounted to the crewmember's seat. The suit included detachable gloves,

[852] USA, *Crew Operations*, 2.10-1, 2.10-13; USA, *Crew Escape Systems* (Houston: United Space Alliance, 2005), 3-30 through 3-33.
[853] USA, *Crew Operations*, 2.10-1, 2.10-13; USA. *Crew Escape*, 3-33 through 3-41.
[854] USA, *Crew Operations*, 2.10-1, 2.10-18; USA. *Crew Escape*, 3-18 through 3-30. The Sky Genie could also be used by crewmembers exiting through the side hatch, in the event of an egress slide failure.

which mated to the sleeves via metal-mating rings that provided an air-tight seal and allowed the gloves to swivel for improved mobility; a similar ring was used for the helmet attachment. The helmet provided a pressurized breathing volume for the crewmember. It was fitted with a clear, rotating pressure visor that sealed the helmet cavity. At the lower right rear of the helmet was an antisuffocation valve, which opened if the oxygen supply to the suit was lost. The helmet also provided an interface for communications.[855]

Each crewmember was issued a parachute harness and parachute for emergency egress. The parachute harness contained a system of interwoven nylon straps worn by the crewmember during launch and entry. It also held an emergency oxygen system, a locking carabiner, a life preserver unit, and emergency drinking water. The parachute assembly was installed into the orbiter as a seat back cushion, and was attached to the harness during crewmember strap-in. The personal parachute assembly contained parachutes (18”-diameter pilot chute, 4.5’-diameter drogue chute, 26’-diameter main canopy), risers, and actuation devices for both automatic and manual deployment of the parachutes. It also contained a personal life raft compartment with a life raft and a personal locator beacon. In the event of an inflight bailout, the crewmember exited their seat with the parachute assembly; if the bailout led to a water landing, the risers were automatically released from the harness once the crewmember was immersed in the water. During a ground egress, the crewmember manually released the four attach points, leaving the parachute assembly in their seat.[856]

Closed Circuit Television System

Discovery's closed circuit television (CCTV) system was used while the vehicle was in orbit to provide support to both orbiter and payload activities. Such activities included transmitting real-time and recorded video from the orbiter to Mission Control through the S-band FM, S-band PM, or Ku-band (analog or digital) communications systems. The crew had the capability to control nearly all of the CCTV system's operations. Mission Control could execute most configuration commands, with the primary exceptions being those for loose CCTV equipment, such as camcorders, video tape recorders, and wireless video system components.[857] The CCTV system consisted of video processing equipment, TV cameras, pan/tilt units, camcorders and video tape recorders, color television monitors, and all of the cabling and accessories required by the components to work together.[858]

The key piece of video processing equipment was the video control unit, which served as the central processor/controller for the CCTV system. The video control unit consisted of the remote control unit and the video switching unit, both of which were located behind the R17 and R18

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[855] USA, *Crew Operations*, 2.10-4 through 2.10-6; USA. *Crew Escape*, 2-2 through 2-21.
[856] USA, *Crew Operations*, 2.10-6 through 2.10-10; USA. *Crew Escape*, 2-22 through 2-31.
[857] The requirements for the CCTV and camera configurations are specified in the Flight Requirements Document created for each shuttle flight. USA, *Crew Operations*, 2.3-1.
[858] The camcorders and video tape recorders were hand-held, commercial off-the-shelf devices, used to record activities within the crew compartment. USA, *Crew Operations*, 2.3-11 through 2.3-14.

panels in the aft flight deck. The remote control unit received all CCTV commands from both the crew and Mission Control. The video switching unit was used to route a video from its source to its destination; it could accommodate up to fourteen video inputs and seven video outputs.[859] Other pieces of video processing equipment included the video processing unit, the digital television system, and the sequential still video system. The video processing unit provided two video signals from the orbiter's CCTV system to the ISS and one video signal from the ISS to the orbiter. It also included the wireless video system interface box, which provided the connection between the wireless extravehicular activity helmet camera system and its associated crew cabin laptop.[860] The digital television system allowed the crew to downlink a video signal in a digital format via the Ku-band system. Its hardware was comprised of a vertical interval processor, a Sony video tape recorder, and a multiplexer. The sequential still video system was used by the orbiter to send sequential snapshots of a video signal to Mission Control through the S-band PM system during Ku-band loss of signal periods.[861]

There were three different types of stationary cameras that were considered part of the CCTV system; all were mounted within the payload bay. The three types were the color television camera, the intensified television camera, and the Videospection camera. The color television camera measured 16"-long x 5.88"-wide x 5.94"-high; the lens was encased within the housing. It had a minimum horizontal field-of-view of 9 degrees, and a maximum of 77 degrees. Images taken by these cameras did not require additional processing at Mission Control prior to distribution to the media. The intensified television camera was essentially a black and white version of the color television camera, except that it was optimized for a low-light environment. The Videospection camera was also a black and white camera, and was only used on a flight-specific basis. It was a fixed focus, fixed field-of-view camera, with no controls to adjust the video it produced.[862] The OBSS was integrated into the television system beginning with STS-144. The OBSS consisted of Sensor Package 1, which contained an intensified television camera and the laser dynamic range imager, and Sensor Pack 2, which included a laser camera system and the ISIS digital camera. Sensor Package 1 was integrated into the CCTV system; Sensor Package 2 was connected to a different part of the vehicle, and controlled by an onboard laptop.

Crew Systems

Crew systems referred to pieces of equipment, provisions, or other systems that focused specifically on crew efficiency and comfort, and were not considered part of another orbiter

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[859] USA, *Crew Operations*, 2.3-6. It should be noted that the controls for the video switching unit on panel A7U allowed for only ten inputs and four outputs.
[860] USA, *Crew Operations*, 2.3-9. The video processing unit first flew on STS-92 (*Discovery*) in October 2000.
[861] USA, *Crew Operations,* 2.3-9, 2.3-10. Sequential still video was occasionally used as a way to send a second video image to Mission Control while a video signal (either live or playback) was downloaded via the Ku-band system. This operation was commonly performed during the OBSS inspection of the RCC panels on the wings and nose cap for ground technicians to compare to photographs taken of these areas prior to vehicle stacking, in an effort to locate any damage that occurred during launch and ascent.
[862] USA, *Crew Operations*, 2.3-2, 2.3-3, 2.3-4.

system.[863] Crew systems included clothing and other worn equipment, sleeping provisions, exercise equipment, housekeeping equipment, restraints and mobility aids, stowage provisions, reaching aids, photography equipment, sighting aids, and the Shuttle Orbiter Medical System.

Prior to the mission, each crewmember selected clothing and other equipment, such as pencils, scissors, and calculators, from a list of required and optional flight equipment. Each crewmember was also provided with standard personal hygiene and grooming items. For each mission, the crew was provided with a piece of exercise equipment, which helped to prevent cardiovascular deconditioning and minimized bone and/or muscle loss. Historically, the piece of equipment was either a treadmill, a rowing machine, or a cycle ergometer; by 2004, the cycle ergometer became the primary option. The cycle attached to the middeck floor studs during launch and reentry, and then reconfigured to attach to the standard seat floor studs while on orbit.[864]

Sleeping provisions were provided for each crewmember, based upon the planned operations for a mission (see Figure Nos. B-82, B-86). If all crewmembers were scheduled to sleep simultaneously, sleeping bags and liners, or rigid sleep stations, were provided. The sleeping bags were typically installed on the starboard middeck wall during launch and landing; they could be relocated throughout the crew compartment based on the crew's preference. If the crew was scheduled to sleep in shifts, the four-tier rigid sleep station was typically installed on the starboard middeck wall for the duration of the flight. All sleeping provisions were fitted with adjustable straps to restrain the crewmember's upper and lower body while sleeping.[865]

Housekeeping equipment, which included materials and equipment for cleaning operations, was considered another crew system. Equipment provided for these tasks included biocidal cleanser, disposable gloves, general-purpose wipes, and a vacuum cleaner. The vacuum was typically stored in a middeck locker or the middeck accommodations rack; the remaining items were typically stored in the waste management compartment.[866] Flexible containers were also provided, and included stowage bags, seat containers, trash containers, and retention nets. This type of stowage was available throughout the crew compartment.[867]

To assist the crew in the zero-gravity environment of space, various restraints and mobility aids were provided throughout the orbiter. Such aids consisted of foot loop restraints, seat restraints, retention nets, Velcro, tape, snaps, cable restraints, clips, bungees, and tethers. Foot loop and seat restraints, and retention nets were typically installed by ground technicians prior to the flight; the remaining aids were stowed in lockers for as needed access during a mission. Reaching and visibility aids were also available to assist the crew in monitoring and manipulating displays and controls over the different phases of flight. Such items consisted of the adjustable mirrors in the

[863] USA, *Crew Operations*, 2.5-1.
[864] USA, *Crew Operations*, 2.5-1, 2.5-4.
[865] USA, *Crew Operations*, 2.5-1, 2.5-2.
[866] USA, *Crew Operations*, 2.5-4, 2.5-5.
[867] USA, *Crew Operations*, 2.24-4 through 2.24-6.

commander and pilot stations, the commander/pilot seat adjustments, and an auxiliary reach mechanism fitted with an end effector that could be used to operate different controls.[868]

Photography equipment was also considered a crew system. Typically, two still cameras were provided for a mission, with additional cameras flown when necessary. These could be digital single lens reflex cameras, an aerial photography camera, a Hasselblad 70mm camera system, or in some cases, a 70mm motion picture camera. Sighting aids, such as binoculars, adjustable mirrors, and spotlights, were provided to help the crew see within and outside the crew compartment. Window shades were also provided for every orbiter window to minimize sun glare in the crew cabin (e.g., during crew sleep periods); they were stowed until required. Interdeck light shades to minimized light transfer between the flight deck and middeck during in-cabin photography.[869]

The Shuttle Orbiter Medical System, which consisted of a medication and bandage kit, an emergency medical kit, and an instrument pack, with items such as a respirator, and intravenous fluid system, and electrocardiograph machine, and a defibrillator, was provided for each flight. This equipment was typically stowed in a middeck modular locker. Along with this health equipment was the Operational Bioinstrumentation System, which was used to provide an amplified electrocardiograph analog signal from any crewmember to the ground. It was typically only used during an EVA or in the event of an emergency situation, at the request of the flight surgeon.[870]

Lighting System

Discovery's lighting system provided both interior and exterior lighting for the vehicle. Interior lighting consisted of floodlights, panel lights, instrument lights, numeric lights, and annunciator lights.[871] The floodlights provided general illumination throughout the crew compartment, allowing the crew to function within the flight deck, the middeck, the airlock, and the tunnel adapter. On the flight deck, dual fluorescent light fixtures were installed below the glareshield, above the mission station, and above the payload station. Single fluorescent light fixtures were located above the commander's and pilot's side consoles, as well as in the ceiling above the aft flight deck. There were two seat/center console floodlights, one for the commander and one for the pilot; each was situated in the ceiling above one of the stations and fitted with two incandescent bulbs. The ceiling of the middeck contained eight floodlights, each of which was fitted with a fluorescent lamp behind a translucent polycarbonate material. A single lamp fluorescent fixture also illuminated the waste management compartment and the middeck sleep

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[868] USA, *Crew Operations*, 2.5-5, 2.5-6.
[869] USA, *Crew Operations*, 2.5-8 through 2.5-10.
[870] USA, *Crew Operations*, 2.5-10 through 2.5-13.
[871] Panel lights, instrument lights, numeric lights, and annunciator lights are discussed in the physical description, and caution and warning system discussions, as appropriate.

station bunks. Fluorescent floodlights were located in the airlock and the tunnel adapter, as required.[872]

Exterior lighting provided illumination for payload bay door operations, EVAs, remote manipulator system operations, stationkeeping, and docking. Floodlights fitted with metal halide lamps were used to light the payload bay. The power supplies for these fixtures were mounted to electronics assemblies that were cooled by the vehicle's Freon loops. The orbiter's docking lights contained incandescent lamps; they were mounted to cold plates cooled by the water loops.[873]

Payload Deployment and Retrieval System

The payload deployment and retrieval system provided the crew with the means to remotely hold and control the movements of a specified object, typically a payload, and to remotely observe or monitor objects or activities. The operation of the remote manipulator system required two crewmembers, one of whom was stationed at the port side of the aft flight deck. This crewmember used a translational hand controller and a rotational hand controller to operate the arm. The translational controller provided commands to move the arm along the x-, y-, or z-axis, while the rotational controller provided pitch, yaw, and roll control of the arm. The second crewmember was stationed at the starboard side of the aft flight deck to control data processing system inputs, the payload retention latch assemblies, and the system's cameras.[874]

The remote manipulator system was capable of performing a wide range of operations while the vehicle was on orbit.[875] Such tasks included maneuvering a payload within the payload bay, releasing a payload, capturing a free-flying payload, installing an ISS element, and serving as a platform for an EVA. To perform any operations, a standard sequence of tasks was required. First, the shoulder brace was released and the manipulator positioning mechanism was deployed. Afterwards, the manipulator retention latches were released and the Canadarm was lifted out of its cradle position. These activities were performed in reverse following the use of the system.[876]

The payload deployment and retrieval system included the remote manipulator system, the manipulator positioning mechanisms, the manipulator retention latches, the manipulator controller interface unit, and dedicated displays and controls.[877] The remote manipulator system, or Canadarm-1, was the mechanical arm portion of the payload deployment and retrieval system (Figure Nos. B-145, B-146). It was mounted to the port side longeron of the payload bay, if required for the mission.[878] The arm had a total length of 50'-3", and a diameter of 15", and

[872] USA, *Crew Operations*, 2.15-1 through 2.15-6.
[873] USA, *Crew Operations*, 2.15-14.
[874] USA, *Crew Operations*, 2.21-2, 2.21-3.
[875] The system was incapable of operating outside of a zero-gravity environment because the arm was too heavy for the motors to move under the influence of gravity. USA, *Crew Operations*, 2.21-2.
[876] USA, *Crew Operations*, 2.21-18 through 2.21-20.
[877] USA, *Crew Operations*, 2.21-1.
[878] Fittings were provided on the starboard side longeron for a second remote manipulator system, but it was never

could handle up to 586,000 pounds. It was fitted with six joints, which were connected via structural members, or “booms,” and a payload capture/release device, or end effector. These joints gave the arm an extensive range of motion, allowing it to reach across the payload bay, over the crew compartment, or to areas underneath the orbiter. The arm could only be deployed when the payload bay doors were open, could only operate in zero gravity, and could be jettisoned through pyrotechnic charges, in the case of a major malfunction. It could perform several tasks, including deploying and retrieving a payload, providing a stable platform for EVA crewmember foot restraints or workstations, mating space station components, and taking payload bay surveys; the controls for the arm were located on the aft flight deck.[879]

The payload deployment and retrieval system contained four manipulator positioning mechanisms. One mechanism was at the shoulder of the arm (X_o = 679.5) and served to attach the arm to the orbiter; it contained one of the four pyrotechnic separation charges for the jettison system. The other three mechanisms were located at X_o = 911.05, 1189, and 1256.5, and served as cradling units for the arm. Each contained a manipulator retention latch to secure the arm during launch, entry, and periods of inactivity, as well as a pyrotechnic separation charge. All four mechanisms were mounted to a torque tube, which drove the rotary actuators that moved the arm between its stowage and operational positions. The jettison system was provided in the event that the arm could not be recradled and restowed; each of the four separation points was individually actuated.[880]

The manipulator controller interface unit handled and evaluated the exchange of information between itself and the systems management general purpose computer, the displays and controls, and the remote manipulator system. It served to manipulate data, analyze and respond to failure conditions, and control the end effector auto capture/release and rigidization/derigidization sequence logic. A spare interface unit was typically flown on a mission in case the installed unit failed.[881]

Additional features of the payload deployment and retrieval system included an active thermal control system, a passive thermal control system, and a closed circuit television system. The active thermal system consisted of redundant heater systems, each of which was comprised of twenty-six heaters, concentrated at the arm’s joint and end effector. The passive system consisted of multilayer insulation blankets and thermal coatings that reflected solar energy away from the arm. The blankets were attached to the arm, and each other, with Velcro. Exposed areas around the moving parts were painted with a special white paint that provided the same service.[882] The closed circuit television system aided the crew in monitoring payload deployment and retrieval

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installed. Instead, the infrastructure was used for the orbiter boom sensor system, which was installed to photograph the thermal protection system on the orbiter’s underside in response to the *Columbia* accident. USA, *Crew Operations*, 2.10-1, 2.21-1.

[879] USA, *Crew Operations*, 2.21-1, 2.21-2.

[880] USA, *Crew Operations*, 2.21-11, 2.21-12.

[881] USA, *Crew Operations*, 2.21-3.

[882] USA, *Crew Operations*, 2.21-8.

system operations. The system consisted of a zoomable, fixed camera and a spotlight mounted to the arm's end effector, and a pan and tilt camera that sat just below the elbow joint. There were also four cameras within the payload bay that could be panned, tilted, and zoomed as required. Keel cameras were sometimes mounted to the bottom of the payload bay depending on the mission.[883]

Payload and General Support Computer

Typically, each Space Shuttle mission flew with one or more payload and general support computers. These computers were off-the-shelf laptop computers that were used either as a standalone computer or as a terminal device for communicating with other electronic systems. Crewmembers on the middeck or flight deck used the laptops to interface with flight-specific experiments that were situated within the crew cabin or the payload bay. In addition, the computers were used to monitor experiment data, and/or issue commands to payloads or experiments within the payload bay. Each computer was provided with standard support equipment, including interface cables, data cables, an expansion tray to provide additional cable ports, an orbiter communications adapter card to interface with the orbiter's communications systems, and a television tuner to interface the computer to the orbiter's CCTV signals.[884]

Waste Management System

The waste management system was an integrated, multifunctional system that was used primarily to collect crew biological wastes in a zero gravity environment. The system collected, dried, and stored fecal waste. In addition, it collected urine and condensate from the crew cabin and EMU, and transferred both to the wastewater tank. The system also provided an interface for venting trash container gases overboard, and dumping atmospheric revitalization wastewater in a contingency situation.[885]

The waste management system (Figure B-147) was situated on the middeck level of the crew cabin, immediately aft of the crew hatch. It contained a commode, a urinal, fan separators, an odor/bacteria filter, a vacuum vent disconnect, and controls. The commode measured 27" x 27" x 29", and was used like a standard toilet. It contained a multilayer hydrophobic porous bag liner for collecting and storing solid waste. The urinal consisted of a flexible hose with attachable funnels to accommodate both men and women. Fan separators were used to separate the waste liquid from the airflow; the liquid waste was transported to the wastewater tank, while the air was returned to the cabin after passing through the odor/bacteria filter. The vacuum vent quick disconnect was used to vent gases directly overboard.[886]

[883] USA, *Crew Operations*, 2.21-9.
[884] USA, *Crew Operations*, 2.20-1, 2.20-2.
[885] USA, *Crew Operations*, 2.25-1.
[886] USA, *Crew Operations*, 2.25-1, 2.25-2.

The waste management system was fitted with a compartment door and two privacy curtains. One of the curtains was attached to the top of the compartment door, and was used to cover the interdeck access opening; the other curtain was connected to the outer edge of the door and interfaced with the middeck accommodations rack, if installed. In addition, various restraints and adjustment mechanisms were provided to aid the crew in achieving the proper body positioning. These included a toe bar, a footrest, body restraints, and handholds. Rubber grommets were provided in the compartment to allow crewmembers to restrain their towels and washcloths.[887]

Extravehicular Activity Systems

An EVA, also commonly referred to as a spacewalk, occurred when a crewmember left the protective environment of the orbiter's pressurized cabin and ventured out into the vacuum of space wearing a space suit. EVAs were used for satellite repair and retrieval, as well as for the assembly of the ISS. All EVAs required the use of a self-contained pressurized space suit, known as the EMU, which provided life support functions for the crewmember. The unit was also supplied with a rechargeable battery, duplex UHF communications, biological and instrument telemetry, and caution/warning electronics. It was designed for a total maximum duration of seven hours, which consisted of fifteen minutes for egress, six hours for EVA tasks, fifteen minutes for ingress, and a thirty-minute reserve. Two EMUs were provided for each baseline mission.[888]

The EMU (Figure B-148) was the anthropomorphic pressure vessel that enclosed the crewmember's torso, limbs, and head; it was primarily composed of the space suit assembly, a life support system, and numerous associated support and ancillary equipment. The space suit consisted of the hard upper torso, with soft material arms, the lower torso assembly, extravehicular gloves, a helmet/extravehicular visor assembly, a liquid cooling and ventilation garment, an operational bioinstrumentation system, a communications carrier assembly, a disposable in-suit drink bag, and a maximum absorption garment (similar to a diaper).[889]

The hard upper torso provided pressure containment for the upper body, except the head, and served as the central component from which the mechanical, electrical, and fluid interfaces of the EMU extended. It was available in four sizes to accommodate different-sized crewmembers, and included a fiberglass shell, assorted mounting brackets, a waterline and vent tube assembly, an electrical harness, shoulder bearing assemblies, and a waist disconnect ring. Attached to the shoulder bearing assemblies were the right and left arm assemblies. Each of the assemblies had an upper arm assembly, a rotating bearing at the armhole, a lower arm assembly, a rotating arm bearing, and a wrist disconnect ring. The sizing of the arm could be changed on the ground or on-orbit, with the use of different segments and sizing rings. The lower torso assembly encompassed the waist, the lower torso, the legs, and the feet. It included a waist assembly with a

[887] USA, *Crew Operations*, 2.25-2, 2.25-3.
[888] USA, *Crew Operations*, 2.11-1.
[889] USA, *Crew Operations*, 2.11-3.

rotating waist bearing, a waist disconnect ring, a trouser assembly, and boot assemblies. As with the arm assemblies, the sizing of the leg assemblies could be changed on ground or on-orbit through the use of different leg segments and sizing rings.[890]

The extravehicular gloves were detachable and were customized to fit the individual crewmembers. Each glove included a wrist disconnect ring with a rotating wrist bearing, two wrist gimbal rings, an adjustable palm restraint bar/strap, a wrist tether strap, and fingertip heaters. The helmet was a "one-size-fits-all" component that consisted of a detachable, transparent, hard pressure vessel encompassing the head. It included a helmet disconnect ring, a helmet purge valve, and a vent pad. It could also be fitted with a Fresnel lens, for improved visibility, or a valsalva device, for clearing ears during pressure changes. The extravehicular visor assembly attached to the helmet and provided the crewmember with visual, thermal, impact, and micrometeoroid protection. The visor assembly included a clear protective visor, a sun visor, center and side eyeshades, and a fiberglass shell.[891]

The liquid cooling and ventilation garment was a form-fitting, elastic garment worn against the body. It included outer restraint fabric, an inner liner assembly, crew optional comfort pads, a biomed pocket, a water tubing network, a ventilation ducting network, a multiple water connector, and a full torso zipper. The water tubing network circulated water over the crewmember's body to provide cooling. The ventilation ducting network drew gas from the suit's extremities and routed it back to the primary life support system. Connections to the hard upper torso were provided through the multiple water connector.[892]

The communications carrier assembly was a cloth, aviator-type cap that positioned and supported the electronics for interfacing with the EMU radio. It contained the microphones and earphones required for the crewmembers performing the EVA to communicate with each other, as well as the orbiter. It also allowed the crewmembers to communicate with Mission Control through the orbiter's communications system. The disposable in-suit drink bag was a single use, heat sealed, flexible bladder assembly that held thirty-two ounces of water. It was mounted to the front interior of the hard upper torso and had a drinking tube that extended to the neck area. The maximum absorption garment was comprised of multiple layers of material, designed to rapidly absorb and store urine. It was disposable after use and had the capacity to hold thirty-two ounces of liquid.[893]

Another EVA system was the life support system, which provided a safe living environment for the crewmember while inside the EMU. It included provisions for breathing oxygen, suit pressurization, crewmember cooling, crewmember communications, displays and controls for EMU operation, and monitors for the EMU consumables and operational integrity. The life

[890] USA, *Crew Operations*, 2.11-3.
[891] USA, *Crew Operations*, 2.11-4.
[892] USA, *Crew Operations*, 2.11-4.
[893] USA, *Crew Operations*, 2.11-5.

support system consisted of a primary oxygen system, a secondary oxygen pack, an oxygen ventilation circuit, a liquid transfer cooling system, a feedwater circuit, electrical interfaces, an extravehicular communicator, a display and control module, and a caution and warning system.[894]

The primary life support subsystem consisted of the primary oxygen system, the oxygen ventilation circuit, the liquid transfer cooling system, the feedwater circuit, electrical interfaces, the extravehicular communicator, and the caution and warning system. The secondary oxygen pack was a separate unit that was attached to the bottom of the primary life support subsystem; together, these two components made up the backpack portion of the EMU. The purpose of the primary oxygen system was to provide the crewmember with breathing oxygen and satisfy pressure requirements for the EVA. The system was charged through a servicing and cooling umbilical to the orbiter's ECLSS. Its functions included suit pressurization, provision of breathing oxygen, and water pressurization. The secondary oxygen system served as the backup to the primary oxygen system. It provided a minimum of thirty minutes of emergency oxygen.[895]

The oxygen ventilation circuit formed a closed loop with the EMU, providing oxygen for breathing, suit pressurization for intravehicular activity and EVA operations, and ventilation for cooling and elimination of exhaled gases. Similar to the orbiter's crew compartment, a lithium hydroxide cartridge, installed within the primary life support subsystem, absorbed carbon dioxide. The liquid transport cooling system used a centrifugal pump to circulate water through the liquid cooling and ventilation garment to cool the crewmember. Its components consisted of the pump, a temperature control valve, a pump check valve, a temperature sensor, and a service and cooling umbilical bypass valve.[896] The feedwater circuit dissipated heat loads by removing moisture from the ventilation circuit and gas from the transport circuit. It consisted of two primary tanks and one reserve feedwater tank, and various pressure sensors, valves, and regulators. The tanks were filled or recharged through the potable water tanks from the orbiter's ECLSS. The EMU's electrical system was composed of a battery, a feedwater shutoff valve, a coolant isolation valve, a motor, instrumentation, an extravehicular communicator, a display and control module, and a caution and warning system. The battery provided the power for the entire system, and consisted of eleven sealed, silver-zinc, high current density cells connected in series.[897]

The extravehicular communicator was comprised of both orbiter-based and EMU-based equipment, including EVA/air traffic control transceivers and antennas (orbiter-based) and an EMU radio and antenna (EMU-based). The system provided voice communications among the EVA crewmembers, between the EVA crewmembers and the orbiter, and between the EVA crewmembers and the ground. The display and control module contained all of the controls and

[894] USA, *Crew Operations*, 2.11-5.
[895] USA, *Crew Operations*, 2.11-5, 2.11-6.
[896] USA, *Crew Operations*, 2.11-6.
[897] USA, *Crew Operations*, 2.11-7.

displays necessary for nominal operation and monitoring of the EMU systems. It was installed on the hard upper torso; its surfaces were faced with a thermal micrometeoroid garment, which contained the labels for the controls. The caution and warning system consisted of instrumentation and a microprocessor, which were used to obtain, process, and visually display information for use by the EVA crewmember in the operation and management of the EMU. Its functions involved display EMU leak check procedures, monitoring and display EMU consumables status, monitoring EMU operational integrity, and alerting crewmembers to EMU anomalies.[898]

IID. Mission Highlights and Discovery "Firsts"

OV-103, known as the "workhorse" of the SSP, flew thirty-nine missions between 1984 and 2011. In her twenty-seven years of service, *Discovery* was distinguished by a number of **"firsts**" and other significant accomplishments; twenty-seven missions included a new and/or noteworthy accomplishment. She was the first to complete twenty missions, marked by STS-63 (February 1995), and the only orbiter selected for NASA's RTF missions, STS-26 (September-October 1988) and STS-114 (July-August 2005), in the wake of the *Challenger* and *Columbia* accidents, respectively. Because of this, she is the only extant orbiter to have flown a designated test flight (STS-26, STS-114, STS-121). She is also the only extant orbiter to have flown successive missions multiple times (STS-51A, STS-51C, and STS-51D [1984-85]; STS-31 and STS-41 [1990]; STS-91 and STS-95 [1998]; and STS-114 and STS-121 [2005-06]).[899] Following the announced close of the SSP, *Discovery* was the first shuttle orbiter to complete transition and retirement processing.

In their "Major Milestones" chapter in *Wings in Orbit*, JSC Historian Jennifer Ross-Nazzal and co-author Dennis Webb, classify all shuttle missions into six major categories, noting that "categories are approximate as many missions feature objectives or payloads that can fit in multiple categories."[900] In accordance with this classification, *Discovery's* thirty-nine missions fall within the following groups, with the number of related missions noted:

- Classified DoD: four (4)
- Satellite deployment, retrieval, or repair: nine (9)
- Deployment or repair of interplanetary probes or observatories: five (5)
- Focus on science: six (6)
- Shuttle/*Mir* support: two (2)
- International Space Station support: thirteen (13)

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[898] USA, *Crew Operations*, 2.11-7, 2.11-8.
[899] *Atlantis* is the only other extant orbiter to have flown successive missions (STS-101 and STS-106 [2000]). Chris Gebhardt, "After 26 Years;" Hale, *Wings In Orbit*, 527-29.
[900] Ross-Nazzal and Webb, "Major Milestones," 18.

These missions reflect the history of the SSP and its evolving priorities. During her first decade of service, *Discovery* released commercial satellites and DoD payloads into orbit. Missions throughout the 1990s focused on scientific advancements, including the deployment and servicing of the HST. Also during this decade, *Discovery* completed a pair of support missions to *Mir* as a prelude to the development of the ISS. Beginning in 1999, and continuing through her final flight in 2011, the missions of *Discovery* focused on the delivery of parts for ISS assembly, and the transport of crews and supplies. A list of Discovery's flights, with associated primary mission category, follows.

Space Shuttle *Discovery* Launch, Landing, and Mission Summary

SSP Flight No.	Mission No.	Orbiter/ Flight No.	Launch Date	Landing Date	Landing Site	Primary Mission Category
12	STS-41D	*Discovery* - 1	August 30, 1984	September 5, 1984	EAFB	Satellite
14	STS-51-A	*Discovery* - 2	November 8, 1984	November 16, 1984	KSC	Satellite
15	STS-51-C	*Discovery* - 3	January 24, 1985	January 27, 1985	KSC	DoD
16	STS-51-D	*Discovery* - 4	April 12, 1985	April 19, 1985	KSC	Satellite
18	STS-51-G	*Discovery* - 5	June 17, 1985	June 24, 1985	EAFB	Satellite
20	STS-51-I	*Discovery* - 6	August 27, 1985	September 3, 1985	EAFB	Satellite
26	STS-26	*Discovery* - 7	September 29, 1988	October 3, 1988	EAFB	Satellite
28	STS-29	*Discovery* - 8	March 13, 1989	March 18, 1989	EAFB	Satellite
32	STS-33	*Discovery* - 9	November 22, 1989	November 27, 1989	EAFB	DoD
35	STS-31	*Discovery* - 10	April 24, 1990	April 29, 1990	EAFB	Interplanetary probe or observatory
36	STS-41	*Discovery* - 11	October 6, 1990	October 10, 1990	EAFB	Interplanetary probe or observatory
40	STS-39	*Discovery* - 12	April 28, 1991	May 6, 1991	KSC	DoD
43	STS-48	*Discovery* - 13	September 12, 1991	September 18, 1991	EAFB	Interplanetary probe or observatory
45	STS-42	*Discovery* - 14	January 22, 1992	January 30, 1992	EAFB	Science
52	STS-53	*Discovery* - 15	December 2, 1992	December 9, 1992	EAFB	DoD
54	STS-56	*Discovery* - 16	April 8, 1993	April 17, 1993	KSC	Science
57	STS-51	*Discovery* - 17	September 12, 1993	September 22, 1993	KSC	DoD
60	STS-60	*Discovery* - 18	February 3, 1994	February 11, 1994	KSC	Science
64	STS-64	*Discovery* - 19	September 9, 1994	September 20, 1994	EAFB	Science

SSP Flight No.	Mission No.	Orbiter/ Flight No.	Launch Date	Landing Date	Landing Site	Primary Mission Category
67	STS-63	*Discovery* - 20	February 3, 1995	February 11, 1995	KSC	*Mir* support
70	STS-70	*Discovery* - 21	July 13, 1995	July 22, 1995	KSC	Satellite
82	STS-82	*Discovery* - 22	February 11, 1997	February 21, 1997	KSC	Interplanetary probe or observatory
86	STS-85	*Discovery* - 23	August 7, 1997	August 19, 1997	KSC	Science
91	STS-91	*Discovery* - 24	June 2, 1998	June 12, 1998	KSC	*Mir* support
92	STS-95	*Discovery* - 25	October 29, 1998	November 7, 1998	KSC	Science
94	STS-96	*Discovery* - 26	May 27, 1999	June 6, 1999	KSC	ISS support
96	STS-103	*Discovery* - 27	December 19, 1999	December 27, 1999	KSC	Interplanetary probe or observatory
100	STS-92	*Discovery* - 28	October 11, 2000	October 24, 2000	EAFB	ISS support
103	STS-102	*Discovery* - 29	March 8, 2001	March 21, 2001	KSC	ISS support
106	STS-105	*Discovery* - 30	August 10, 2001	August 22, 2001	KSC	ISS support
114	STS-114	*Discovery* - 31	July 26, 2005	August 9, 2005	EAFB	ISS support
115	STS-121	*Discovery* - 32	July 4, 2006	July 17, 2006	KSC	ISS support
117	STS-116	*Discovery* - 33	December 9, 2006	December 22, 2006	KSC	ISS support
120	STS-120	*Discovery* - 34	October 23, 2007	November 7, 2007	KSC	ISS support
123	STS-124	*Discovery* - 35	May 31, 2008	June 14, 2008	KSC	ISS support
125	STS-119	*Discovery* - 36	March 15, 2009	March 28, 2009	KSC	ISS support
128	STS-128	*Discovery* - 37	August 28, 2009	September 11, 2009	EAFB	ISS support
131	STS-131	*Discovery* - 38	April 5, 2010	April 20, 2010	KSC	ISS support
133	STS-133	*Discovery* -39	February 24, 2011	March 9, 2011	KSC	ISS support

Classified Department of Defense Missions

Between 1985 and 1992, *Discovery* flew four of the total ten classified DoD shuttle missions. These four missions were STS-51C, STS-33, STS-39, and STS-53. The missions broke from NASA's usually unclassified approach as launch times and payloads were kept secret, no astronaut interviews were allowed, and the media was not privy to air-to-ground communications.

Discovery's third flight, STS-51C, was the first SSP mission dedicated to the DoD. Because of the classified payload, little is known about the three-day mission in January 1985.[901] The USAF used the Inertial Upper Stage booster to deploy the payload, reportedly an eavesdropping satellite, ORION-1.[902] STS-31, *Discovery's* ninth flight, launched on November 22, 1989, was the fifth mission dedicated to the DoD. While unconfirmed, ORION-2, another eavesdropping satellite, may have been deployed.[903] STS-39, launched on April 28, 1991, was the first unclassified DoD mission, and the first time that flight details were released to the public. It included experiments sponsored by the USAF and the Strategic Defense Initiative.[904] The unclassified payload included Air Force Program-675 (AFP-675); Infrared Background Signature Survey (IBSS) with Critical Ionization Velocity (CIV), Chemical Release Observation (CRO) and Shuttle Pallet Satellite-II (SPAS-II) experiments; and Space Test Payload-1 (STP-1). Classified payload consisted of the Multi-Purpose Release Canister. Also on board was Radiation Monitorin Equipment III (RME III) and Cloud Logic to Optimize Use of Defense Systems-1A (CLOUDS-I).[905]

STS-53, *Discovery's* fifteenth flight and the final dedicated DoD mission of the SSP, launched on December 2, 1992. The partially classified payload included SDS B-3, assumed to be a data relay satellite.[906] *Discovery* also carried two unclassified secondary payloads and nine unclassified middeck experiments.[907]

Satellite Deployment, Retrieval, and Repair

Nine of *Discovery's missions*, launched between 1984 and 1995, were devoted to communication satellite deployment and repairs, including RTF-1 after the *Challenger* accident. These missions included STS-41D, -51A, -51D, -51G, -51I, -26, -29, -51, and -70. Communication satellites were *Discovery*'s main mission objective during her first two years of service. However, after the *Challenger* accident in 1986, "satellite retrieval and repair missions all but disappeared from the shuttle manifest."[908]

Three satellites were deployed on *Discovery's* maiden flight, STS-41D, launched on August 30, 1984. These included Satellite Business System SBS-D, SYNCOM IV-2 (also known as LEASAT2), and TELSTAR. The mission was nearly flawless, and the three satellites were

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[901] NASA KSC, "STS-51C," November 23, 2007, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-51C.html; Boeing, *OV-103, Volume II*, 96.
[902] Cassutt, "Secret Space Shuttle," 3.
[903] Cassutt, "Secret Space Shuttle," 3.
[904] Rumerman, *U.S. Human Spaceflight*, 49.
[905] NASA KSC, "STS-39 (40)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-39/mission-sts-39.html; Boeing, *OV-103, Volume II*, 100.
[906] Cassutt, "Secret Space Shuttle," 3.
[907] NASA KSC, "STS-53 (52)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-53/mission-sts-53.html; Boeing, *OV-103, Volume II*, 102.
[908] Ross-Nazall and Webb, "Major Milestones," *25*.

successfully deployed. Also carried in the payload bay was an experimental 102’ x 13’ solar array, named the Office of Application and Space Technology, or OAST-1.[909] The knowledge gained from testing the device led to the arrays that later powered the ISS.[910] STS-41D also was the first flight to carry a commercially sponsored payload specialist.[911]

STS-51A was marked by the deployment of two satellites, Canadian communications satellite TELESAT-H (ANIK) and Defense communications satellite SYNCOM IV-I (also known as LEASAT-1).[912] In addition, two communications satellites, Palapa B-2 and Westar VI, were retrieved as separate EVAs. These satellites had been deployed nine months earlier, but failed to achieve their desired orbits. Astronauts Joseph Allen and Dale Gardner captured and secured both satellites in *Discovery’s* payload bay.[913] This marked the first occasion satellites were retrieved from orbit and returned to Earth.[914]

Discovery deployed two communications satellites on her fourth flight, STS-51D, which launched on April 12, 1985, almost one month after the originally scheduled date. TELESAT-1 (ANIK C-1) was released satisfactorily, but SYNCOM IV-3 (also known as LEASAT-3) failed to activate. Two mission specialists were sent on an unplanned EVA in an unsuccessful effort to repair it.[915] The mission included two firsts: US Senator Jake Garn became the first member of Congress to fly aboard a shuttle, and astronauts participated in Toys in Space, an experiment targeted at schoolchildren.[916] The nearly seven-day flight concluded April 19 when *Discovery*’s front right tire blew while landing at KSC. The blown tire and extensive brake damage prompted the landing of future flights at Edwards AFB until implementation of the nose wheel steering system.

STS-51G, *Discovery*’s fifth flight, which launched on June 17, 1985, carried three communication satellites: MORELOS-A, for Mexico; ARABSAT-A, for Arab Satellite Communications Organization; and TELSTAR-3D, for AT&T. The crew included Prince Sultan

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909 NASA KSC, “41-D (12),” June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/41-d/mission-41-d.html; NASA KSC, “STS-41D,” February 18, 2010, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-41D.html.

910 The rest of the cargo included: a large format camera; an IMAX camera to shoot footage later used in the film *The Dream Is Alive*; a Continuous Flow Electrophoresis System III, built by a pharmaceutical company; Radiation Monitoring Equipment; Shuttle Student Involvement Program experiments devised by high school students; and Cloud Logic to Optimize Use of Defense Systems, an Air Force experiment. NASA KSC, “STS-41D,” February 18, 2010, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-41D.html.

911 In 1983, NASA confirmed Charles D. Walker as the first industrial payload specialist. He was the first non-astronaut to fly on a shuttle. As a crew member, he accompanied the continuous flow electrophoresis equipment, developed for the McDonnell Douglas Corporation, on STS-41D, STS-51D, and STS-61B. NASA JSC, “Biographical Data, Charles D. Walker, February 1999, http://www.jsc.nasa.gov/Bios/PS/Walker.html.

912 NASA KSC, “51-A (14),” June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/51-a/mission-51-a.html.

913 Ross-Nazall and Webb, “Major Milestones,” 23.

914 NASA, *United States Space Shuttle Firsts*, 8.

915 NASA KSC, “STS-51D,” February 18, 2010, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-51D.html.

916 NASA, *Space Shuttle Firsts*, 9.

Salman Al Saud of Saudi Arabia as a payload specialist, the first Arab and member of a royal family to travel to space.[917] During this mission, the Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN) was released for the first time to survey the Milky Way galaxy.[918]

STS-51I, launched on August 27, was *Discovery's* third mission in 1985 that deployed communications satellites. Three satellites were deployed: ASC-1, for American Satellite Company; AUSSAT-1, an Australian Communications Satellite; and SYNCOM IV-4 also known as LEASAT-4), the Synchronous Communications Satellite. SYNCOM IV-4 failed to function after reaching geosynchronous orbit. Additionally, Mission Specialists William F. Fisher and James D.A. van Hoften retrieved, repaired, and redeployed LEASAT-3, originally deployed on mission STS-51-D.[919]

The primary payload carried aboard both missions STS-26 and STS-29, launched in September 1988, and March 1989, respectively, were NASA's Tracking and Data Relay Satellites, TDRS-C and TDRS-D. Each satellite was attached to an Inertial Upper Stage, which propelled them to a geosynchronous orbit.[920] STS-26 also was the first flight to use the redesigned SRBs, and the first to feature an all-veteran astronaut crew since the flight of Apollo 11.[921]

Discovery's seventeenth flight, STS-51, launched on September 12, 1993, after numerous delays, deployed the Advanced Communications Technology Satellite, or ACTS. This satellite served as a test bed for advanced communications satellite concepts and technology. Its Transfer Orbit Stage booster was used for the first time to propel a communications satellite into geosynchronous altitude on the first day of the mission. The first attempt to deploy ACTS was delayed when two-way communications were temporarily lost with Mission Control.[922] It also marked the first time a Shuttle payload was controlled from KSC.[923] The mission ended with the first nighttime shuttle landing at KSC.

The last *Discovery* mission to deploy a satellite was STS-70, launched on July 13, 1995. The primary objective was to release the seventh TDRS satellite, TDRS-G, and the sixth placed in operational use. The deploy operations used three separate control centers to manage orbit operations. The White Sands ground station controlled the TDRS, the JSC Mission Control Center controlled the shuttle, and the booster stage was controlled from Onizuka AFB in

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[917] Gebhardt, "After 26 Years;" Rumerman, *U.S. Human Spaceflight*, 44-45.
[918] NASA KSC, "STS-51-G (18)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/51-g/mission-51-g.html.
[919] NASA KSC, "STS-51-I (20)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/51-i/mission-51-i.html.
[920] NASA KSC, "STS-26," February 18, 2010, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-26.html; NASA KSC, "STS-29," August 30, 2008, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-29.html.
[921] Rumerman, *U.S. Human Spaceflight,* 46.
[922] NASA KSC, "STS-51 (57)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-51/mission-sts-51.html.
[923] This payload was the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrograph-Shuttle Pallet Satellite, a joint German-US astrophysics payload. Rumerman, *U.S. Human Spaceflight*, 54.

Sunnyvale, California. This mission marked the completion of NASA's TDRS system that provided communication, tracking, telemetry, data acquisition, and command services to the shuttle and other low-orbital spacecraft missions.[924] STS-70 was the first time a Space Shuttle flew with the new Block I SSME, which featured improvements that increased their stability and safety.[925]

Deployment and Repair of Interplanetary Probes and Observatories

Discovery flew five missions between 1990 and 1999 that included the deployment or repair of interplanetary probes and observatories, the most notable of which was the Hubble Space Telescope (HST). The HST is the "first large optical telescope ever to be placed above Earth's atmosphere and the first of NASA's Great Observatories."[926] *Discovery* deployed the telescope in 1990, and returned to the HST for two of the five servicing missions; *Columbia*, *Atlantis*, and *Endeavour* each flew one servicing mission. The vehicle's other two space science missions included the release of the *Ulysses* observatory and the Upper Atmospheric Research Satellite interplanetary probe.

Discovery deployed the HST during STS-31, the vehicle's tenth flight. The mission was first scheduled for April 18, 1990, but that date was moved forward to April 10, marking the first time a shuttle launch was expedited.[927] However, the launch that day was scrubbed when the orbiter's APU failed. Rescheduled for April 24, a malfunctioning LO2 valve briefly held up liftoff before *Discovery* launched.[928] Because of the need to place the HST above most of the atmosphere, the orbiter reached an altitude of 329.22 statute miles, the highest shuttle orbit at that time.[929] The HST was deployed on the second day of the mission, but a faulty sensor delayed the release of one of the solar arrays needed to power the telescope. Carbon brakes were used on an orbiter for the first time when *Discovery* touched down on April 29 at Edwards AFB.[930]

Subsequently, in 1997 and 1999, *Discovery* flew two servicing missions to repair the HST. The first, STS-82, was launched on February 11, 1997. This was the second in a series of planned servicing missions; the first was performed by the *Endeavour* crew on STS-61 (December 1993). Two older instruments, the Goddard High Resolution Spectrometer and the Faint Object Spectrograph, were removed. Two new astronomy instruments were installed: the Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). In addition, other existing hardware was replaced with upgrades and

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[924] Rumerman, *U.S. Human Spaceflight*, 58.
[925] NASA KSC, "STS-70 (70)," June 29, 2001, http://www.nasa.gov/shuttle/missions/sts-70/mission-sts-70.html.
[926] Rumerman, *U.S. Human Spaceflight*, 48.
[927] Jenkins, *Space Shuttle*, 297.
[928] NASA KSC, "STS-31 (35)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-31/mission-sts-31.html.
[929] Rumerman, *U.S. Human Spaceflight*, 48.
[930] NASA, *Space Shuttle Firsts*, 13; Rumerman, *U.S. Human Spaceflight*, 48; Carol Christian, Kamlesh Lulla, and David Leckrone, "The Space Shuttle and Great Observatories," in Hale, *Wings In Orbit.*

spares. The HST received a refurbished Fine Guidance Sensor to provide pointing information for the spacecraft; it was also used as a scientific instrument for astrometric science. A reel-to-reel tape recorder was replaced with a Solid State Recorder. One of four Reaction Wheel Assemblies (RWAs) was replaced with a refurbished spare. The RWAs help move the telescope into position and also maintain the position of the spacecraft.[931] The mission included five EVAs, which totaled thirty-three hours and eleven minutes.

STS-103, *Discovery*'s twenty-seventh mission and second servicing mission to the HST, launched on December 19, 1999, after several delays. Four EVAs were scheduled to renew and refurbish the telescope. Since the last servicing mission flown in February 1997, three gyroscopes had failed (in 1997, 1998, and 1999, respectively). During the STS-103 mission, all six gyroscopes were replaced. Also, the Fine Guidance Sensor was replaced with a refurbished unit that was returned from the second servicing mission. The spacecraft's computer was replaced, and a new voltage/temperature kit was installed to prevent battery overcharging and overheating. A new transmitter, solid state recorder, and S-Band Single Access Transmitter (SSAT) also were installed. New thermal insulation blankets were added to replace the degraded outer insulation. [932]

Discovery's eleventh flight, STS-41, launched on October 6, 1990, deployed *Ulysses*, an ESA-built deep space probe, to study the polar regions of the sun. Two upper stages, the Inertial Upper Stage and a mission-specific Payload Assist Module-S, combined for the first time to send *Ulysses* toward out-of-ecliptic trajectory.[933] The following year, STS-48, launched on September 12, 1991, deployed the Upper Atmospheric Research Satellite to study the Earth's stratosphere, mesosphere, and lower thermosphere.[934] The satellite was a component of NASA's Earth Science Enterprise program, an initiative to better understand how humans affect the planet.

Science Research

During the 1990s, Spacelab and SPACEHAB modules carried data-collecting satellites aboard *Discovery*. Beginning with STS-42 in 1992, experiments in areas such as life, Earth, and material sciences were the primary manifest for six *Discovery* missions.[935] These included STS-42, -56, -60, -64, -85, and -95.

STS-42, *Discovery*'s fourteenth flight, began on January, 22, 1992. It carried the International Microgravity Laboratory-1, a pressurized manned Spacelab module. The mission objective was to explore in depth the complex effects of weightlessness on living organisms and materials

[931] NASA KSC, "STS-82 (82)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-82/mission-sts-82.html.
[932] NASA KSC, "STS-103 (96)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-103/mission-sts-103.html.
[933] NASA KSC, "STS-41 (36)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-41/mission-
[934] Rumerman, *U.S. Human Spaceflight*, 50.
[935] Ross-Nazzal and Webb, "Major Milestones," 27.

processing. The crew divided into two teams to conduct experiments on the human nervous system's adaptation to low gravity and the effects of microgravity on other life forms. Low-gravity materials processing experiments included crystal growth from a variety of substances. The mission was extended one day to finish additional experiments.[936]

Discovery's sixteenth flight, STS-56, began on April 8, 1993, two days later than planned. The flight's primary payload was the Atmospheric Laboratory for Applications and Science (ATLAS-2), designed to collect data on the relationship between the sun's energy output and the Earth's middle atmosphere, and how these factors affect the ozone layer. ATLAS-2 was one element of NASA's Mission to Planet Earth program. All seven ATLAS-2 instruments were first flown on ATLAS-1 during the STS-45 mission flown by *Atlantis* in March 1992. The STS-56 crew also deployed the SPARTAN-201, a free-flying science instrument platform designed to study velocity and acceleration of solar wind and to observe the sun's corona. In addition, experiments were done on microgravity and tissue loss in space.[937] STS-56 also marked the first contact between a Shuttle and *Mir* using amateur radio equipment.

Discovery's eighteenth mission, STS-60, which launched on February 3, 1994, and returned on February 11, carried a variety of SPACEHAB module experiments. These included the Organic Separations payload, designed to investigate cell separation techniques for possible pharmaceutical and biotechnology processing, and the Equipment for Controlled Liquid Phase Sintering Experiment package, a furnace designed to study stronger, lighter and more durable metals. Other experiments included the Three-Dimensional Microgravity Accelerometer, Astroculture, Bioserve Pilot Lab, Commercial Generic Bioprocessing Apparatus, Commercial Protein Crystal Growth, Controlled Liquid Phase Sintering, and Immune Response Studies, among others. Another primary mission payload was the Wake Shield Facility, used to grow innovative thin film materials for use in electronics.[938]

STS-64, *Discovery*'s nineteenth mission, launched on September 9, 1994, carried the Lidar in Space Technology Experiment (LITE), which was used to perform atmospheric research. This was the first flight of LITE, which involved the use of lasers for environmental research. During the mission, the crew also released and retrieved the SPARTAN-201. The flight included the first untethered EVA since *Discovery*'s STS-51-A ten years earlier.[939]

Discovery's twenty-third mission, STS-85, launched on August 7, 1997, was dedicated to scientific experiments and testing hardware for the ISS. The primary mission was to deploy and retrieve the Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere-Shuttle Pallet

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[936] NASA KSC, "STS-42 (45)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-42/mission-sts-42.html.
[937] NASA KSC, "STS-56 (54)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-56/mission-sts-56.html.
[938] NASA KSC, "STS-60 (60)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-60/mission-sts-60.html.
[939] Rumerman, *U.S. Human Spaceflight*, 56.

Satellite-2 (CRISTA-SPAS-2), previously flown on STS-66 in 1994. It was the fourth in a series of cooperative ventures between the German Space Agency and NASA. This payload measured trace gases and dynamics of the Earth's middle atmosphere. CRISTA-SPAS-2 flew for about 200 hours before *Discovery*'s crew retrieved it. A number of experiments were conducted throughout the mission, including the study of a robotic arm created by the Japanese Space Agency for use on the ISS.[940]

Astronaut John Glenn gained fame in 1962 when he was the first American to orbit Earth. Thirty-eight years later, Glenn, then a 77-year-old United States senator, returned to space as a payload specialist for STS-95, *Discovery*'s twenty-fifth mission. The effect of microgravity on human aging was studied. The launch on November 29, 1998, was witnessed by President Bill Clinton, a first for a sitting president.[941] The primary objectives of the mission were to conduct a variety of science experiments in the pressurized SPACEHAB module, focusing on life sciences, microgravity sciences and advanced technology. In addition, the SPARTAN satellite was deployed and retrieved to study the sun. The crew also tested components planned for installation on the HST during the next servicing mission.[942]

Mir Support

Two *Discovery* missions, STS-63 in 1995 and STS-91 in 1998, supported the Shuttle/*Mir* Program. The first was to practice a rendezvous with the Russian space station, and the second marked the last time a shuttle docked with the station.[943]

STS-63 launched without incident on February 3, 1995. The primary focus of the mission was to perform a rendezvous and fly around of *Mir* to verify flight techniques, communications, and navigation sensor interfaces, and engineering analyses associated with shuttle/*Mir* proximity operations in preparation for future docking missions.[944] *Discovery* came within just 37' of *Mir*, and photographs taken by the space station's crew marked the first time a shuttle was captured on film in space from another manned spacecraft. *Discovery*'s payload included the SPARTAN-204, which was deployed and successfully retrieved. STS-63 is associated with a number of "firsts," including the first spacewalk by an African American, Mission Specialist Bernard Harris, and the first female shuttle pilot, Eileen Collins.[945] Also, with this flight, *Discovery* became the first orbiter to complete twenty missions.

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[940] NASA KSC, "STS-85 (86)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-85/mission-sts-85.html; Rumerman, *U.S. Human Spaceflight*, 62.
[941] John Glenn's presence drew a lot of media attention, and the crew was interviewed by CBS news anchor Walter Cronkite and *The Tonight Show* host Jay Leno while in orbit.
[942] NASA KSC, "STS-95 (92)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-95/mission-sts-95.html.
[943] Ross-Nazzal and Webb, "Major Milestones," 27.
[944] NASA KSC, "STS-63 (67)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-63/mission-sts-63.html.
[945] Rumerman, *U.S. Human Spaceflight,* 53.

STS-91, *Discovery*'s sole mission to *Mir*, was the ninth and last time an orbiter docked with the Russian space station. The goal of this mission was to bring home Andrew Thomas, the seventh and final American astronaut to live aboard *Mir;* Thomas spent 130 days aboard the station. When *Discovery* launched on June 2, 1998, her payload held the SPACEHAB module, which contained supplies for *Mir*'s crew. The payload also contained an Alpha Magnetic Spectrometer, built by an international team of researchers to study the universe. The shuttle's robotic arm's new electronics and software were tested in preparation for the construction of the ISS.[946] After the orbiter docked with *Mir*, cargo was exchanged and Thomas boarded *Discovery* for the flight back to Earth. STS-91 also marked the first use of the new super lightweight tank.[947]

International Space Station Support

Discovery flew thirteen of her final fourteen missions to construct, supply, and exchange crews with the space station.[948] Two of these ISS support missions were part of RTF-2. *Discovery*'s goal for STS-96, her twenty-sixth flight, was to transport supplies to the as yet unmanned station. The shuttle launched on May 27, 1999, and carried the SPACEHAB module packed with equipment. She also carried both a U.S-built crane and a Russian-built crane, which were installed on the station. The STARSHINE satellite, partially built by an international group of high school students, was successfully deployed during the flight. Three days into the mission, *Discovery* became the first orbiter to dock with the ISS, and 3,567 pounds of supplies were unloaded. The crew also installed two new portable foot restraints, and attached three bags of tools and handrails to aid future ISS assembly operations.[949] After undocking, *Discovery* performed a flyaround of the ISS to obtain a detailed photographic record.[950]

STS-92, *Discovery*'s twenty-eighth flight, was the 100th mission of the SSP and included the 100th spacewalk. The orbiter launched on October 11, 2000, after four days of delays. *Discovery* carried the Zenith Port, or Z1, truss structure, which was installed on top of the *Unity* connecting node, and also delivered the Pressurized Mating Adaptor 3 (PMA-3), which was used as a docking port. After successful completion of four EVAs to attach the truss and set up the power supply, the shuttle landed at Edwards AFB on October 24, delayed two days because of bad weather.[951]

OV-103's twenty-ninth mission, STS-102, began at sunrise on March 8, 2001. The primary objectives of this mission were to replace the Expedition 1 crew and to unload supplies, equipment and science racks from the *Leonardo* MPLM. The crew attached a coolant pump and

[946] Rumerman, *U.S. Human Spaceflight*, 64.
[947] Gebhardt, "After 26 Years;" Rumerman, *U.S. Human Spaceflight*, 64.
[948] Duggins, *Final Countdown*, 112-161.
[949] NASA KSC, "STS-96 (94)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-96/mission-sts-96.html.
[950] Rumerman, *U.S. Human Spaceflight*, 65.
[951] NASA KSC, "STS-92 (100)," June 29, 2001, http://science.ksc.nasa.gov/shuttle/missions//sts-92/mission-sts-92.html.

an External Storage Platform to the outside of the *Destiny* module.[952] *Discovery's* next mission, STS-105, launched on August 10, 2001, also carried the *Leonardo* MPLM, which contained additional scientific racks, equipment, and supplies. Another payload was the Materials International Space Station Experiments (MISSE), a project to fly materials and other types of space exposure experiments on the station. The MISSE experiments were the first externally mounted experiments conducted on the ISS.[953] During two spacewalks, the Early Ammonia Servicer was installed to provide a backup source of energy supply to the ISS, and heater cables and handrails were attached for the station's Starboard-zero (S0) truss structure, which was scheduled for delivery on a future mission. ISS Expedition Crew 2 was replaced by Expedition Crew 3.

After the *Columbia* accident on February 1, 2003, *Atlantis* originally was selected for RTF-2. However, corrosion was discovered on *Atlantis*' rudder speed brake system. Although *Discovery* had the same problem, NASA engineers calculated that OV-103's brakes could be fixed more quickly. Thus, *Discovery* was chosen to fly STS-114, her thirty-first flight and the first of two RTF-2 test missions. Following delays, *Discovery* finally lifted off on July 26, 2005. *Discovery's* flight was extensively documented through a system of new and upgraded ground-based and airborne cameras, as well as radar systems, laser systems on the OBSS, and sensors in the shuttle's wings. The primary objectives of this mission were to test and evaluate new safety procedures, and to conduct assembly and maintenance tasks on the ISS. On flight day three, the orbiter executed a rendezvous pitch maneuver, which flipped the shuttle end over end, allowing the crew to photograph the underside of *Discovery* and her heat-resistant tiles in detail. The payload included scientific experiments contained within the *Raffaello* MPLM. During the first two EVAs, in-orbit shuttle repair techniques were tested and work was completed on the space station. A third EVA tasked the crew with the first on-orbit repair of the shuttle heat shield, which entailed the removal of two protruding gap fillers.[954]

STS-121, the second RTF test flight, launched on July 4, 2006. This mission demonstrated techniques for inspection and protection of the shuttle's TPS and replacement of critical hardware needed for future ISS assembly. *Discovery*'s crew unloaded about 7,400 pounds of equipment and supplies from the *Leonardo* MPLM, including a new heat exchanger for the common cabin air assembly, a new window and window seals for the Microgravity Sciences Glovebox, and a spare EVA suit and emergency jetpack. This mission restored the station to a three-person crew for the first time since May 2003. It was also the most photographed shuttle mission in history.[955]

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[952] Rumerman, *U.S. Human Spaceflight*, 68; NASA KSC, "STS-102 (103)," July 25, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-102/mission-sts-102.html.
[953] NASA KSC, "STS-105 (106)," October 2, 2001, http://science.ksc.nasa.gov/shuttle/missions/sts-105/mission-sts-105.html.
[954] NASA, "STS-114," November 23, 2007, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-114.html.
[955] NASA, "STS-121," November 23, 2007, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-121.html.

Discovery's thirty-third mission, STS-116, was among her most challenging. After a two-day weather delay, the spacecraft lifted off at 8:47 p.m. on December 9, 2006, the first night launch since the *Columbia* accident. *Discovery* carried several tons of equipment and supplies, most of which was contained in the SPACEHAB module. During four spacewalks, the crew added the P5 spacer truss segment, rewired the station's power system to support the ISS's final configuration and arrival of additional modules, and retracted the solar arrays that had folded improperly.[956]

Discovery began STS-120 on October 23, 2007, the shuttle's thirty-fourth flight. The payload bay held the Harmony Node 2 module that was used to connect the ISS to two laboratories. For the first time in history, both the Space Shuttle commander and ISS commander were women: Pamela Melroy on *Discovery* and Peggy Whitson on the ISS. The mission included an ISS crew exchange, and a risky spacewalk was completed to repair a torn solar array using improvised tools.[957] To maximize their time in orbit, *Discovery*'s crew reentered the atmosphere over the middle of the United States by the descending node reentry, a maneuver of descent discouraged after the *Columbia* accident.[958]

The goal of *Discovery*'s thirty-fifth mission, STS-124, was to deliver *Kibo*, the 32,500-pound Japanese Aerospace Exploration Agency's (JAXA) pressurized module, to the ISS. This mission was the second of three flights that brought components to complete the *Kibo* laboratory. The module was so large that *Discovery*'s orbiter boom was left at the ISS during STS-120 to provide sufficient space in the orbiter's payload bay. STS-124 marked the first time the JAXA flight control team activated and controlled a module from Kibo Mission Control in Tsukuba, Japan. In the third and final mission spacewalk, astronauts exchanged a depleted nitrogen tank, and removed thermal covers and launch locks from the newly installed *Kibo* hardware, and reinstalled a repaired television camera to the left P1 truss.[959]

STS-119, launched on March 15, 2009, was the 100th SSP mission since the *Challenger* accident. *Discovery* delivered two solar arrays and the S6 truss, which were installed during three EVAs. This addition expanded the capacity of the ISS, and enabled an increase from three to six resident astronauts. The crew also repaired the station's water recycling system before returning to KSC on March 27 after a crew exchange.[960] *Discovery's* next mission, STS-128, launched on August 28, 2009. The lift off for STS-128 was delayed a day by weather and then three more

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[956] Anna Heiney, "STS-116 Delivers Permanent Power," December 22, 2006, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts116/launch/sts116_summary.html; NASA, "STS-116," April 2, 2008, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts116/main/index.html.
[957] NASA, "STS-120 (23rd Space Station Flight)," *NASA Facts,* 2007, http://www.nasa.gov/pdf/216375main_STS-120.pdf.
[958] Gebhardt, "After 26 Years."
[959] Anna Heiney, "*Discovery* Delivers a Module 'Filled With Dreams,'" June 19, 2008, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts124/launch/124_overview.html; NASA, "STS-124," June 20, 2008, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts124/launch/124_overview.html.
[960] Elaine M. Marconi, "NASA's STS-119 Mission: Boosting the Station Power," April 6, 2009, http://www.nasa.gov/mission_pages/shuttle/behindscenes/119_overview.html; NASA, "STS-119 Mission Information," April 16, 2009, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts119/main/index.html.

days by a faulty fuel valve on the ET. The *Leonardo* MPLM carried support racks, science racks, a freezer for sample storage, a new sleeping compartment, and the COLBERT, the Combined Operational Load Bearing External Resistance Treadmill. STS-128 also included an ISS crew member exchange. After three ISS maintenance EVAs, *Discovery* landed at Edwards AFB on September 11, delayed a day because of poor weather.[961]

Discovery's thirty-eighth mission began on April 5, 2010. STS-131 accomplished several milestones, including the last nighttime shuttle launch, the first time four women were in space together, the last SSP flight to include first-time astronauts, and the first time two Japanese astronauts were in space together.[962] *Discovery* carried the *Leonardo* MPLM containing over 17,000 pounds of supplies and equipment. During three EVAs, the crew replaced an ammonia tank assembly, retrieved a Japanese experiment, and switched out a rate gyro assembly on the S0 truss element. The Ku-band data transmission system failed to work once in orbit.[963] *Discovery* returned to KSC on April 20 after a day's delay.[964] The STS-131 mission lasted fifteen days, two hours, forty-seven minutes, and ten seconds, *Discovery's* longest duration flight.

Discovery's final flight, STS-133, was originally scheduled to launch on November 1, 2010. However, due to a variety of problems, including an O-ring seal failure, failure of the SSME-3 redundant controller, an ET leak, and damaged ET stringers, the launch date was incrementally pushed up to February 24, 2011.[965] The crew for STS-133 included Commander Steve Lindsey; Pilot Eric Boe; and Mission Specialists Michael Barratt, Nicole Stott, Alvin Drew, and Steve Bowen. Bowen replaced Tim Kopra, who was injured a month before *Discovery* launched. *Discovery*'s payload included Robonaut 2, the first human-like robot in space. Similar to a human in appearance and movement, Robonaut 2 was built to assist astronauts aboard the ISS with commonplace or dangerous tasks. OV-103 also carried the Permanent Multipurpose Module (converted from the *Leonardo* module), which contained scientific experiments and provided the ISS with storage space, and the Express Logistics Carrier 4, an external platform that holds large equipment. The crew unloaded the cargo, attached the Permanent Multipurpose Module, the last permanent pressurized piece of the ISS, and completed maintenance and repairs on the ISS during a pair of spacewalks. After extending her stay two days, *Discovery* landed at KSC on March 9 and became the first Space Shuttle to retire after a flight of twelve days, nineteen hours, four minutes and fifty seconds.[966]

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[961] Steve Siceloff, "STS-128 Outfits Station for New Science," September 23, 2009, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts128/launch/128_overview.html.
[962] Gebhardt, "After 26 Years."
[963] NASA, "STS-131 Mission Information," April 27, 2010, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts131/main/index.html.
[964] Cheryl L. Mansfield, "STS-131: Teamwork Overcomes Mission's Challenges," April 23, 2010, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts131/launch/131mission_overview.html.
[965] Gebhardt, "After 26 Years."
[966] NASA, "STS-133 Mission Information," March 15, 2011, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts133/main/index.html.

IIE. Process Flow: Ground and Ferry Operations

Ground Operations

Typical Landing Procedures

Throughout an entire Space Shuttle mission, weather conditions at KSC were monitored by JSC's Spaceflight Meteorology Group. Considered part of the National Weather Service, they worked with the Range Weather Operations at CCAFS to prepare landing forecasts, using data gathered by instrumentation throughout KSC and at CCAFS. About five hours before touchdown, when the shuttle's crew began to prepare the orbiter for its return to Earth, other NASA astronauts flew reconnaissance planes along the planned landing approach to assist in the evaluation of weather conditions. Based on the gathered data, as well as how many days the orbiter had been in space, Flight Controllers at Mission Control decided if the orbiter would land at KSC's SLF as scheduled, later in the day, or over the next day or two.[967] Weather conditions that dictated if a landing at the SLF was possible included the amount of observed cloud cover below 8,000', the range of visibility, crosswind speeds, and thunderstorms in the vicinity. The decision to land at KSC, as well as the final "go/no go" for landing, occurred approximately thirty minutes prior to the deorbit burn (about ninety minutes prior to the landing).[968]

In addition to deciding whether the orbiter would land at KSC, Flight Controllers had to determine which of the two runway approaches would be used. There were two approaches to the KSC SLF Runway, Runway 15 from the northwest and Runway 33 from the southeast. The Flight Controllers used the wind direction and the angle of the sun to determine which runway approach was used. In ideal conditions, the orbiter landed into the wind, and the sun was outside of the pilot's field of view.[969]

Roughly two hours before touchdown, KSC's Orbiter Recovery Convoy began their preparations at the SLF. The Convoy consisted of approximately twenty-five specially designed vehicles and units, and 150 trained personnel, who performed safing operations, assisted the crew in leaving the vehicle, and prepared the orbiter for transfer to the OPF. Also around this time, SLF personnel began to periodically fire air cannons and circle the runway perimeter to clear the area of wildlife; they also walked along the Runway to check for foreign object debris (FOD) that

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[967] If a landing at KSC was not possible, the principle alternative was a landing at Edwards AFB in California. Thus, similar weather monitoring procedures were carried out at both locations. NASA, *National Space Transportation System: An overview*, September 1988, 13; NASA KSC, "Landing the Space Shuttle Orbiter at KSC," news release, March 1992, revised October 1995, 7, http://www-pao.ksc.nasa.gov/kscpao/release/1992/1-92.htm.

[968] Since the orbiter reentered the atmosphere and landed in an unpowered, high-speed glide, once the deorbit burn was performed, the orbiter had to land; where the deorbit burn occurred was dictated by the landing site chosen. Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Shuttle Landing Facility (John F. Kennedy Space Center)," HAER No. FL-8-11-J. Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, April 2011, 17-18.

[969] Slovinac, "Shuttle Landing Facility," 18.

could potentially damage the orbiter. The walking activities continued until roughly fifteen minutes before landing; air cannons were regularly fired until touchdown.[970]

Approximately one hour before touchdown, the orbiter performed the deorbit burn. About twenty-five minutes before landing, the vehicle began to pass through the reentry blackout period, from which it emerged roughly twelve minutes before touchdown. At this point, the orbiter was roughly 550 miles from the SLF, at an altitude of about 34 miles (179,520’). When the vehicle reached the Gulf of Mexico (within 300 miles of the Runway and at an altitude of no more than 145,000’), the SLF’s TACAN system began to communicate with the vehicle, providing azimuth and distance measurements to the on-board computers. About two minutes prior to touchdown, when the orbiter was approximately 10 miles from the designated Runway approach and at an altitude of roughly 15,500’, the MSBLS took over for the TACAN system, to provide more precise guidance signals on slant range, azimuth, and elevation to the orbiter. As the orbiter approached an altitude of 12,000’, the commander and pilot began to use different visual aids at the SLF to ensure that the vehicle was at the proper angle. The orbiter touched down at roughly the 2,500’ mark on the Runway with its main landing gear, traveling at a speed of roughly 213 to 216 miles per hour.[971]

Once the orbiter came to a complete stop, the Orbiter Recovery Convoy began their work. First, a safety assessment team, fitted with special suits and breathing attire, checked vapor readings and tested for explosive and toxic gases, at a distance of about 1,250’ from the orbiter. Once they declared the area clear, the special Purge and Coolant Umbilical Access Vehicles were brought in behind the orbiter, where they checked for hydrogen vapors. If there was no hydrogen, the umbilicals were connected and the vehicle was purged with air to remove any residual explosive or toxic fumes. All of this occurred within forty-five to sixty minutes following full stop.[972] When it was determined that the area in and around the orbiter was clear, the crew exited the orbiter into a crew transport vehicle.[973]

Once the orbiter’s crew had left the vehicle, a team of support personnel entered the orbiter to prepare it for towing operations. Outside of the vehicle, technicians installed landing gear lock pins, disconnected the nose landing gear drag link, and positioned the towing vehicle in front of the orbiter. The orbiter was attached to the tow vehicle with a tow bar. Approximately four hours after landing, the tow vehicle pulled the orbiter from the Runway, along the Orbiter Towway, to

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[970] Slovinac, “Shuttle Landing Facility,” 18. For more information about the SLF and its design features, see Slovinac, “Shuttle Landing Facility.”
[971] Slovinac, “Shuttle Landing Facility,” 19.
[972] Slovinac, “Shuttle Landing Facility,” 19. If hydrogen was detected, which never happened, the crew was immediately evacuated and the convoy personnel are cleared from the area. These same procedures were followed at EAFB. NASA, *An overview*, 13.
[973] It was at this point that responsibility for the vehicle passed from JSC to KSC. Slovinac, “Shuttle Landing Facility,” 20. The same procedures were followed if the orbiter landed at EAFB. The orbiter was then ferried to KSC via a Shuttle Carrier Aircraft.

one of the OPF High Bays for between mission processing, which nominally required 125 days to complete.[974]

Orbiter Processing Activities

The first set of processing activities performed in the OPF High Bay were generally referred to as the "end-of-mission roll-in operations." Once the vehicle was aligned inside the High Bay, its "T-0" umbilicals were connected to ground support equipment within the facility, the orbiter's systems were connected to facility-provided utilities, and the vehicle's fuel cells were powered down. The orbiter was raised with hydraulic floor lifts, and mated to four orbiter jacks, two at the forward end and two at the aft end. The vehicle was then leveled, the connections were tightened, and the floor lifts were lowered. Two additional activities were begun during the "end-of-mission roll-in operations," and finished during the second set of operations. One task involved purging the three SSMEs to remove any moisture that was produced by the combustion of the LH2 and LO2. In addition, the cryogenic tanks for the orbiter's fuel cells were drained of residual reactants, and filled with gaseous nitrogen (oxidizer tanks) or gaseous helium (fuel tanks) to render them inert. A third task was to open the payload bay doors and install access platforms as required to support processing and safing activities.[975]

The second general set of operations performed in the OPF High Bay included "system safing and deservicing" activities. During this period, any remaining OMS and RCS oxidizer and fuel were drained, and the systems were purged. If necessary, the OMS pods and the FRCS module were removed and sent to KSC's Hypergol Maintenance Facility for further processing and maintenance. In addition, the three SSMEs were removed from the orbiter and taken to the SSME Processing Facility for processing.[976] Other activities included in the safing process were the removal, deservicing, and flushing of the waste control system; draining, filter removal, and purging of the potable water system and the water spray boilers; venting high pressure gases from the vehicle's ECLSS; and draining and purging the APUs.[977]

[974] Slovinac, "Shuttle Landing Facility," 20; USA, "Orbiter Processing Facility (Day One)," (presentation materials used for training, no date), 44. KSC had three OPF High Bays, distributed between two facilities (OPF and OPF-3). Prior to the *Columbia* accident in February 2003, when there were four active orbiters, the High Bays were assigned on a "first available" basis. Afterwards, the two bays in the OPF, High Bay No. 1 and High Bay No. 2, were devoted to *Atlantis* and *Endeavour*, respectively, and the OPF-3 High Bay (or High Bay No. 3) was dedicated to *Discovery*. Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Orbiter Processing Facility, High Bay No. 3 (John F. Kennedy Space Center)," April 2011, 23.

[975] Slovinac, "Orbiter Processing Facility," 23-24; USA, "Day One," 44; USA, "Orbiter Processing Facility (Day Two)," (presentation materials used for training, no date), 3. See Slovinac, "Orbiter Processing Facility," for more information about the OPF and its design features.

[976] The SSME Processing Facility was attached to OPF-3. Slovinac, "Orbiter Processing Facility," 24; USA, "Day Two," 6. See Slovinac, "Orbiter Processing Facility," for more information about the SSME Processing Facility and its design features.

[977] Slovinac, "Orbiter Processing Facility," 24; USA, "Day One," 44; USA, "Day Two," 6-8.

The major phase of orbiter processing operations was the "system testing, verification, and servicing" of every required functional orbiter system. This included the OMS/RCS, the fuel cell system, the window cavity conditioning system, the GNC system, the communications system, the OBSS (following the *Columbia* accident), the RMS, the APUs, the mechanical systems, and structural inspections. As part of these routine operations, individual components of each system could be removed, inspected, tested independently, and then reinstalled. If the component sustained significant wear or damage, it was generally replaced and tested as part of the system to ensure compatibility. At the same time, if a particular component presented problems during the mission, the troubleshooting of those problems occurred during this phase, and included removal of the element and its repair or replacement.[978]

Also during this phase of operations, visual inspections were conducted on the orbiter's TPS, the landing gear, and selected structural elements to determine if they sustained any damage during the flight. If technicians discovered significant damage to a TPS tile, either they created a foam version of the tile using the tile cavity as a mold, or they took a set of photographic images of the tile cavity. They then sent this information to the Thermal Protection System Facility, where a new tile was produced and delivered to the OPF for installation.[979] If damage to an insulation blanket was discovered, the component could be removed and sent to the Thermal Protection System Facility for repair if appropriate, or to be used as a pattern for a replacement.[980] In addition, after every flight, NASA engineers re-waterproofed all components of the vehicle's TPS. The procedure was necessary because the dimethylethoxysilane burned out when the temperature reached 1,050 degrees F, and exposed the TPS to water absorption.[981]

All of the tires from the nose and main landing gear were sent to the Shuttle Wheel and Tire Shop within the VAB.[982] Here, a bead breaker was used to remove the tire from the rim, which was then split and cleaned. The old tire was sent to the Logistics Facility for scrap, and the new tire was brought in from Logistics and installed on the rim.[983] After this, the tire underwent an initial inflation and a twenty-four hour pressure check. If it passed, an electrical check was performed on the tire, followed by a second pressure check that lasted for forty-eight hours. If all went well, the tire was then placed in a large freezer for 96 hours, after which it was checked for air and nitrogen loss.[984] Once all of this was completed, three longer-term checks were

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[978] Slovinac, "Orbiter Processing Facility," 24-25; USA, "Day Two," 9.
[979] In general, approximately seventy tiles were replaced on an orbiter after a flight.
[980] Slovinac, "Orbiter Processing Facility," 25; Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Thermal Protection System Facility (John F. Kennedy Space Center)," HAER No. FL-8-11-L, Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, April 2011, 18-21.
[981] Jenkins, *Space Shuttle*, 395-401.
[982] Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Vehicle Assembly Building (John F. Kennedy Space Center)," HAER No. FL-8-11-B, Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, July 2009, 18-19.
[983] The main tires (aft end) were generally good for one flight; the nose tires were good for two flights. Slovinac, "Vehicle Assembly Building," 18.
[984] This freezer test is highly important since it mimics conditions in space, and ensures that the tires are capable of being used for landing after a mission. Slovinac, "Vehicle Assembly Building," 19.

performed on the tires to certify them for flight. All of this required roughly sixty days to complete. Once certified, the tires were taken back to the OPF for installation on the orbiter.[985]

Another key task conducted during the "system testing, verification, and servicing" phase of orbiter operations was payload processing. The first step was to deconfigure the vehicle from the previous mission. This included disconnecting any vehicle power or mechanical systems that were attached to the previous payloads, removing any remaining payloads and their supports, and deconfiguring the appropriate control panels on the aft flight deck. The vehicle was then reconfigured for the next mission's payload requirements. Tasks included in this process were to install payload support mechanisms in designated places, perform payload pre-mate testing, configure the appropriate control panels on the aft flight deck, install the payloads, connect the payloads to the vehicle power and mechanical systems as required, and complete a payload integration verification test.[986]

OPF technicians also used this time to perform planned vehicle modifications, which were carried out in conjunction with the routine procedures. These changes to the vehicle were made based on future mission requirements, the need to resolve an identified deficiency, or to replace existing equipment with new, improved components designed to enhance the orbiter's performance.[987] The OPF High Bay also periodically served as the location for OMDPs and OMMs.[988]

One of the last tasks in the "system testing, verification, and servicing" phase of operations was a crew equipment interface test. For this procedure, the crewmembers for the upcoming mission traveled to KSC from their headquarters at JSC. They inspected the payload bay for sharp edges, which could pose a hazard to on-orbit operations, and familiarized themselves with the locations of specific payloads and how they would be accessed during the mission. In addition, the crew familiarized themselves with the arrangement of the middeck level of the crew cabin, including

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[985] Slovinac, "Vehicle Assembly Building," 19.

[986] Slovinac, "Orbiter Processing Facility," 25; USA, "Day Two," 16-19. Payloads were processed separately from the orbiter. Historically, payloads fell into one of two categories, horizontal payloads, meaning they were built up, integrated, and installed into the orbiter horizontally, or vertical, meaning they were built up, integrated, and installed into the orbiter vertically. Typically, all of the payload components were fabricated at their sponsor's laboratories, before being delivered to one of several facilities at KSC or CCAFS for additional processing for flight. The components were then moved to one of four facilities for final integration and testing; afterwards, one of two payload canisters, carried by one of two canister transporters, picked up the payload at its processing facility for transport to either the OPF (horizontal payloads) or the launch pad (vertical payloads) for installation into the orbiter. Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Canister Rotation Facility (John F. Kennedy Space Center)," HAER No. FL-8-11-K, Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, April 2011, 14-15.

[987] Slovinac, "Orbiter Processing Facility," 25-26.

[988] Up through February 2001, the OPFs at KSC shared this duty with the Shuttle Orbiter Final Assembly Building (Building 150) at AFP 42 in Palmdale, California. Beginning with *Discovery's* third OMDP in September 2002, all Down Period and Major Modifications were completed at KSC. ACI and Weitze Research, "NASA-wide Survey and Evaluation of Historic Facilities and Properties in the Context of the US Space Shuttle Program, Air Force Plant 42, 1 North, Palmdale, California" (survey report, NASA JSC, 2007).

the stowage locations of equipment planned for use during the mission, as well as the airlock configuration.[989]

The final set of operations conducted in the OPF High Bay was referred to as "vehicle closeouts/preparations for roll-over." One of the tasks included reinstalling the SSMEs, which then underwent a leak test to ensure the integrity of the entire main propulsion system. The maneuvering capabilities of the engine gimbals, as well as all vehicle aerosurfaces, were then checked. Also during this time period, any issues discovered during the crew equipment interface test were resolved, an orbiter compartment positive pressure check was performed, and a final checkout of the TPS was conducted. Technicians also serviced the potable water system, the gaseous nitrogen pressure vessels, and installed the electrically-initiated pyrotechnic devices. As the final checks were completed for each of the systems, the access panels were reattached to the vehicle.[990]

Various additional activities were completed in the OPF High Bay just prior to the vehicle's roll-over to the VAB. First, a weight and center of gravity verification of the vehicle was performed. Then, the orbiter transporter was brought into the High Bay, and the orbiter was mated to it through one forward attach point and two aft attach points. Then, the final landing gear strut inspection was performed, the tires were pressurized, and the wheel wells were inspected. Following these steps, the landing gear was retracted, and the doors closed. Once this was completed, the technicians performed the final power down of the vehicle and removed all connections to facility services, the attach points between the orbiter and the transporter were confirmed, and the transporter carried the orbiter out of the High Bay.[991]

Space Shuttle Vehicle Stacking Operations

In preparation for vehicle stacking procedures in the VAB, the Crawler Transporter (Crawler) left its parking site, and using the special "Crawlerway," was driven to the MLP parking site.[992] There, one of three MLPs was attached to the Crawler at four places; the Crawler lifted the platform and carried it to the east side of the VAB, where it entered either High Bay 1 or 3. Once in position in the specified High Bay, the MLP was lowered and mated to six support pedestals,

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[989] Slovinac, "Orbiter Processing Facility," 26; USA, "Day Two," 20.
[990] Slovinac, "Orbiter Processing Facility," 26-27; USA, "Day Two," 21.
[991] Slovinac, "Orbiter Processing Facility," 27; USA, "Day Two," 22-25.
[992] The Crawlers were constructed during the Apollo era, with the specific task of transporting assembled space flight vehicles from the VAB to the launch pad. For a detailed description of the Crawler, see Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Crawler Transporters (John F. Kennedy Space Center)," HAER No. FL-8-11-C, Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, September 2009. The MLP provided a base for the vertical integration and stacking of the complete Space Shuttle vehicle, and served as a launch platform. For a detailed description of the MLP, see Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Mobile Launcher Platforms (John F. Kennedy Space Center)," HAER No. FL-8-11-D, Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, September 2009.

and the platform was then detached from the Crawler, which was lowered and driven out of the VAB.[993]

With the MLP in place, the first part of the shuttle to be stacked was either the starboard or port SRB aft motor, which was brought to the VAB from the Rotation, Processing, and Surge Facility. The motor was placed on its designated hold down posts, to which it was attached using pyrotechnic bolts. Then, either the next segment for that SRB, or the second aft motor was brought in and attached to its hold down posts. The SRB stacking operations followed these procedures until each booster was four segments high, with the joint seals being visually inspected after every segment was mated. Once all four segments for each SRB were in place, a leak check and decay test was performed to verify the system's integrity. After verification, the forward skirt/nose assemblies were brought to the VAB from the SRB Assembly and Refurbishment Facility for integration. Then, an alignment check was performed, and the integrated and automated systems were tested using the Launch Processing System (LPS) to simulate the ET and the orbiter. This entire process generally required eighteen to twenty-two working days to complete, assuming no problems.[994]

When stacking and testing of the two SRBs was complete, the ET was lifted out of storage in VAB High Bay 4. It was positioned alongside the bay where the vehicle was being stacked, and moved into place. The ET was then mated to the SRBs, after which an interface test was conducted to ensure that the SRBs and ET were communicating with each other properly. Typically, the ET mating process was completed over one working day, and the close-out and interface tests required two to three working days. Once this was complete, the orbiter was brought to the VAB for stacking.[995]

The orbiter (*Discovery*, *Atlantis*, or *Endeavour*) entered the VAB atop the orbiter transporter, and was positioned next to the High Bay where the stacking was taking place. While in the transfer aisle, the two overhead cranes were attached to the orbiter with special slings, and the orbiter was rotated to a vertical position. While in the vertical position, photographs were taken of the wing leading edges and the underside of the orbiter.[996] The orbiter was then lifted, carried into the High Bay, and lowered into position. The orbiter was first attached to the ET at its aft end, and then at the forward end. This process generally required seven working days. Afterwards, various check-out procedures were completed. As part of this process, all umbilicals were connected, and then electrical and mechanical verification tests were conducted to verify all connections.

[993] Slovinac, "Vehicle Assembly Building."
[994] Slovinac, "Vehicle Assembly Building," 16-17.
[995] Slovinac, "Vehicle Assembly Building," 17.
[996] This action was initiated in response to the *Columbia* accident. Once in space, the orbiter conducted a roll-over, which allowed the astronauts in the ISS to photograph the same areas. These images were sent to KSC, where they were compared with those taken in the VAB, to ensure the TPS was intact. Slovinac, "Vehicle Assembly Building," 17.

Following this, all vehicle and vehicle-to-ground interfaces were checked using the LPS. Finally, the pyrotechinic devices were installed on the vehicle.[997]

Once the Space Shuttle vehicle was ready to go to the launch pad, the Crawler returned to the High Bay, and was mated to the MLP. Then, the Crawler carried the Shuttle and MLP combination along the Crawlerway to either LC 39A (3.5 miles) or LC 39B (5 miles), at a speed of one mile per hour, requiring 160 gallons of fuel per mile.[998] With its leveling system, the Crawler was able to keep the Shuttle within one foot of vertical during the approximate six hour trip from the VAB to the launch complex. Inside the launch complex gate, the Crawler was slowed to approximately one-third of a mile per hour to travel up the 0.25 mile, five degree inclining ramp to the launch pad.[999]

Launch Pad Preparations

At the pad, the Shuttle and MLP combination was aligned and attached to the six standard support pedestals, as well as four additional supports, which help to stiffen the platform against rebound loads in the case of main engine cutoff.[1000] Afterwards, all ground electrical power, data and communications interfaces, and ET propellant transfer lines between the launch pad and the Space Shuttle were connected through the MLP's Tail Service Masts and validated.[1001] Once this was complete, the Crawler was driven to the outside of the launch complex's perimeter fence, where it waited to carry the MLP back to its parking site after the Shuttle was launched.[1002]

At the pad, the orbiter's propulsion, EPS, and ECLSS, as well as the vehicle itself, underwent their final preparations for flight. When the Space Shuttle reached the launch pad, the orbiter was missing its base heat shield carrier panels, a part of its TPS, because technicians needed to access the orbiter's aft compartment to complete the final processing of the SSMEs. At the pad, the SSMEs were subjected to a walkdown inspection, followed by a helium signature test to check for any systems leaks, an electrical system checkout, a ball seal leak check, and finally, a Flight Readiness Test to ensure that all of the hydraulic systems were working properly. The final closeout of the aft compartment typically occurred within one week prior to launch, after the "aft

[997] Slovinac, "Vehicle Assembly Building," 17-18.
[998] Unloaded, the Crawler can travel up to two miles per hour. The Crawlerway is an Alabama River Rock-covered roadway designed during the Apollo era to support the combined weight of the Crawler and the spacecraft. Slovinac, "Crawler Transporters," 16.
[999] Although the driving time typically amounted to six hours, the entire process could take twelve to fourteen hours. Slovinac, "Crawler Transporters," 16; Linda Herridge, "Crawler group keeps shuttle rolling along," *Spaceport News,* May 30, 2008, 8.
[1000] For a more detailed description of the Launch Pad, see Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Pad A (John F. Kennedy Space Center)," HAER No. FL-8-11-F, Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, August 2010.
[1001] Slovinac, "Mobile Launcher Platform," 14. The Launch Processing System, which controlled all launch operations from the LCC, was linked to the Space Shuttle/MLP through the Pad Terminal Connection Room within the pad hardstand. Slovinac, "Launch Complex 39, Pad A," 15.
[1002] Slovinac, "Crawler Transporter," 17.

confidence test," in which all aft systems were powered up to ensure everything was working properly. Once the aft compartment was closed, the base heat shield carrier panels were installed, and various checkouts and systems purges were performed in preparation for propellant loading; the final SSME checkouts were conducted the day before the scheduled launch.[1003]

Processing of the orbiter's OMS and RCS began approximately one week after the vehicle's arrival at the pad. Over a period of roughly seven days, these two systems underwent a propellant servicing process, which included filling the fuel and oxidizer tanks and checking for leaks or other problems. The orbiter's APU/hydraulic system also underwent final processing at the pad, which included filling the fuel tanks. Additional work on the APU system included servicing the gaseous nitrogen pressurization tanks; a hot fire of the APUs to be sure all components were working properly; and a leak test. The hydraulic components underwent their own specific tests.[1004]

Typically, small payloads were installed in the orbiter's payload bay while it was in the OPF High Bay; larger payloads, however, were installed at the launch pad. These payloads were brought to the launch pad inside one of two payload canisters, usually before the arrival of the Space Shuttle vehicle. The payload canister was lifted and aligned with the payload changeout room doors, and the payloads were then moved into the changeout room. After the Space Shuttle vehicle was in place and the rotating service structure was moved into position, enclosing the orbiter's Payload Bay, the payloads were transferred to the vehicle. Once the payloads were installed, all payload connections were made and a payload/orbiter interface test was conducted, followed by a payload contamination walkdown. After all these tasks were completed, the payload bay doors were closed.[1005]

Approximately two days before launch, the EPS's power reactant storage and distribution system tanks were loaded with LO2 and LH2. The three fuel cells were activated roughly fifteen hours before launch so technicians could perform a variety of tests to check for leaks or other problems.[1006] The processing of the orbiter's ECLSS was aided by the Environmental Control Systems Room below the pad surface, which provided air to the orbiter's crew cabin at specified temperatures, humidities, and pressures to maintain a controlled environment in these areas. Final checkout procedures on the ECLSS included a flash evaporator purge, necessary to ensure the system functions properly, as well as the removal of the plugs on the ammonia boiler, vacuum, and flash evaporator vent ports. Subsequently, the vacuum vent was purged every twenty-four hours in the event of launch scrubs, when the fuel cells were kept on-line.[1007] Approximately one week prior to the launch, pad personnel installed all of the equipment lockers and flight seats into the orbiter's middeck.[1008]

[1003] Slovinac, "Launch Complex 39, Pad A," 16.
[1004] Slovinac, "Launch Complex 39, Pad A," 17.
[1005] Slovinac, "Launch Complex 39, Pad A," 20-21.
[1006] Slovinac, "Launch Complex 39, Pad A," 17.
[1007] Slovinac, "Launch Complex 39, Pad A," 17-18.
[1008] Slovinac, "Launch Complex 39, Pad A," 18.

There was little processing work to be done on the SRBs at the launch pad. The only booster-specific process was the use of moveable carts to fill the SRBs' hydraulic power units with MMH. Additional work on the boosters fell under the procedures for overall Space Shuttle systems processing, which included various electrical tests and checkouts to ensure that the electrical systems and connections between the shuttle components were operational. One such test was the Range Safety System functional test to ensure that the shuttle's range safety system, meant to destroy the SRBs and ET in the event of a trajectory violation, was operational. Also performed was a checkout of the shuttle's pyrotechnic system, which included completing the wiring of all circuitry, resistance and load testing, and the final "Pyro Initiator Controller" test.[1009]

Launch Countdown

A call to stations from KSC's Launch Control Center firing room initiated the Shuttle countdown sequence.[1010] A typical Space Shuttle launch countdown began approximately seventy-two hours prior to launch, at T-43 hours and counting.[1011] For the next sixteen hours, final checkouts of the vehicle were conducted, software was loaded, and the middeck and flight deck platforms were removed. Around T-28 hours, preparations began for loading the orbiter's fuel cell power reaction and storage distribution systems. At T-27 hours and holding, a four-hour hold commenced while the launch pad was cleared of all non-essential personnel. When the countdown began again, the cryogenic reactants for the fuel cells were officially loaded into the storage tanks. Another hold began at T-19 hours and holding, when the orbiter's midbody umbilical unit was demated; this hold usually lasted about four hours.[1012] When the countdown began again, at T-19 hours and counting, final preparations were made for loading the ET with the fuel and oxidizer for the main engines, filling the water tank for the sound suppression system, and closing out the Tail Service Masts on the MLP.[1013]

At T-11 hours and holding, the orbiter's communications systems were activated. This hold sequence typically lasted twelve to thirteen hours. Once countdown resumed, the orbiter's fuel cells were activated, and non-essential personnel were cleared from the blast area. At T-6 hours and holding, typically a two-hour hold, the launch team verified that there were no violations of the launch commit criteria, and all personnel were cleared from the launch pad. In addition,

[1009] Slovinac, "Launch Complex 39, Pad A," 18.
[1010] For additional information on the Launch Control Center, see Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Launch Control Center (John F. Kennedy Space Center)," HAER No. FL-8-11-A, Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, January 2009.
[1011] The discrepancy between the official designation of T-43 hours and the reality that the clock was started roughly seventy-two hours prior to launch, was due to built in hold periods throughout the sequence, in which certain actions were performed, and conditions and processes were verified. These holds lasted from as little as ten minutes to as long as thirteen hours, assuming there were no unanticipated delays. Slovinac, "Launch Control Center," 17.
[1012] The orbiter midbody umbilical unit was comprised of flexible hoses that fed propellants, GN2 and GHe into the orbiter's fuel cells. Slovinac, "Launch Complex 39, Pad A," 17.
[1013] Slovinac, "Launch Control Center," 17.

fueling procedures for the ET began; ET fueling continued through the T-6 hours and counting stage. The two propellants, LO2 and LH2, were loaded onto the tank, through the two Tail Service Masts on the MLP; LO2 through the starboard mast and LH2 through the port mast. Gaseous nitrogen was pumped to a vent arm, with a vent hood at its end (commonly referred to as the "beanie cap"), to warm the oxygen vapors being vented at the top of the ET from the LO2 tank. This prevented ice from forming at the top of the tank, which could potentially break loose during launch and damage the orbiter.[1014]

At T-3 hours and holding, the final inspection team proceeded to the launch pad for a detailed analysis of the Space Shuttle vehicle. In addition, the closeout crew began to configure the crew module for countdown and launch. After this two hour hold, at T-3 hours and counting, the astronauts arrived at the launch pad and began their entry into the orbiter. Additional air-to-ground voice checks were conducted between the Launch Control Center and Mission Control. The orbiter crew hatch was closed and checked for leaks before the closeout crew retreated to the fallback area.[1015]

Beginning at T-20 minutes and holding, the Shuttle Test Director conducted the final briefings for the launch team, and preflight alignments of the inertial measurement units were completed. After this ten-minute hold, the countdown began again at T-20 minutes and counting. During this period, the orbiter's GPCs and backup flight system were switched to launch configuration, and the thermal conditioning for the fuel cells was begun. The final built-in hold occurred at T-9 minutes and counting, when the Launch Director, the Shuttle Test Director and the Mission Management Team confirmed a go/no go for launch. This hold varied in length depending on the mission. Final countdown began at T-9 minutes and counting. At this time, the automatic ground launch sequencer was started, and final tests and preparations for launch were completed.[1016]

At about two-and-a-half minutes before launch, the ET vent hood was raised, and its arm was retracted. The arm was not latched into place until SRB ignition (at lift-off) in the event of a hold on the launch, which allowed the arm to be re-extended. Ten seconds prior to SSME ignition, the hydrogen burnoff system, located within the MLP Tail Service Masts, engaged. This system eliminated any hydrogen molecules floating around the engines to prevent an explosion at launch. At sixteen seconds prior to SRB ignition, the water-based sound suppression system initialized from the water tower to the northeast of the launch pad. This water blanketed the surfaces of the MLP to absorb the acoustical pressures and prevent damage to the orbiter and its payloads.[1017]

[1014] Slovinac, "Launch Control Center," 17, Slovinac, "Launch Complex 39, Pad A," 18. At different stages during launch preparation and countdown, these lines fed propellants to the two OMS pods, the FRCS, the orbiter fuel cells, and the ET. Additionally, the masts provided umbilicals for various gases, including GH2, GO2, GHe, and GN2; connections for ground and flight coolants; lines for electrical power and purge air; and links for ground-to-vehicle data and communications.
[1015] Slovinac, "Launch Control Center," 17.
[1016] Slovinac, "Launch Control Center," 17-18.
[1017] Slovinac, "Launch Complex 39, Pad A," 18-20; Slovinac, "Mobile Launcher Platform," 15.

The Right SSME was ignited at T-6.60 seconds, followed by the Left SSME at T-6.48 seconds and the Center SSME at T-6.36 seconds. The SRBs were ignited at liftoff, or T-0. At SRB ignition, the pyrotechnic bolts that attached the boosters to their hold-down posts exploded. With this explosion, the stud to which the SRB was mounted was forced downward into a deceleration stand, and the pieces of the bolt assembly were captured within a spherical debris catcher at the top of the hold-down post. Once the Space Shuttle successfully launched, the MLP was left in place at the pad to cool, and was then washed down to remove any chemicals from the vehicle's propellants. Afterwards, all umbilicals and interfaces were disconnected from the launch pad, and the MLP was transported back to the VAB or the maintenance site by the Crawler.[1018]

Mission Control

Once the Space Shuttle cleared the Launch Pad's Fixed Service Structure, responsibility for the vehicle was transferred to Mission Control. Approximately two days before launch, the Ground Controller (see below) began to man his station, and communicate with the now powered-up vehicle at the launch pad. At T-12 hours to launch, the remainder of the flight controllers arrived at the flight control room, and began their preparations for the flight. The flight control team operated over three shifts, to cover the entire twenty-four hour day. There were twenty-three designated flight controller positions, as follows:

1. The Flight Director (FLIGHT) was the designated leader of the team, who controlled the overall mission and payload operations and made decisions with regards to the crew's safety.
2. The Mission Operations Directorate Manager (MOD) provided an interface between the Flight Control Room (FCR) and top NASA officials and mission managers.
3. The Spacecraft Communicator (CAPCOM) served as the link between the FCR and the astronauts.
4. The Flight Activities Officer (FAO) planned and supported all crew checklists, procedures and schedules, and planned and managed the orientation of the orbiter in space.
5. The Payload Deployment and Retrieval Systems (PDRS) Manager supported the operations of the remote manipulator system, or robot arm, and coordinated the deployment, retrieval, and positioning of satellites and other cargo.
6. The Public Affairs Officer (PAO) provided mission commentary to the news media and the public.
7. The Instrumentation and Communications Officer (INCO) monitored the in-flight communications and instrument systems, and controlled the orbiter's TV system.
8. The Data Processing Systems Engineer (DPS) Manager monitored the status of the data processing systems, including the five GPCs on the orbiter, the flight-critical and launch data lines, and the multifunction display systems. In addition, the manager watched the mass memories and systems level software.

[1018] Slovinac, "Mobile Launcher Platform," 15-16.

9. The Payloads Officer (PAYLOADS) coordinated the interfaces between the flight crew and the payload users, and monitored the on-board experiments and satellites.
10. The PAYLOADS console was shared with the Assembly and Checkout Officer (ACO), who was responsible for the development of ISS.
11. The Guidance, Navigation and Control Systems Engineer (GNC) monitored the vehicle's GNC system and advised the crew of any guidance hardware malfunctions. He/she also notified the flight director and crew of any impending aborts.
12. The Propulsion Officer (PROP) monitored and evaluated the orbiter's RCS and OMS jets and propellants.
13. The Flight Dynamics Officer (FDO) planned maneuvers and monitored trajectories.
14. The Trajectory Officer (TRAJECTORY) assisted the FDO during the dynamic phases of flight, and was responsible for maintaining the trajectory processors in Mission Control.
15. The Ground Controller (GC) monitored Mission Control hardware, software and support facilities. In addition, he/she maintained the links between the Ground Space Flight Tracking and Data Network (GSTDN) and the TDRSS, with Goddard Space Flight Center.
16. The Maintenance, Mechanical, Arm and Crew Systems Officer (MMACS) monitored the orbiter's structural and mechanical systems, and on-board crew hardware and equipment.
17. The Electrical Generation and Illumination Engineer (EGIL) monitored the orbiter's electrical systems, fuel cells and their cryogenics, the ac and dc circuits, pyrotechnics, lighting, and the caution and warning systems.
18. The Emergency, Environment and Consumables Operations Manager (EECOM) monitored the passive and active thermal controls, the cabin atmosphere, the avionics cooling, the supply and waste water system, and the fire detection and suppression system.
19. The Surgeon (SURGEON) monitored the crew's health and coordinated any medical operations.
20. The Rendezvous Guidance and Procedures Officer (RENDEZVOUS) monitored a shuttle mission during deployment, rendezvous and proximity operations, and docking and undocking operations.
21. The Ascent/Entry Guidance and Procedures Officer (GUIDANCE), who monitored the guidance and navigation systems and execution of crew procedures in an ascent abort contingency, shared a console with RENDEZVOUS.
22. The Booster Systems Engineer (BOOSTER) monitored and evaluated the MPS, SSMEs, SRBs, and ET during launch and ascent, and the MPS during entry.
23. The Extravehicular Systems Activities Director (EVA) coordinated spacewalks from both the shuttle and the ISS and shared a console with BOOSTER.[1019]

During the mission, each of the flight controllers had three to five specialists who monitored both ground and orbiter systems. This enabled a quick response to a contingency situation.

[1019] Patricia Slovinac and Joan Deming, "Mission Control Center (Building 30)" (documentation package, NASA JSC, 2011), 21-23.

Additionally, these specialists provided detailed analysis information to the controllers, if requested.[1020]

Ferry Flights

Turnaround Operations

According to Donald L. McCormack, NASA Ferry Operations manager, preparing the orbiter for ferry operation from Edwards AFB to KSC was done over a period of seven days. This was referred to as a "turnaround operation." After landing at Edwards, the orbiter was towed to Shuttle Area A at DFRC (at Edwards AFB), and "spotted" in the MDD.[1021] Operations performed during this time included the following:

- A dry nitrogen purge of the SSMEs to remove moisture
- Power reactant and storage distribution system off-load to remove the cryogenic oxygen and hydrogen from the tanks as well as fuel cell purging
- De-stowing the crew module to remove middeck payloads, the EMUs, and various other equipment
- Installing mechanical locks on the SSMEs and the elevon flight control surfaces to lock them into the position required for ferry
- Draining a small quantity of propellant from the OMS engine ball valves to prevent seal deterioration
- Installing the tail cone for the reduction of aerodynamic drag. The tail cone was attached to the orbiter's base heat shield at eight attach points. This was one of the last operations performed prior to actual mating, and took two to three shifts to accomplish. Tail cone installation typically began about five days after landing.
- Raising the orbiter about fifty feet. The SCA was towed into the MDD, and the orbiter was lowered into position on the SCA and attached at two aft and one forward points. These three attach locations were the same as those used when the orbiter was mated to the ET. The mate process typically took about twelve hours.[1022]

The around-the-clock turnaround operation team at Edwards AFB consisted of approximately 150 people, which included a large group from KSC who arrived about twenty-four hours after the shuttle landed.[1023] Typically, the orbiter was mated to the SCA and ready to be ferried within seven to nine days of landing.

[1020] Slovinac and Deming, "Mission Control," 23.
[1021] The MDDs located at both Edwards AFB and at the KSC SLF were specially designed and built to provide structural support for the mate (attachment) and demate (detachment) of the orbiter and the SCA. The mate and demate processes are relatively straightforward, and are essentially opposite of one another. Slovinac, "Shuttle Landing Facility."
[1022] McCormack, interview, 2-4.
[1023] McCormack, interview, 3.

Flight Procedures

The crew for the post-mission ferry flight consisted of two pilots and two flight engineers aboard the SCA. The flight path was not the same for each ferry operation. McCormack stated that “the weather always drives when we fly and the route we take.”[1024] The orbiter could not be flown through rain, to prevent damage to the tiles. Severe weather also was avoided. Temperature and pressure were additional constraints; the minimum temperature was 15 degrees F and the minimum ambient pressure was 8 psia. Because of these limits, the SCA generally flew low, in the range of 11,000’ to 16,000’.[1025] Before every flight leg, a weather briefing was conducted to determine if the flight could proceed. The SCA also was required to fly only during daylight hours. According to Flight Engineer Henry Taylor, the SCA was allowed to take off up to twenty minutes before sunrise, and had to land no later than twenty minutes after sunset. The mated SCA/orbiter could weigh no more than 710,000 pounds at takeoff.[1026]

The weight of the orbiter impacted the performance of the SCA. Variable orbiter weight resulted, foremost, from what was returned in the payload bay. The typical weight range for end-of-mission ferry flights was about 195,000 to 230,000 pounds.[1027] When the orbiters were initially delivered to KSC their estimated weights ranged from 158,289 pounds (*Columbia*) to 151,205 pounds (*Endeavour*), without the engines installed[1028]. Following the eight major modifications performed at Palmdale, orbiter weight ranged between approximately 154,000 and 161,000 pounds. The heaviest orbiter ever ferried was *Discovery* after STS-114; it carried a MPLM in the payload bay, and weighed almost 228,000 pounds.

A “pathfinder” aircraft, flown by an experienced SCA pilot, took off prior to the SCA and flew approximately 100 miles ahead. The type of aircraft used as the pathfinder varied. In the winter, there were requirements to provide a heated purge of the orbiter at overnight stopovers if the overnight temperature was expected to be below 45 degrees F for more than four hours. Therefore, specialized purge equipment was needed. In these cases, a USAF C-141 or C-17 was used. When purge equipment was not needed, a NASA JSC aircraft, such as a KC-135 or a C-9, typically served as the pathfinder vehicle. The pilot in the pathfinder was in radio contact with the pilots in the SCA, providing guidance to safely navigate through challenging weather conditions.[1029] This aircraft also transported all required support equipment and the thirty to thirty-five person ferry flight team, including the ferry manager, weather officers, all the KSC support personnel, the mechanics and maintenance crew, and safety and security personnel.[1030]

[1024] McCormack, interview, 6.
[1025] McCormack, interview, 6.
[1026] Taylor, interview, 7.
[1027] McCormack, interview, 8.
[1028] The SSMEs added approximately 20,000 pounds to the total empty weight of each orbiter. NASA KSC, “Orbiter Vehicles,” http://www.pao.ksc.nasa.gov/shuttle/resources/orbiters.html.
[1029] McCormack, interview, 8-9.
[1030] Taylor, interview, 22.

During the transcontinental trip between California and Florida, the SCA typically stopped several times to refuel. A heavier orbiter required at least three refueling stops, sometimes four. Historically, more than twenty military bases and a few international airports located across the southern one-third of the US supported ferry operations. Military bases were used almost all the time because of their security and support capabilities.[1031] Under the most favorable conditions, with good weather and a light orbiter, the cross country trip could be made in one day with two legs; with bad weather, it could stretch out to four days or more. Typically, a ferry flight was accomplished in three or four legs flown over a period of two to three days, with one or two rest stops. A refuel required only a few hours on the ground. The average fuel burn for the SCA during a ferry flight was about 5,750 gallons per hour.[1032] Each SCA contained seven fuel tanks, including four main, one center wing, and two reserve. "We normally only use fuel out of the mains and reserves," Taylor related.[1033]

Upon landing at a stopover, a safety assessment was performed before the flight crew could depart the SCA. This consisted of toxic vapor tests and visual inspections for damage performed by KSC personnel. In the case of an overnight stop, base security personnel set up a perimeter that was at least 200' from the SCA. Military personnel controlled the single entry point established and monitored the restricted area.[1034] When the plane landed at KSC, a safety assessment was conducted, and then the mated vehicle was towed to the MDD. Typically, within about sixteen hours, the orbiter was demated from the SCA and towed to the OPF.[1035]

[1031] Taylor, interview, 21.
[1032] McCormack, interview, 10, 12.
[1033] Taylor, interview, 7.
[1034] McCormack, interview, 12.
[1035] McCormack, interview, 15.