

2.8 ELECTRICAL POWER SYSTEM (EPS)

CONTENTS	
Description	2.8-1
Power Reactants Storage and Distribution System	2.8-1
Fuel Cell System	2.8-10
Electrical Power Distribution and Control	2.8-20
Operations	2.8-30
EPS Caution and Warning Summary	2.8-32
EPS Summary Data	2.8-38
EPS Rules of Thumb	2.8-38

Description

The electrical power system (EPS) consists of the equipment and reactants that produce electrical power for distribution throughout the orbiter vehicle, and fulfill all the orbiter external tank, solid rocket booster, and payload power requirements, when not connected to ground support equipment. The EPS operates during all flight phases. For nominal operations, very little flight crew interaction is required by the EPS.

The EPS is functionally divided into three subsystems: power reactants storage and distribution (PRSD), three fuel cell power plants (fuel cells), and electrical power distribution and control (EPDC).

Through a chemical reaction, the three fuel cells generate all 28-volt direct-current electrical power for the vehicle from launch minus 3 minutes 30 seconds through landing rollout. Prior to that, electrical power is provided by ground power supplies and the onboard fuel cells.

Power is controlled and distributed by assemblies located in the forward, mid, and aft sections of the orbiter. Each assembly is a housing for

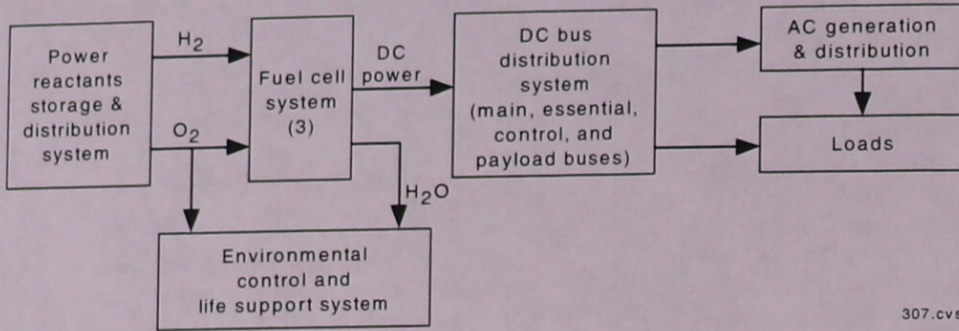
electrical components such as remote switching devices, buses, resistors, diodes, and fuses. Each assembly usually contains a power bus or buses and remote switching devices for distributing bus power to subsystems located in its area.

Power Reactants Storage and Distribution System

The power reactants storage and distribution system stores the reactants (cryogenic hydrogen and oxygen) and supplies them to the three fuel cells that generate all the electrical power for the vehicle during all mission phases. In addition, the subsystem supplies cryogenic oxygen to the environmental control and life support system (ECLSS) for crew cabin pressurization. The hydrogen and oxygen are stored in tanks at cryogenic temperatures (-285°F for liquid oxygen and -420° F for liquid hydrogen) and supercritical pressures (above 731 psia for oxygen and above 188 psia for hydrogen).

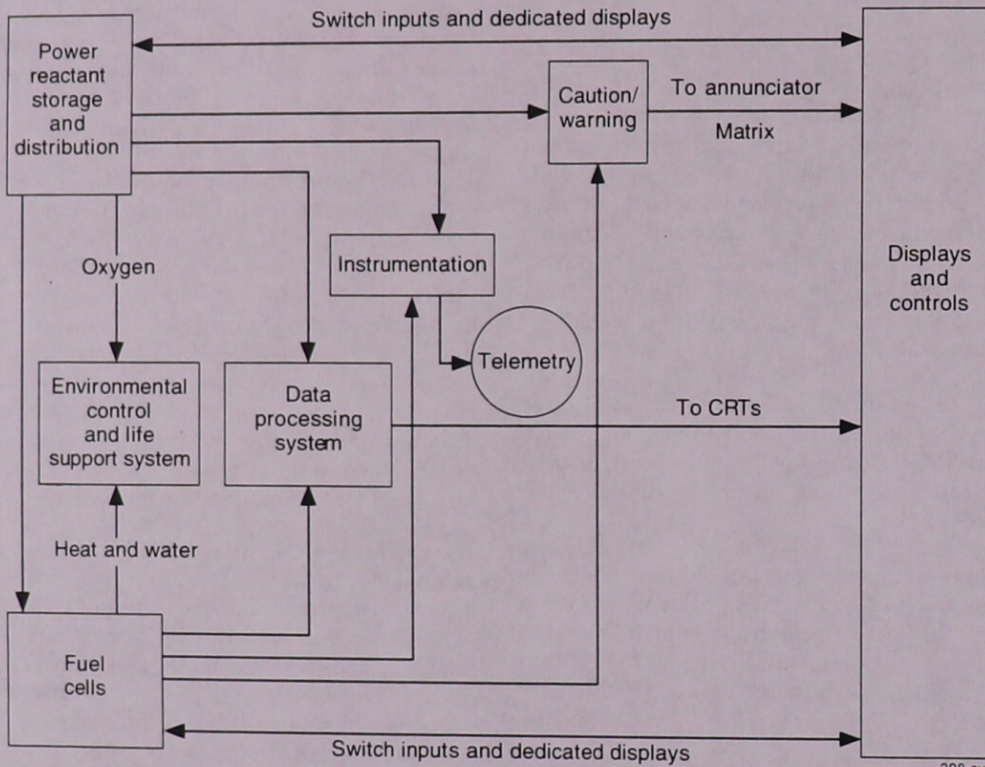
The PRSD system components are located in the orbiter midbody underneath the payload bay liner or on a payload bay pallet for 10+ day missions in extended duration orbiter (EDO) vehicles. The system stores the reactants hydrogen and oxygen in double-walled, thermally insulated spherical tanks with a vacuum annulus between the inner pressure vessel and outer tank shell. Each tank has heaters to add energy to the reactants during depletion to control pressure. Each tank is capable of measuring quantity remaining.

The tanks are grouped in sets of one hydrogen and one oxygen tank. The number of tank sets installed depends on the specific mission requirement and vehicle. Up to five tank sets can be installed in the midfuselage under the payload bay liner of OV-102, -103, -104, and -105. Up to four additional tank sets can be flown on the EDO pallet in the payload bay of OV-102 and -105. OV-105 may be configured at a later date to fly up to four additional tank sets (total of eight additional sets). Switches to control these tanks are already installed.



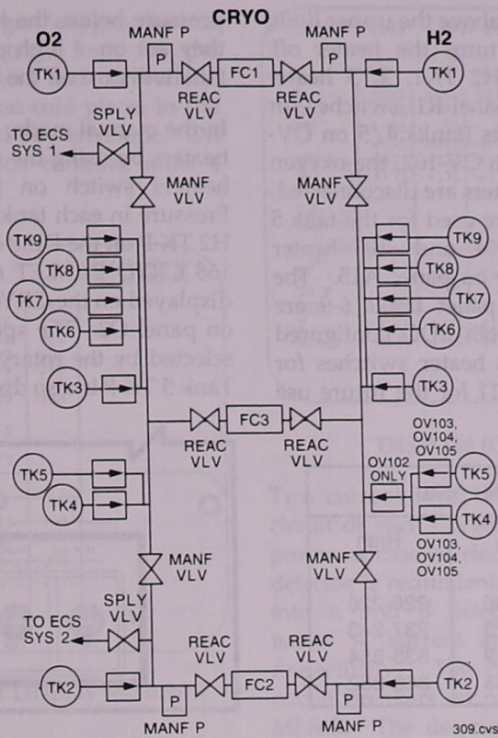
307.cvs

The Electrical Power System



308.cvs

Electrical Power System Interfaces



The PDRS System

Cryogenic Storage Tanks

All oxygen tanks are identical and consist of inner pressure vessels of Inconel 718 and outer shells of aluminum 2219. The inner vessel is 33.435 inches in diameter and the outer shell is 36.8 inches in diameter. Each tank has a volume of 11.2 cubic feet and stores up to 781 pounds of oxygen. The dry weight of each tank is 215 pounds. Maximum fill time is 45 minutes.

All hydrogen tanks also are identical. Both the inner pressure vessel and the outer shell are constructed of aluminum 2219. The inner vessel's diameter is 41.51 inches and the outer shell's is 45.5 inches. The volume of each tank is 21.39 cubic feet, and each stores up to 92 pounds of hydrogen. Each tank weighs 227 pounds dry. Maximum fill time is 45 minutes.

The inner pressure vessels are kept supercold by minimizing conductive, convective, and radiant heat transfer. Twelve low-conductive supports suspend the inner vessel within the outer shell. Radiant heat transfer is reduced by a shield between the inner vessel and outer shell

(hydrogen tanks only), and convective heat transfer is minimized by maintaining a vacuum between the vessel and shell. During ground operations, a vacuum ion pump maintains the required vacuum level and is also used as a vacuum gauge to determine the vacuum's integrity. The pump consists of an electrical power supply and an anode, which absorbs free ions between the tank walls.

Cryogenic Tank Heaters

Each hydrogen tank has one heater probe with two elements; each oxygen tank has two heater probes with two elements per probe. As the reactants are depleted, the heaters add heat energy to maintain a constant pressure in the tanks.

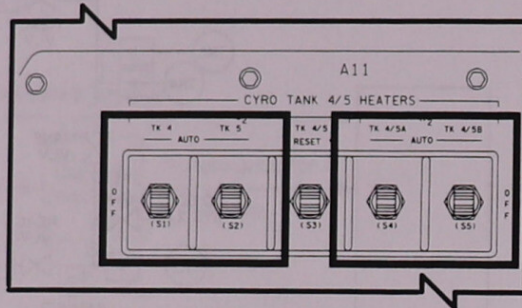
The heaters operate in automatic and manual modes. In the automatic mode, the heater is controlled by a tank heater controller. Each heater controller receives a signal from a tank pressure sensor. If pressure in a tank is less than or equal to a specific pressure, the controller turns the heater on. When the

pressure in the tanks goes above the upper limit, the respective controller turns the heater off. The O₂ TK1, 2, 3, and H₂ TK1, 2, 3 heater switches are located on panel R1; switches for the O₂ and H₂ TK4 heaters (tanks 4/5 on OV-102) are on panel A11. (On OV-102, the oxygen and hydrogen tank 4 B heaters are disconnected, and the logic and power are used for the tank 5 A heaters.) OV-103, -104, and -105 heater switches for tank set 5 are on panel A15. The heater switches for EDO pallet tanks 6-9 are located on panel A15 in both EDO configured vehicles. OV-105 also has heater switches for tank sets 10-13 on panel A11 for the future use of a second EDO pallet.

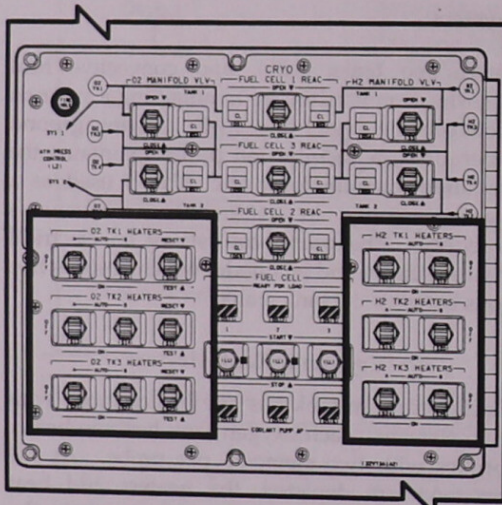
pressure before the heaters will turn on. Once they are on, a high pressure signal from either tank will turn off the heaters in both tanks.

In the manual mode, the flight crew controls the heaters by using the *ON OFF* positions for each heaters switch on panel R1, A11, or A15. Pressure in each tank is shown as O₂ TK P and H₂ TK P on the DISP 68 CRYO SYSTEM or DISP 168 CRYO PALLET displays. Pressure is also displayed on the CRYO O₂ and H₂ PRESS meters on panel O2. The specific tank (1, 2, 3, or 4) is selected by the rotary switch below the meters. Tank 5 TK P is also displayed on OV-105.

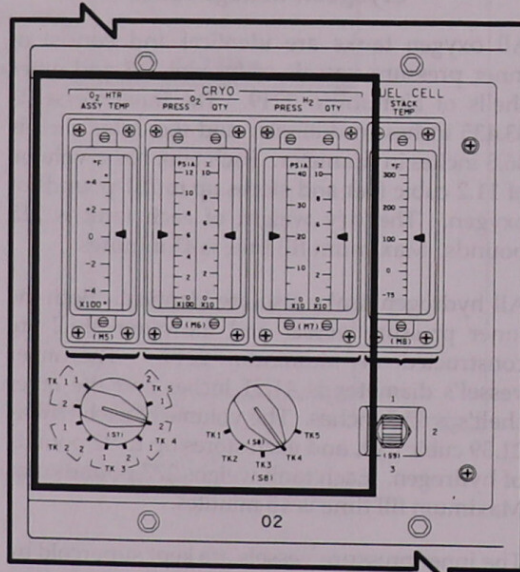
Heater controller psia		
Pressure limits (psia)	Low	High
H ₂ tank 1, 2	200-206	220-226
H ₂ tank 3-9	217-223	237-243
O ₂ tank 1,2	803-819	838-854
O ₂ tank 3-9	832-848	866-882



CRYO TANK 4 HEATER Switches on Panel A11



O2 and H2 TK HEATERS Switches on Panel R1



Cryogenic System Meters and Switches on Panel O2

Dual-mode heater operation is available for pairs of oxygen and hydrogen tanks. If the heaters of both tanks 1 and 2, or tanks 3 and 4, are put in the automatic mode, the tank heater logic is interconnected. In this case, the heater controllers of both tanks must sense a low

Each tank set has a hydrogen/oxygen control box that contains the electrical logic for the hydrogen and oxygen heaters and controllers. The control box is located on cold plates in the midbody under the payload bay envelope. On OV-102, a single control box controls tanks 4 and 5.

2011/ /068 CRYO SYSTEM 4 000/02:34:40 000/00:00:00					
O2	TK				
P	827	826	871	826	826
TK P	828	828	871	828	828
QTY	99	99	100	100	100
T	-249	-249	-249	-249	-249
HTR T 1	-249	-249	-182	-249	-249
2	-249	-249	-182	-249	-249
HTR 1A					
CUR 1B				4/5	
SNSR 2A					
2B				4/5	
MANF P	871	871			
VLV	OP	OP			
H2					
P	215	213	224	213	213
TK P	215	214	224	214	214
QTY	97	97	99	99	99
T	-417L	-417L	-417L	-417L	-417L
HTR T	-417L	-417L	-417L	-417L	-417L
MANF P	222	222			
VLV	OP	OP			

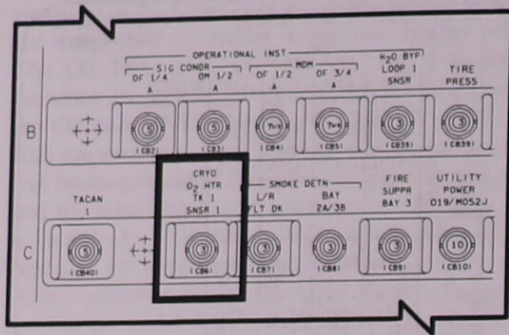
DISP 68 CRYO SYSTEM Display (on orbit)

The CRYO O₂ HTR ASSY TEMP meter on panel O2, in conjunction with the rotary switch below it, selects one of the two heaters in each tank and permits the temperature of the heater element to be displayed. The range of the display is from -425° F to +475° F. The temperature sensor in each heater also is hard-wired directly to the caution and warning system, which drives the yellow O₂ HEATER TEMP light on panel F7. This light is illuminated if the temperature is at or above 344° F. A signal also is sent to the GPCs where software checks the limit; if the temperature is at or above 349° F, the BACKUP C/W ALARM light on panel F7 is illuminated. This signal also is displayed on DISP 68 CRYO SYSTEM and transmitted to the ground.

2011/ /168 CRYO PALLET 4 000/02:38:52 000/00:00:00					
O2	TK				
P	515L	515L	515L	515L	PALLET
TK P	0L	0L	0L	0L	STB
QTY	- 5L	- 5L	- 5L	- 5L	STB
T	-417L	-417L	-417L	-417L	POP
HTR T 1	-417L	-417L	-417L	-417L	POP
2	-417L	-417L	-417L	-417L	
HTR 1A					PALLET
CUR 1B					PPO
SNSR 2A					
2B					
H2					
P	145L	145L	145L	145L	
TK P	0L	0L	0L	0L	
QTY	- 6L	- 6L	- 6L	- 6L	
T	-417L	-417L	-417L	-417L	
HTR T	-417L	-417L	-417L	-417L	

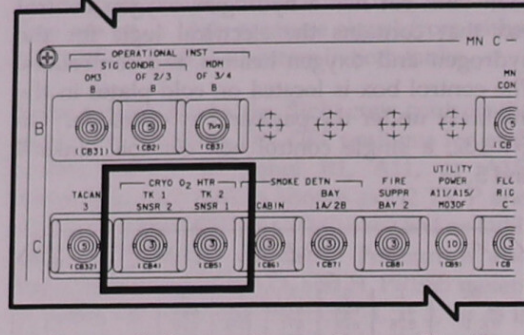
DISP 168 (CRYO PALLET)

Two current level detectors are built into the circuit of each oxygen tank heater to interrupt power in case of electrical shorts. The second detector is redundant. Each detector is divided into A and B detectors, which monitor the heater A current and the heater B current respectively. The detectors are powered by circuit breakers on panels O14, O15, O16, and ML86B. The detectors monitor the current in and out of a heater. If the current difference is 0.9 amp or greater for 1.5 milliseconds, a trip signal is sent to the heater logic to remove power from the heaters regardless of the heater switch position. If one element of a heater causes a "trip-out," power to both elements is removed. The O₂ TK 1, 2, 3 HEATERS RESET/TEST switches on panel R1 and the O₂ RESET/TEST switches on panels A11 and A15 can be used to reapply power to that heater by positioning them to RESET. The TEST position will cause a 1.5-amp delta current to flow through all four detectors of a specified oxygen tank, causing them to trip out. During on-orbit operations, the flight crew will be alerted to a current level detector trip-out by an SM ALERT, S68 CRYO O2 message, or S168 CRYO message.



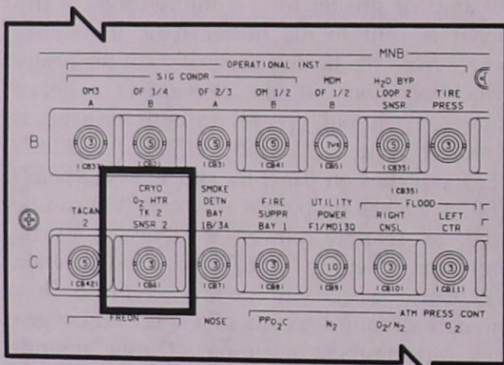
Cryogenic System Heater Sensor Circuit Breaker on Panel O14

Each oxygen and hydrogen tank has a quantity sensor powered by a circuit breaker. These are identified on panel O13 as CRYO QTY O₂ (or H₂) TK 1 and TK 2 and on panel ML86B as CRYO QTY O₂ (or H₂) TK 3, TK 4, and TK 5. Data from the quantity sensors are sent to panel O2, where the rotary switch below the meters is used to select the tank for display on the CRYO O₂ (or H₂) QTY meters. The range of the meters is zero to 100 percent. The data are also displayed on DISP 68 or DISP 168.



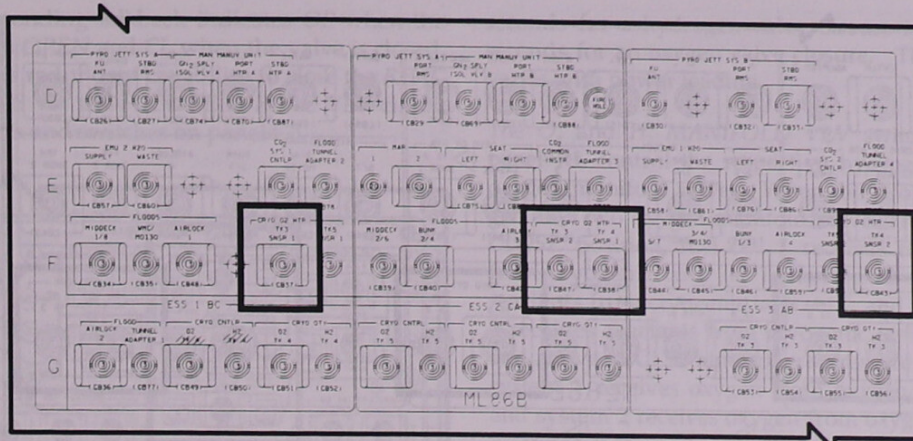
Cryogenic System Heater Sensor Circuit Breaker on Panel O16

There are two pressure sensors for each oxygen and hydrogen tank. One sensor transmits its data to the tank heater controllers, the caution and warning matrix on panel F7, and is displayed as "P" on DISPs 68 and 168. The yellow O₂ PRESS light is illuminated if oxygen tank pressure is below 540 psia or above 985 psia. The yellow H₂ PRESS light illuminates if hydrogen tank pressure is below 153 psia or above 293.8 psia. Data from the other sensor is displayed as TK P on DISPs 68 and 168 and the PRESS meters on panel O2. The SM ALERT and BACKUP C/W ALARM lights on panel F7 are also driven by the data. The range of the O₂ meter is 0 to 1,200 psia. The H₂ meter's range is 0 to 400 psia. The range of "P" displayed on the PASS and BFS SM SYS SUMM 1 and DISPs 68 and 168 is 515 to 1,215 psia for oxygen and 145 to 305 psia for hydrogen.

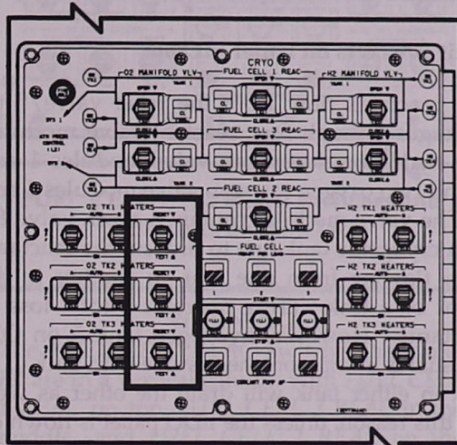


Cryogenic System Heater Sensor Circuit Breaker on Panel O15

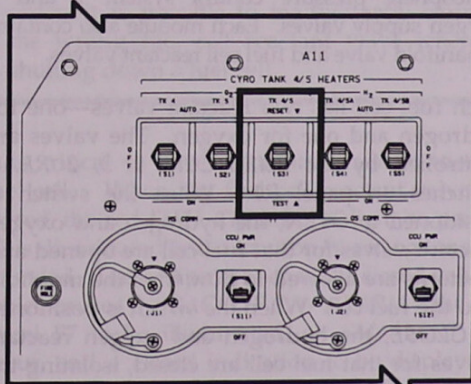
The data from oxygen and hydrogen fluid temperature sensors is displayed on DISP 68 or DISP 168 and transmitted to the ground.



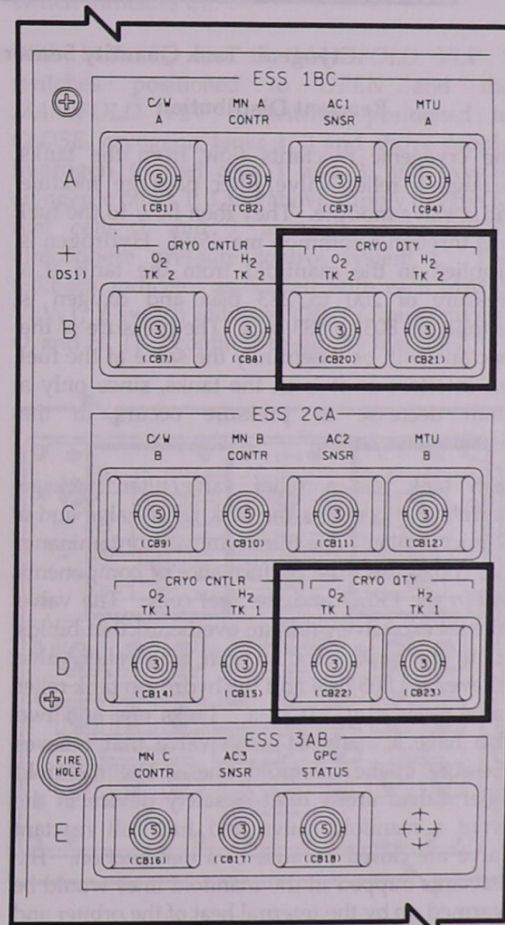
Cryogenic System Heater Sensor Circuit Breaker on Panel ML86B



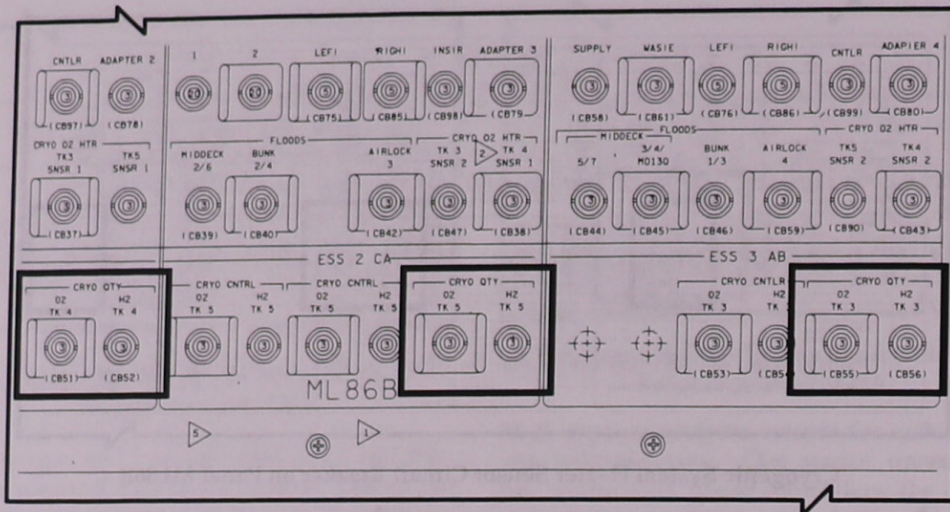
O2 TK1, TK 2 HEATERS RESET/TEST Switches on Panel R1



O2 TK 4/5 RESEST/TEST SWITCH ON Panel A11 (OV-102)



Cryogenic Tank Quantity Sensor Circuit Breakers on Panel O13



Cryogenic Tank Quantity Sensor Circuit Breakers on Panel ML86B

Reactant Distribution

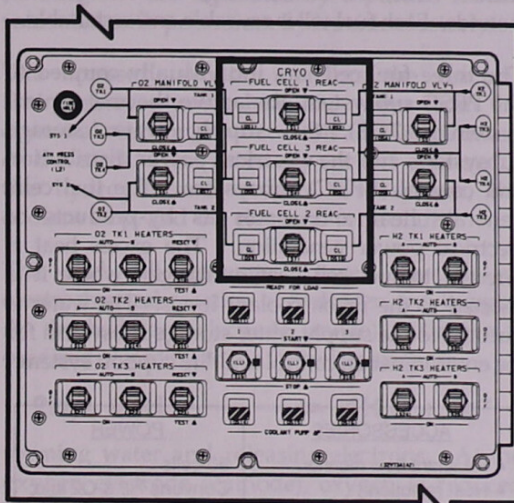
The cryogenic reactants flow from the tanks through a relief valve/filter package module and a valve module. They then flow to the fuel cells through a common manifold. Hydrogen is supplied to the manifold from the tank at a pressure of 200 to 243 psia and oxygen is supplied at 803 to 883 psia. The pressure of the reactants will be essentially the same at the fuel cell interface as it is in the tanks, since only a small decrease in pressure occurs in the distribution system.

Each tank has a relief valve/filter package module that contains the tank relief valve and a 12-micron filter. The filter removes contaminants that could affect the performance of components within the PRSD and the fuel cells. The valve relieves excessive pressure overboard that builds up in the tank. The oxygen tank relief valve relieves at 1,005 psia and the hydrogen tank relief valve relieves at 302 psia. Tanks one and two also have a manifold relief valve that relieves pressure in the manifold lines. The manifold relief valves are a built-in safety device in the event a manifold valve and fuel cell reactant valve are closed because of a malfunction. The reactants trapped in the manifold lines would be warmed up by the internal heat of the orbiter and overpressurize. The manifold relief valve will open at 290 psi for hydrogen and 975 psi for oxygen to relieve pressure and allow the trapped reactants to flow back to their tanks.

The reactants flow from the relief valve/filter packages through four reactant valve modules: two hydrogen (hydrogen valve modules 1 and 2) and two oxygen (oxygen valve modules 1 and 2). The valve modules contain a check valve for each cryogenic tank line to prevent the reactants from flowing from one tank to another in the event of a leak. (This prevents a total loss of reactants. However, hydrogen tank 5 on OV-102 shares a common check valve with tank 4. A leak in either tank will drain the other as well. For this reason, unless the EDO pallet is flown on OV-102, hydrogen tanks 4 and 5 are used first.) The oxygen valve modules also contain the environmental control and life support system atmosphere pressure control system 1 and 2 oxygen supply valves. Each module also contains a manifold valve and fuel cell reactant valves.

Each fuel cell has two reactant valves—one for hydrogen and one for oxygen. The valves are controlled by the *FUEL CELL 1, 3, 2 REAC* switches on panel R1. When the switch is positioned to *OPEN*, the hydrogen and oxygen reactant valves for that fuel cell are opened and reactants are allowed to flow from the manifold into the fuel cell. When the switch is positioned to *CLOSE*, the hydrogen and oxygen reactant valves for that fuel cell are closed, isolating the reactants from the fuel cell and rendering that fuel cell inoperative. Each *FUEL CELL REAC* switch on panel R1 also has two talkback indicators, one on each side of the switch. The

corresponding talkback indicates *OP* when the valve is *OPEN* and *CL* when the valve is closed. There is redundant capability to close the *REAC VALVES* via the *FUEL CELL REAC VLV* circuit breakers and switches on panel C3.



FUEL CELL 1, 3, 2 REAC Switches and Talkbacks on Panel R1

WARNING

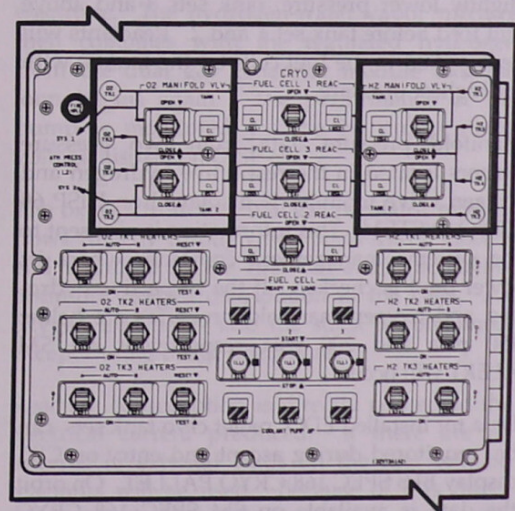
The *FUEL CELL REAC* switches on panel R1 are in a vertical column with *FUEL CELL 1 REAC* on top, *FUEL CELL 3 REAC* in the middle, and *FUEL CELL 2 REAC* on the bottom. This was done to allow the schematic to be placed on the panel. Because the switches are not in numerical order, it is possible to inadvertently close the wrong fuel cell reactant valve when shutting down a fuel cell.

It is critical to have reactants available to the fuel cells. When any fuel cell reactant valve is closed, the red *FUEL CELL REAC* light on panel F7 is illuminated and a caution/warning tone is sounded. The computers sense the closed valve, which causes the *BACKUP C/W ALARM* light on panel F7 to be illuminated, an *SM ALERT* to occur, and a closed indication to be displayed on DISP 69 and SM SYS SUMM 1. This alerts the flight crew that the fuel cell will be inoperative within approximately 20 to 30

seconds for a hydrogen valve closure and 130 seconds for an oxygen valve closure. The time varies with power loading.

The O_2 and H_2 *MANIFOLD VLV* switches on panel R1 control the respective hydrogen and oxygen manifold valves. When the two hydrogen and two oxygen manifold valves are in the *CLOSE* position, fuel cell 1 receives reactants from cryogenic tank set 1, fuel cell 2 receives reactants from cryogenic tank set 2, and fuel cell 3 receives reactants from cryogenic tank sets 3 and above. ECLSS atmosphere pressure control system 1 receives oxygen from oxygen tank 1, and system 2 receives oxygen from oxygen tank 2. When the switches are positioned to *CLOSE*, the talkback indicator associated with each switch indicates *CL*.

With both H_2 and O_2 *MANIFOLD VLV 1* switches positioned to *OPEN* and the *MANIFOLD VLV 2* switches positioned to *CLOSE*, cryogenic tanks 1, 3 and above supply hydrogen to fuel cells 1 and 3, and oxygen cryogenic tanks 1, 3 and above supply oxygen to fuel cells 1 and 3, as well as to ECLSS atmosphere pressure control system 1. The talkback indicator associated with each *MANF VLV 1, 2* switch indicates *OP*, *CL*, respectively. O_2 and H_2 TK 2 continue to supply fuel cell 2.



O2 and H2 MANIFOLD VLV Switches and Talkbacks on Panel R1

CAUTION

There are no relief valves for O₂ and H₂ manifold 3's with manifold valves 1 and 2 closed. This configuration should be avoided except for leak isolation and troubleshooting

When the H₂ and O₂ MANIFOLD VLV 2 switches are positioned to OPEN, and the MANIFOLD VLV 1 switches are positioned to CLOSE, hydrogen cryogenic tanks 2 and 3 and above supply hydrogen to fuel cells 2, 3, and oxygen cryogenic tanks 2 and 3 and above supply oxygen to fuel cells 2 and 3, as well as to ECLSS atmosphere pressure control system 2. The talkback indicator associated with each MANF VLV 1, 2 switch indicates OP, CL, respectively. H₂ and O₂ tank 1 continue to supply fuel cell 1.

With the H₂ and O₂ MANIFOLD VLV 1 and 2 switches positioned to OPEN, all hydrogen cryogenic tanks are available to supply hydrogen to all three fuel cells, and all oxygen cryogenic tanks are available to supply oxygen to all three fuel cells, as well as to ECLSS atmosphere pressure control systems 1 and 2. Because tank sets 1 and 2 are regulated at a slightly lower pressure, tank sets 3 and above will feed before tank set 1 and 2. Reactants will be supplied to the fuel cells by the tank(s) with the highest pressure.

Manifold pressure data from two pressure sensors located in the respective hydrogen and oxygen valve modules is displayed on DISP 68 CRYO SYSTEM. This information is also sent to the systems management computer where its lower limit is checked. If the respective hydrogen and oxygen manifold pressures are below 150 psia and 200 psia respectively, an SM ALERT will occur.

Data for installed EDO pallet cryo tank sets can be monitored during ascent and entry on CRT display BFS SPEC 168 CRYO PALLET. On orbit the data is available on SM SPEC 168 CRYO PALLET.

Fuel Cell System

The three fuel cells are located under the payload bay liner in the forward portion of the orbiter's midfuselage. Each fuel cell is 14 inches high, 15 inches wide, 40 inches long, and weighs 255 pounds. Each fuel cell is reusable and restartable.

The three fuel cells are individually coupled to the PRSD subsystem, the active thermal control system (ATCS), the supply water storage subsystem, and the electrical power distribution and control (EPDC) subsystem. The fuel cells generate heat and water as by-products of electrical power generation. The excess heat is directed to fuel cell heat exchanger, where it is rejected to the Freon coolant loops. The water is directed to the supply water storage subsystem for the environmental control and life support system.

ACCESSORIES	POWER
<ul style="list-style-type: none">• Reactant flow monitor• Heat rejection• Water rejection• Thermal control• Cell performance monitor• Electrical control unit	96 cells Converts H ₂ & O ₂ into: <ul style="list-style-type: none">• Power• Potable water• Heat

Fuel Cell Block Diagram

The nominal voltage and current range of each fuel cell is 2 kW at 32.5 volts dc, 61.5 amps to 12 kW at 27.5 volts dc, 436 amps. Each is capable of supplying up to 10 kW maximum continuous power in nominal situations, 12 kW continuously in off-nominal situations (with one or more fuel cells failed), and up to 16 kW for 10 minutes. The average on-orbit power consumption of the orbiter is approximately 14 kW, leaving additional capability available for payloads. Each fuel cell is serviced between flights and reused until it has accumulated 2,000 hours of on-line service.

The orbiter's three fuel cells operate as independent electrical power sources, each supplying its own isolated, simultaneously operating dc bus. Each fuel cell consists of a power section and an accessory section. The power section, where hydrogen and oxygen are transformed into electrical power, water, and

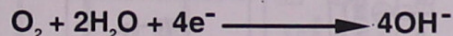
heat, consists of 96 cells contained in three substacks. Manifolds run the length of these substacks and distribute hydrogen, oxygen, and coolant to the cells. The cells contain an oxygen electrode (cathode), and a hydrogen electrode (anode) that are separated by a porous matrix saturated with potassium hydroxide electrolyte.

The accessory section monitors the reactant flow, removes waste heat and water from the chemical reaction, and controls the temperature of the stack. The accessory section consists of the hydrogen and oxygen flow system, the coolant loop, and the electrical control unit.

The fuel cell generates power through an electrochemical reaction of hydrogen and oxygen. At the hydrogen electrode (anode), hydrogen is oxidized according to the following reaction:



forming water and releasing electrons. At the oxygen electrode (cathode), oxygen is reduced in the presence of water. It forms hydroxyl ions according to the following relationship:



The net reaction consumes one oxygen molecule and two hydrogen molecules in the production of two water molecules, with electricity and heat formed as by-products of the reaction.

The fuel cell coolant system circulates a liquid fluorinated hydrocarbon and transfers the waste heat from the cell stack through the fuel cell heat exchanger to the Freon coolant loop system in the midfuselage. Internal control of the circulating fluid maintains the cell stack at a load-dependent operating temperature of approximately 200° F.

When the reactants enter the fuel cells, they flow through a preheater (where they are warmed from a cryogenic temperature to 40° F or greater), a 6-micron filter, and a two-stage, integrated dual gas regulator module. The first stage of the regulator reduces the pressure of the hydrogen and oxygen to 100 to 120 psia. The second stage reduces the oxygen pressure to a range of 60 to 62 psia and maintains the hydrogen pressure at 4.5 to 6 psia differential below the oxygen pressure. The regulated

oxygen lines are connected to the accumulator, which maintains an equalized pressure between the oxygen and the fuel cell coolant. If oxygen and hydrogen pressure decrease, the coolant's pressure is also decreased to prevent a large differential pressure inside the stack that could deform the cell stack structural elements.

Upon leaving the dual gas regulator module, the incoming hydrogen mixes with the hydrogen-water vapor exhaust from the fuel cell stack. This saturated gas mixture is routed through a condenser, where the temperature of the mixture is reduced, condensing a portion of the water vapor to form liquid water droplets. The liquid water is then separated from the hydrogen-water mixture by the hydrogen pump /water separator. A centrifugal water separator extracts the liquid water and pressure-feeds it to potable tanks in the lower deck of the pressurized crew cabin. Water from the potable water storage tanks can be used for crew consumption and for cooling the Freon loops by feeding the flash evaporator system.

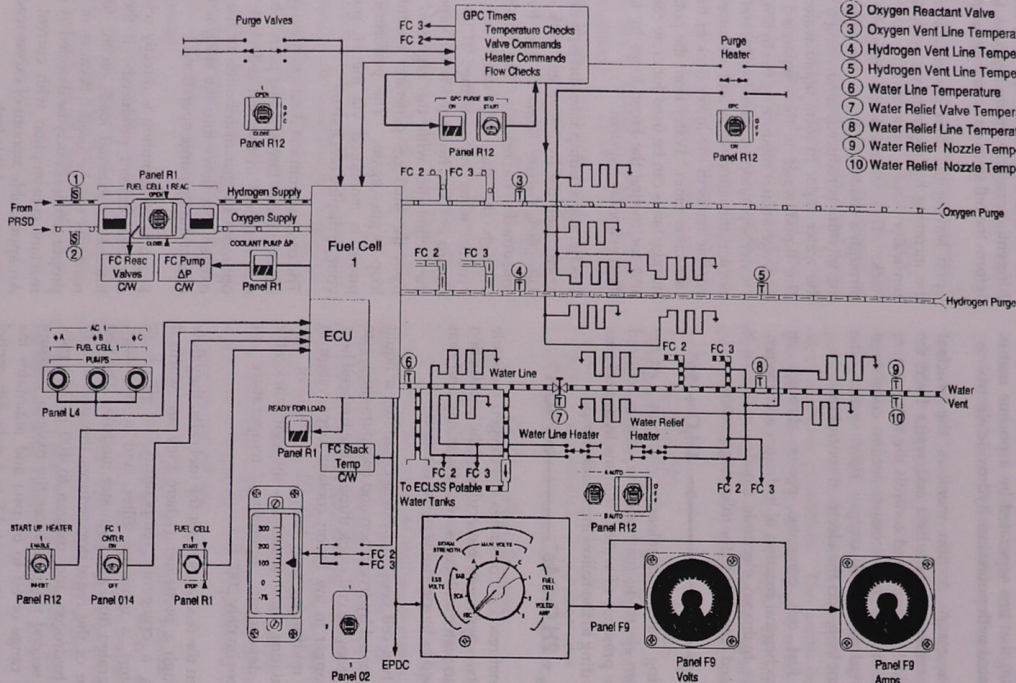
The hydrogen pump uses three-phase ac power to circulate the hydrogen gas back to the fuel cell stack, where some of the hydrogen is consumed in the reaction. The remainder flows through the fuel cell stack, removing the product water vapor formed at the hydrogen electrode. The hydrogen-water vapor mixture then combines with the regulated hydrogen from the dual gas generator module and the loop begins again. The performance at the pump is monitored via the H₂ pump status voltage display on DISP 69.

The oxygen from the dual gas regulator module flows directly through two ports into a closed-end manifold in the fuel cell stack, achieving optimum oxygen distribution in the cells. All oxygen that flows into the stack is consumed, except during purge operations.

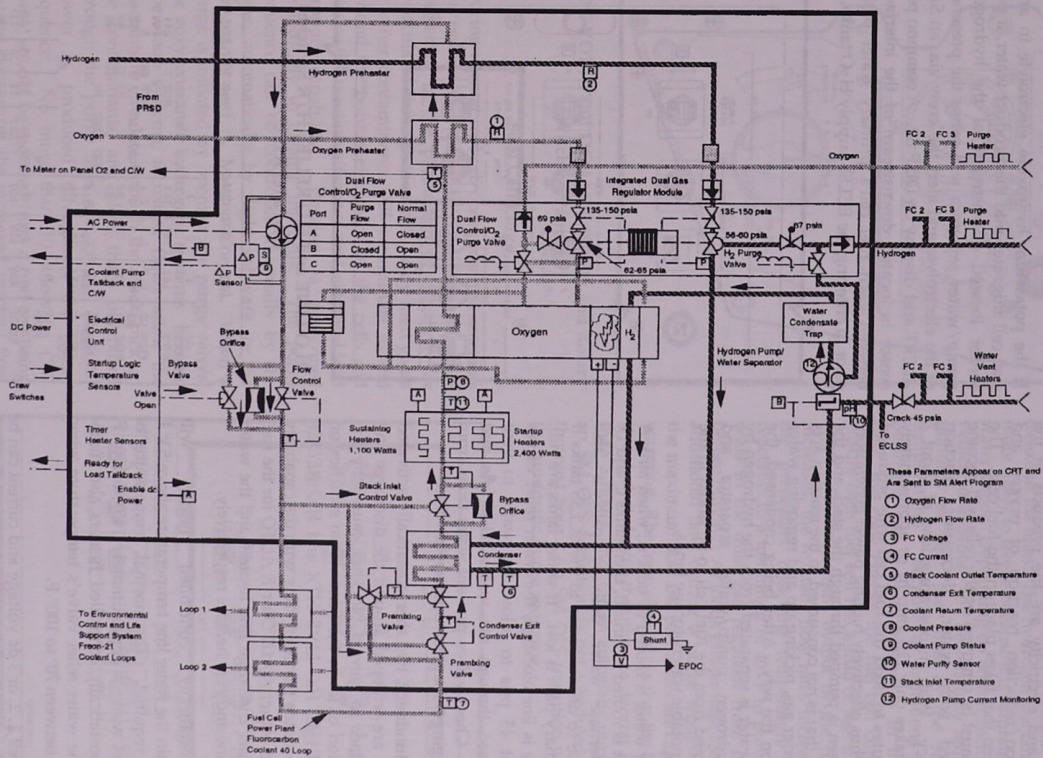
Reactant consumption is directly related to the electrical current produced: if there are no internal or external loads on the fuel cell, no reactants will be used. Because of this direct proportion, leaks may be detected by comparing reactant consumption with current produced. An appreciable amount of excess reactants used indicates a probable leak.

These Parameters Appear on CRT and Are Sent to SM Alert Program

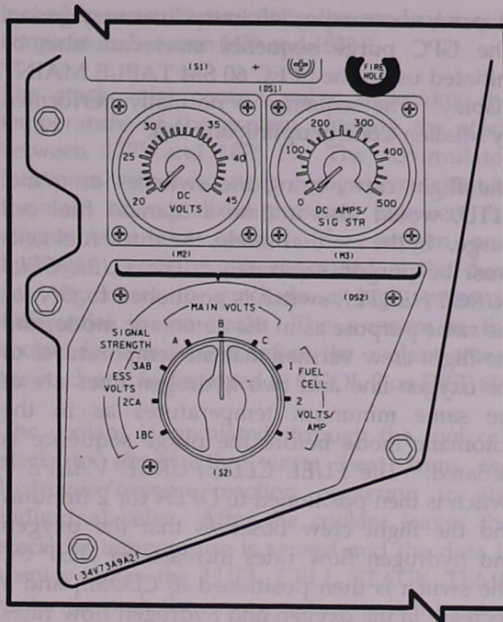
- ① Hydrogen Reactant Valve
- ② Oxygen Reactant Valve
- ③ Oxygen Vent Line Temperature
- ④ Hydrogen Vent Line Temperature 1
- ⑤ Hydrogen Vent Line Temperature 2
- ⑥ Water Line Temperature
- ⑦ Water Relief Valve Temperature
- ⑧ Water Relief Line Temperature
- ⑨ Water Relief Nozzle Temperature 1
- ⑩ Water Relief Nozzle Temperature 2



Fuel Cell 1 Typical Display and Controls



Fuel Cell - Typical



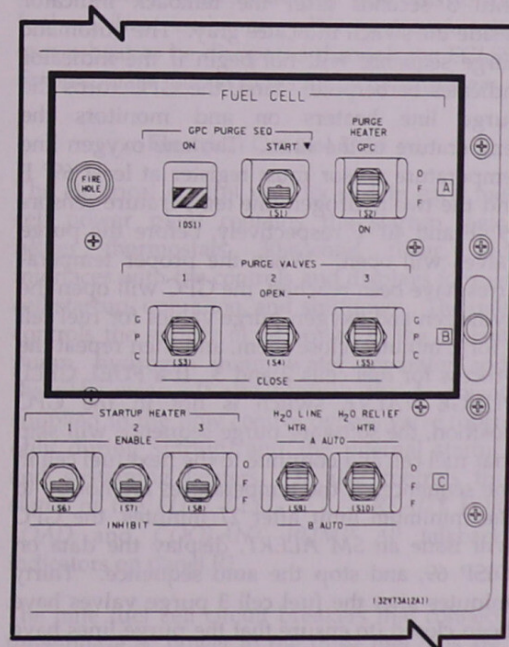
DC VOLTS and DC AMPS Meters and Rotary Switch on Panel F9

Fuel Cell Purge

During normal fuel cell operation, the reactants are present in a closed-loop system and either consumed in the production of electricity or recirculated through the stack. Any inert gases or other contaminants will accumulate in and around the porous electrodes in the cells and reduce the reaction efficiency and electrical load support capability. Purging is performed periodically to cleanse the cells. The purge sequence can be controlled manually by the crew, automatically by flight software, or via commands sent by Mission Control. When a purge is initiated by opening the purge valves, the oxygen and hydrogen systems become open-loop systems; increased flows allow the reactants to circulate through the stack, pick up the contaminants, and blow them overboard through the purge lines and vents. Electrical power is produced throughout the purge sequence. No more than 10 kilowatts (350 amps) should be required from a fuel cell being purged because of the increased reactant flow and preheater limitations.

Fuel cell purge can be activated automatically or manually via switches on panel R11U. At the initiation of either an auto or manual purge, the

purge line heaters are turned on to heat the purge lines and ensure that the reactants do not freeze in the lines. The hydrogen reactant is the more likely to freeze because it is saturated with water vapor. Depending on orbit trajectory and vehicle orientation, the heaters may require 27 minutes to heat the lines to the required temperatures. Because of limitations on the hydrogen and oxygen preheaters in the fuel cells, the crew checks the fuel cell current to ensure each fuel cell has a load of less than 350 amps. As the current output of the fuel cell increases, the reactant flow rates increase and the preheaters raise the temperature of the reactants to a minimum of 40° F to prevent the seals in the dual gas regulator from freezing before purging. At loads greater than 350 amps, additional flow during a purge would exceed the maximum flow the preheaters are capable of warming. The crew also checks that the fuel cell is not shut down, that time to deorbit is more than 3 hours, and, for an automatic purge, that an SM OPS transition is not scheduled within the next hour. An SM OPS transition will halt the automatic purge sequence.



FUEL CELL Purge Switches on Panel R11U

The purge lines from all three fuel cells are manifolded together downstream of their purge

valves and associated check valves. The line leading to the purge outlet is sized to permit unrestricted flow from only one fuel cell at a time.

NOTE

If more than one fuel cell is purged simultaneously, back pressure may build in the purge line. Due to the sizing of the hydrogen and oxygen purge lines, the back pressure in the H_2 line can cause the hydrogen pressure to rise above the oxygen pressure. Although the dual gas regulator is designed to prevent this from happening, it would not be advisable to expose all three fuel cells to this condition at the same time. If there is a generic problem with the dual gas regulator, this could cause all three fuel cells to fail simultaneously.

For an automatic purge, the FUEL CELL PURGE heater switch is positioned to GPC and the FUEL CELL PURGE VALVES 1, 2, and 3 switches on panel R11U are positioned to GPC. The FUEL CELL GPC PURGE SEQ switch is then positioned to START and must be held until 3 seconds after the talkback indicator beside the switch indicates gray. The automatic purge sequence will not begin if the indicator indicates barberpole. First, the GPC turns the purge line heaters on and monitors the temperature of the lines. The one oxygen line temperature sensor must register at least 69° F and the two hydrogen line temperature sensors 79° F and 40° F respectively, before the purge valves will open. When the proper temperatures have been reached, the GPC will open the hydrogen and oxygen purge valves for fuel cell 1 for 2 minutes, close them, and then repeat the process for fuel cells 2 and 3. If a FUEL CELL PURGE VALVE switch is not in the GPC position, the software purge sequence will skip that fuel cell and continue to the next fuel cell in the sequence. If the temperatures are not up to the minimum limit after 27 minutes, the GPC will issue an SM ALERT, display the data on DISP 69, and stop the auto sequence. Thirty minutes after the fuel cell 3 purge valves have been closed (to ensure that the purge lines have been totally evacuated of water vapor by the heaters), the GPC will turn off the purge line heaters. This provides sufficient time and heat to bake out any remaining water vapor. If the heaters are turned off before 30 minutes have

elapsed, water vapor left in the lines may freeze. The GPC purge sequence start can also be initiated using the SPEC 60 SM TABLE MAINT display. The sequence is normally performed by Mission Control uplink on orbit.

The flight crew, using the switches on panel R11U, would also initiate a manual fuel cell purge. In the manual mode, the three fuel cells must be purged separately. The FUEL CELL PURGE HEATER switch is positioned to ON for the same purpose as in the automatic mode, and the flight crew verifies that the temperatures of the oxygen line and two hydrogen lines are at the same minimum temperatures as in the automatic mode before the purge sequence is initiated. The FUEL CELL PURGE VALVE 1 switch is then positioned to OPEN for 2 minutes and the flight crew observes that the oxygen and hydrogen flow rates increase on DISP 69. The switch is then positioned to CLOSE, and a decrease in the oxygen and hydrogen flow rates is observed on DISP 69, confirming the purge valves are closed. Fuel cell 2 is purged in the same manner using the FUEL CELL PURGE VALVES 2 switch. Fuel cell 3 is then purged in the same manner using the FUEL CELL PURGE VALVES 3 switch. After the 30-minute line bakeout period, the FUEL CELL PURGE HEATER switch is positioned to OFF. Manual purges use different heaters than automatic purges. At least one manual purge is scheduled per flight

Fuel Cell Cooling/Temperature Control

In order to cool the fuel cell stack during its operations, distribute heat during fuel cell start-up, and warm the cryogenic reactants entering the stack, the fuel cell circulates fluorinated hydrocarbon throughout the fuel cell. The fuel cell coolant loop and its interface with the ECLSS Freon coolant loops are identical in fuel cells 1, 2, and 3.

The temperature of the coolant returning from the Freon coolant loops is sensed before it enters the fuel cell. This is displayed as COOL T on DISP 69. It then enters the fuel cell and passes through a 75-micron filter. After the filter, two temperature-controlled mixing valves allow some of the hot coolant to mix with the cool returning coolant to prevent the condenser exit control valve from oscillating. The control valve adjusts the flow of the coolant through the condenser to maintain the

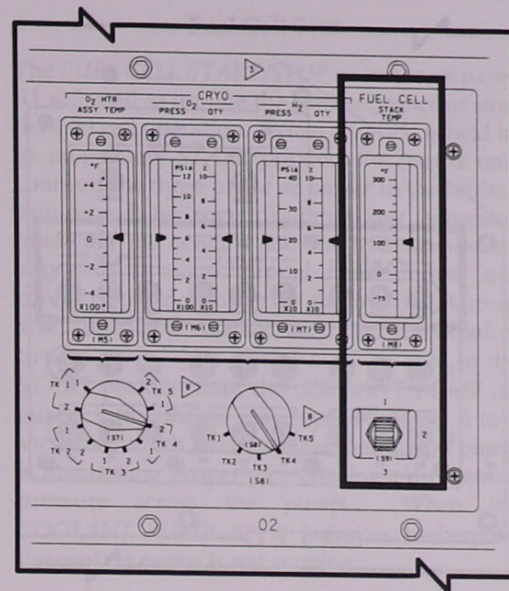
hydrogen-water vapor exiting the condenser at a temperature between 148° and 153° F.

The stack inlet control valve maintains the temperature of the coolant entering the stack between 177° and 187° F. The accumulator interfaces with the oxygen cryogenic reactant to maintain an equalized pressure between the oxygen and the coolant (the oxygen and hydrogen pressures are controlled at the dual gas regulator) to preclude a high pressure differential in the stack. The pressure in the coolant loop is sensed before the coolant enters the stack and is displayed as COOL P on DISP 69.

The coolant is circulated through the fuel cell stack to absorb the waste heat from the hydrogen/oxygen reaction occurring in the individual cells. After the coolant leaves the stack, its temperature is sensed and the data is displayed on the FUEL CELL STACK TEMP meter through the three-position switch located below the meter on panel O2 and on the DISP 69 display as STACK T. The yellow *FUEL CELL STACK TEMP*, the red *BACKUP C/W ALARM* light, and the *SM ALERT* light on panel F7 will be illuminated if fuel cell and stack temperatures exceed upper or lower limits. The hot coolant from the stack flows through the oxygen and hydrogen preheaters where it warms the cryogenic reactants before they enter the stack.

The coolant pump utilizes three-phase ac power to circulate the coolant through the loop. The differential pressure sensor senses a pressure differential across the pump to determine the status of the pump. The *FUEL CELL PUMP* light on panel F7 will be illuminated if fuel cell 1, 2, or 3 coolant pump delta pressure is lost and a fault message will be sent to the CRT. If the coolant pump for fuel cell 1, 2, or 3 is off, the *BACKUP C/W ALARM* light will be illuminated and a fault message and a $\Delta P \downarrow$ will be displayed.

The temperature-actuated flow control valve downstream from the pump adjusts the coolant flow to maintain the fuel cell coolant exit temperature between 190° and 210° F. The stack inlet control valve and flow control valve have bypass orifices to allow coolant flow through the coolant pump and to maintain some coolant flow through the condenser for water condensation, even when the valves are fully



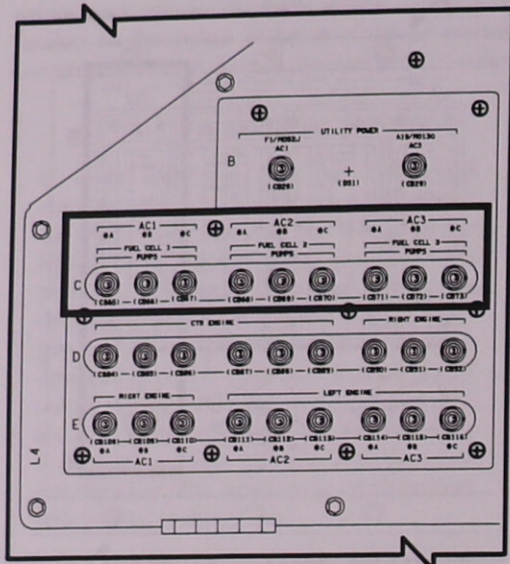
FUEL CELL STACK TEMP Meter and FUEL CELL 1, 2, 3 Switch on Panel O2

closed due to the requirements of thermal conditioning. The hot coolant that is not used at the mixing valves exits the fuel cells to the fuel cell heat exchanger where it transfers its excess heat to be dissipated through the ECLSS Freon coolant loop systems in the midfuselage.

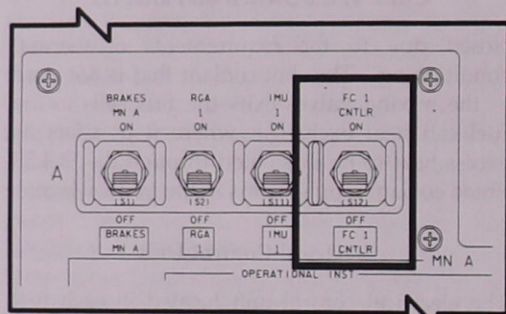
Electrical Control Unit

The electrical control unit located in each fuel cell power plant contains the startup logic, heater thermostats, 30-second timer, and interfaces with the controls and displays for fuel cell startup, operation, and shutdown. The unit controls the supply of ac power to the coolant pump, hydrogen pump/water separator and the pH sensor. It also controls the dc power supplied to the flow control bypass valve (open only during startup) and the internal startup and sustaining heaters. It also controls the status of the *FUEL CELL 1, 2, 3 READY FOR LOAD* and *COOLANT PUMP ΔP* talkback indicators on panel R1.

The nine fuel cell circuit breakers that connect three-phase ac power to the three fuel cells are located on panel L4. Each fuel cell electrical control unit receives its power from an essential bus through the *FC CNTLR* switch on panels O14, O15 and O16.



FUEL CELL Circuit Breakers on Panel L4



FC1 CNTRL Switch on Panel O14

Cell Performance Monitor

As fuel cell life increased with the introduction of the third substack, the likelihood of individual cell failures caused by "wearout" or age increased. Consequently, the cell performance monitor (CPM) was designed to detect individual cell performance problems or imminent failures such as cell crossover.

Crossover is defined as an uncontrolled mixing of the reactants that results in the generation of excessive product heat. The combination of hydrogen and oxygen requires little heat to explode. During normal fuel cell operation, hydrogen and oxygen are diffusely mixed to produce electricity. The matrix, a fibrous asbestos blotter device within each cell, holds

the KOH electrolyte and limits the H_2/O_2 mixing. A crossover occurs when the matrix fails to do its job. A manufacturing flaw in the matrix or an impurity in the matrix fibers may cause a pin hole to develop after hours and hours of exposure to the caustic KOH in the presence of the waste heat within the cell.

As the direct combination of the reactant molecules occurs at the pin hole, increased waste heat may cause the pin hole to burn and enlarge allowing more reactants to combine. If this reaction continues, it might uncontrollably propagate and possibly result in a violent explosion. A crossover may proceed rapidly or gradually. Before the introduction of the cell performance monitor prior to STS-9, the electrical performance indicators of a crossover-distressed cell were not detectable, since the lost electrical performance of the substack with the degraded cell was picked up by the healthy substacks.

The cell performance monitor compares each half substack voltage and calculates a delta volts measurement. By comparing both halves of a substack, the cell performance monitor can detect cell changes. Since all the cells in a substack are producing the same current, both halves of the substack should be at approximately identical voltages. Ideally $\Delta V = 0$ but small fluctuations are common. A significant voltage loss in any one cell will produce a change in the ΔV with 300 mV being a critical performance loss. ΔV can be either positive or negative, so the cell performance monitor converts the positive/negative ΔV between the upper and lower substack halves to an absolute value and then outputs that value (0 to 500 mV). To provide margin and accommodate the absolute value, the C/W limit is set at 150 mV. The output is then converted to a 0 to 5 V dc signal for telemetry and crew display systems by a "times 10" amplifier. Calibration curves rescale this to electronic units (EU) (0 to 50 mV).

Every 7.5 minutes the cell performance monitor performs a self-test to ensure data accuracy and to prevent fuel cell shutdown due to faulty data. During the self-test period:

- The voltage measurement of the substack halves ceases.

- A test signal of 50 mV is input to the voltage measurement logic.
- The output of the "times 10" amplifier is examined for 425 to 575 mV.
- If the test fails, the output voltage is driven to 5 volts until the next self-test is performed 7 ± 1 minute later. A test voltage of 50 mV is introduced and the sequence repeats itself.
- If the self-test is passed, the unit resumes substack half voltage measurements.

Fuel Cell Monitoring System

The fuel cell monitoring system (FCMS) is a data collection system that provides insight into the single cell voltages in the orbiter fuel cell powerplants.

The FCMS is a PGSC program that records voltage in each individual cell as well as in all three fuel cells and saves these readings into an ASCII data file. This file is then downlinked to MCC for evaluation.

FCMS has two recording modes, full rate and interval. Full rate records a sample every second until the maximum file size is reached. In interval, FCMS records samples at crew-specified intervals for a certain amount of time, also specified by the crew. In this mode, if the amount of data exceeds maximum file size, the crew receives a message that the program will stop recording when the maximum size is reached. File size is limited to 1.2 Mb to ensure that it will fit onto a single disk.

One data sample consists of a GMT time tag for fuel cell 1 – the cell 1 reading followed by 288 voltage readings; i.e., 96 cells/fuel cell powerplant times 3 fuel cell powerplants.

FCMS uses the PCMMU 2 port on the flight deck (panel O5) and a special FCMS cable to collect data for the PGSC program. FCMS data also can be recorded prelaunch directly through the T-0 umbilicals.

Baseline recordings normally are recorded at the beginning of each mission for comparison in the event of a subsequent failure.

Fuel Cell Start

The *FUEL CELL START/STOP* switches on panel R1 are used to initiate the start sequence or stop the fuel cell operation. When a switch is held in its momentary *START* position, the control unit connects the three-phase ac power to the coolant pump and hydrogen pump/water separator (allowing the coolant and the hydrogen-water vapor to circulate through these loops) and connects the dc power to the internal startup and sustaining heaters and the flow control bypass valve. The switch must be held in the *START* position until the *COOLANT PUMP ΔP* talkback (tb) shows gray (approximately 3 to 4 seconds), which indicates that the coolant pump is functioning properly by creating a differential pressure across the pump. When the *COOLANT PUMP ΔP* tb indicates barberpole, the coolant pump is not running.

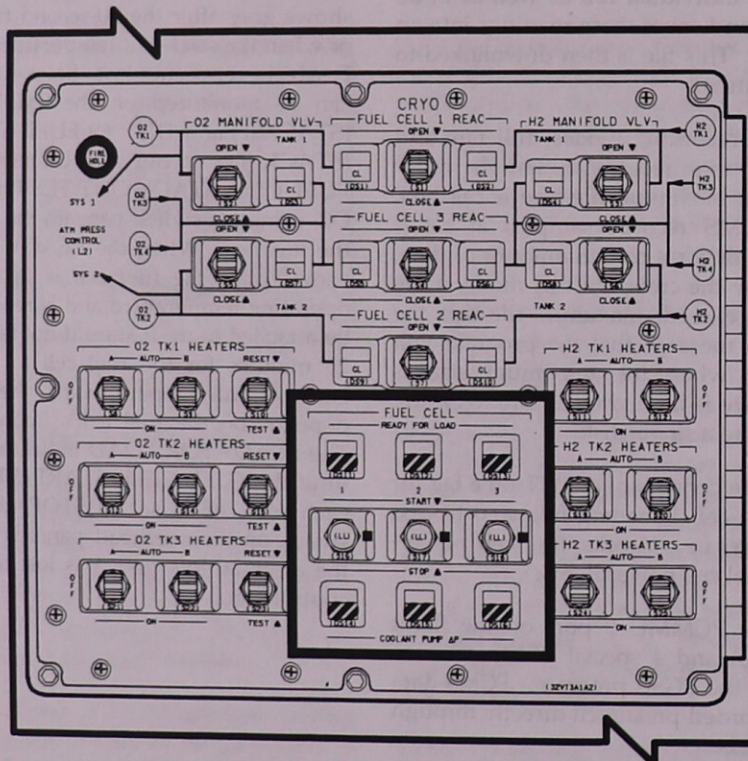
The *READY FOR LOAD* tb for each fuel cell shows gray after the 30-second timer times out or when the stack-out temperature is above 187° F, whichever occurs last. Stack-out temperature can be monitored on the SM SYS SUMM 1 (STACK T) and DISP 69 FUEL CELLS displays (STACK T). It can also be monitored on the FUEL CELL STACK OUT TEMP meter on panel O2, using the switch beneath the meter to select the fuel cell. When the *READY FOR LOAD* tb shows gray, the fuel cell is up to the proper operating temperature and is ready for loads to be attached to it. It should not take longer than 25 minutes for the fuel cell to warm up and become fully operational; the actual time depends on the fuel cell's initial temperature. The *READY FOR LOAD* indicator remains gray until the *FUEL CELL START/STOP* switch for each fuel cell is set to *STOP*, the *FC CNTLR* switch on the overhead panel is set to *OFF*, or the essential bus power is lost to the electrical control unit.

2011/ /078		SM SYS SUMM 1		4 000/14:44:12	
				000/00:00:00	
SMOKE	1/A 2/B	DC VOLTS	1/A 2/B 3/C		
CABIN	0.0	FC	30.6 30.1 31.0		
L/R FD	0.0 0.0	MAIN	30.6 30.1 31.0		
AV BAY	1 0.3 0.3	ESS	29.6 29.6 29.3		
	2 0.3 0.4				
	3 0.3 0.3	CNTL	A B C A		
CABIN					
PRESS	14.0		1 29.4 29.4 29.6		
QP/DT-BQ	+0.0 +0.00	AC	2 29.4 29.4 29.4		
O2 CONC		VOLT	3 29.4 29.4 29.4		
FP02	3.00 3.00	ΦA	118 118 117		
FAN ΔP	5.00	ΦB	117 117 118		
HX OUT T	46	ΦC	117 117 118		
O2 FLOW	0.0 0.0	AMPS	ΦA 4.3 6.3 2.1		
N2 FLOW	0.0 0.0	ΦB 5.5 6.6 2.2			
IMU FAN	A B C	ΦC 3.1 5.0 3.2			
AV FC1 FC2 FC3		FUEL CEL			
SS1	22 21 22	AMPS	180 232 146		
SS2	22 22 23	REAC VLV	OP OP OP		
SS3	23 21 21	STACK T	+202 +206 +200		
TOTAL AMPS	557	EXIT T	150 152 149		
KW	17	COOL P	61 60 61		
		PUMP			

SM SYS SUMM 1 (DISP 78)

Electrical Power Distribution and Control

The electrical power distribution and control subsystem controls and distributes ac and dc electrical power to the orbiter subsystems, the solid rocket boosters, the external tank, and payloads. The 28 volts dc generated by each of the three fuel cells is distributed to a main dc bus. The three main dc buses (MN A, MN B, and MN C) are the prime sources of power for the vehicle's dc loads. Each of the three dc main buses supplies power to three solid-state (static), single-phase inverters, each of which powers one three-phase alternating-current bus; thus, the nine inverters convert dc power to 117 +3. -1 volt rms, 400-hertz ac power for distribution to three ac buses (AC 1, AC 2, and AC 3) for the vehicle's ac loads.



FUEL CELL START/STOP Switches and READY FOR LOAD and COOLANT PUMP P Talkback Indicators on Panel R1

Bus System

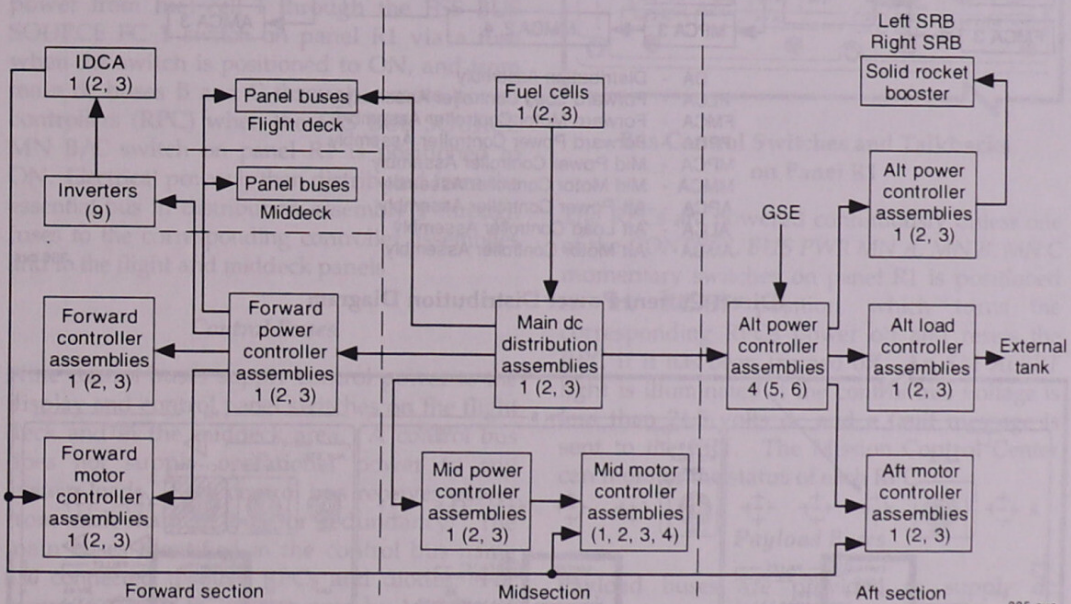
The three main dc buses are main A (MN A), main B (MN B), and main C (MN C). Three ac buses, AC 1, AC 2, and AC 3, supply ac power to the ac loads. Three essential buses, ESS1BC, ESS2CA, and ESS3AB, supply dc power to selected flight crew controls and electrical loads that are deemed essential. Nine control buses - CNTL AB 1, 2, 3; CNTL BC 1, 2, 3; and CNTL CA 1, 2, 3 - are used to supply control power to flight crew controls. Two preflight buses, PREFLT 1 and PREFLT 2, are used only during ground operations.

Depending on the criticality of orbiter electrical equipment, some electrical loads may receive redundant power from two or three main buses. If an electrical load receives power from two or three sources, it is for redundancy only and not for total power consumption.

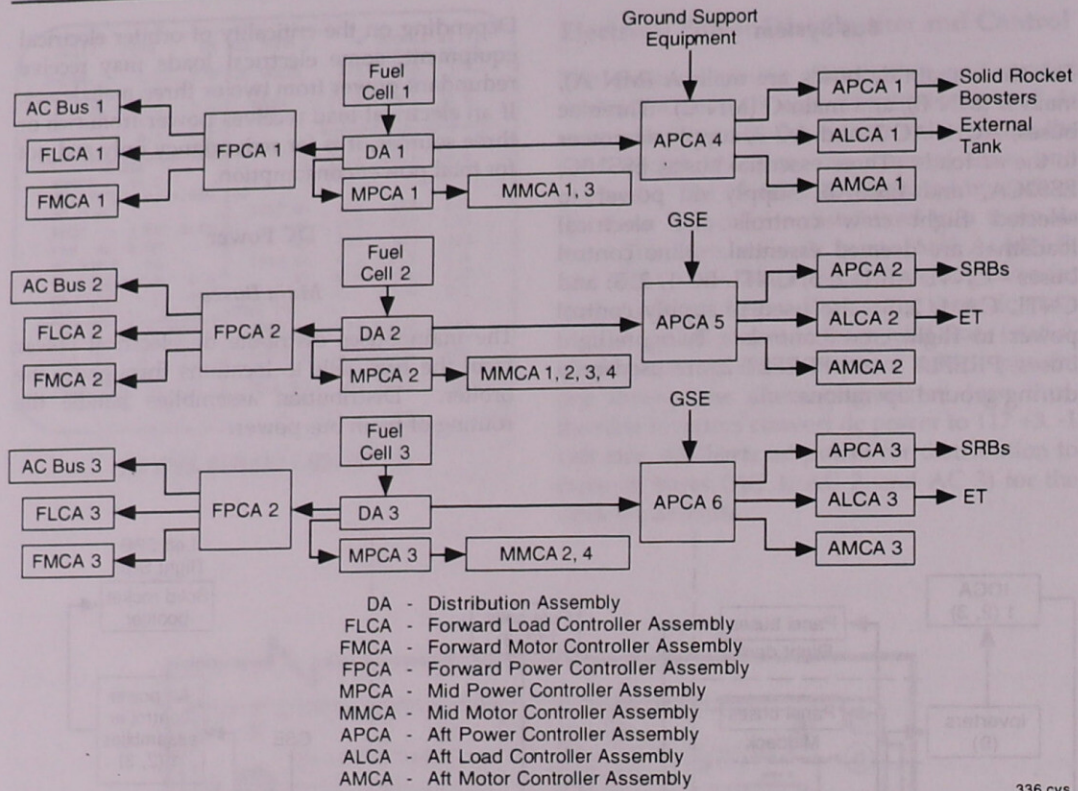
DC Power

Main Buses

The main buses distribute dc electrical power from the fuel cells to locations throughout the orbiter. Distribution assemblies handle the routing of main bus power.

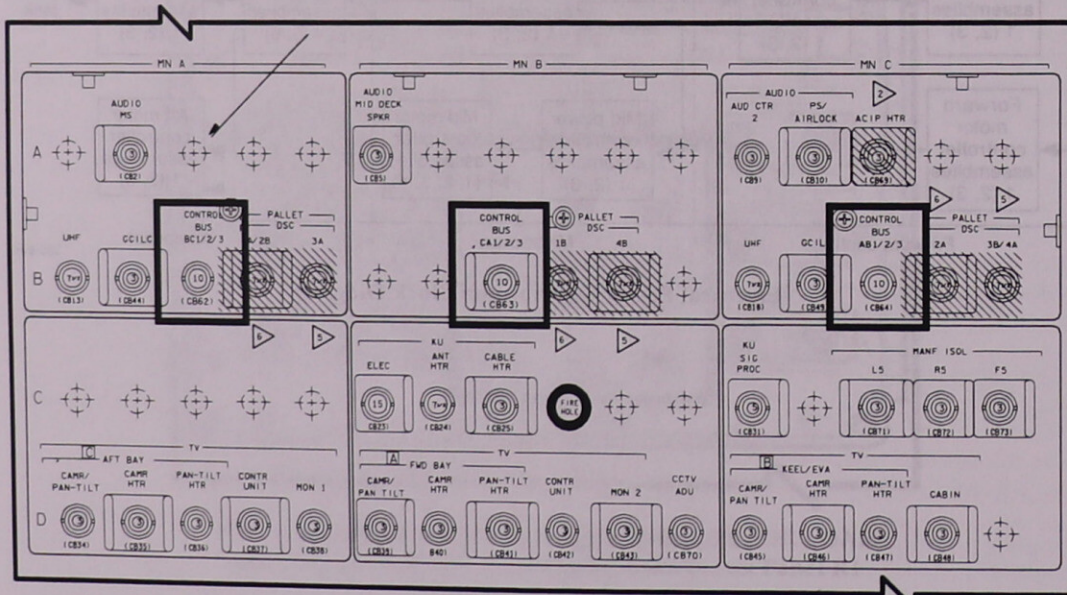


Electrical Power Distribution Block Diagram



336.cvs

Direct Current Power Distribution Diagram



CONTROL BUS Circuit Breakers on Panel R15

Essential Buses

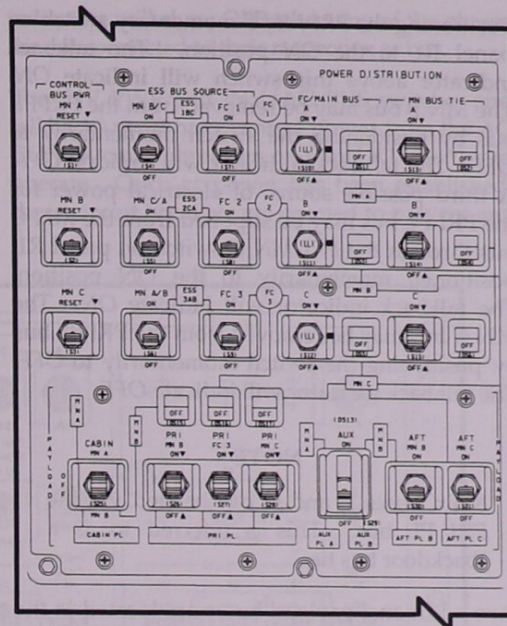
Essential buses supply power to switches that are necessary to restore power to a failed main dc or ac bus and to essential electrical loads and switches. In some cases, essential buses are used to power switching discretely to multiplexers/demultiplexers. Examples of the selected flight crew switches and loads are the EPS switches, GPC switches, TACAN, radar altimeter and microwave scan beam landing system power switches, the caution and warning system, emergency lighting, audio control panel, and master timing unit.

Three essential buses, ESS1BC, ESS2CA, and ESS3AB receive power from three redundant sources. For example, ESS1BC receives dc power from fuel cell 1 through the ESS BUS SOURCE FC 1 switch on panel R1 via a fuse when the switch is positioned to ON, and from main dc buses B and C through remote power controllers (RPC) when the ESS BUS SOURCE MN B/C switch on panel R1 is positioned to ON. Electrical power is then distributed from the essential bus in distribution assembly 1 through fuses to the corresponding controller assemblies and to the flight and middeck panels.

Control Buses

Nine control buses supply control power to the display and control panel switches on the flight deck and in the middeck area. A control bus does not supply operational power to any system loads. Each control bus receives power from each main dc bus for redundancy. The main buses identified in the control bus name are connected through RPCs and diodes. For example, CNTL BC1 is powered by MN B and MN C through remote power controllers. The "unnamed bus", which in this example is MN A, provides power to the control bus through a circuit breaker and a fuse. The number in each control bus name does not refer to a power source for the bus; it is merely a numeric designator for the bus.

The control buses are enabled by the CONTROL BUS PWR MN A, MN B, and MN C switches on panel R1 and the MN A CONTROL BUS BC1/2/3, the MN B CONTROL BUS CA1/2/3 and the MN C CONTROL BUS AB1/2/3 circuit breakers on panel R15.



**Bus Control Switches and Talkbacks
on Panel R1**

The RPCs are powered continuously unless one of the CONTROL BUS PWR MN A, MN B, MN C momentary switches on panel R1 is positioned to the RESET position, which turns the corresponding RPCs power off and resets the RPC if it has been tripped off. An SM ALERT light is illuminated if the control bus voltage is less than 24.5 volts dc and a fault message is sent to the CRT. The Mission Control Center can monitor the status of each RPC.

Payload Buses

Payload buses are provided to supply dc electrical power to the payloads. Fuel cell 3 may be connected to the primary payload bus by positioning the PRI FC3 momentary switch on panel R1 to the ON position. The talkback indicator above the switch will indicate ON when fuel cell 3 is connected to the PRI PL bus. The PRI PL bus is the prime bus for supplying power to the payloads. Fuel cell 3 may be disconnected from the payload bus by positioning the PRI FC3 switch to the OFF position. The talkback indicator above the switch will indicate OFF.

A second source of electrical power for the PRI PL bus may be supplied from the MN B bus by

positioning the *PRI MN B* momentary switch on panel R1 to the *ON* position. The talkback indicator above this switch will indicate *ON*. The *MN B* bus may be removed from the *PRI PL* bus by positioning the switch momentarily to *OFF*. The talkback indicator will indicate *OFF*. A third possible source of electrical power for the *PRI PL* bus may be supplied from the *MN C* bus through the *PRI MN C* switch on panel R1, positioned momentarily to the *ON* position. The talkback indicator will indicate *ON*. The *MN C* bus may be removed from the *PRI PL* bus by positioning the switch momentarily to *OFF*. The talkback indicator will indicate *OFF*.

NOTE

Main buses B and C can be tied via the *PRI PL* bus. This is referred to as a "backdoor bus tie."

Two additional payload buses are located in the aft section of the payload bay at the aft bulkhead station. The aft payload B bus may be powered up by positioning the *AFT MN B* switch on panel R1 to *ON*. The aft payload C bus may be powered up by positioning the *AFT MN C* switch on panel R1 to *ON*. The *OFF* position of each switch removes power from the corresponding aft payload bus.

The *AUX* switch on panel R1 permits main bus A and main bus B power to be supplied to the *AUX PL A* and *AUX PL B* buses when the switch is positioned to *ON*. The auxiliary payload buses can provide power for emergency equipment or controls associated with payloads. The *OFF* position removes power from the *AUX PL A* and *PL B* buses. The two auxiliary payload buses may be dioded together to form one bus for redundancy.

The *CABIN* switch on panel R1 provides *MN A* or *MN B* power to patch panels located behind the payload specialist and mission specialist stations on the aft flight deck. These patch panels supply power to the payload-related equipment located on panels at these stations. Two three-phase circuit breakers, *AC 2 PAYLOAD 3 ϕ* and *AC 3 PAYLOAD 3 ϕ* on panel MA73C, provide ac power to the payload patch panels.

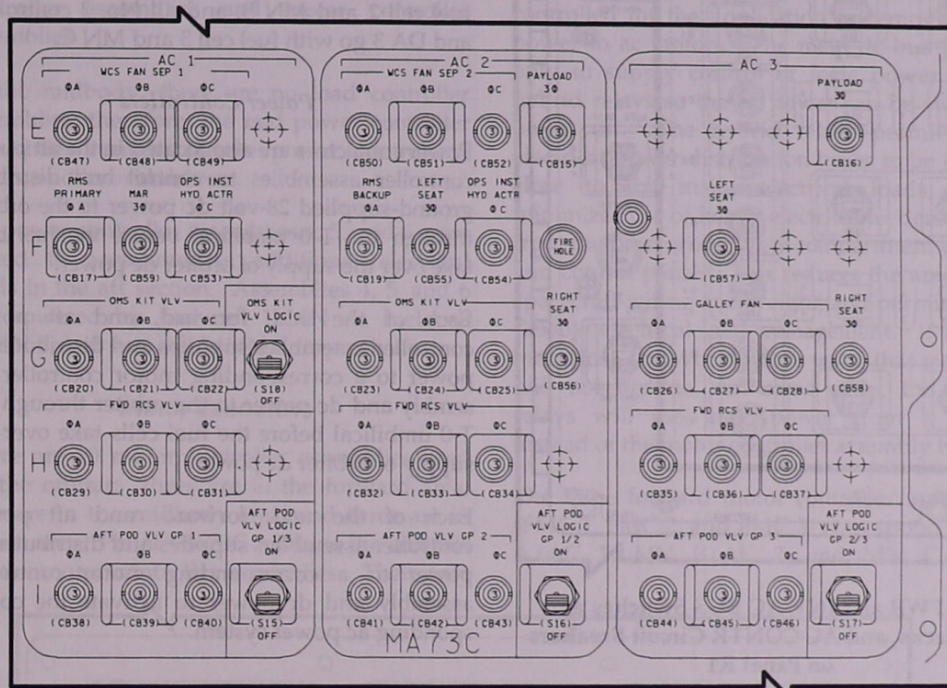
AC Power Generation

Alternating-current power is generated and made available to system loads by the electrical power distribution and control subsystem using three independent ac buses, *AC 1*, *AC 2*, and *AC 3*. The ac power system includes the ac inverters for dc conversion to ac and inverter distribution and control assemblies containing the ac buses and the ac bus sensors. The ac power is distributed from the inverter distribution and controller assemblies to the flight and middeck display and control panels and from the motor controller assemblies to the three-phase motor loads.

Each ac bus consists of three separate phases connected in a three-phase array. Static inverters, one for each phase, are located in the forward avionics bays. Each inverter has an output voltage of 116 to 120 volts rms at 400 hertz, ± 7 hertz.

indicators will show OFF when any of the phases are not connected to their respective ac bus.

The INV PWR and INV/AC BUS switches and talkbacks must have control power from the AC CONTR circuit breakers on panel R1 in order to operate. Once ac power has been established, these circuit breakers are opened to prevent any



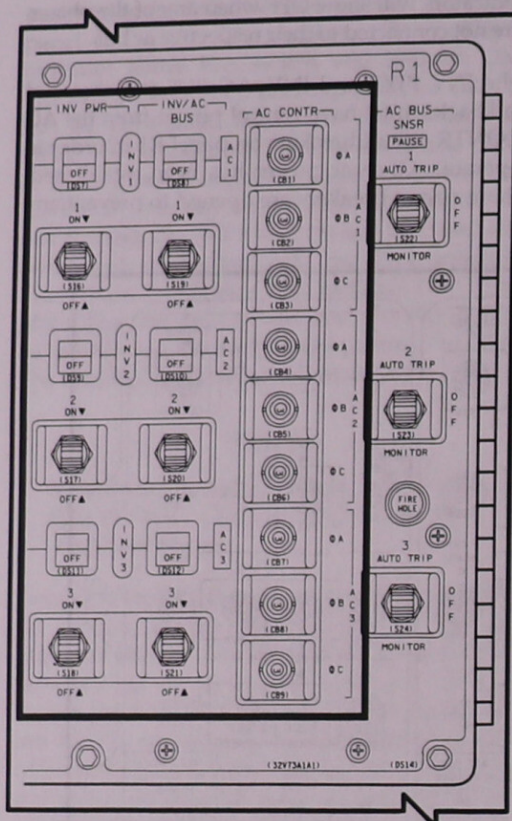
AC2 Cabin PAYLOAD 3Ø AND AC3 Cabin PAYLOAD 3Ø Circuit Breakers on Panel MA73C

Input power to the inverters is controlled by the INV PWR 1, 2, 3 switches on panel R1. INV PWR 1 routes power to AC 1 from MN A, INV PWR 2 to AC 2 from MN B, and INV PWR 3 to AC 3 from MN C. All three inverters of AC 1 receive MN A bus power when the INV PWR 1 switch is positioned to ON, and all three must be in operation before the talkbacks above the switches indicate ON. The indicators will show OFF when main bus power is not connected to the inverters. The INV/AC BUS 1, 2, 3 switches on panel R1 are used to apply each inverter's output to its respective ac bus. An indicator above each switch shows its status, and all three inverters must be connected to their respective ac buses before the indicators show ON. The talkback

inadvertent disconnection, whether by switch failure or accidental movement of the INV PWR or INV/AC BUS switches.

Electrical Power Distribution and Control Assemblies

Electrical power is controlled and distributed by assemblies. Each assembly (main distribution assembly, power controller assembly, load controller assembly, and motor controller assembly) is in an electrical equipment container.



INV PWR and INV/AC BUS Switches and Talkbacks, and AC CONTR Circuit Breakers on Panel R1

Distribution Assemblies

The dc power generated by each of the fuel cells is supplied to a corresponding distribution assembly (DA). Fuel cell 1 powers DA 1, fuel cell 2 powers DA 2, and fuel cell 3 powers DA 3. Each distribution assembly contains fuses, relays, and remotely controlled motor-driven switches called power contactors. The DAs control and distribute dc power to a corresponding mid power controller assembly, forward power controller assembly, and aft power controller assembly.

The FC MAIN BUS A switch on panel R1 positioned to ON connects fuel cell 1 to the MN A DA 1 and controllers and disconnects fuel cell 1 from the MN A DA 1 and controllers when positioned to OFF. The talkback indicator next to the FC MAIN BUS A switch will indicate ON

when fuel cell 1 is connected to main bus A distribution assembly and controllers, and OFF when fuel cell 1 is disconnected from main bus A distribution assembly and controllers. The FC MAIN BUS B and C switches and talkback indicators on panel R1 function in the same manner. The No. 1 distribution assembly and all No. 1 controllers go with fuel cell 1 and MN A bus, all No. 2 controllers and DA 2 go with fuel cell 2 and MN B, and all No. 3 controllers and DA 3 go with fuel cell 3 and MN C.

Power Controllers

Power contactors are also located in the aft power controller assemblies to control and distribute ground-supplied 28-volt dc power to the orbiter through the T-0 umbilical before the fuel cells take over the supply of orbiter dc power.

Each of the mid, forward, and aft power controller assemblies supplies and distributes dc power to a corresponding motor controller assembly and dc power to the orbiter through the T-0 umbilical before the fuel cells take over the supply of orbiter dc power.

Each of the mid, forward, and aft power controller assemblies supplies and distributes dc power to a corresponding motor controller assembly and dc power to activate the corresponding ac power system.

Remote Power Controllers

Each power controller assembly contains RPCs and relays. The RPCs are solid-state switching devices; they have the capability to limit the output current to a maximum of 150 percent of rated value for 2 to 3 seconds. Within 3 seconds, the RPC will trip out, removing the output current. To restore power to the load, the RPC must be reset. This is accomplished by cycling a control switch. If multiple control inputs are required before a RPC is turned on, hybrid drivers are usually used as a logic switch, which then drives the control input of the RPC.

Load Controllers

Each load controller assembly contains hybrid drivers, which are solid-state switching devices (no mechanical parts) used as logic switches and for low-power electrical loads. When the drivers

are used as a logic switch, several control inputs are required to turn on a load. Hybrid drivers are also used in the mid power controller assemblies. The hybrid drivers are current protected by internal fuses. Hybrid relays requiring multiple control inputs are used to switch three-phase ac power to motors.

Relays are also used for loads in power controller assemblies and motor controller assemblies.

In the midbody, there are no load controller assemblies; therefore, the mid power controller assemblies contain remote power controllers, relays, and hybrid drivers.

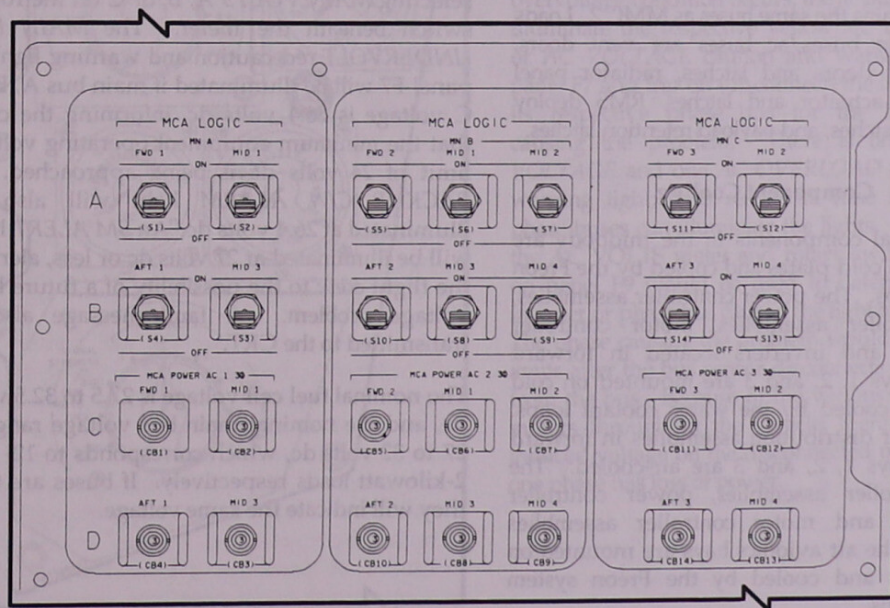
Aft power controller assemblies 4, 5, and 6 were added to accommodate additional electrical loads in the aft section. Assemblies 4, 5, and 6 are powered by fuel cell 1/MN A, fuel cell 2/MN B, and fuel cell 3/MN C respectively.

Motor Controllers

There are 10 motor controller assemblies used on the orbiter: three are in the forward area, four are in the midbody area, and three are in the aft area. Panel MA73C contains the controls for the motor controller assemblies. Their only

function is to supply ac power to noncontinuous ac loads for ac motors used for vent doors, air data probe, star tracker doors, payload bay doors, payload bay latches, ET doors and latches, RMS deploy motors and latches, and reaction control system/orbital maneuvering system motor-actuated valves. Each motor controller assembly contains main dc buses, ac buses, and hybrid relays that are remotely controlled for the application or removal of ac power to ac motors. The main dc bus is used only to supply control or logic power to the hybrid relays so the ac power can be switched on or off. The hybrid relays permit major electrical power distribution buses to be located close to the major electrical loads, which minimizes use of heavy electrical feeders to and from the pressurized crew compartment display and control panels. This reduces the amount of spacecraft wiring and weight, and permits more flexible electrical load management. If a main bus is lost, the hybrid relays using that main bus will not operate. In some cases, the hybrid relays will use logic power from a switch instead of the motor controller assembly bus.

The three forward motor controller assemblies (FMC 1, FMC 2, and FMC 3) correspond to MN A/AC 1, MN B/AC 2, and MN C/AC 3



Motor Controller Assembly Controls on Panel MA37C

respectively. Each FMC contains a main bus, an ac bus, and an RCS ac bus. The main bus supplies control or logic power to the relays associated with both the ac bus and RCS ac bus. The ac bus supplies power to the forward left and right vent doors, the star tracker Y and Z doors, and the air data left and right doors. The RCS ac bus supplies power to the forward RCS manifold and tank isolation valves.

The aft motor controller assemblies (AMC 1, AMC 2, and AMC 3) correspond to MN A/AC 1, MN B/AC 2, and MN C/AC 3 respectively. Each aft motor controller assembly receives power from a main bus and its corresponding ac bus and a main RCS/OMS bus and its corresponding RCS/OMS ac bus. Both main buses are used for control or logic power for the hybrid relays. The ac bus is used by the aft RCS/OMS manifold and tank isolation and crossfeed valves, the aft left and right vent doors, and the ET umbilical doors.

The mid motor controller assemblies (MMC 1, MMC 2, MMC 3, and MMC 4) contain two main dc buses and two corresponding ac buses. MMC 1 contains main bus A and B and their corresponding buses, AC 1 and AC 2. MMC 2 contains MN B and C and AC 2 and AC 3 buses. MMC 3 contains the same buses as MMC 1, and MMC 4 contains the same buses as MMC 2. Loads for the main buses/ac buses are vent doors, payload bay doors and latches, radiator panel deployment actuator and latches, RMS deploy motors and latches, and payload retention latches.

Component Cooling

The electrical components in the midbody are mounted on cold plates and cooled by the Freon coolant loops. The power controller assemblies, load controller assemblies, motor controller assemblies, and inverters located in forward avionics bays 1, 2, and 3 are mounted on cold plates and cooled by the water coolant loops. The inverter distribution assemblies in forward avionics bays 1, 2, and 3 are air-cooled. The load controller assemblies, power controller assemblies, and motor controller assemblies located in the aft avionics bays are mounted on cold plates and cooled by the Freon system coolant loops.

Bus Tie

In the event of an electrical failure, or to load share between fuel cells, any main bus can be connected to another main bus through the use of the *MN BUS TIE* switches on panel R1 and power contactors in the distribution assemblies. For example, main bus A can be connected to main bus B by positioning both the *MN BUS TIE A* and the *MN BUS TIE B* switch to *ON*. The talkback indicators next to the switches will indicate *ON* when main bus A is connected to main bus B. Other indications of an effective bus tie are matching voltages for the two buses. To disconnect main bus A from main bus B, the *MN BUS TIE A* and *B* switches must be positioned to *OFF*; the talkback indicators next to the switches will then indicate *OFF*.

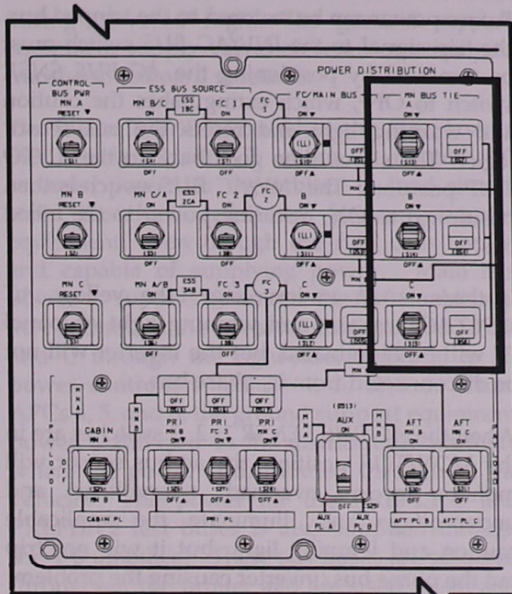
NOTE

It is also possible to tie the main buses B and C together via the PRI switches. This is done by connecting each main bus to the primary payload bus.

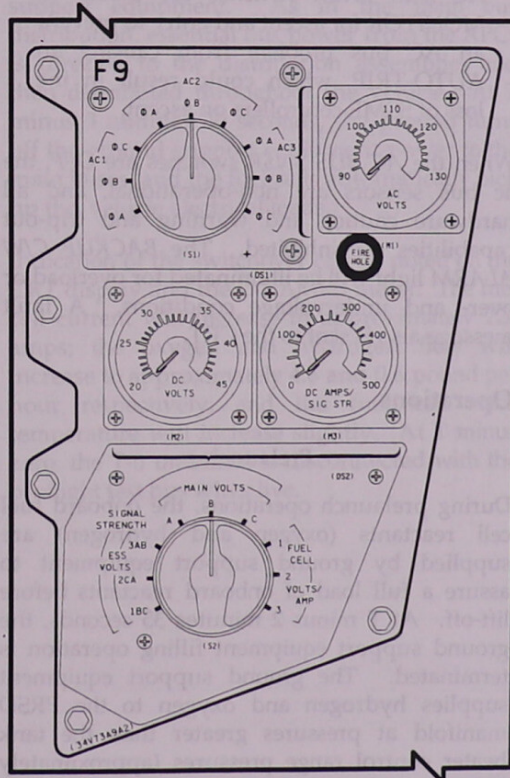
Instrumentation and System Monitoring

Main bus A, B, or C voltages can be displayed on the DC VOLTS meter on panel F9 by selecting *MAIN VOLTS A*, *B*, or *C* on the rotary switch beneath the meter. The *MAIN BUS UNDERVOLT* red caution and warning light on panel F7 will be illuminated if main bus A, B, or C voltage is 26.4 volts dc, informing the crew that the minimum equipment operating voltage limit of 24 volts dc is being approached. A *BACKUP C/W ALARM* light will also be illuminated at 26.4 volts dc. An *SM ALERT* light will be illuminated at 27 volts dc or less, alerting the flight crew to the possibility of a future low-voltage problem. A fault message also is transmitted to the CRT.

The nominal fuel cell voltage is 27.5 to 32.5 volts dc, and the nominal main bus voltage range is 27 to 32 volts dc, which corresponds to 12- and 2-kilowatt loads respectively. If buses are tied, they will indicate the same voltage.



MN BUS TIE Switches on Panel R1

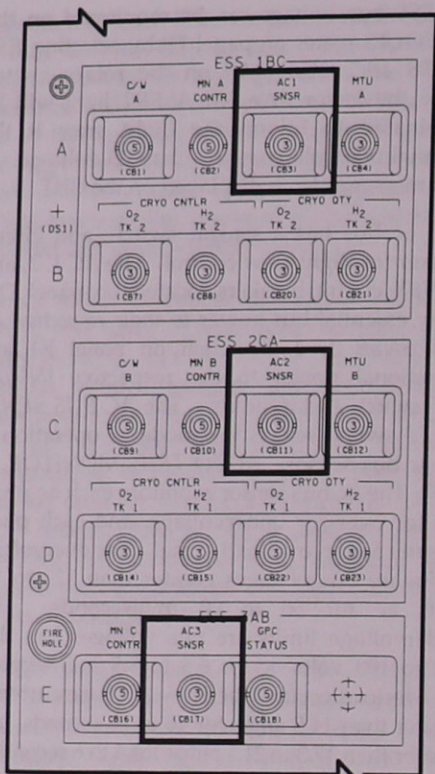


EPS Meters and Switches on Panel F9

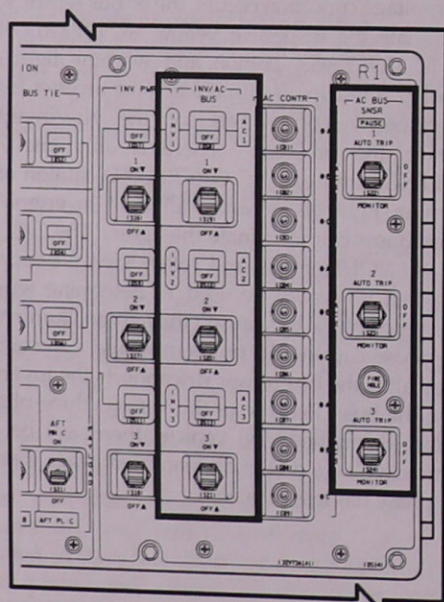
The ESS bus voltage can be monitored on the DC VOLTS meter on panel F9 by selecting *ESS VOLTS 1BC, 2CA, 3AB* on the rotary switch below the meter. An *SM ALERT* light will be illuminated to inform the flight crew if the essential bus voltage is less than 25 volts dc. A fault message also is displayed on the CRT.

Each ac bus has a sensor, switch, and circuit breaker for flight crew control. The AC 1, 2, and 3 *SNSR* circuit breakers located on panel O13 apply essential bus power to their respective AC BUS *SNSR 1, 2, 3* switch on panel R1 and operational power to the respective *INV/AC BUS* switch and indicator. The AC BUS *SENSR 1, 2, 3* switch selects the mode of operation of the ac bus sensor: *AUTO TRIP, MONITOR, or OFF*. The ac bus sensor monitors each ac phase bus for over- or undervoltage, and each phase inverter for an overload signal. The overvoltage limits are bus voltages greater than 123 to 127 volts ac for 50 to 90 milliseconds. The undervoltage limits are bus voltages less than 102 to 108 volts ac for 6.5 to 8.5 milliseconds. An overload occurs when any ac phase current is greater than 14.5 amps for 10 to 20 seconds, or is greater than 17.3 to 21.1 amps for 4 to 6 seconds.

When the respective AC BUS *SNSR* switch is in the *AUTO TRIP* position, and an overload or overvoltage condition occurs, the ac bus sensor will illuminate the respective yellow *AC OVERLOAD* or *AC VOLTAGE* caution and warning light on panel F7 and trip off (disconnect) the inverter from its respective phase bus for the bus/inverter causing the problem. There is only one *AC VOLTAGE* and one *AC OVERLOAD* caution and warning light; as a result, all nine inverters/ac phase buses can illuminate the lights. The CRT or the AC VOLTS meter and rotary switch beside it on panel F9 would be used to determine which inverter or phase bus caused the light to illuminate. The phase causing the problem would approach 0 amps after the bus sensor disconnects the inverter from the bus. Because of the various three-phase motors throughout the vehicle, there will be an induced voltage on the disconnected phase if only one phase has loss of power.



AC 1, 2, 3 SNSR Circuit Breakers on Panel O13



AC BUS SNSR Switches and INV/AC BUS Switches and Talkback Indicators on Panel R1

Before power can be restored to the tripped bus, the trip signal to the *INV/AC BUS* switch must be removed by positioning the *AC BUS SNSR* switch to OFF, which extinguishes the caution and warning light and resets the bus sensor logic. The signal then goes back to the *AUTO TRIP* position. The *INV/AC BUS* switch is then positioned to ON, restoring power to the failed bus.

If there is an undervoltage, the yellow *AC VOLTAGE* caution and warning light on panel F7 will be illuminated, but the inverter will not be disconnected from its phase bus.

When the *AC BUS SNSR 1, 2, 3* switches are in the *MONITOR* position, the ac bus sensor will monitor for an overload, overvoltage, and undervoltage and illuminate the applicable caution and warning light; but it will not trip out the phase bus/inverter causing the problem.

NOTE

AC BUS SNSR switches are placed in *MONITOR* for ascent and entry to prevent an AC bus problem from causing an *AUTO-TRIP*, which could result in the loss of SSME controllers on ascent.

When the *AC BUS SNSR* switches are OFF, the ac bus sensors are non-operational, and all hardware caution and warning and trip-out capabilities are inhibited. The *BACKUP C/W ALARM* light will be illuminated for overload or over- and undervoltage conditions. A fault message also is sent to the CRT.

Operations

Prelaunch

During prelaunch operations, the onboard fuel cell reactants (oxygen and hydrogen) are supplied by ground support equipment to assure a full load of onboard reactants before lift-off. At T minus 2 minutes 35 seconds, the ground support equipment filling operation is terminated. The ground support equipment supplies hydrogen and oxygen to the PRSD manifold at pressures greater than the tank heater control range pressures (approximately 280 psia for hydrogen and 960 psia for oxygen). This helps to prevent cryo tank heater cycling

during powered flight. The ground support equipment supply valves close automatically to transfer to onboard reactants.

The fuel cells will be on when the crew boards the vehicle. Until T minus 3 minutes 30 seconds, power to the orbiter is load shared with the fuel cells and ground support equipment, even though the fuel cells are on and capable of supplying power. Main bus power is supplied through the T-0 umbilicals, MN A through the left-side umbilical and MN B and C through the right-side umbilical to aft power controllers (APCs) 4, 5, and 6. From APCs 4, 5, and 6, the ground support equipment power is directed to the distribution assembly where the power is distributed throughout the vehicle. The power for the PREFLT 1 and PREFLT 2 test buses is also supplied through the T-0 umbilical. These test buses are scattered throughout the orbiter and are used to support launch processing system control of critical orbiter loads, although they also power up the essential buses in the APCs when on ground support equipment. As in the main bus distribution, essential bus power from the APCs is directed to the distribution assemblies and then distributed throughout the vehicle. At T minus 3 minutes 30 seconds, the ground turns off the ground support equipment power to the main buses, and the fuel cells automatically pick up the vehicle electrical loads.

Indication of the switchover can be noted on the CRT display and the DC AMPS meter. The fuel cell current will increase to approximately 220 amps; the oxygen and hydrogen flow will increase to approximately 4.6 and 0.6 pound per hour respectively; and the fuel cell stack temperature will increase slightly. At T minus zero, the T-0 umbilical is disconnected with the preflight test bus wires live.

Prelaunch and On-Orbit Tank Heater Management

Before lift-off, the O2 TK1 HEATERS A, O2 TK2 HEATERS A, H2 TK1 HEATERS A, and H2 TK2 HEATERS A switches on panel R1 are set on AUTO. As part of the Post OMS 1 Burn procedures, all the switches on O2 and H2 tanks 1 & 2 are positioned to AUTO, while the other tank heaters remain OFF. On orbit, the cryo tank heaters are managed to provide for tank quantity balancing. When hydrogen tanks 4 and 5 are installed on OV-102, they are depleted first due to their common check valve. Because the tank 3 and 4/5 heater controller pressure limits are higher than those of tanks 1 and 2, tanks 3 and 4/5 supply the reactants to the fuel cells when all tank heaters are set to AUTO. For entry, tanks 1 and 2 supply the reactants to the fuel cells.

Fuel Cell Operating Modes

Fuel cell standby consists of removing the electrical loads from a fuel cell but continuing operation of the fuel cell pumps, controls, instrumentation, and valves, while electrical power is supplied by the remaining fuel cells. A small amount of reactants is used to generate power for the fuel cell internal heaters. If the temperature in the fuel cell compartment beneath the payload bay is lower than 40° F, the fuel cell should be left in STANDBY instead of being shut down to prevent it from freezing.

Fuel cell shutdown, after standby, consists of stopping the coolant pump and hydrogen pump/water separator by positioning that FUEL CELL START/STOP switch on panel R1 to the STOP position.

Fuel cell safing consists of closing the fuel cell reactant valves and consuming the reactants inside the fuel cell by either leaving the fuel cell connected to its main bus or by keeping the pump package operating with the internal heaters.

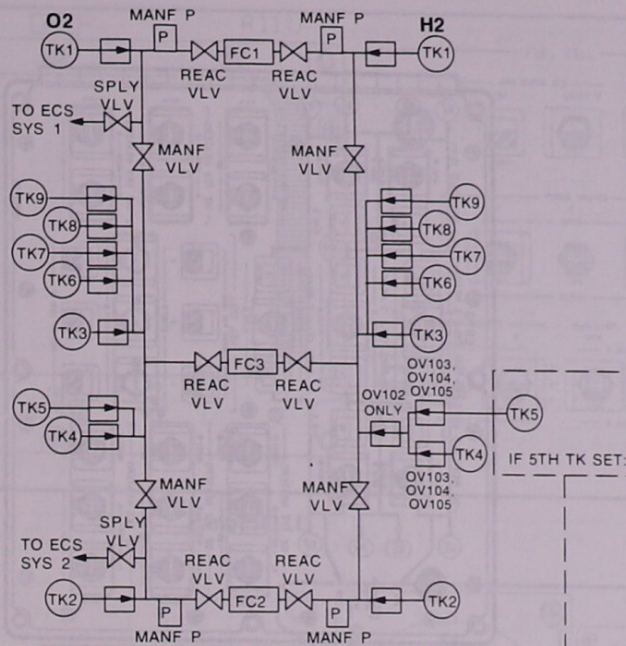
EPS Caution and Warning Summary

- The *SM ALERT* will illuminate if a cryo heater current level sensor detects a short on a heater circuit.
- The yellow *O₂ PRESS* and the red *BACKUP C/W ALARM* lights illuminate if oxygen tank pressure is below 540 psia or above 985 psia.
- The yellow *H₂ PRESS* and the red *BACKUP C/W ALARM* lights illuminate if hydrogen tank pressure is below 153 psia or above 293.8 psia.
- When any fuel cell reactant valve is closed, the red *FUEL CELL REAC* light is illuminated, a tone is sounded and the *BACKUP C/W ALARM* is illuminated.
- The yellow *FUEL CELL STACK TEMP* light will illuminate if fuel cell and stack temperatures are below 170.7° F or above 241.9° F. The red *BACKUP C/W ALARM* and blue *SM ALERT* will also light for similar limits.
- The yellow *FUEL CELL PUMP* light will illuminate if fuel cell 1, 2, or 3 coolant pump delta pressure is lost. If the coolant pump for fuel cell 1, 2, or 3 is off, the *BACKUP C/W ALARM* will be illuminated.
- The yellow *O₂ HEATER TEMP* light on panel F7 illuminates if the temperature sensor senses the oxygen tank temperature is at or above 344° F. Software checks the limit; if it is above 349° F, the *BACKUP C/W ALARM* light illuminates as well.
- The red *MAIN BUS UNDERVOLT* light and the *BACKUP C/W ALARM* illuminate if main bus A, B, or C voltage is 26.4 volts dc.
- The yellow *AC VOLTAGE* light illuminates for an overvoltage or undervoltage condition in the ac bus. The red *BACKUP C/W ALARM* will also illuminate.
- The yellow *AC OVERLOAD* light illuminates for an overload condition in the ac bus.

O ₂ PRESS	H ₂ PRESS	FUEL CELL REAC	FUEL CELL STACK TEMP	FUEL CELL PUMP
CABIN ATM (R)	O ₂ HEATER TEMP	MAIN BUS UNDERVOLT (R)	AC VOLTAGE	AC OVERLOAD
FREON LOOP	AV BAY/ CABIN AIR	IMU	FWD RCS (R)	RCS JET
H ₂ O LOOP	RGA/ACCEL	AIR DATA (R)	LEFT RCS	RIGHT RCS (R)
—————	LEFT RHC (R)	RIGHT/AFT RHC	LEFT OMS (R)	RIGHT OMS (R)
PAYLOAD WARNING (R)	GPC	FCS (R) SATURATION	OMS KIT	OMS TVC (R)
PAYLOAD CAUTION	PRIMARY C/W	FCS CHANNEL	MPS (R)	—————
BACKUP C/W ALARM (R)	APU TEMP	APU OVERSPEED	APU UNDERSPEED	HYD PRESS

346.cvs

EPS Caution and Warning Lights on Panel F7



02/H2 HTR LOSS (ALL EXCEPT OV 102)

BUS LOSS	PAIRED				PAIRED							
	TK1		TK2		TK3		TK4		TK5			
	A	B	A	B	A	B	A	B	A	B		
MNA DA1	A/M		AUTO	A/M	A/M	A/M	AUTO	A/M	A/M			
MNB DA2			A/M	A/M			A/M	A/M				
MNC DA3	AUTO	A/M	A/M	A/M			A/M	A/M			AUTO	A/M
CNTL AB1		MAN										
AB2		A/M										
CNTL BC1			MAN					MAN				MAN
BC2			A/M					A/M				A/M
BC3				MAN				MAN				
CNTL CA1	MAN										MAN	A/M
CA2	A/M										A/M	
CA3				A/M					A/M			
ESS 1BC	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*
2CA	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO
3AB	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO

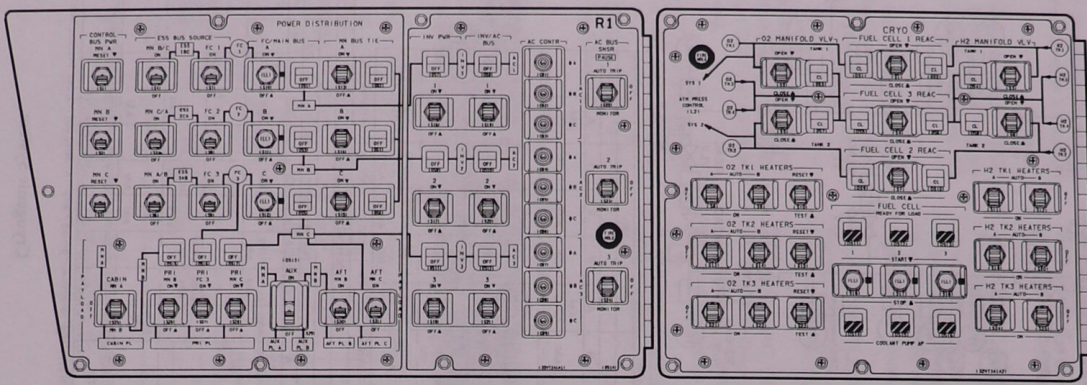
* Auto operation regained if both A and B HTR SW of other paired tank(s) are not in auto. A/M = Auto and manual loss.

02/H2 HTR LOSS (OV 102 ONLY)

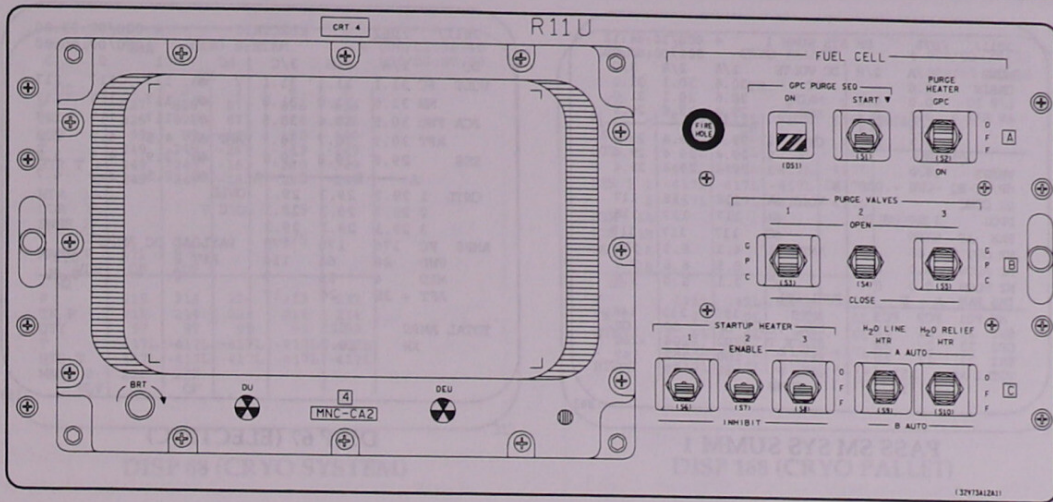
BUS LOSS	PAIRED				PAIRED				PAIRED				PAIRED					
	TK1		TK2		TK3		TK4		TK5		TK6		TK7		TK8		TK9	
	A	B	A	B	A	B	O2	H2A	H2B	O2	H2A	H2B	A	B	A	B	A	B
MNA DA1	A/M		AUTO	A/M	A/M	A/M	AUTO	AUTO	A/M	A/M	AUTO	A/M	A/M					
MNB DA2			A/M	A/M			A/M	A/M			A/M	A/M						
MNC DA3	AUTO	A/M	A/M	A/M			A/M	A/M			A/M	A/M						
CNTL AB1		MAN											MAN					
AB2		A/M											A/M					
AB3																		
CNTL BC1			MAN				MAN	MAN			MAN	MAN						
BC2			A/M				A/M	A/M			AUTO	A/M						
BC3				MAN					MAN	MAN								
CNTL CA1	MAN						MAN						MAN					MAN
CA2	A/M						A/M						A/M					A/M
CA3				A/M					A/M	A/M								
ESS 1BC	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*	AUTO*
2CA	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO
3AB	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO

* Auto operation regained if both A and B HTR SW of other paired tank(s) are not in auto. TK1 paired with TK2, and TK3 paired with TK4/5. A/M = Auto and manual loss.

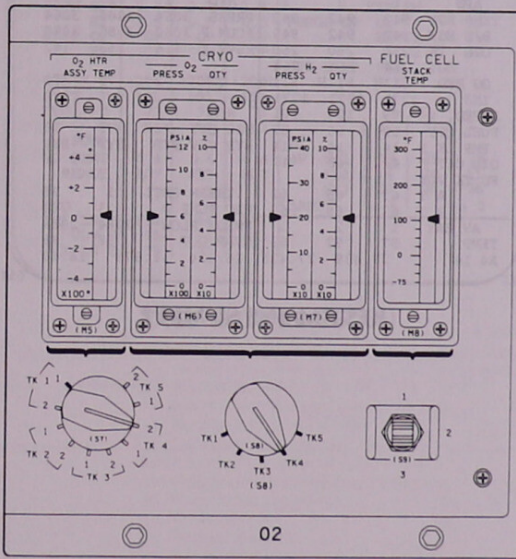
Cryogenic System



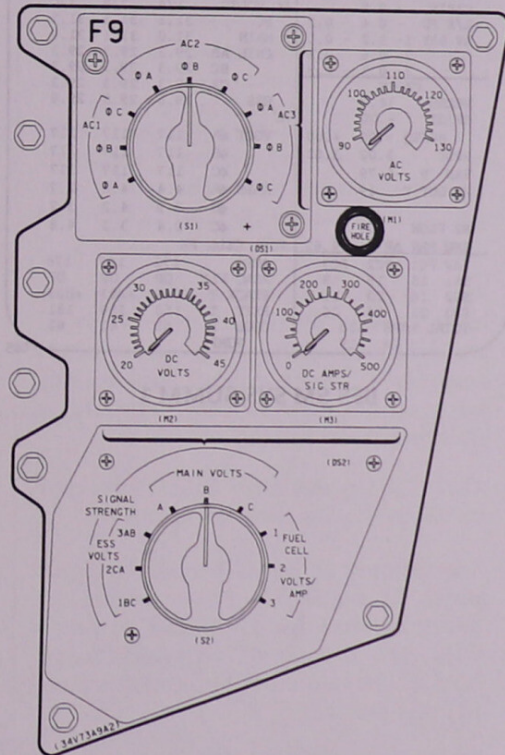
Panel R1



Panel R11U



Panel O2



Panel F9

2011/ /068		CRYO SYSTEM					4 000/02:34:40 000/00:00:00	
		TK						
O2	1	2	3	4	5			
P	827	826	871	826	826			
TK P	828	828	871	828	828			
QTY	99	99	100	100	100			
T	-249	-249	-249	-249	-249			
HTR T 1	-249	-249	-182	-249	-249			
HTR T 2	-249	-249	-182	-249	-249			
HTR 1A								
CUR 1B				4/5				
SNSR 2A								
2B				4/5				
MANF P	871	871						
VLV	OP	OP						
H2								
P	215	213	224	213	213			
TK P	215	214	224	214	214			
QTY	97	97	99	99	99			
T	-417L	-417L	-417L	-417L	-417L			
HTR T	-417L	-417L	-417L	-417L	-417L			
MANF P	222	222						
VLV	OP	OP						

313

DISP 68 (CRYO SYSTEM)

2011/ /168		CRYO PALLET				4 000/02:38:52 000/00:00:00	
		TK					
O2	6	7	8	9			
P	515L	515L	515L	515L	PALLET		
TK P	0L	0L	0L	0L	STB		
QTY	- 5L	- 5L	- 5L	- 5L	STB		
T	-417L	-417L	-417L	-417L	POP		
HTR T 1	-417L	-417L	-417L	-417L	POP		
HTR T 2	-417L	-417L	-417L	-417L	POP		
HTR 1A					PALLET		
CUR 1B					PPO		
SNSR 2A							
2B							
H2							
P	145L	145L	145L	145L			
TK P	0L	0L	0L	0L			
QTY	- 6L	- 6L	- 6L	- 6L			
T	-417L	-417L	-417L	-417L			
HTR T	-417L	-417L	-417L	-417L			

314

DISP 168 (CRYO PALLET)

2011/ /069		FUEL CELLS			4 000/02:35:11 000/00:00:00	
		FC				
O2	1	2	3			
VOLTS	31.3	31.2	31.2	H2O RLF LINE T	72	
AMPS	161	164	163	NOZ T A	244	
FLOW O2	2.7	2.7	2.6	B	244	
H2	0.5	0.5	0.5	HTR SW	A	
REAC O2	OP	OP	OP	PURGE LN O2 T	32	
H2	OP	OP	OP	H2 T1	40	
				T2	40	
STACK T	+204	+204	+204	H2O LINE PH		
EXIT T	151	151	151			
COOL T	73	73	73			
P	61	61	61			
PUMP						
H2 PUMP	0.4	0.4	0.4	PH		
READY	RDY	RDY	RDY	AV	SS1 15 18 18	
				SS2	16 20 11	
				SS3	22 26 26	
H2O				ΔAMPS	- 3 + 1 + 2	
PRI LN T	144	144	144			
VLV T	93	93	93			
ALT LN T	79	79	79			

328

DISP 69 (FUEL CELLS)

EPS Summary Data

- The EPS operates during all flight phases and consists of the equipment and reactants that produce electrical power for distribution throughout the orbiter.
- The fuel cell picks up full power load support after ground equipment is turned off at T minus 3 minutes 30 seconds, supporting power requirements for the solid rocket booster, orbiter, and payloads.
- EPS subsystems are: power reactants storage and distribution, fuel cells, and electrical power distribution and control.
- The power reactants storage and distribution system stores cryogenic hydrogen and oxygen and supplies them to the fuel cells. It also supplies oxygen to the ECLSS. The components are located in the orbiter midbody underneath the payload bay.
- The fuel cell system (three fuel cells) transforms hydrogen and oxygen to electricity by a chemical reaction. The system supplies potable water to the ECLSS and consists of power and accessory sections.
- The electrical power distribution and control system distributes electrical power throughout the orbiter. It has five types of assemblies: power control, load control, motor control, main dc distribution, and ac distribution and control.
- The EPS requires very little flight crew interaction during nominal operations.
- The majority of the EPS controls are on panels R1 and R11U. Power sources and circuit breakers are distributed on panels O13, O14, O15, O16, ML86B, R15, and MA73C. Heaters are controlled from panel R1, A11 and A15.
- Meters for monitoring EPS parameters are located on panels F9 and O2.
- CRTs that display EPS data are BFS SM SYS SUMM 1 & 2, DISP 67 (ELECTRIC), DISP 68 (CRYO SYSTEM), DISP 69 (FUEL CELLS), PASS SM SYS SUMM 1 & 2, and DISP 168 (CRYO PALLET).

EPS Rules of Thumb

- Never close a circuit breaker or reset an RPC found out of configuration without MCC coordination.
- Loss of cooling to a fuel cell requires crew action within 9 minutes to prevent a catastrophic loss of crew/vehicle due to possible fuel cell fire and explosion.
- Fuel cell run limit prior to shutdown for loss of cooling is 9 minutes at a 7 kW nominal load. Run time is inversely proportional to fuel cell load.
- Any interruption of continuous ac power during ascent may result in the loss of main engine controller redundancy. Reconfiguration of ac powered equipment prior to MECO should be avoided.
- Never connect or reconnect power to a known shorted or failed component; this includes switch throws, circuit protection device resets, or bus ties.
- Three oxygen and hydrogen tanks are good for up to 8 days on orbit; five oxygen and hydrogen tanks are good for up to 12 days on orbit; eight oxygen and hydrogen tanks are good for up to 18 days on orbit. Exact duration varies with crew complement and power load.
- A fuel cell hydrogen pump uses 0.3 amps/AC phase; a coolant pump uses 0.5 amps/AC phase.

2.9 ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS)

CONTENTS

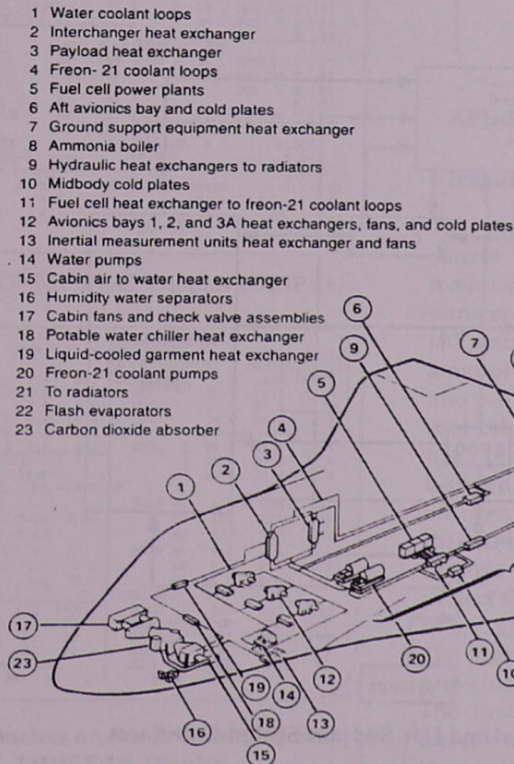
Description	2.9-1
Pressure Control System	2.9-3
Atmospheric Revitalization System...	2.9-12
Active Thermal Control System	2.9-21
Supply and Waste Water Systems	2.9-32
Operations	2.9-40
ECLSS Caution and Warning	
Summary	2.9-43
ECLSS Summary Data	2.9-44
ECLSS Rules of Thumb	2.9-55

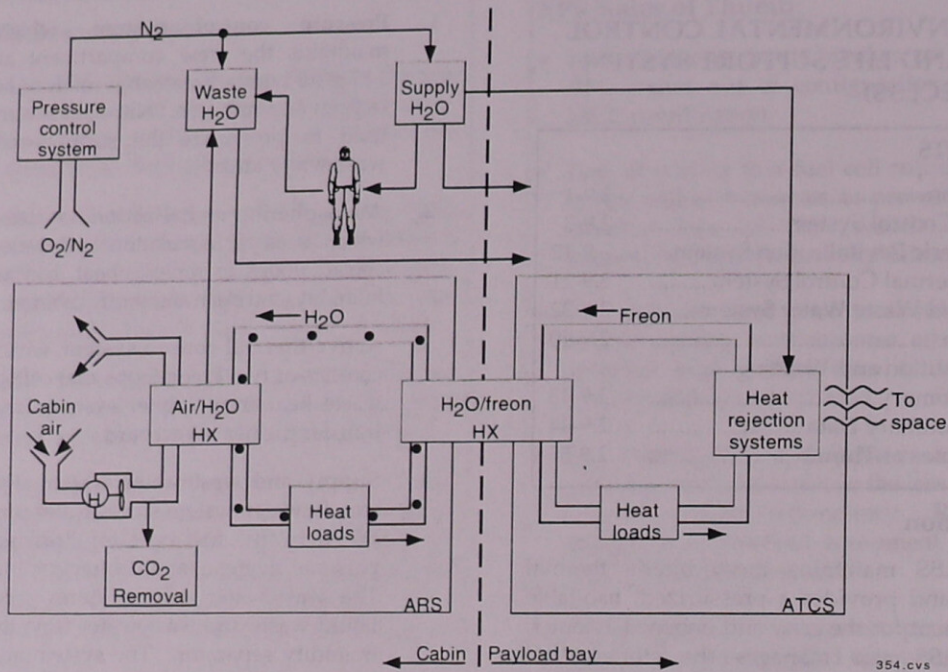
Description

The ECLSS maintains the orbiter's thermal stability and provides a pressurized, habitable environment for the crew and onboard avionics. The ECLSS also manages the storage and disposal of water and crew waste.

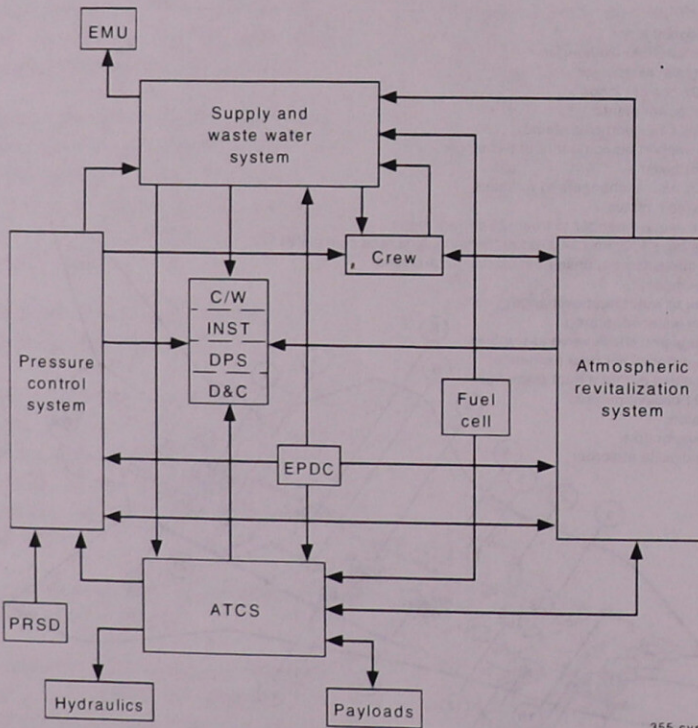
ECLSS is functionally divided into four systems:

1. **Pressure control system**, which maintains the crew compartment at 14.7 psia with a breathable mixture of oxygen and nitrogen. Nitrogen is also used to pressurize the supply and wastewater tanks.
2. **Atmospheric revitalization system**, which uses air circulation and water coolant loops to remove heat, control humidity, and clean and purify cabin air.
3. **Active thermal control system**, which consists of two Freon loops that collect waste heat from orbiter systems and transfer the heat overboard.
4. **Supply and wastewater system**. The supply water system stores water produced by the fuel cells for drinking, personal hygiene, and orbiter cooling. The wastewater system stores crew liquid waste and wastewater from the humidity separator. The system also has the capability to dump supply and wastewater overboard.





Environmental Control and Life Support System Overview



Environmental Control and Life Support System Interfaces

The crew compartment provides a life-sustaining environment for the flight crew. The crew cabin volume with the airlock inside the mid-deck is 2,475 cubic feet (2,325 cubic feet for the orbiter cabin and 150 cubic feet for the airlock). For EVA, the airlock is depressurized and repressurized. Under normal circumstances, the cabin may be depressed to 10.2 psia to ease pre-breathe requirements prior to an EVA. When the airlock is located outside the middeck in the payload bay, the crew cabin volume is 2,625 cubic feet. The external airlock volume varies and is based on mission-specific configuration. The external airlock is covered in detail in the Orbiter Docking System (ODS) section of this document.

Most ECLSS parameters can be monitored during ascent and entry on BFS DISP 78 (SM SYS SUMM 1) and BFS DISP 79 (SM SYS SUMM 2) displays. On orbit ECLSS parameters are also available on SM DISP 66 (ENVIRONMENT) and SM DISP 88 (APU/ENVIRON THERM) displays.

0001/ /079		SM SYS SUMM 2		5 008/23:29:22	
CRYO TK	1 2 3 4	BFS 000/00:00:00		5 MANFL MANFZ	
H2 PRESS	208 208 206 206	206 206		208 207	
O2 PRESS	816 815 814 814	814 814		815 815	
HTR T1	-248 -248 -248 -248	-248 -248			
T2	-248 -248 -248 -248	-248 -248			
APU	3	HYD	1 2 3		
TEMP EGT	942 942 942	PRESS	3064 3064 3064		
B/U EGT	942 942 942	ACIM P	3080 3080 3080		
OIL IN	250 250 250	RSVR T	116 153 142		
OUT	264 264 264	QTY	72 74 71		
GG BED	511H 511H 511H	W/B			
INJ	1271 1271 1271	H2O QTY	78 73 78		
SPEED %	99 102 101	BYP VLV	BYP BYP BYP		
FUEL QTY	59 60 62	W/B			
PMP LK P	14 14 14	THRM CNTL	1 28		
OIL OUT P	42 42 41	H2O PUMP P	23 63		
FU TK VLV		FREON FLOW	2384 2384		
A T	63 65 62	EVAP OUT T	38 38		
B T	63 65 62	TEMP	97 97 83		
AV BAY	1 2 3	A4 14	27.439 27.435		
TEMP	97 97 83				
A4 14					

ECLSS Parameters on the BFS SM SYS SUMM 2 (DISP 79) Display

2011/ /066		ENVIRONMENT		4 000/02:33:38	
CABIN		AV BAY		1 2 3	
dp/dt +.01	CABIN P 14.7	TEMP	90 90 78		
PP02	AIRLK P 14.8	FAN AP	3.80 3.77 3.92		
A 3.04	FAN AP 5.55	SUPPLY H2O			
B 3.04	HK OUT T 45L	QTY A 67	PRESS 32		
C 3.04	CABIN T 71	B 18	DMP LN T 77		
PPC02 1.9		C 94	NOZ T A 64		
		D 94	B 64		
O2 FLOW	0.0L 0.0L	WASTE H2O			
REG P	100 100	QTY 1 15	PRESS 17		
N2 FLOW	0.0L 0.0L		DMP LN T 58		
REG P	202 202		NOZ T A 82		
O2/N2 CNTL VLV	N2 02		B 82		
H2O TK N2 P	17 17		VAC VT NOZ T 224		
N2 QTY	131 131	CO2 CNTLR	1 2		
EMER O2 QTY	1	FILTER P	0.00L		
REG P	4L	PPC02	0.0L		
		TEMP	32.0L		
IMJ FAN	A B C AP	BED A PRESS	0.0L 0.0L		
HUMID SEP	*	B PRESS	0.0L 0.0L		
		AP	0.00L 0.00L		
		VAC PRESS	0.0L		

ENVIRONMENTAL Display (DISP 66)

2011/ /088		APU/ENVIRON THERM		4 000/02:36:51	
FREON LOOP		H2O LOOP		000/00:00:00	
ACCUM QTY	27 27	PUMP OUT P	1 2		
FREON FLOW	2193 2190	OUT T	64 62		
PL HX FLOW	290 285	P	64 63		
AFT CP FLOW	279 278		30L 38		
RAD IN T	97 96	ICH FLOW	564L 777		
RAD OUT T	38 38	OUT T	41 38		
EVAP OUT T	38 38	CAB HX IN T	42 38		
EVAP TEMP	DUCT NOZ	ACCUM QTY	45 55		
HI LOAD INBD	259 312	APU FUEL T 1	2 3		
OUTBD	259 312	TK SURF	+69 +67 +68		
TOPPING FWD	257	TK HTR	+70 +68 +69		
AFT 257		TEST LN 1	+62 +62 +63		
L 162 50		TEST LN 2	+62 +63 +63		
R 152 50		FEEED LN	+57 +58 +58		
EVAP FDLN T A B		PUMP IN	+57 +58 +58		
FWD 80 80		DRN LN 1	+62 +62 +63		
MID 1 80 80		DRN LN 2	+62 +62 +63		
MID 2 79 75		OUT	+92 +90 +88		
AFT 75 79		BYP LN	+108 +106 +102		
TOPPING 75 79		GG SPLY LN 113	111 107		
ACCUM 75 79		H2O LN INJ+	71 92 +72		
HI LOAD 75 79					

APU/ENVIRON THERM Display (DISP 88)

Pressure Control System

The pressure control system normally pressurizes the crew cabin to 14.7 ± 0.2 psia. It maintains the cabin at an average 80-percent nitrogen (130 pounds) and 20-percent oxygen (40 pounds) mixture that closely resembles the atmosphere at sea level on Earth. The system also provides the cabin atmosphere necessary to cool cabin-air-cooled equipment. Oxygen partial pressure is maintained automatically between 2.95 and 3.45 psi, with sufficient nitrogen pressure of 11.5 psia added to achieve the cabin total pressure of 14.7 ± 0.2 psia. Positive and negative pressure relief valves protect the structural integrity of the cabin from over- and underpressurization respectively. The pressure control system nitrogen is used to pressurize the supply and wastewater tanks. The system also provides breathing oxygen directly to the launch and entry suit helmets and to emergency breathing masks.

2011/ /078		SM SYS SUMM 1		4 000/14:44:12	
SMOKE		DC VOLTS		000/00:00:00	
CABIN	0.0	1/A	2/B	3/C	
L/R FD	0.0 0.0	FC	30.6 30.1 31.0		
AV BAY	1 0.3 0.3	MAIN	30.6 30.1 31.0		
	2 0.3 0.4	ESS	29.6 29.6 29.3		
	3 0.3 0.3	A B C A			
CABIN		CNTL	1 29.4 29.4 29.6		
PRESS	14.0	2 29.4 29.4 29.4			
dp/dt-EQ	+.00 +.000	3 29.4 29.4 29.4			
O2 CONC		VOLT	ea 118 118 117		
PP02	3.00 3.00	eb	117 117 118		
FAN AP	5.00	ec	117 117 118		
HK OUT T	46	AMPS	ea 4.3 6.3 2.1		
O2 FLOW	0.0 0.0	eb	5.5 6.6 2.2		
N2 FLOW	0.0 0.0	ec	3.1 5.0 3.2		
IMU FAN	A B C	FUEL CEL			
AV FC1 FC2 FC3		AMPS	180 232 146		
SS1	22 21 22	REAC VLV	OP OP OP		
SS2	22 22 23	STACK T	+202 +206 +200		
SS3	23 21 21	EXIT T	150 152 149		
TOTAL AMPS	557	COOL P	61 60 61		
KW	17	PUMP			

ECLSS Parameters on the BFS SM SYS SUMM 1 (DISP 78) Display

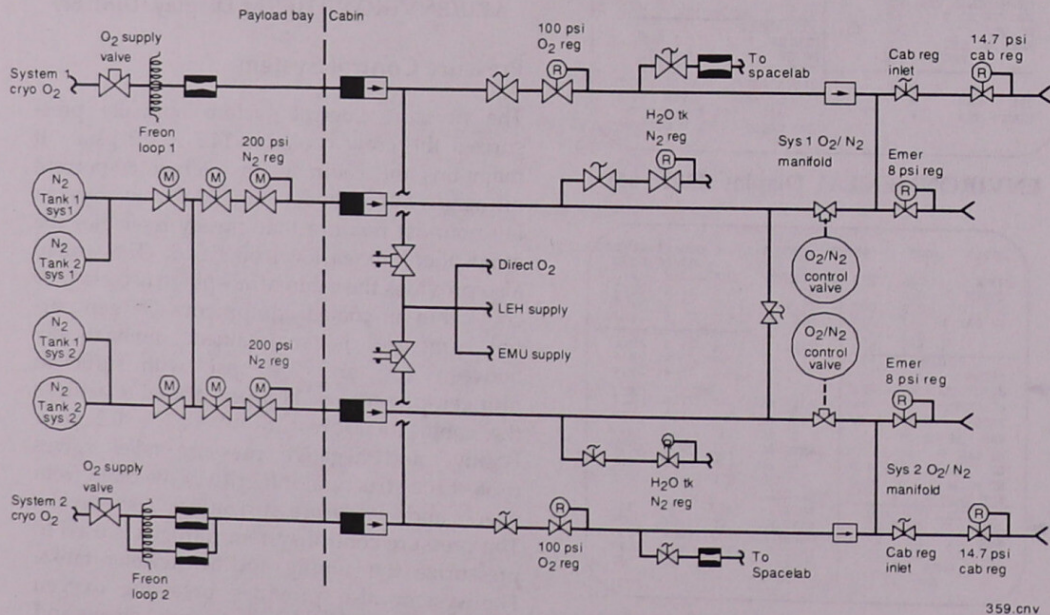
Cabin pressure is maintained by either of two pressure control systems (designated PCS 1 and PCS 2). Each PCS consists of a liquid oxygen storage system and a gaseous nitrogen storage system. The PCS oxygen is supplied from the electrical power system's (EPS) cryogenic oxygen in the midfuselage of the orbiter. The cryogenic supercritical oxygen storage system is controlled by electrical heaters within the tanks and supplies oxygen to the ECLSS pressure control system at a pressure of 803 to 883 psia in a gaseous state. The nitrogen storage tanks are serviced to a nominal pressure of 2,964 psia at 80° F. Normal on-orbit operations use one oxygen and one nitrogen supply system.

Cabin pressure is controlled by the nitrogen/oxygen control and supply panels, the PPO₂ sensor, and the pressure relief valves. The nitrogen/oxygen control panel regulates PCS1 and PCS2 oxygen and nitrogen. Typically, PCS1 is activated for the first half of the mission and PCS2 is activated for the second half. System 1 and system 2 nitrogen/oxygen supply panels are located in the middeck (panel MO10W) and the forward flight deck (panel L2). Both O₂ and N₂ supply systems 1 and 2 have a crossover capability, which allows the respective systems to be tied together.

The oxygen supply system provides the "makeup" cabin oxygen for flight crew consumption and makeup for normal cabin leakage. The nitrogen system provides nitrogen for pressurizing the cabin and the potable and wastewater tanks. Each crew member uses an average of 1.76 pounds of oxygen per day. Up to 7.7 pounds of nitrogen and 9 pounds of oxygen are used per day for normal loss of crew cabin gas to space and metabolic usage. The potable and wastewater tanks are pressurized to 17 psig in order to expel water from the tanks for use by the crew or dumping overboard.

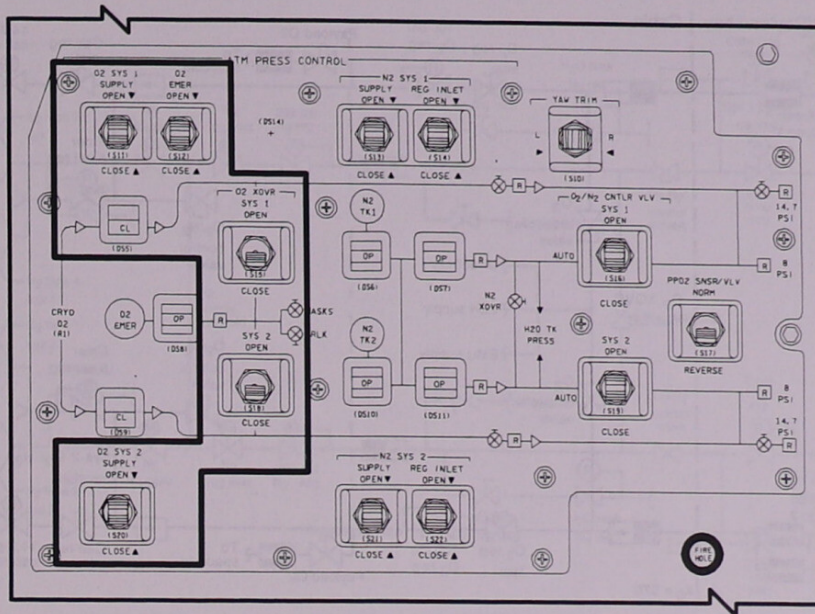
Oxygen System

Oxygen from the power reactant storage and distribution system (cryogenic oxygen supply system) is routed to the pressure control oxygen system 1 and system 2 supply valves. These valves are controlled by the *ATM PRESS CONTROL O2 SYS 1 SUPPLY* and *O2 SYS 2 SUPPLY* switches on panel L2. When one of the switches is momentarily positioned to *OPEN*, the corresponding valve opens to permit oxygen to flow through an oxygen restrictor at a maximum flow of approximately 25 pounds per hour for either system 1 or 2. The oxygen restrictor also functions as a heat exchanger with the Freon coolant loop, warming the oxygen supplied to the



359.cnv

Pressure Control System



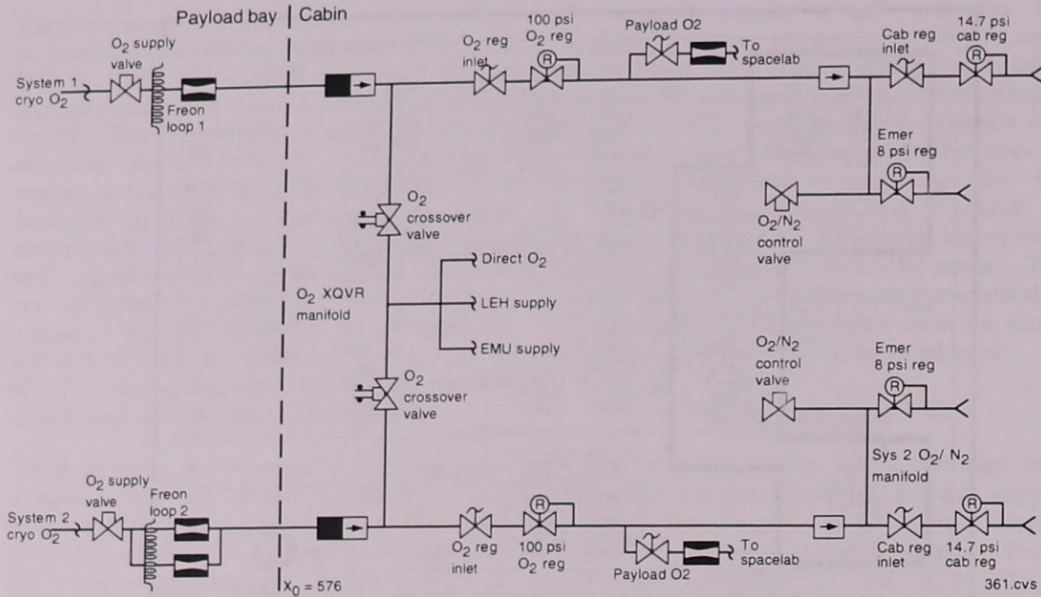
**ATM PRESS CONTROL 02 SYS SUPPLY and
XOVR Switches and Talkbacks on Panel L2**

oxygen regulator of that system before it flows into the cabin. Freon loop 1 warms system 1 oxygen, and loop 2 warms system 2. A talkback indicates *OP* when the O₂ supply valve is open. When the switch is momentarily positioned to *CLOSE*, the valve is closed, isolating that oxygen supply system. The talkback indicates *CL*.

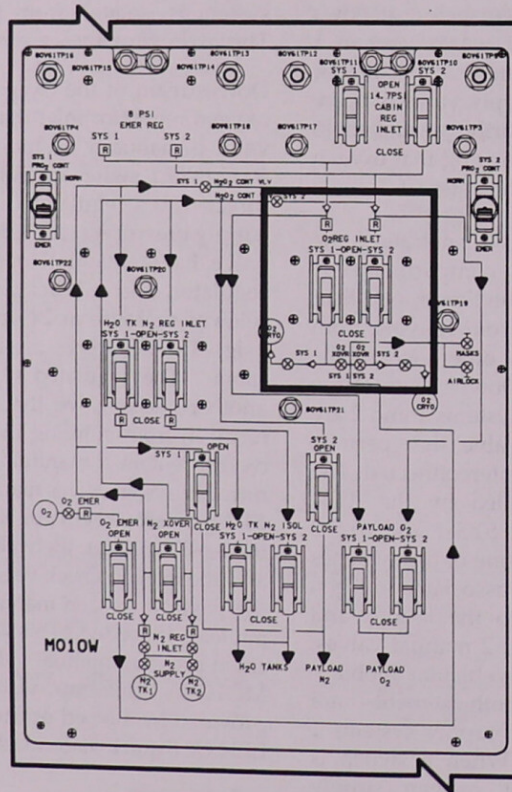
Next, the oxygen piping penetrates the bulkhead and enters the crew compartment. A check valve downstream of the Freon loop heat exchanger prevents oxygen from flowing from one supply source to the other when the crossover valves are open. Downstream of the oxygen check valve, oxygen systems 1 and 2 are connected by a crossover valve that permits system 1 and system 2 to be interconnected. The crossover valves are controlled by the *ATM PRESS CONTROL 02 XOVR SYS 1* and *SYS 2* switches on panel L2. When one of the switches is positioned to *OPEN*, the associated oxygen supply system is directed to the launch and entry helmet O₂ supply 1 and 2 manual valves, airlock oxygen 1 and 2 extravehicular mobility unit, and direct O₂. If both switches are positioned to *OPEN*, oxygen supply systems 1 and 2 are interconnected. When a switch is positioned to *CLOSE*, that oxygen supply

system is isolated from the crossover feature. The crossover valves are normally open.

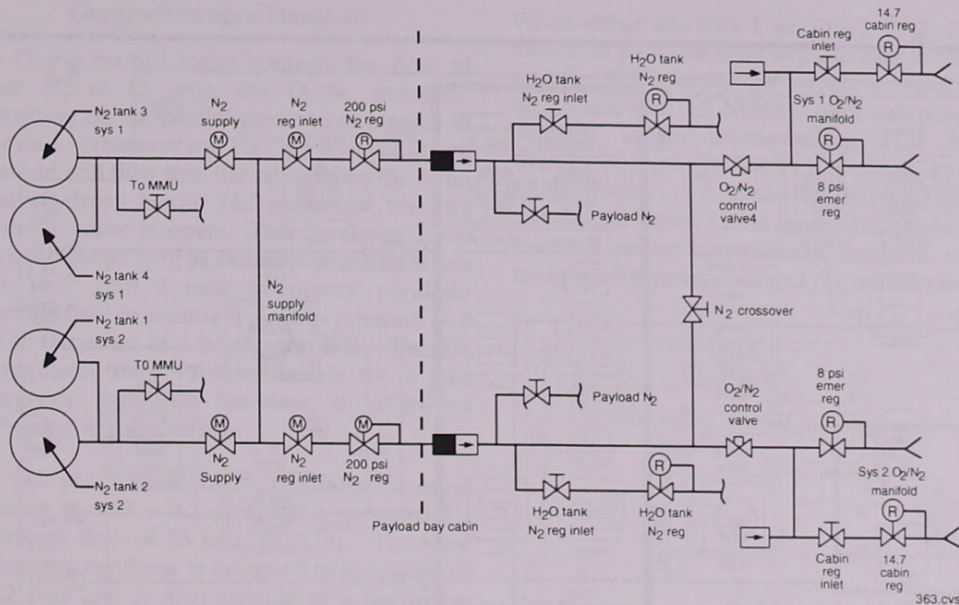
Downstream of the oxygen crossover line is an oxygen regulator inlet manual valve. When the valve is manually positioned to *OPEN* by the O₂ *REG INLET* switch on panel MO10W, oxygen is directed to a regulator that reduces the oxygen supply pressure to 100 ± 10 psig. Each regulator valve has a manual toggle ON/OFF valve, a regulator, and a relief valve. The relief valve relieves pressure at 245 psig and reseats at 215 psig. The relief pressure is vented into the crew cabin. The regulated O₂ then passes through another check valve that prevents downstream nitrogen from entering the oxygen system. The oxygen enters a manifold that is shared by the nitrogen system. This manifold is connected to its 14.7 psi cabin regulator inlet manual valve and the 8 psi regulator. Between the oxygen regulator and the oxygen check valve, the oxygen is fed to the payload oxygen manual valve for use by the payload, if needed. This valve, as well as the 14.7 psi cabin pressure manual valve, is located on panel MO10W. "Make up" O₂ for metabolic usage is provided by a bleed orifice inserted on orbit into LEH O₂ 8 quick disconnect on panel MO69M.



Oxygen System



O₂ REG INLET Switches on Panel MO10W



Nitrogen System for Nominal Mission OV-102

Nitrogen System

Gaseous nitrogen is supplied from two nitrogen systems, consisting of either two or three nitrogen tanks (depending on orbiter) per system that are permanently mounted in the payload bay. System 1 is mounted on the port side and system 2 is on the starboard side. All four orbiters have been modified to perform extended duration orbiter (EDO) missions. OV-102 is the only orbiter that has the four-tank configuration. OV-103, -104, and -105 have a standard six-tank configuration. On each of the vehicles, additional tanks may be flown as mission kits.

OV-102

- System 1 tanks 3, 4
- System 2 tanks 1, 2

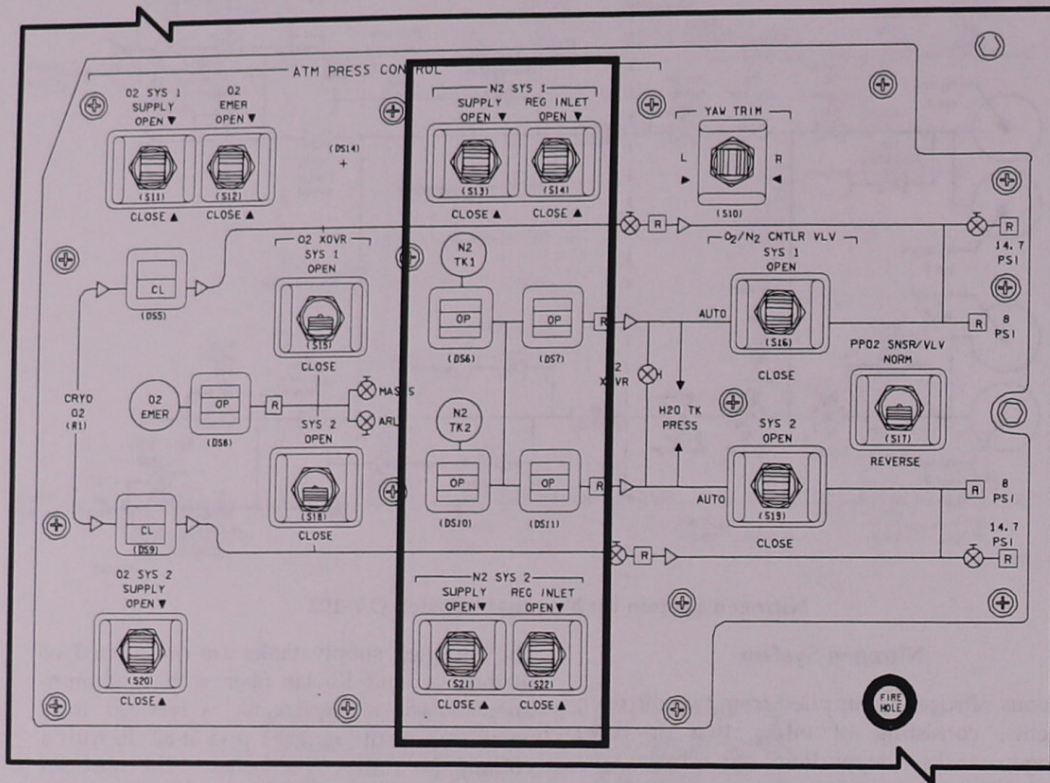
OV-103, -104, -105

- System 1 tanks 2, 3, 4
- System 2 tanks 1, 2, 4

Note: The N₂ tank configuration and number of tanks flown may vary by flight, based on mission requirements.

The nitrogen supply tanks are constructed of filament-wound Kevlar fiber with a titanium liner. Each nitrogen tank is serviced to a nominal pressure of 2,964 psia at 80° F, with a volume of 8,181 cubic inches. The nitrogen tanks in each system (two or three nominally, with up to four tanks on EDO missions) are manifolded together.

The PCS1 and PCS2 nitrogen supply systems are controlled by the atmosphere pressure control nitrogen supply valves in each system. Each valve is controlled by its corresponding *ATM PRESS CONTROL N2 SYS 1* and *SYS 2 SUPPLY* switch on panel L2. When a switch is momentarily positioned to *OPEN*, nitrogen flows to both atmosphere pressure control system regulator inlet valves, since both sets of tanks are manifolded together downstream of the supply valve. A talkback near the switch indicates barberpole when the motor-operated valve is in transit, and *OP* when the supply valve is open. When the switch is positioned to *CLOSE*, that nitrogen supply system is isolated from the nitrogen system regulator inlet valve, and the talkback indicator shows *CL*.



**ATM PRESS CONTROL N2 SYS SUPPLY and
REG INLET Switches and Talkbacks on Panel L2**

The nitrogen regulator inlet valve in each nitrogen system is controlled by its respective *ATM PRESS CONTROL N₂ SYS REG INLET* switch on panel L2. When the switch is positioned to *OPEN*, that system's nitrogen at source pressure is directed to the system's nitrogen regulator. A talkback indicator below the *SYS 1* switch and above the *SYS 2* switch indicates barberpole when the motor-operated valve is in transit, and *OP* when the valve is open. When the switch is positioned to *CLOSE*, the supplied nitrogen is isolated from the system's nitrogen regulator, and the talkback indicator indicates *CL*.

The nitrogen regulators in supply systems 1 and 2 reduce the pressure to 200 ± 15 psig. Each nitrogen regulator is a two-stage regulator with a relief valve. The relief valve relieves pressure at 295 psig into the vacuum vent line and reseats at 245 psig.

The pressure regulated nitrogen of each system is directed to the nitrogen manual crossover valve, the manual water tank regulator inlet valve, the payload manual nitrogen supply valve, and the oxygen and nitrogen controller valve in each system. The manual valves are controlled from panel MO10W, and the controller valve is controlled from the panel L2 *O₂/N₂ CNTLR VLV* switch.

The nitrogen crossover manual valve connects both regulated nitrogen systems when the valve is open and isolates the nitrogen supply systems from each other when closed. Normally, the valve is always closed. A check valve between the nitrogen regulator and nitrogen crossover valve in each nitrogen-regulated supply line prevents back flow from one nitrogen source supply to the other if the nitrogen crossover valve is open. The nitrogen system can supply at least 125 lb/hr from each system.

Oxygen/Nitrogen Manifold

The O₂/N₂ control valve controls the flow of either N₂ or O₂ into the O₂/N₂ manifold, depending on the partial pressure of oxygen in the cabin. Whatever gas (O₂/N₂) is in the O₂/N₂ manifold will flow into the cabin when the cabin pressure drops below 14.7 psia, and the 14.7 regulator valve is open. This "makeup" flow will continue as long as the cabin pressure is less than 14.7. An 8 psia emergency regulator provides flow to maintain a cabin pressure of 8 psia in the event of a large cabin leak. There is no regulator inlet valve to isolate the 8 psia emergency regulator; therefore, it is always configured to provide flow.

The 14.7 psi cabin regulator regulates the cabin pressure to 14.7 ± 0.2 psia and is capable of a maximum flow of 75 to 1245 lb/hr. The 8 psi emergency regulator is designed to regulate to 8 ± 0.2 psia and is also capable of a maximum flow of 75 to 1245 lb/hr. Both the 14.7 and 8 psi regulators flow into the cabin through a port in panel MO10W located above the waste management system compartment. Regulators consist of two stages: a low-flow regulator (0 to 0.75 lb/hr) for small demand when the cabin pressure is near 14.7 psia and a high flow regulator (0.75 to at least 75 lb/hr) for high demand when cabin pressure is significantly below 14.7 psia.

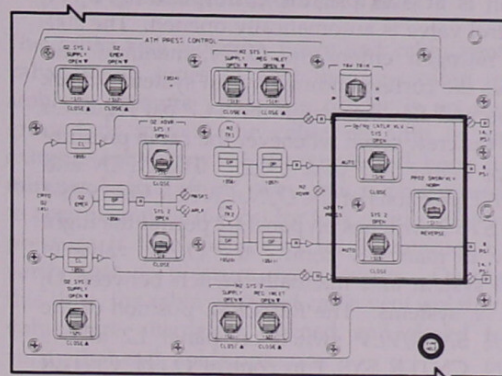
NOTE

Crewmembers should be aware that the regulators make a noticeable sound when they flow oxygen or nitrogen into the cabin. It is most noticeable in the vicinity of the waste management system compartment. Additionally, use of the WCS during high N₂ flow is not advisable due to the possibility of hypoxia.

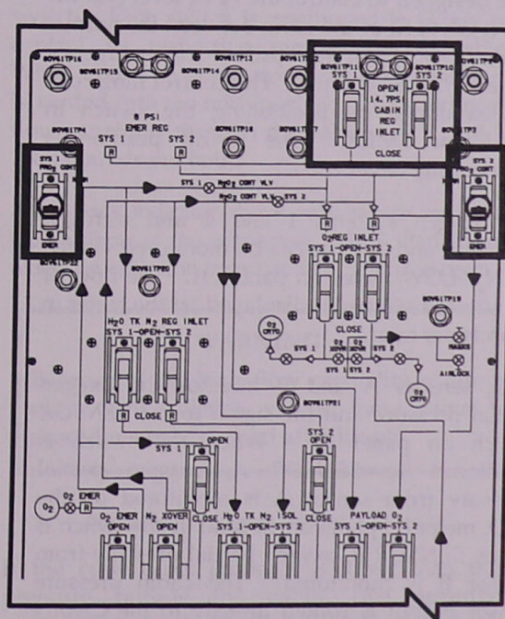
PPO₂ Control

The partial pressure of oxygen (PPO₂) in the crew cabin is controlled automatically during orbit by one of two O₂/N₂ controllers. Two PPO₂ sensors (A and B) located under the mission specialist station provide inputs to the PPO₂ control systems 1 and 2 controller and switches, respectively.

When either the SYS 1 or SYS 2 PPO₂ CONT switch on panel MO10W is positioned to *NORM*, and the PPO₂ SNSR/VLV switch on panel L2 is also positioned to *NORM*, electrical power is supplied to the corresponding ATM PRESS CONTROL O₂/N₂ CNTLR VLV switches on panel L2 for system 1 or 2. When the O₂/N₂ CNTLR VLV switch on panel L2 is positioned to *AUTO*, electrical power automatically energizes or de-energizes the corresponding O₂/N₂ control valve.



PPO₂ SNSR/VLV and O₂/N₂ CNTLR VLV Switches on Panel L2



PPO₂ CONT and CABIN REG INLET Switches on Panel MO10W

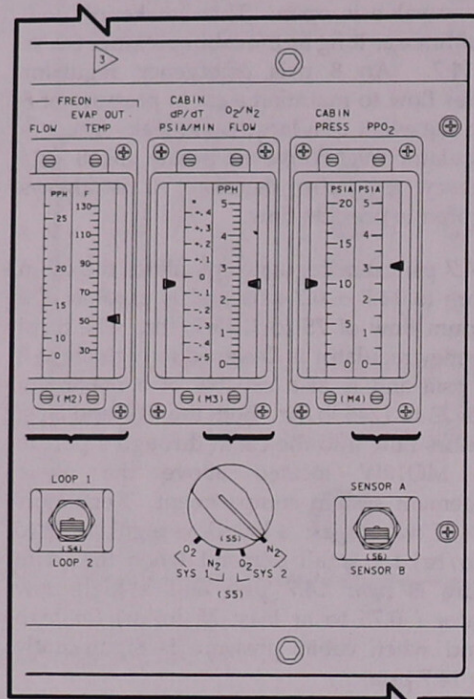
When the corresponding PPO₂ sensor determines that oxygen is required in the crew cabin to maintain the level above 2.95 psi, the O₂/N₂ control valve is automatically closed. When the 200-psi nitrogen in the manifold drops below 100 psi, the corresponding oxygen system flows oxygen through its check valve into the manifold and through the 14.7 psi cabin regulator into the crew cabin. When the PPO₂ sensor determines that the oxygen in the crew cabin is at 3.45 psi, the corresponding O₂/N₂ control valve is automatically opened. The 200-psi nitrogen enters the O₂/N₂ manifold and closes the corresponding oxygen system's check valve and flows through the 14.7 psi regulator into the crew cabin whenever the cabin pressure drops below 14.7 psia ± 0.2. The OPEN and CLOSE positions of the O₂/N₂ CNTLR VLV SYS 1 and SYS 2 switches on panel L2 permit the flight crew to manually control the O₂/N₂ valve in each system and manually switch between O₂ and N₂ systems. The REVERSE position of the PPO₂ SNSR/VLV switch on panel L2 allows O₂/N₂ CNTLR SYS 1 to control O₂/N₂ CNTLR VLV SYS 2, and vice versa.

The SYS 1 and SYS 2 PPO₂ CNTLR switches were designed to control the PPO₂ level (via the O₂/N₂ CNTLR) of the cabin between the normal range (2.95-3.45 at 14.7 psi) or the emergency range (1.95-2.45 at 8 psi). The control range can be determined by positioning the switch in NORM or EMER. The EMER position is procedurally never used.

The oxygen systems 1 and 2 and nitrogen systems 1 and 2 flows can be monitored via the O₂/N₂ FLOW meter on panel O1. The flow of the selected system is displayed on the meter in pounds per hour.

PPO₂ sensors A and B monitor the oxygen partial pressure and the signal to the SENSOR switch on panel O1. When the switch is positioned to SENSOR A, oxygen partial pressure from sensor A is monitored on the PPO₂ meter on panel O1 in psia. If the switch is set on SENSOR B, oxygen partial pressure from sensor B is monitored. The cabin pressure sensor output is routed directly to the CABIN PRESS meter on panel O1 and is displayed in psia. These parameters can also be viewed on CRT displays SM SYS SUMM 1 (PPO₂) and DISP 66, ENVIRONMENT (PPO₂ A, B, C).

If the change in pressure versus change in time (dP/dT) decreases at a rate of 0.08 psi per minute or greater, a klaxon will sound in the crew cabin, and the MASTER ALARM pushbutton light indicators will be illuminated. The normal cabin dP/dT is zero psi per minute plus or minus 0.01 psi.



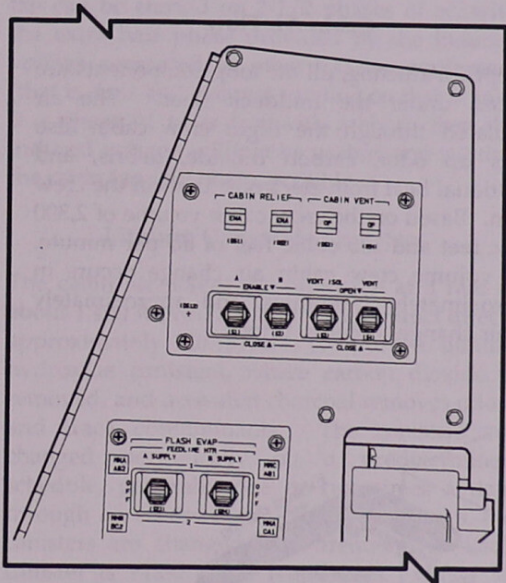
Meters and Switches on Panel O1
(Transducers also supply information for SM SYS SUMM 1, DISP 66, and C/W.)

2011/ /078	SM SYS SUMM 1	4 000/14:44:12	
		000/00:00:00	
SMOKE 1/A 2/B	DC VOLTS 1/A 2/B 3/C		
CABIN 0.0	FC 30.6 30.1 31.0		
L/R FD 0.0 0.0	MAIN 30.6 30.1 31.0		
AV BAY 1 0.3 0.3	ESS 29.6 29.6 29.3		
2 0.3 0.4			
3 0.3 0.3			
CABIN			
PRESS 14.0	CNTL 1 29.4 29.4 29.6		
dP/dT-EQ +.00 +.000	2 29.4 29.4 29.4		
O2 CONC	3 29.4 29.4 29.4		
PPO2 3.00 3.00	AC		
FAN ΔP 5.00	VOLT 0A 118 118 117		
HX OUT T 46	0B 117 117 118		
O2 FLOW 0.0 0.0	0C 117 117 118		
N2 FLOW 0.0 0.0	AMPS 0A 4.3 6.3 2.1		
IMU FAN A B C	0B 5.5 6.6 2.2		
AV FC1 FC2 FC3	0C 3.1 5.0 3.2		
SS1 22 21 22	FUEL CEL		
SS2 22 22 23	AMPS 180 232 146		
SS3 23 21 21	REAC VLV OP OP OP		
TOTAL AMPS 557	STACK T +202 +206 +200		
KW 17	EXIT T 150 152 149		
	COOL P 61 60 61		
	PUMP		

The SM SYS SUMM 1 display is an SM display (DISP78) available in SM OPS and 4

2011/ /066	ENVIRONMENT	4 000/02:33:38
CABIN	AV BAY	1 000/00:00:00
ΔP/GT +.01 CABIN P 14.7	TEMP	90 90 3
PPO2 AIRLK P 14.8	FAN ΔP	3.80 3.77 3.92
A 3.04 FAN ΔP 5.55	SUPPLY H2O	
B 3.04 HK OUT T 45L	QTY A 67 PRESS 32	
C 3.04 CABIN T 71	B 18 DMP LN T 77	
PPO2 1.9	C 94 NOZ T A 64	
	D 94 B 64	
O2 FLOW 0.0L 0.0L	WASTE H2O	
REG P 100 100	QTY 1 15 PRESS 17	
N2 FLOW 0.0L 0.0L	DMP LN T 58	
REG P 202 202	NOZ T A 82	
O2/N2 CNTL VLV N2 02	VAC VT NOZ T 224	
H2O TK N2 P 17 17	CO2 CNTLR 1 2	
N2 QTY 131 131	FILTER P 0.00L	
EMER O2 QTY 1	PPCO2 - 0.0L	
REG P 4L	TEMP 32.0L	
	BED A PRESS 0.0L 0.0L	
IMU FAN A B C ΔP	B PRESS 0.0L 0.0L	
HUMID SEP *	ΔP 0.00L 0.00L	
	VAC PRESS 0.0L	

The ENVIRONMENT display is an SM display (DISP 66) available in SM OPS 2 and 4



CABIN RELIEF and CABIN VENT Switches and Talkbacks on Panel L2

Cabin Relief Valves

Two positive pressure relief valves are in parallel to provide overpressurization protection of the crew module cabin above 15.5 psid. The valves will crack at 15.5 psid, reach full flow by 16.0 psid, and reseal again below 15.5 psid. Each cabin relief valve is controlled by its corresponding CABIN RELIEF switch on panel L2. When the switch is positioned to ENABLE, the motor-operated valve opens, exposing cabin pressure to a corresponding positive pressure

relief valve. The relief valve maximum flow capability is 150 pounds per hour at 16.0 psid. A talkback indicator above the switch indicates barberpole when the motor-operated valve is in transit, and ENA when the motor-operated valve is open. When the switch is positioned to CLOSE, the corresponding motor-operated valve isolates cabin pressure from the relief valve and the talkback indicator indicates CL.

Vent Isolation and Vent Valves

The cabin vent isolation valve and cabin vent valve are in series to vent the crew cabin to ambient pressure while the orbiter is on the ground or to vent the cabin on orbit in an extreme emergency. Approximately 1 hour 30 minutes before lift-off, the cabin is pressurized to approximately 16.7 psi for leak checks. Cabin pressure is then monitored for 35 minutes to verify that no pressure decay occurs. During this time, the cabin vent and cabin vent isolation valves are alternately opened and closed to verify that each holds pressure.

The cabin vent isolation valve is controlled by the VENT ISOL switch on panel L2, and the cabin vent valve is controlled by the VENT switch. Each switch is positioned to OPEN to control its respective motor-operated valve. When both valves are open, the cabin pressure is vented into the mid-fuselage. The maximum flow capability through the valves at 2.0 psid is 1080 pounds per hour.

A talkback indicator above each switch indicates the position of the respective valve: Barberpole when the valve is in transit and OP when it is open.

WARNING

Because of the high flow capability of the cabin vent isolation valves, these valves should never be opened after lift-off.

Negative Pressure Relief Valves

If the crew cabin pressure is lower than the pressure outside the cabin, two negative pressure relief valves in parallel will open at 0.2 psid, permitting flow of ambient pressure into the cabin. Caps over each valve provide a positive pressure seal and will pop off when the valve opens. No crew controls are necessary.

Water Tank Regulator Inlet Valve

The H₂O TK N₂ REG INLET valve in each nitrogen system permits nitrogen to flow to its regulator and H₂O TK N₂ ISOL SYS 1, 2 valve. The REG inlet and isolation manual valves are on panel MO10W. The regulator in each nitrogen system reduces the 200-psi supply pressure to 15.5 to 17.0 psig. Each regulator is a two-stage regulator with the second stage relieving pressure into the crew cabin at a differential pressure of 18.5 ± 1.5 psig.

Airlock Depressurization and Equalization Valves

The airlock pressure is maintained equal with cabin pressure via the airlock equalization valves located on the cabin/airlock hatch. During normal operations the airlock hatch is open. The airlock depressurization valve is used to depressurize the cabin to 10.2 psia and to depressurize the airlock for EVA.

Atmospheric Revitalization System

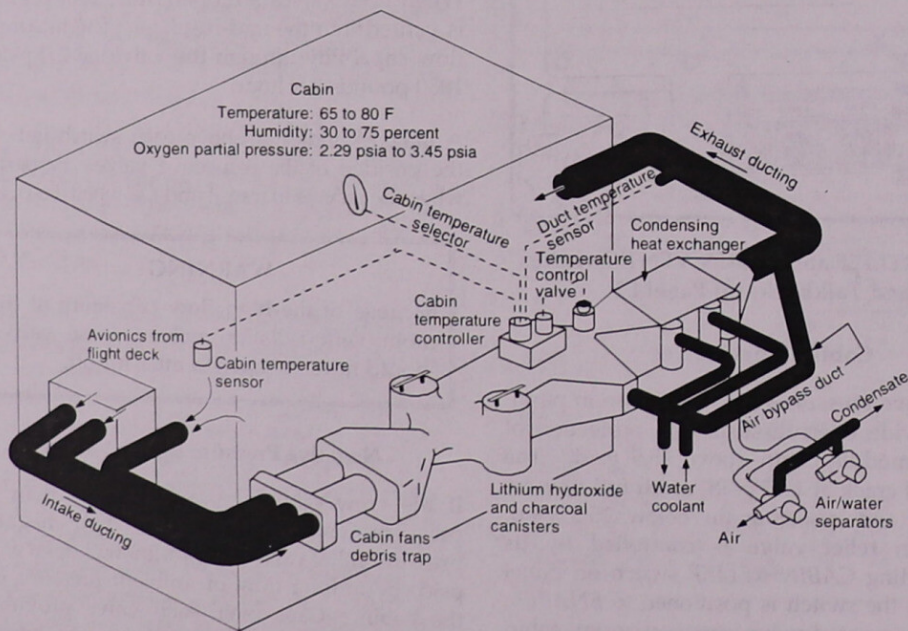
The atmospheric revitalization system (ARS) circulates air and water throughout the cabin to control ambient heat, relative humidity (between 30 and 65 percent), carbon dioxide,

and carbon monoxide levels. The ARS also provides cooling for cabin avionics.

Cabin air is circulated around the cabin to remove heat and humidity. The heated air is then ducted (via cabin fans) to the cabin heat exchanger, where the heat is removed by the water coolant loops. The water coolant loop system collects heat from the cabin heat exchanger, the inertial measurement unit heat exchanger, the cold-plated electronic units in the avionics bays, and the avionics bay heat exchangers. The water coolant loop transfers the heat collected to the Freon/water heat exchanger of the active thermal control system. The active thermal control system then expels the heat overboard.

Cabin Air Flow

Except for ducting, all air loop components are located under the middeck floor. The air circulated through the flight crew cabin also picks up odor, carbon dioxide, debris, and additional heat from electronic units in the crew cabin. Based on the crew cabin volume of 2,300 cubic feet and 330 cubic feet of air per minute, one volume crew cabin air change occurs in approximately 7 minutes, and approximately 8.5 air changes occur in 1 hour.



Cabin Air

371.cvs

The heated cabin air is drawn through the cabin loop and through a 300-micron filter by one of two cabin fans. Each cabin fan (A and B) is controlled by its respective *CABIN FAN* switch on panel L1. Normally, only one fan is used.

Each fan is powered by a three-phase, 115-volt ac motor. These 495-watt motors produce a nominal flow rate of 1,400 lb/hr through the cabin air ducting. A check valve located at the outlet of each fan prevents air from backflowing through the non-operating fan. This flapper-type check valve will open if there is a 2-inch H₂O (.0723 psi) differential pressure across the valve. A cabin fan will not start on two phases of ac. However, if the cabin fan is already operating when a phase of ac is lost, the fan will continue to run on two phases of ac. A cabin fan can be started on 2-1/2 phases of ac, with the extra half phase provided by the induced voltage generated by other rotating equipment (that is, fans and pumps) running on that ac bus. If a phase of ac is lost with a short, then the induced voltage will not be usable, and starting the cabin fan will not be possible.

Lithium Hydroxide Canisters

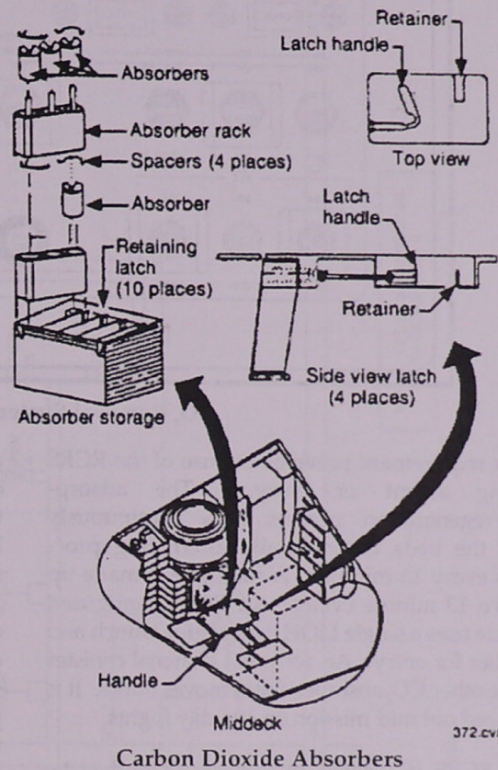
The cabin air leaves the cabin fan at a rate of about 1,400 lb/hr. An orifice in the duct directs approximately 120 lb/hr to each of two lithium hydroxide canisters, where carbon dioxide is removed, and activated charcoal removes odors and trace contaminants. The canisters are changed periodically on a predetermined schedule, generally one or two times a day, through an access door. (For larger crews, the canisters are changed more frequently.) Each canister is rated at 48 man-hours. Up to 30 spare canisters are stored under the middeck floor in a locker between the cabin heat exchanger and water tanks.

CAUTION

During lithium hydroxide canister changeout, the cabin fan(s) should be turned off. Dust from the canisters kicked up by a cabin fan has caused eye and nose irritation. Lithium hydroxide dust may also be a contributing factor to humidity separator failures.

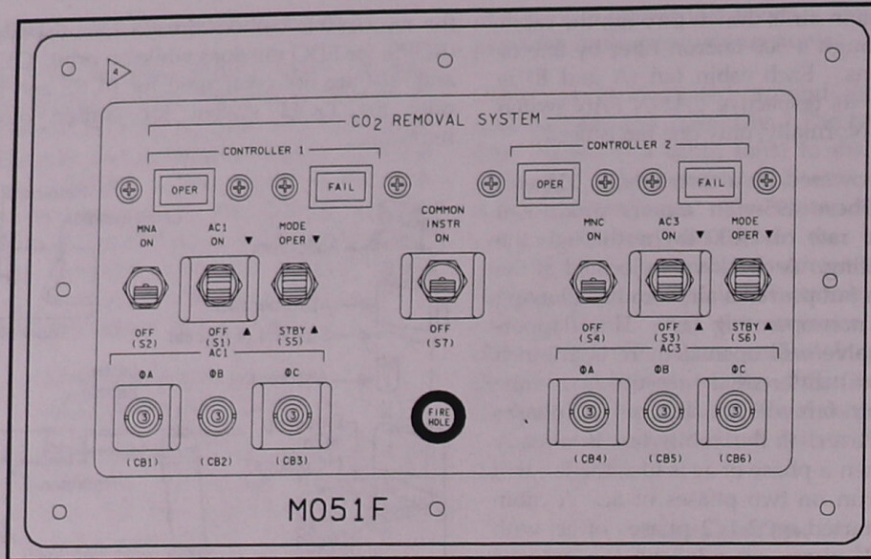
For non-EDO missions, the lithium hydroxide canisters are the primary means of CO₂ control. OV-102 and -105 have been modified to utilize

the regenerable carbon dioxide removal system (RCRS) for EDO missions while on orbit. OV-103 and -104 are not configured for RCRS and have only the LiOH system for carbon dioxide removal.



Regenerable Carbon Dioxide Removal System

The ability to use the RCRS in the EDO orbiters solved a major weight and volume stowage problem encountered when attempting to conduct 10 to 16 day duration missions for a crew of up to seven astronauts. Carbon dioxide removal is accomplished by passing cabin air through one of two identical solid amine resin beds. The resin consists of a polyethylenimine (PEI) sorbent coating on a porous polymeric substrate. Upon exposure to carbon dioxide laden cabin air, the resin combines with water vapor in the air to form a hydrated amine which reacts with carbon dioxide to form a weak bicarbonate bond. Water is required for the process since dry amine cannot react with the carbon dioxide directly. While one bed adsorbs carbon dioxide, the other bed regenerates with thermal treatment and vacuum venting. This



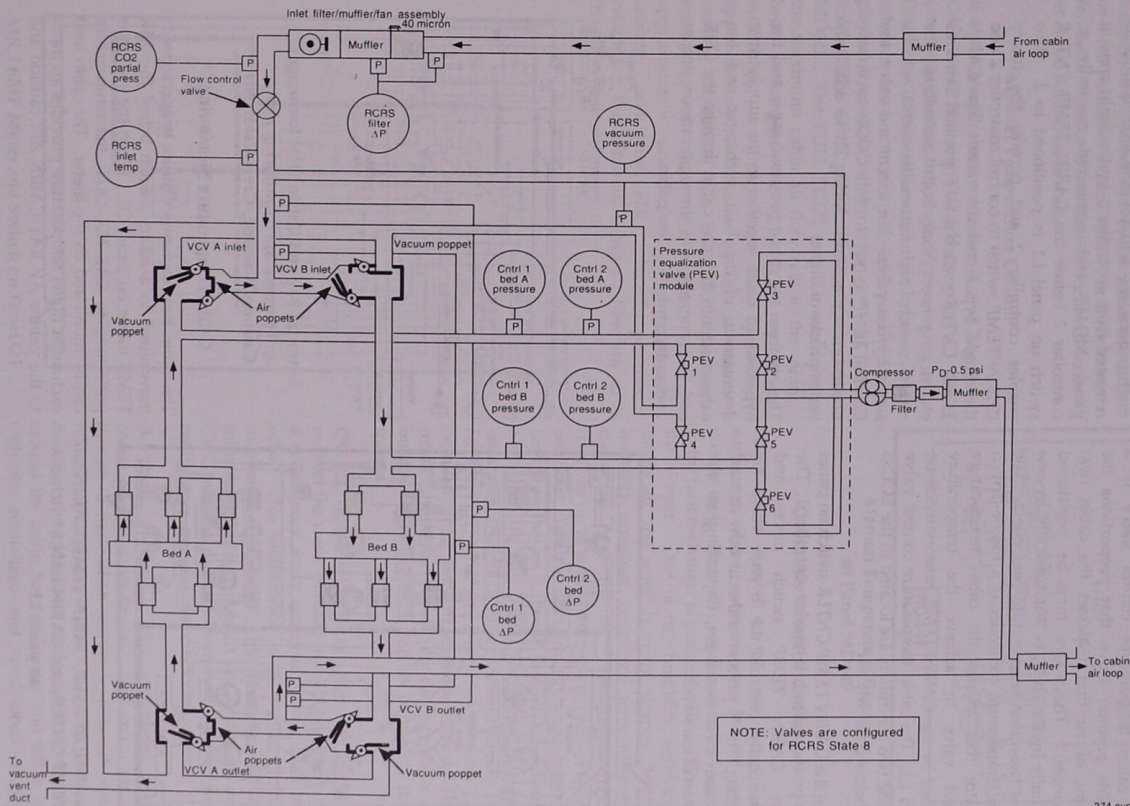
CO₂ Removal System Panel MO51F

latter requirement prevents the use of the RCRS during ascent or entry. The adsorption/regeneration process runs continuously with the beds automatically alternating processes every 13 minutes. A full cycle is made up of two 13 minute cycles. An RCRS configured vehicle uses a single LiOH canister for launch and another for entry. An activated charcoal canister in the other CO₂ absorber slot removes odors. It is changed out mid mission on 10+ day flights.

The RCRS is located in volume D under the middeck floor. In addition to the two chemical beds, the major components of the RCRS include a set of vacuum cycle and pressure equalization valves, an RCRS fan, an airflow control valve, an ullage-save compressor, and two redundant controllers (1 and 2). The

airflow control valve is set prelaunch for either a crew size of "4" or "5 to 7" crewmembers. These two positions select airflow through the RCRS of 72 or 110 lb/hr respectively. The control switches for the RCRS are located on panel MO51F. Both ac and dc power for the 1 and 2 controllers are operated from this panel. Each controller has a three position momentary switch for selection of *OPER* or *STBY*. This panel also has status lights for each controller which illuminate *OPER* or *FAIL* as appropriate. Crew insight into RCRS operation is found on SPEC 66 ENVIRONMENT in OPS 2 or 4.

The scrubbed air is then forced through the cabin heat exchanger.



Regenerable Carbon Dioxide Removal System (RCRS)

374 cvs

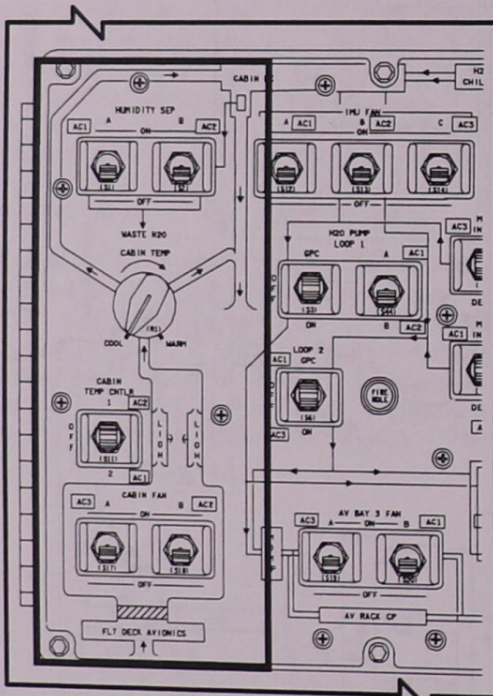
Cabin Air Temperature Control

The cabin temperature control valve is a variable position valve that proportions the volume of air that bypasses the cabin heat exchanger. The valve may be positioned manually by the crew, or automatically by one of the two cabin temperature controllers. The cabin temperature controller is a motor-driven actuator that adjusts the cabin temperature control valve to achieve the temperature selected by the *CABIN TEMP* rotary switch on panel L1. The cabin temperature control valve and the two controllers are located in the ECLSS bay below panel MD44F.

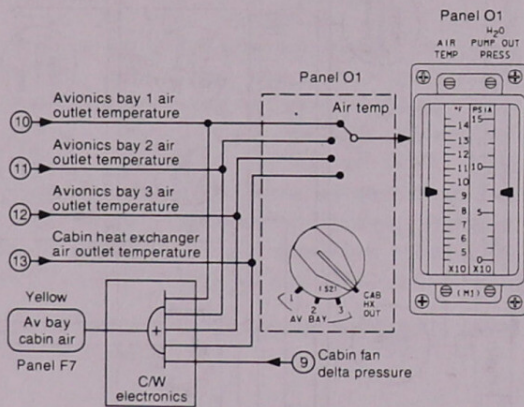
When the *CABIN TEMP CNTLR* switch on panel L1 is positioned to 1, it enables controller 1. The rotary *CABIN TEMP* switch elects and automatically controls the bypass valve by diverting 0 to 70 percent of the air flow around the cabin heat exchanger, depending on the position of the switch.

The controllers are attached to a single bypass valve by an actuator arm. If controller 1 malfunctions, the actuator arm linkage must be removed from controller 1 by the flight crew at panel MD44F and connected manually to controller 2 before the *CABIN TEMP CNTLR* switch on panel L1 is positioned to 2. This enables controller 2 and permits the rotary *CABIN TEMP* switch to control controller 2 and the single bypass control valve. The *CABIN TEMP CNTLR* switch's *OFF* position removes electrical power from both controllers, the rotary switch, and automatic control of the single bypass valve. For ascent and entry, the *CABIN TEMP* is set to full *COOL* to ensure maximum air cooling during these relatively warm phases of flight.

The air from the cabin heat exchanger and the bypassed air come together in the supply duct downstream of the heat exchanger and are exhausted into the crew cabin through the CDR and PLT consoles and through various station duct outlets into the crew cabin.



HUMIDITY SEP, CABIN TEMP, CABIN TEMP CNTLR, and CABIN FAN Switches on panel L1



Avionics Bay and Cabin Heat Exchanger Temperature Monitoring and Caution/Warning, Crew Cabin Air

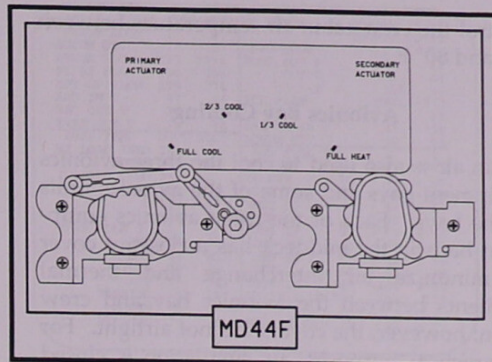
Cabin Temperature Monitoring

The cabin heat exchanger outlet temperature is transmitted to a rotary switch below the *AIR TEMP* meter on panel O1. When the switch is positioned to *CAB HX OUT*, the temperature can be monitored on the meter. The cabin heat exchanger outlet temperature provides an input to the yellow *AV BAY/CABIN AIR* caution and

warning light on panel F7. The light is illuminated if the cabin heat exchanger outlet temperature is above 145° F, if avionics bay 1, 2, or 3 temperatures exceed 130° F, or if the cabin fan delta pressure is less than 4.2 inches of water or above 6.8 inches of water.

Manual Temperature Control

If cabin temperature controllers 1 and 2 or the *CABIN TEMP* rotary switch on panel L1 are unable to control the single bypass valve, the flight crew can position the single bypass valve actuator drive arm to the desired position and pin the bypass valve arm to one of four fixed holes (*FULL COOL*, *FULL HEAT*, etc.) on panel MD44F. The *FULL COOL* position establishes the maximum cabin air flow rate to the cabin heat exchanger, the *2/3 COOL* position establishes a flow rate that provides approximately two-thirds of the maximum cooling capability, the *1/3 COOL* position establishes a flow rate that provides approximately one-third of the maximum cooling, and the *FULL HEAT* position establishes the minimum cabin air flow rate to the cabin heat exchanger.



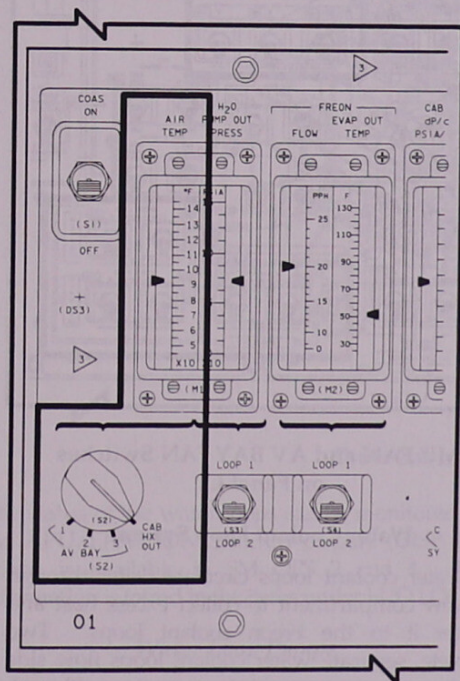
Manual Temperature Controls
on Panel MD44F

Cabin Air Humidity Control

Cabin air is directed to the crew cabin heat exchanger, where heat is transferred to the water coolant loop. Humidity condensation that forms in the heat exchanger is pushed by the air flow to the slurper. One of two humidity separators draws air and water from the slurper. In the humidity separator, centrifugal force separates the water from the air. The fan separator removes up to approximately 4 pounds of water per hour. The water is routed to the wastewater tank, and the air is ducted through the exhaust for return to the cabin. There are two fan separators (A and B) controlled individually by *HUMIDITY SEP A* and *B* switches on panel L1. Normally, only one fan separator is used. The relative humidity in the crew cabin typically is maintained between 30 and 65 percent in this manner.

OV-103, -104, and -105 have been modified to redirect the water from the humidity separator to a contingency water container (CWC) while on orbit. This modification is in support of ISS missions where waste tank dumping will be minimized while docked. Once undocked, the CWC will be dumped overboard through the contingency crossie waste quick disconnect.

A small portion of the revitalized and conditioned air from the cabin heat exchanger is ducted to the carbon monoxide removal unit, which converts carbon monoxide to carbon dioxide. A bypass duct carries warm cabin air around the cabin heat exchanger and mixes it with the revitalized and conditioned air to



AIR TEMP Meter and Switch on Panel O1

control the crew cabin air temperature between 65° and 80° F.

Avionics Bay Cooling

Cabin air is also used to cool the three avionics equipment bays and some of the avionics units in the bays. Each of the three avionics equipment bays in the middeck has a closeout cover to minimize air interchange and thermal gradients between the avionics bay and crew cabin; however, the covers are not airtight. For all practical purposes, air circulation is closed loop within the bay. The electronic avionics units in each avionics bay meet outgassing and flammability requirements to minimize toxicity levels.

Each of the three avionics equipment bays has identical air-cooling systems. Two fans per bay are controlled by individual AV BAY 1, 2, 3 FAN A and B switches on panel L1. Normally, only one fan is used at a time. When the A or B switch for an avionics bay is positioned to ON, the fan draws air from the floor of the avionics bay through the applicable air-cooled avionics units and a 300-micron filter into the avionics bay fan.

Note: The fan duct work for AV bay 3A on OV-103, -104, and -105 has been modified to accept a larger cabin fan for additional middeck cooling for payloads that will be stowed in the middeck for ISS missions. The standard avionics bay fans will be flown until the larger fan is needed.

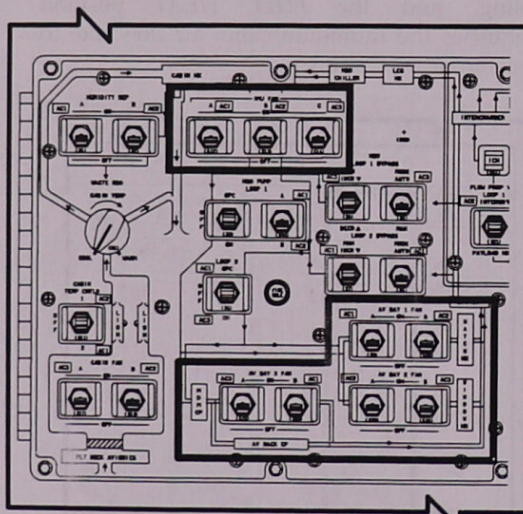
The avionics bay fan outlet directs the air through that avionics bay heat exchanger, located beneath the middeck crew compartment floor. The water coolant loops flow through the heat exchanger to cool the fan outlet air, and the cooled air is returned to the avionics bay. A check valve in the outlet of the fan that is not operating prevents a reverse flow through that fan.

The air outlet from the fan in each avionics bay is monitored and transmitted to a rotary switch on panel O1. When the switch is positioned to AV BAY 1, 2, or 3, that avionics bay's fan outlet temperature can be displayed on the AIR TEMP meter. The air outlet temperature of each avionics bay also provides an input to the yellow AV BAY/CABIN AIR caution and

warning light on panel F7. This light is illuminated if any of the avionics bay outlet temperatures are above 130° F. The OFF position of the A or B switch removes power from that avionics bay fan.

Inertial Measurement Unit (IMU) Cooling

The three IMUs are cooled by one of three fans drawing cabin air through a 300-micron filter and across the three IMUs. The fans are located in avionics bay 1. The fan outlet air flows through the IMU heat exchanger located on the flight deck and is cooled by the water coolant loops before returning to the crew cabin. Each IMU fan is controlled by the IMU FAN switches on panel L1. The ON position turns the corresponding fan on, and the OFF position turns it off. Normally, one fan is sufficient because one fan cools all three IMUs. A check valve is installed on the outlet of each fan to prevent a reverse air flow through the fans that are not operating.



IMU FAN and AV BAY FAN Switches
on Panel L1

Water Coolant Loop System

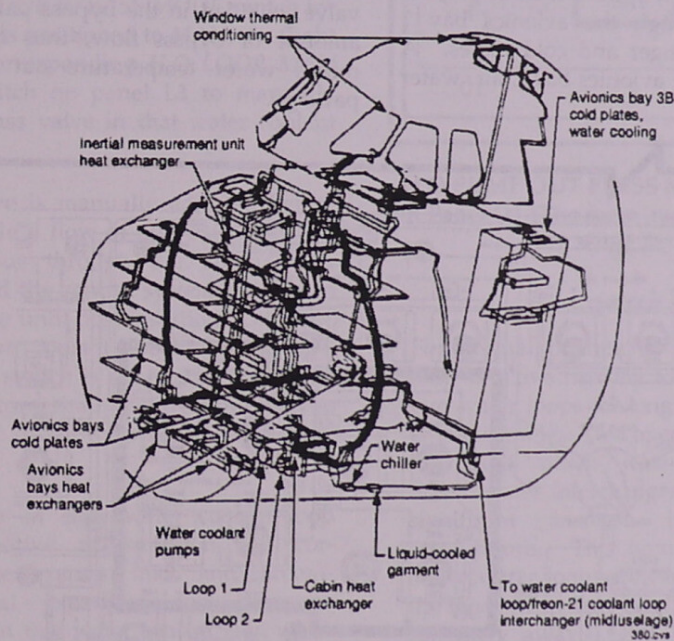
The water coolant loops circulate water through the crew compartment to collect excess heat and transfer it to the Freon coolant loops. Two complete, separate water coolant loops flow side by side and can operate at the same time, although only one is active at any given time. Loop 2 is

normally the active loop. The only difference between loops 1 and 2 is that loop 1 (the backup) has two water pumps, and loop 2 has one pump. The water pumps are located in the ECLSS bay below the forward lockers. The pumps are powered by three-phase, 115-volt ac motors.

Some electronic units in each of the avionics equipment bays and in the cabin are mounted on cold plates. The water coolant loops flow through the cold plates, and the heat generated by the electronics unit is transferred to the cold plate and then to the water coolant loop, which carries heat from the electronic unit. The cold plates mounted on the shelves in each avionics equipment bay are connected in a series-parallel arrangement with respect to the water coolant loop flow.

2011/ /088 APU/ENVIRON THERM		4 000/02:36:51	
FREON LOOP	1 2	H2O LOOP	000/00:00:00
ACCUM QTY	27 27	PUMP OUT P	1 2
FREON FLOW	2193 2190	OUT T	64 62
PL HX FLOW	290 286	OUT T	64 63
AFT CP FLOW	279 278	ICH FLOW	30L 38
RAD IN T	97 96	OUT T	564L 777
RAD OUT T	38 38	CAB HX IN T	41 38
EVAP OUT T	38 38	ACCUM QTY	42 38
EVAP TEMP	DUCT NOZ	APU FUEL T 1	45 55
HI LOAD INBD	259	TK SURF	+ 69 + 67 + 68
OUTBD	259 312	TK HTR	+ 70 + 68 + 69
TOPPING	FWD 257	TEST LN 1	+ 62 + 62 + 63
AFT 257	L 162 50	TEST LN 2	+ 62 + 63 + 63
L 162 50	R 162 50	FEED LN	+ 57 + 58 + 58
EVAP FDLN T	A B	PUMP IN	+ 57 + 58 + 58
FWD 80 80	MID 1 80 80	DRN LN 1	+ 62 + 62 + 63
MID 2 79 75	AFT 75 75	DRN LN 2	+ 62 + 62 + 63
TOPPING	75 75	OUT	+ 92 + 90 + 88
ACCUM	75 75	BYP LN	+108 +106 +102
HI LOAD	75 75	GG SPLY LN 113	111 107
		H2O LN INJ+	71 92 + 72

APU/ENVIRON THERM Display (DISP 88)



Crew Cabin Water Coolant Loops

The status of the water loops can be monitored on the APU/ENVIRON THERM display (DISP 88), which is available in SM OPS 2 and 4. The information is found in the items under H2O LOOP.

Water Loop Pumps

The water pumps in coolant loop 1 are controlled by the H₂O PUMP LOOP 1 A and B

switch on panel L1 in conjunction with the H₂O PUMP LOOP 1 GPC, OFF, ON switch beside it. The GPC position enables the general-purpose computer to command the loop 1 pump, which is selected by the H₂O PUMP LOOP 1 A or B switch, to circulate water through water coolant loop 1 for 6 minutes every 4 hours while on orbit to thermally condition the normally static

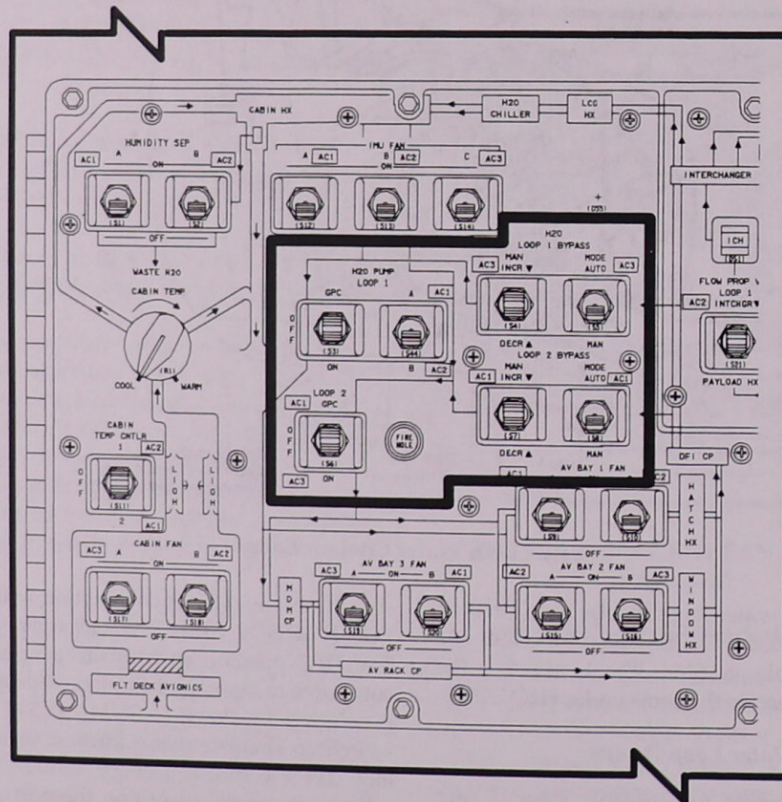
loop. The *ON* position energizes the loop 1 pump continuously. A ball-type check valve downstream of each water pump in loop 1 prevents reverse flow through the non-operating pump. The *OFF* position removes electrical power from both the A and B pumps of loop 1.

Water pump 2 is controlled by the *H₂O PUMP LOOP 2* switch on panel L1. When the switch is positioned to *GPC*, water pump 2 is commanded by the GPC to circulate water through water coolant loop 2 for 6 minutes every 4 hours. The *ON* position energizes water pump 2 continuously. The *OFF* position removes electrical power from water coolant loop 2 pump.

Water Loop Flow

Water loops 1 and 2 are routed side by side through the same areas. Downstream of each water pump, water flow splits into three parallel paths. One is through the avionics bay 1 air/water heat exchanger and cold plates. A second is through the avionics bay 2 air/water

heat exchanger and cold plates, payload bay floodlight cold plates, and thermal conditioning of the crew cabin windows. A third is through the crew cabin MDM flight deck cold plates, the avionics bay 3A air/water heat exchanger and cold plates, and the avionics bay 3B cold plates. The three parallel paths in each coolant loop then rejoin upstream of the Freon/water heat interchanger. The flow path splits again with one parallel path in each water coolant loop flowing through the Freon/water interchanger, where the water loop is cooled. The cooled water then flows through the liquid-cooled garment heat exchanger, potable water chiller, cabin heat exchanger, and IMU heat exchanger to the respective water coolant loop 1 and 2 pump package. The other parallel path in each water coolant loop, containing warm water, bypasses the interchanger and heat exchanger, rejoining the loop at the loop pump package. A valve installed in the bypass path controls the amount of bypass flow, thus controlling the mixed water temperature out of the pump package.



H₂O Loop Switches on Panel L1

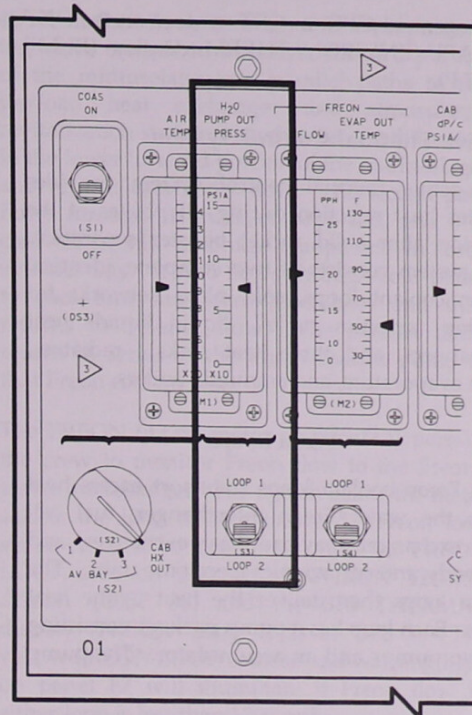
The bypass valve is controlled by bypass controllers either manually or automatically via *H₂O LOOP 1 and 2 BYPASS MODE* switches on panel L1. When the switch is positioned to *AUTO*, the water bypass controller and bypass valve automatically control the amount of water in the coolant loop that bypasses the Freon/water interchanger and heat exchangers. When the water pump's outlet temperature is 65.5° F, the loop's bypass valve is fully closed, and all the loop flow is directed to the Freon/water interchanger to provide maximum cooling.

When the bypass controller senses that the water pump's outlet temperature is 60.5° F, the controller bypasses a maximum amount of water around the Freon/water interchanger, reducing the heat rejection rate and increasing the water temperature out of the pump outlet. When the *H₂O LOOP BYPASS MODE* switch for the coolant loop is positioned to *MAN*, the flight crew sets the corresponding *H₂O LOOP MAN INCR/DECR* switch on panel L1 to manually control the bypass valve in that water coolant loop.

The bypass valve is manually adjusted before launch to provide a flow of approximately 950 pounds per hour through the Freon/water interchanger, and the control system remains in the manual mode until post insertion. On orbit, the active water coolant loop's *H₂O LOOP BYPASS MODE* switch is set to *AUTO* and the bypass valve automatically controls the loop so that the water pump's outlet temperature remains at 63° F.

The accumulator in each water coolant loop provides a positive pressure on the corresponding water pump inlet and accommodates thermal expansion and dampens pressure surges in that water coolant loop when the pump is turned on or off. Each accumulator is pressurized with gaseous nitrogen at 19 to 35 psi.

The pressure at the outlet of the water pump in each water coolant loop is monitored and transmitted to the *H₂O PUMP OUT PRESS* meter on panel O1. The appropriate loop is selected by the switch below the meter. When the switch is positioned to *LOOP 1* or *LOOP 2*, the corresponding water coolant loop's pressure in psia is monitored on the meter.



H₂O PUMP OUT PRESS Meter and Switch on Panel O1 (The same transducer feeds SM DISP 88)

NOTE

For normal operations, only one water loop is active (usually loop 2). Running two water loops for long periods of time is undesirable. Two operating loops will flow too much water through the Freon/water interchanger and result in a significant increase in the cabin temperature. This occurs because two active water loops are capable of picking up more heat than the two Freon loops can carry away. Over time, the water loops will start to heat up, and cooling efficiency will decrease.

The yellow *H₂O LOOP* caution and warning light on panel F7 will be illuminated if the outlet pressure of the water coolant loop 1 pump is less than 19.5 psia or greater than 79.5 psia, or if the outlet pressure of the loop 2 pump is less than 45 psia or greater than 81 psia. The pump inlet and outlet pressure of each coolant loop are monitored and transmitted to the systems

management GPC for CRT readout on the DISP 88 APU/ENVIRON THERM display (PUMP OUT P).

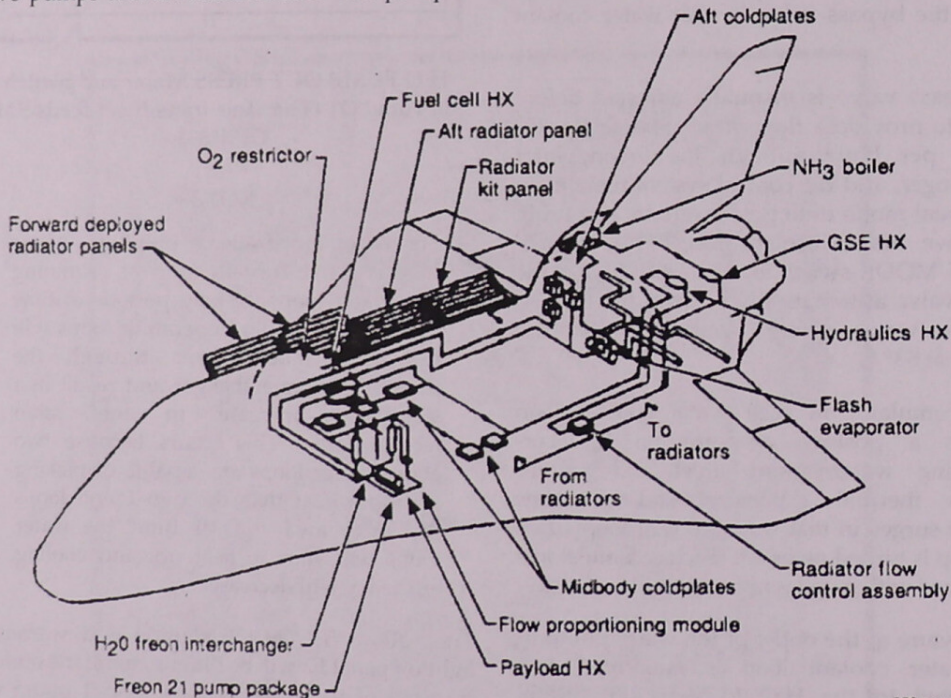
Active Thermal Control System

The active thermal control system provides orbiter heat rejection during all phases of the mission after solid rocket booster separation. The system consists of two complete, identical Freon coolant loops, cold plate networks for cooling avionics units, liquid/liquid heat exchangers, and three heat sinks: radiators, flash evaporators, and ammonia boilers.

Freon Loops

Two Freon coolant loops transport excess heat from the water/Freon interchanger, fuel cell heat exchanger, payload heat exchanger, and midbody and aft avionics electronic units. The Freon loops then deliver the heat to the heat sinks. Each loop has a pump package consisting of two pumps and an accumulator. The pump

package is located in the midbody of the orbiter below the payload bay liner. One pump in each loop is active at all times. The metal bellows-type accumulator in each loop is pressurized with gaseous nitrogen to provide a positive pressure on the pumps and permit thermal expansion in that coolant loop. When the accumulator bellows is fully extended, approximately 80 lb of Freon is in the accumulator (normally only 20 to 30 percent of this amount is used). A ball check valve downstream of the pumps in each coolant loop prevents a reverse flow through the non-operating pump in the loops. The pumps in each coolant loop are controlled individually by the *FREON PUMP* switches on panel L1. When either switch is positioned to *A* or *B*, the corresponding Freon pump in that loop operates. The *OFF* position of each switch prohibits either Freon pump in that coolant loop from operating.



383 cvs

Active Thermal Control System Component Locations

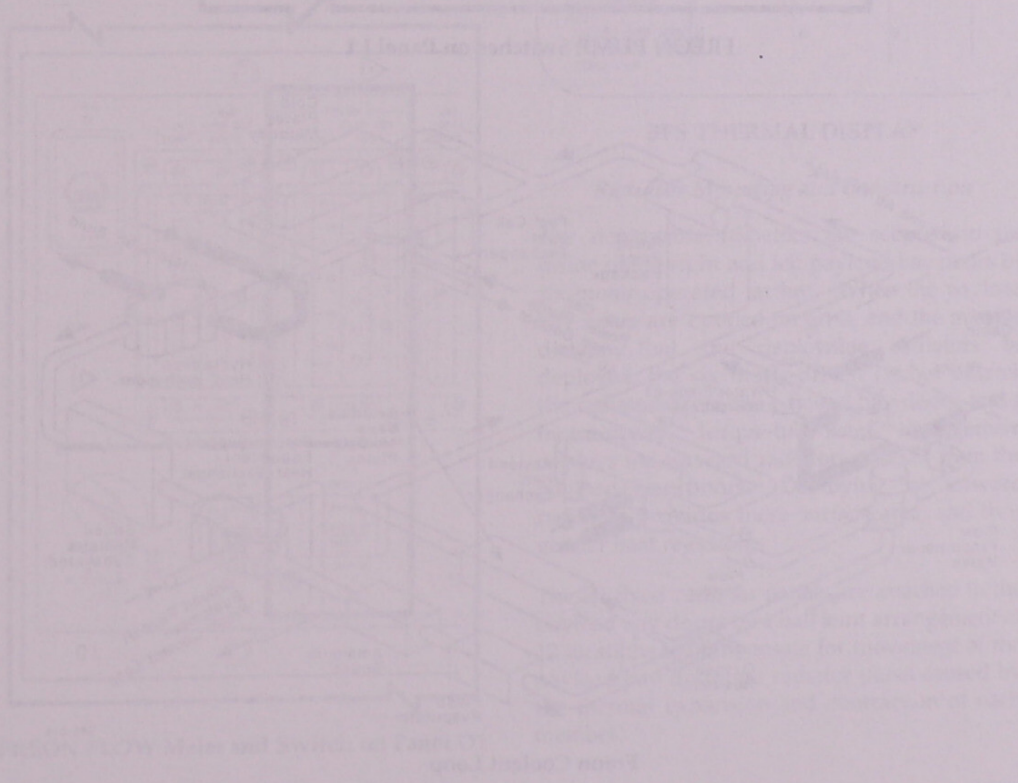
When a Freon pump is operating, Freon is routed in parallel paths through the fuel cell heat exchanger and the midbody cold plate network to cool electronic avionics units. The Freon coolant converges to one flow path before entering the hydraulics heat exchanger.

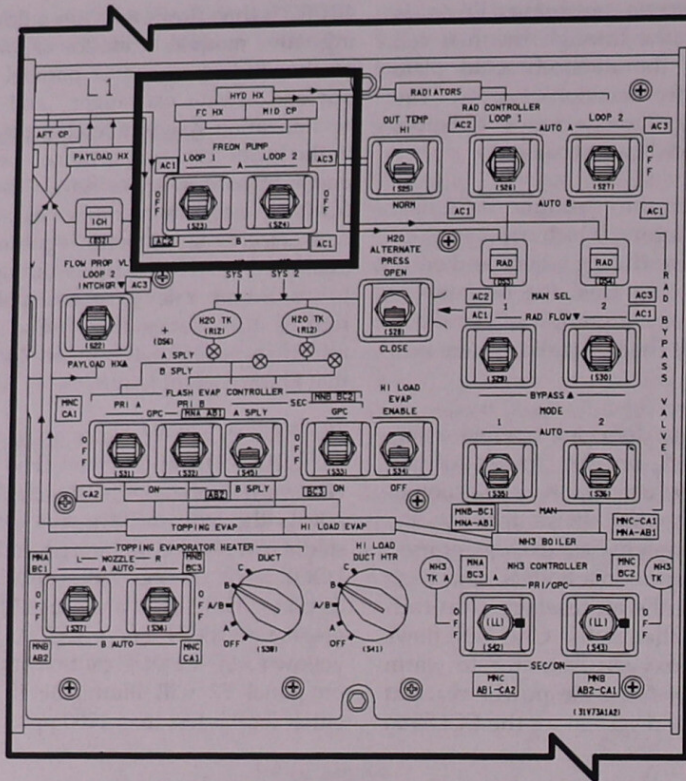
The Freon flows from the hydraulic fluid heat exchanger to the radiators, which are bypassed through a bypass valve during ascent and entry unless cold soak cooling from the radiators is being used. The warmest portion of the Freon loop is at the outlet of the hydraulic system heat exchanger.

When the payload bay doors are opened on orbit, radiators located on the inside of the payload bay doors are used for heat rejection to space. The Freon coolant flows through the ground support equipment heat exchanger used for ground cooling, ammonia boilers, and flash evaporator located in the aft fuselage. It is then divided into two parallel paths. One path flows through the ECLSS oxygen restrictor to warm the cryogenic oxygen from the power reactant storage and distribution system for the ECLSS to

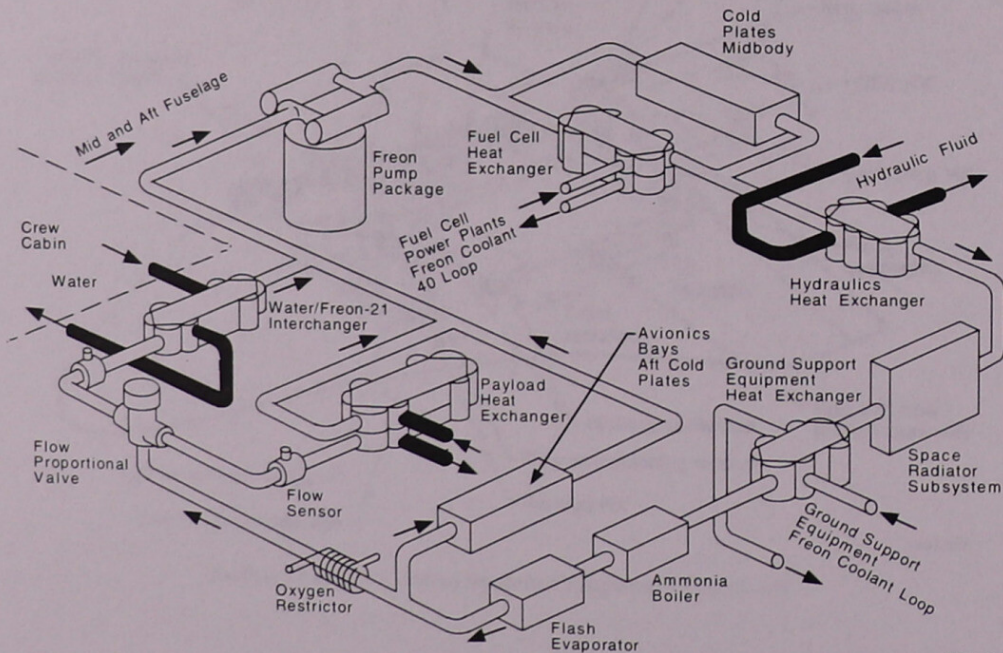
40° F. It then flows through a flow-proportioning valve module in the lower forward portion of the midfuselage into parallel paths to the payload heat exchanger and atmospheric revitalization system interchanger (both located in the lower forward portion of the midfuselage) and returns to a series flow. The second path flows through aft avionics bays 4, 5, and 6 to cool electronic avionics equipment in each avionics bay. It also flows through cold plates to cool four rate gyro assemblies and then returns to a series flow. The parallel paths return in series to the Freon coolant pump in that Freon coolant loop.

The FREON FLOW meter on panel O1 permits the crew to monitor Freon flow to the Freon/water interchanger. The switch below the meter selects the loop to be monitored. Freon loop status can also be monitored under the FREON LOOP area on the APU/ENVIRON THERM display (DISP 88) and the BFS THERMAL display (FREON Loop 1, 2) in OPS 1. The yellow *FREON LOOP* caution and warning light on panel F7 will illuminate if Freon flow in either loop is less than 1200 pph.





FREON PUMP Switches on Panel L1



Freon Coolant Loop

385.cvs

Radiators

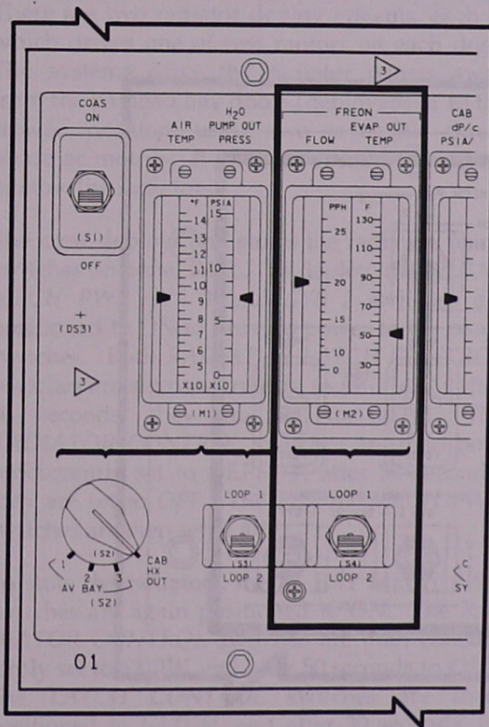
Radiators act as a heat sink for the coolant loops. The radiator system consists of four radiator panels attached to the inside of each payload bay door. The two forward radiator panels on each payload bay door are deployable when the doors are opened on orbit. The heat rejection requirements of the orbiter for a specific mission will determine if the forward radiators are to be deployed. The third and fourth radiator panels are fixed to the aft underside of the aft right and left payload bay doors and are not deployable.

The maximum heat rejection capability is 61,100 Btu per hour. When the payload bay doors are closed, the radiators are usually bypassed.

The radiator panels on the left and right sides are configured to flow in series, while flow within each panel is parallel through a bank of tubes connected by an inlet and outlet connector manifold. The radiator panels on the left side are connected in series with Freon coolant loop 1. The radiator panels on the right side are connected in series with Freon coolant loop 2.

The radiator panels provide an effective heat dissipation area of 1,195 square feet on orbit. Each radiator panel is 10 feet wide and 15 feet long. The Freon tubing in the radiator panels is more than 1 mile long.

For ascent, the radiators are normally bypassed since the doors are closed. Radiator flow is established shortly before the doors are opened on orbit. During deorbit preparations, prior to closing the doors, the Freon in the radiators is "cold-soaked" by positioning the orbiter in a tail Sun attitude. This cold soak is saved for use as a heat sink during the latter stages of entry.



FREON FLOW Meter and Switch on Panel O1

0001/	THERMAL		5 000/00:00:00			
			BFS 000/00:00:00			
HYD	SYS TEMP	BDYFLP RD/SB	L OB	L IB	R IB	R OB
	PRIME	+ 99 + 79	+ 76	+ 79	+ 76	+ 79
	STBY 1	+ 89 + 79	+ 79	+ 79	+ 79	+ 79
	BRAKE PRESS					
	HYD SYS 1/3		92	92	92	92
	2/3		92	92	92	92
HTR TEMP	L/A	R/B	FREON LOOP	1	2	
PRELT			ACCUM QTY	34	34	
POD			RAD OUT T	109	109	
OMS CRSFD			H2O SUP	P	0	
EVAP			TIRE PRESS			
HI LOAD			MG	LEFT	RIGHT	
TOP DUCT			IB	429	420	418
NOZ			OB	421	421	416
FDLN			NG	397	397	381
				1	2	3
HYD BLR/HTR						
APU						
GG/FU PMP HTR	H			H		H
TK/FU LN HTR						
PUMP/VLV						

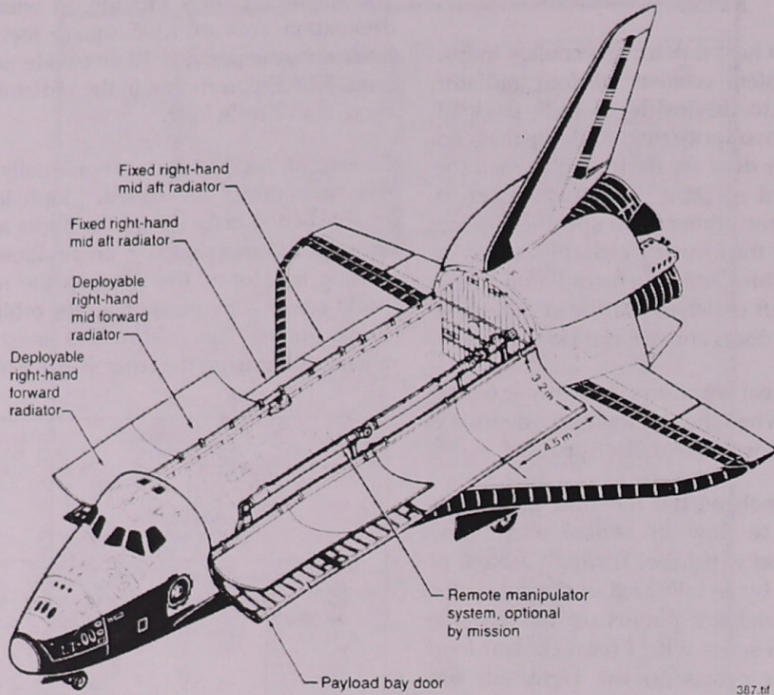
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BFS THERMAL DISPLAY

Radiator Mounting and Construction

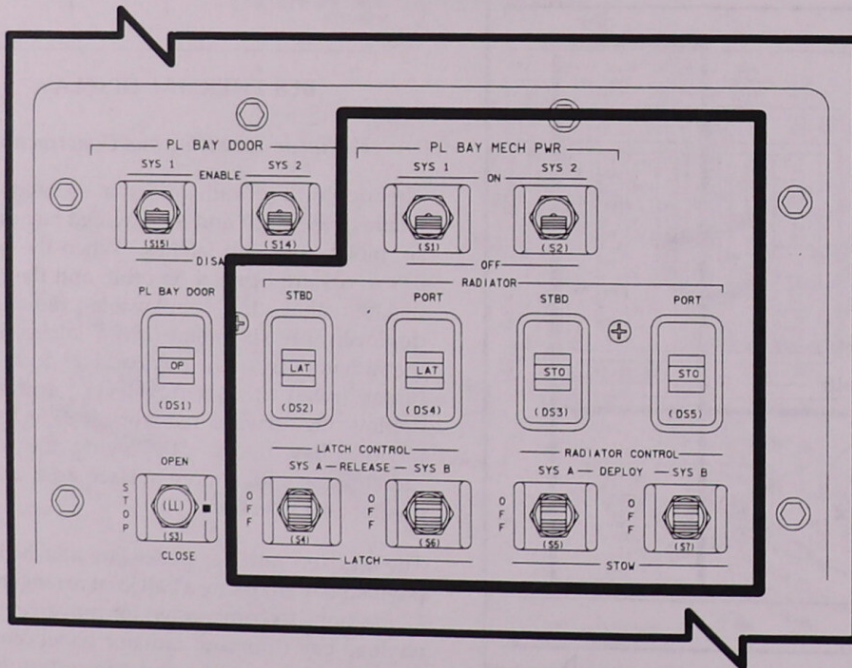
The deployable radiators are secured to the inside of the right and left payload bay doors by six motor-operated latches. When the payload bay doors are opened on orbit, and the mission dictates that the deployable radiators be deployed, the six motor-driven latches unlatch the radiators from the payload bay doors, and a motor-driven torque-tube-lever arrangement deploys the forward radiators at 35.5° from the payload bay doors. Deploying the forward radiators provides more surface area, and thus greater heat rejection.

The aft fixed radiator panels are attached to the payload bay doors by a ball joint arrangement at 12 locations to compensate for movement of the payload bay door and radiator panel caused by the thermal expansion and contraction of each member.



387 mf

Payload Bay Radiators



RADIATOR DEPLOY and STOW Switches and Talkbacks on Panel R13L

The radiator panels are constructed of an aluminum honeycomb face sheet 126 inches wide and 320 inches long. The forward deployable radiator panels are two-sided and have a core thickness of 0.9 of an inch. They have longitudinal tubes bonded to the internal side of both face sheets. Each of the forward deployable panels contains 68 tubes spaced 1.9 inches apart.

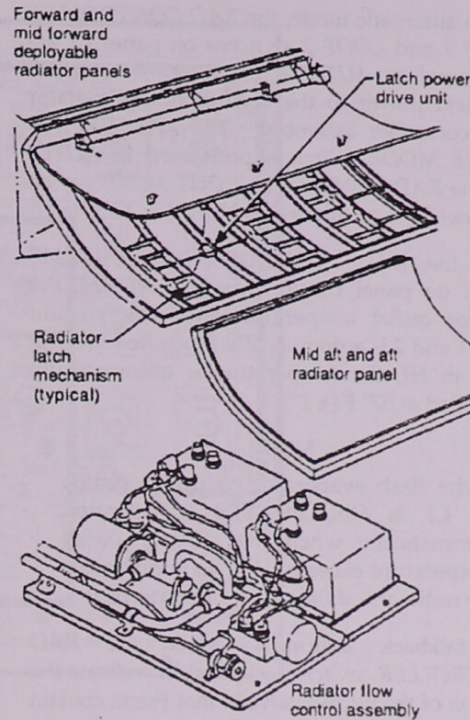
Each tube has an inside diameter of 0.131 of an inch. Each side of the forward deployable radiator panels has a coating bonded by an adhesive to the face sheet consisting of silver-backed Teflon tape for proper emissivity properties. The aft fixed panels are one-sided, and their cores are 0.5 inch thick. They have tubes only on the exposed side of the panel and a coating bonded by an adhesive to the exposed face sheet. The aft panels contain 26 longitudinal tubes spaced 4.96 inches apart. Each tube has an inside diameter of 0.18 inch. The additional thickness of the forward radiator panels is required to meet deflection requirements when the orbiter is exposed to ascent acceleration.

Radiator Deploy Systems

There are two radiator deploy systems, each of which drives one of two motors on each door. The systems drive the radiator panels away from the payload bay doors (deployed) or to the stowed position, using two reversible three-phase ac motors. It takes 40 seconds to deploy or stow the radiators.

The crew deploys and stows the radiators using switches on panel R13L. To deploy, the *PL BAY MECH PWR SYS 1* and *SYS 2* switches are positioned to *ON* to provide power to the panel switches. Both *RADIATOR LATCH CONTROL* switches are set concurrently to *RELEASE*; after 30 seconds, they are set to *OFF*. The *RADIATOR CONTROL* switches are then both concurrently set to *DEPLOY*; after 50 seconds, they are set to *OFF*. The *PL BAY MECH PWR* switches are then set to *OFF*.

To stow the radiators, the *PL BAY MECH PWR* switches are again positioned to *ON*. The *RADIATOR CONTROL* switches are both concurrently set to *STOW*, and after 50 seconds to *OFF*. The *LATCH CONTROL* switches are then positioned to *LATCH*, and after 30 seconds, to *OFF*. The *PL BAY MECH PWR* switches are then positioned to *OFF*.



Radiators and Radiator Flow Control Valve Assembly

Single Radiator Operations

It is possible to deploy either the port side or the starboard side radiator independently. This cannot be done directly with switches, because each controls motors on both sides. In order to deploy only one radiator, circuit breakers must be pulled to disable motors on one side. Single radiator operations may be done in case of a contingency situation, such as failure of one radiator or necessary Ku-Band antennae pointing, or a planned situation, such as flying in an attitude such that one door must remain partially closed to protect against debris strikes.

Radiator Flow Control

A radiator flow control valve assembly in each Freon coolant loop controls the temperature of that loop through the use of variable flow control, which mixes hot bypassed Freon coolant flow with the cold Freon coolant from the radiators. The radiator bypass valve allows Freon to either flow through the radiator or bypass the radiator completely.

In the automatic mode, the *RAD CONTROLLER LOOP 1* and *LOOP 2* switches on panel L1 are positioned to *AUTO A* or *AUTO B* to apply electrical power to the corresponding radiator flow controller assembly. The *RAD BYPASS VALVE MODE* switch is positioned to *AUTO*, and the *RAD CONTROLLER OUT TEMP* switch on panel L1 is positioned to *NORM* or *HI*.

With the *RAD CONTROLLER OUT TEMP* switch on panel L1 positioned to *NORM*, the radiator outlet temperature in Freon coolant loops 1 and 2 is automatically controlled at 38° F ($\pm 2^\circ$); in *HI*, the temperature is automatically controlled at 57° F ($\pm 2^\circ$).

NOTE

If the flash evaporator controller switch on L1 is ON, the FES is activated automatically when the radiator outlet temperature exceeds 41° F to supplement the radiators' ability to reject excess heat.

The talkback indicators below the *RAD CONTROLLER* switches on panel L1 indicate the position of the bypass valve in that Freon coolant loop. The indicators show *BYP* when the bypass valve in that Freon coolant loop is in the bypass position, barberpole when the motor-operated bypass valve is in transit, and *RAD* when the bypass valve is in the radiator flow position.

When the *RAD BYPASS VALVE MODE* switch on panel L1 is positioned to *MAN* for the Freon coolant loop selected, automatic control of the radiator bypass valve in that loop is inhibited, and the flight crew controls the bypass valve manually using the *RAD BYPASS VALVE LOOP 1*, *LOOP 2*, *MAN SEL* switches on panel L1.

When the switch is set to *BYPASS*, the loop's motor-operated bypass valve permits that Freon coolant loop to bypass the radiators. When the switch is positioned to *RAD FLOW*, the valve permits coolant to flow through the radiators. The *RAD BYPASS VALVE LOOP 1* and *2* talkback indicators for the Freon coolant loop indicate *BYP* when the bypass valve in that loop is in bypass, and barberpole when it is in transit.

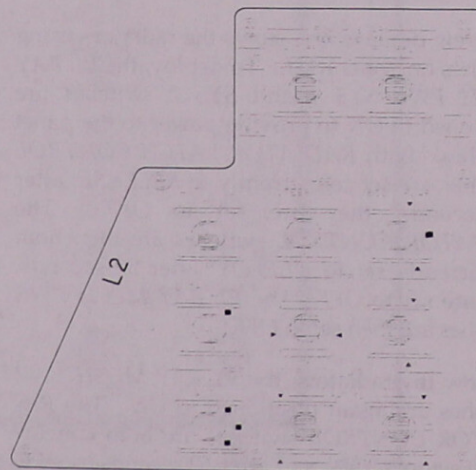
NOTE

The flow control valve cannot be controlled manually, only automatically via the controller. The bypass valve can be operated manually or automatically.

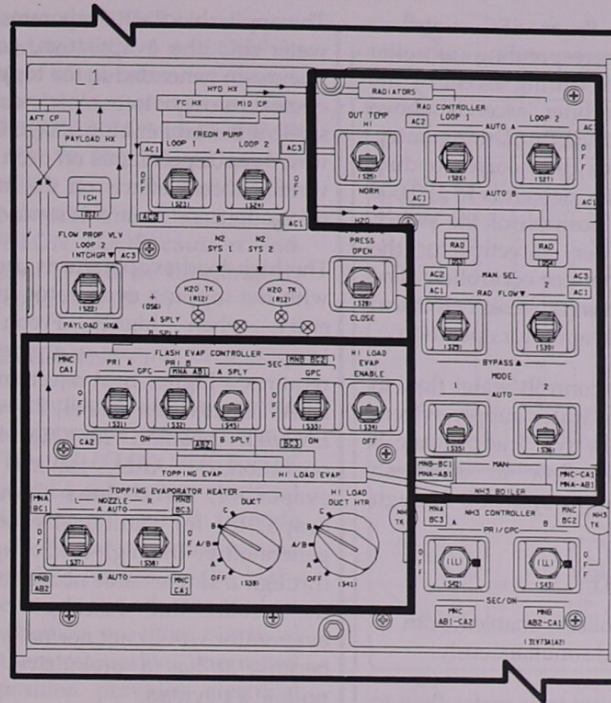
Freon Radiator Isolation Valves

Orbital debris could damage the orbiter Freon loop radiators located on the inner surface of the payload bay doors. Debris striking a Freon coolant line in the radiator could cause loss of Freon in that loop. To preclude this loss, a method was designed to isolate the punctured radiator from the rest of the loop.

To isolate the affected radiator from the Freon loop, ac-powered isolation valves and directional control valves with associated plumbing were added to the Freon loops. Switches on L2 provide control of the isolation valves; power to the valves and control logic are provided via circuit breakers on panels L4 and O14. The ac-powered isolation valve has automatic and manual controls. With the Mode switch in *AUTO*, if the affected Freon loop accumulator quantity drops below 12 percent for at least 5 seconds, a class 3 SM alert will annunciate and a command will be sent to the isolation valve on the affected loop to isolate the affected radiator. In *MAN*, the crew has to isolate the affected radiator manually if a leak is detected by holding the affected loops switch in *ISOL* until the radiator is isolated (~5 sec). Manual control of the valve can override the auto control in "both" directions (*RAD FLOW* or *ISOL*) to reset the valve to the normal flow condition for a system test or for a false failure that may have caused the isolation valve to isolate the radiator.



Panel L2 - Freon Loop Isolation



**RAD CONTROLLER SWITCHES and Talkbacks and
FLASH EVAP CONTROLLER Switches on Panel L1**

Flash Evaporator System

The flash evaporators reject heat loads from Freon coolant loops 1 and 2 by evaporating supply water in a vacuum. The flash evaporators are used during ascent above 140,000 feet, and they supplement the radiators on orbit if required. They also reject heat loads during deorbit and entry to an altitude of approximately 100,000 feet.

The flash evaporators are located in the aft fuselage of the orbiter. There are two evaporators, a high-load evaporator and a topping evaporator. Two major differences are that the high-load evaporator has a higher cooling capacity and only one overboard vent on the left side of the vehicle. The topping evaporator vents steam equally to the left and right sides of the orbiter to minimize propulsiveness. The evaporators are cylindrical shells with dual water spray nozzles at one end and a steam exhaust duct at the other end. The shell is composed of two separate finned packages, one for each Freon loop. The hot

Freon from the coolant loops flows around the finned shell, and water is sprayed onto the shell by water nozzles from either evaporator. The water vaporizes, cooling the Freon coolant loops. In the low-pressure atmosphere above 100,000 feet, water vaporizes quickly. Changing water liquid to vapor removes approximately 1,000 Btu per hour per pound of water. The water for the evaporators is obtained from the potable water storage tanks through FES water supply feedlines A and B.

Flash Evaporator Controllers

The flash evaporators have three controllers: primary A, primary B, and secondary. The primary A and B controllers have two separate, functionally redundant shutdown logic paths (undertemperature and rate of cooling). Secondary has no shutdown. The flash evaporator controllers are enabled by the *FLASH EVAP CONTROLLER* switches on panel L1. The *PRI A* switch controls primary controller A, the *PRI B* switch controls primary controller B, and the *SEC* switch controls the secondary controller.

When the *PRI A*, *PRI B*, or *SEC* switch is positioned to *GPC*, the corresponding controller is turned on automatically during ascent by the BFS computer as the orbiter ascends above 140,000 feet (MM103/SRB SEP). During entry, the BFS computer turns the corresponding controller off as the orbiter descends to 100,000 feet (MM305). The *ON* position of the switch provides electrical power directly to the corresponding flash evaporator controller. The *OFF* position of the switch removes all electrical power and inhibits flash evaporator operation.

The primary A controller controls water flow to the flash evaporator from water supply system A through water feed line A. The primary B controller controls water flow to the flash evaporator from water supply system B through water feed line B.

NOTE

When a primary controller is enabled, both evaporators can be used simultaneously.

The secondary controller controls water flow to the high load flash evaporator from water supply system A through feed line A if the *FLASH EVAP CONTROLLER SEC* switch on panel L1 is in the *A SPLY* position, and if the *HI LOAD EVAP* switch is in the *ENABLE* position. If the switch is in the *B SPLY* position, and the *HI LOAD EVAP* switch is in the *ENABLE* position, the secondary controller controls water flow to the flash evaporator from water supply system B through feed line B. When the secondary controller is used, and the *HI LOAD EVAP* switch is *OFF*, both the A and B water supply systems will feed the topping evaporator in an alternate pulsing fashion. When the secondary controller is used, and the *HI LOAD EVAP* switch is in the *ENABLE* position, the topping evaporator is disabled.

The primary A and B controllers modulate the water spray in the evaporator to keep the Freon coolant loops' evaporator outlet temperature stable at 39° F. The secondary controller modulates the water spray in the evaporator to control the Freon coolant loops' evaporator outlet temperature at 62° F. The temperature sensors are located at the outlets of both evaporators.

The applicable flash evaporator controller pulses water into the evaporators, cooling the Freon. The steam generated in the topping evaporator is ejected through two sonic nozzles at opposing sides of the orbiter aft fuselage to reduce payload water vapor pollutants on orbit and to minimize venting thrust effects on the orbiter's guidance, navigation, and control system.

The high-load evaporator is used in conjunction with the topping evaporator during ascent and entry when higher Freon coolant loop temperatures impose a greater heat load that requires a higher heat rejection. The *HI LOAD EVAP* switch on panel L1 must be in the *ENABLE* position for high-load evaporator operation. After leaving the high-load evaporator, Freon flows through the topping evaporator for additional cooling. The steam generated by the high-load evaporator is ejected through a single sonic nozzle on the left side of the orbiter aft fuselage. The high-load evaporator would not normally be used on orbit because it has a propulsive vent and might pollute a payload.

NOTE

Norm jets are required to control vehicle attitude when the FES high load is used on orbit.

FES Auto Shutdown

Each primary controller has an automatic shutdown capability to protect the evaporator from over- or undertemperature conditions. The evaporator's outlet temperature is monitored to determine whether a thermal shutdown of the evaporator is warranted. If the evaporator outlet temperature goes below 37° F for 20 seconds or more, an undertemperature shutdown of the evaporator occurs. If the evaporator outlet temperature is greater than 41° F for 55 seconds, an overtemperature shutdown of the evaporator occurs. If the evaporator is shut down, electrical power to the affected controller must be recycled to re-enable operations.

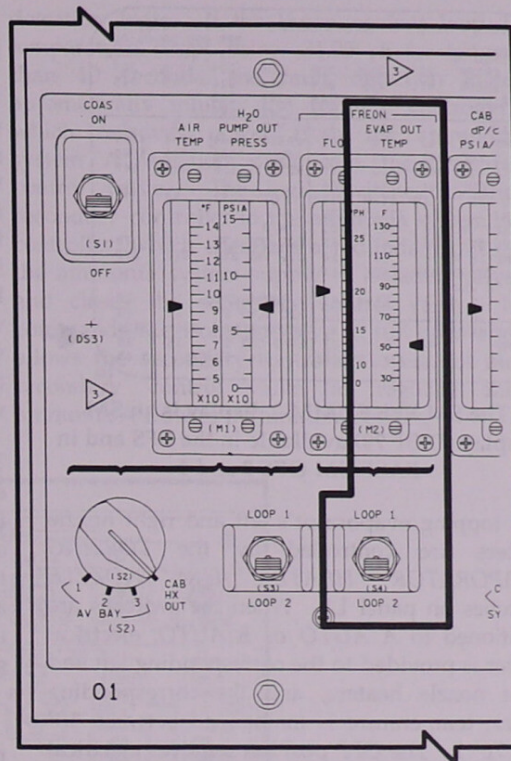
Temperature Monitoring

The evaporator outlet temperature of Freon coolant loops 1 and 2 is transmitted to panel O1.

When the switch below the FREON meter on panel O1 is positioned to *LOOP 1* or *LOOP 2*, the evaporator outlet temperature of Freon coolant loops 1 or 2 can be monitored in degrees Fahrenheit or on the DISP 79 SM SYS SUMM 2 display (EVAP OUT T). If the outlet temperature drops below 32.2° F or rises above 64.8° F, the red *FREON LOOP* caution and warning light on panel F7 will be illuminated. (The upper limit for ascent is 115° F.)

FES Heaters

Electrical heaters are employed on the topping and high-load flash evaporators' steam ducts to prevent freezing. The *HI LOAD DUCT HTR* rotary switch on panel L1 selects the electrical heaters. Switch positions *A* and *B* provide electrical power to the corresponding thermostatically controlled heaters on the high-load evaporator steam duct and steam duct exhaust. The *A/B* position provides electrical power to both thermostatically controlled heaters. The *C* position provides electrical power to both thermostatically controlled C heaters. The *OFF* position removes electrical power from all the heaters.



FREON EVAP OUT TEMP Meter and Switch on Panel O1

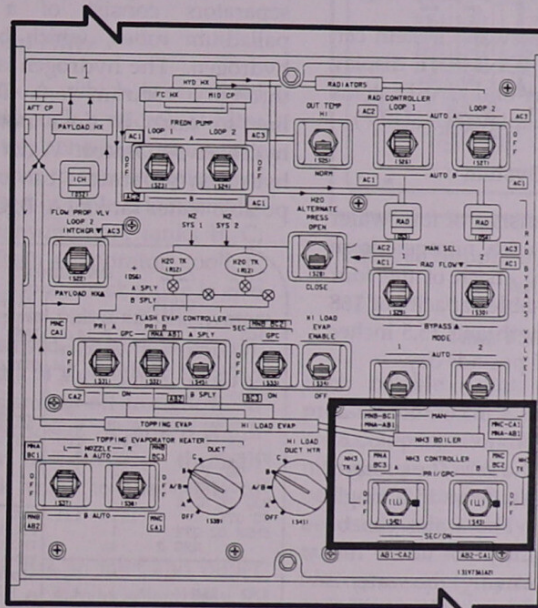
The *TOPPING EVAPORATOR HEATER DUCT* rotary switch on panel L1 selects the thermostatically controlled electrical heaters on the topping evaporator. Positions *A* and *B* provide electrical power to the corresponding heaters, while *A/B* provides electrical power to both *A* and *B* heaters. The *C* position provides power to the *C* heaters and part of the *B* heaters. The *OFF* position removes electrical power from all the heaters.

electrical power to the primary and secondary controllers within the ammonia controllers. When the orbiter descends through 120,000 feet, the backup flight system computer commands the selected ammonia system controller on.

Ammonia Boiler Control Sensors

Three temperature sensors are located on each Freon coolant loop. One sensor is associated with the primary controller and its motor-operated valve to regulate ammonia system A flow to maintain Freon coolant loop 1 and 2 temperatures at the outlet of the ammonia boiler at 35° F, ± 3° F. A second sensor is associated with the ammonia system A controller fault

detection logic. If the Freon coolant loop 1 temperature drops below 31.25° F for longer than 10 seconds, the fault detection logic automatically inhibits the primary controller, which removes power from the ammonia system A isolation valve and the primary control valve. The logic switches to the secondary controller in the ammonia system A controller, which energizes a redundant coil in the ammonia system supply A isolation valve and closes the secondary control valve. It commands the isolation valve to full open and allows the secondary controller to control the secondary control valve to regulate the ammonia A flow to the ammonia boiler.



NH₃ CONTROLLER Switches on Panel L1

The third sensor is associated with the secondary controller and secondary motor-operated valve. It regulates ammonia supply system A flow to maintain the Freon coolant loop 1 and 2 temperatures at the outlet of the ammonia boiler at 34° F. This automatic switchover is only from the primary to the secondary.

Secondary Controller

When the NH₃ CONTROLLER A or B switch on panel L1 is positioned to SEC/ON, the A or B ammonia system controller is electrically powered and enabled directly (no computer

command is required). The secondary controller in the ammonia system controller energizes the system's isolation valve open, permitting ammonia to flow to two motor-operated controller valves. The secondary controller commands the primary controller's motor-operated valve to the open position and the secondary controller's motor-operated valve to regulate the ammonia flow to the ammonia boiler. The three temperature sensors on each Freon coolant loop operate and control Freon coolant loop 1 and 2 temperature in the same manner as in the PRI/GPC mode. Fault detection logic does not exist in the secondary controller.

The OFF position of the NH₃ CONTROLLER switches removes all electrical power from the ammonia system controller, rendering the ammonia system inoperative.

Supply and Wastewater Systems

The supply water system provides water for flash evaporator system cooling, crew consumption, and hygiene. The supply water system stores water generated by the fuel cells, and the wastewater system stores waste from the crew cabin humidity separator and from the flight crew. Four supply water tanks and one wastewater tank are located beneath the crew compartment middeck floor.

Data on the supply and wastewater system can be monitored on the ENVIRONMENT display (DISP 66) under H₂O SUPPLY and WASTE items and on the BFS THERMAL display (H₂O SUP P).

Supply Water System

The supply water system consists of four water tanks that are pressurized with nitrogen from the pressure control system. Each of the four potable water tanks has a usable capacity of 168 pounds, is 35.5 inches in length and 15.5 inches in diameter, and weighs 39.5 pounds dry.

The three fuel cells generate a maximum of 25 pounds of potable water per hour (about 0.81 pound of water per kilowatt hour). The product water from all three fuel cells flows to a single water relief control panel. The water can be directed to potable water tank A or to the fuel cell water relief nozzle. Normally, the water is directed to water tank A.

The product water lines from all three fuel cells were modified to incorporate a parallel (redundant) path of product water to potable water tank B in the event of a blockage of the primary water path to the tanks. If such a blockage were to occur, pressure would build up and relieve through the redundant paths to potable water tank B.

Instrumentation

Temperature sensors are installed on each of the redundant paths; in addition, a pressure sensor is transmitted to telemetry and can be monitored on the BFS THERMAL display. A

pH sensor is located at the common product water outlet of the water relief panel. It provides a redundant measurement of fuel cell health and water purity. A single measurement of water purity in each fuel cell is also provided. If a single fuel cell pH sensor indicated high, the flight crew would be required to sample the potable water to verify the proper pH.

Hydrogen Separators

The hydrogen-enriched water from the fuel cells flows through the single water relief panel through two hydrogen separators to potable water tank A. The separator removes 85 percent of the excess hydrogen. The hydrogen separators consist of a matrix of silver palladium tubes, which have an affinity for hydrogen. The hydrogen is dumped overboard through a vacuum vent. The redundant water line to tank B does not pass through the hydrogen separator. Water passing through the hydrogen separators can be stored in all four potable water tanks: A, B, C, and D.

2011/ /066 ENVIRONMENT		4 000/02:33:38	
		000/00:00:00	
CABIN		AV BAY	1 2 3
dP/dT +.01	CABIN P 14.7	TEMP	90 90 78
PPO2	AIRLK P 14.8	FAN AP	3.80 3.77 3.92
A 3.04	FAN AP 5.55	SUPPLY H2O	
B 3.04	HX OUT T 45L	QTY A	67 PRESS 32
C 3.04	CABIN T 71	B 18	DMP LN T 77
PPCO2 1.9		C 94	NOZ T A 64
		D 94	B 64
O2 FLOW	0.0L 0.0L	WASTE H2O	
REG P	100 100	QTY 1	15 PRESS 17
N2 FLOW	0.0L 0.0L		DMP LN T 58
REG P	202 202		NOZ T A 82
O2/N2 CNTL VLV	N2 O2		B 82
H2O TK NZ P	17 17	VAC VT NOZ T 224	
N2 QTY	131 131	CO2 CNTLR	1 2
EMER O2	1	FILTER P	0.00L
REG P	4L	PPCO2	- 0.0L
		TEMP	32.0L
		BED A PRESS	0.0L 0.0L
IMU FAN	A B C AP	B PRESS	0.0L 0.0L
HUMID SEP	* * * 4.5	AP	0.00L 0.00L
		VAC PRESS	0.0L

H₂O System Parameters on the ENVIRONMENT Display (DISP 66)

0001/		THERMAL		5 000/00:00:00	
				BFS 000/00:00:00	
HYD SYS TEMP	BDYFLP RD/SB	L OB	L IB	R IB	R OB
PRIME	+ 99 + 79	+ 76	+ 79	+ 76	+ 79
STBY 1	+ 89 + 79	+ 79	+ 79	+ 79	+ 79
BRAKE PRESS					
HYD SYS 1/3		92	92	92	92
2/3		92	92	92	92
HTR TEMP	L/A	R/B	FREON LOOP 1 2		
PRPLT			ACCUM QTY	34	34
POD			RAD OUT T	109	109
OMS CRSFD			H ₂ O SUP P	0	
EVAP		TIRE PRESS			
HI LOAD			MG LEFT	RIGHT	
TOP DUCT			IB 429	420	418
NOZ			OB 421	421	416
FDLN			NG 397	397	381
HYD BLR/HTR			1	2	3
APU					
GG/FU PMP HTR	H		H		H
TK/FU LN HTR					
PUMP/VLV					

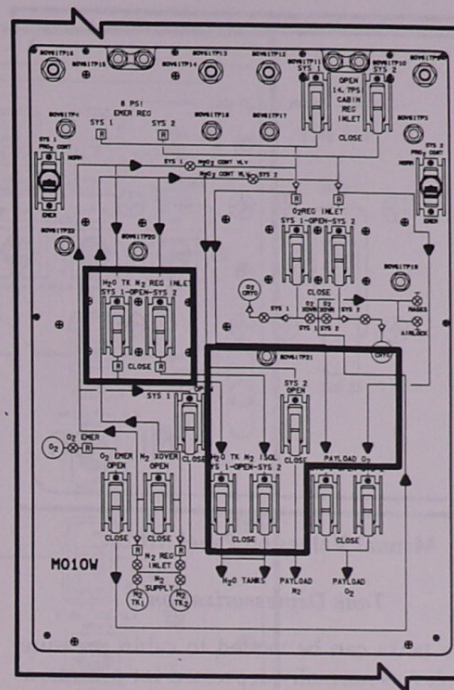
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BFS THERMAL Display

Microbial Filter

The water entering tank A, which is sterilized before launch, passes through a microbial filter that adds approximately one-half parts per million iodine to the water to prevent microbial growth. The water stored in tank A is normally used for flight crew consumption; tanks B, C, and D are used for flash evaporator cooling. The water from the microbial check valve is also directed to a galley supply valve. If the water tank A inlet valve is closed, or tank A is full, water is directed to tank B through a 1.5 psid check valve where it branches off to tank B. If the tank B inlet valve is closed, or tank B is full of water, the water is directed through another 1.5 psid check valve to the inlets to tanks C and D.

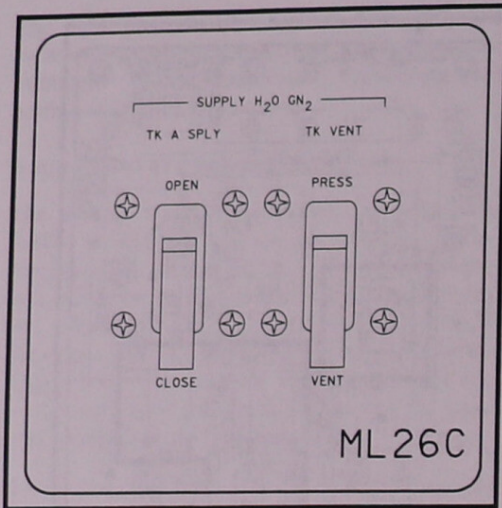
Each potable water tank has an inlet and outlet valve that can be opened or closed selectively to use water; however, the tank A outlet valve normally remains closed to isolate the treated water from the untreated water in the other tank.



Nitrogen Supply System Valves on Panel MO10W

Tank Pressurization

Each potable water and wastewater tank is pressurized with gaseous nitrogen from the crew compartment nitrogen supply system. The nitrogen and water are separated by a metal bellows. Nitrogen supply systems 1 and 2 can be used individually to pressurize the water tanks with nitrogen at 15.5 to 17.0 psig. Nitrogen supply system 1 is controlled by the H₂O TK N₂ REG INLET and H₂O TK N₂ ISOL SYS 1 manual valves on panel MO10W. Nitrogen supply system 2 is controlled by the SYS 2 manual valves on panel MO10W. The regulator in each nitrogen supply system controls the nitrogen pressure to the tanks at 15.5 to 17 psig, and a relief valve in each nitrogen supply system will relieve into the crew cabin if the nitrogen supply increases to 18.5 ± 1.5 psig, to protect the tanks from overpressurization.



Manual Valves on Panel ML26C

Tank Depressurization

All the tanks can be vented to cabin pressure, but tank A is normally depressed for ascents, as described here. For only tank A, inlet nitrogen pressure is controlled by the *SPLY H₂O GN₂ TK A SPLY* and *TK VENT* manual valves on panel ML26C. When the tank A supply valve is closed, the tank is isolated from the nitrogen supply. When the tank A valve is opened, the tank is pressurized by the crew cabin atmosphere. For launch, the tank A supply valve is closed, and the tank vent is opened, which lowers tank A pressure. The fuel cell water head pressure is lower to help prevent flooding of the fuel cells during ascent. On orbit, the tank A supply valve is opened, and the tank A vent to the cabin is closed, allowing nitrogen supply pressure to tank A.

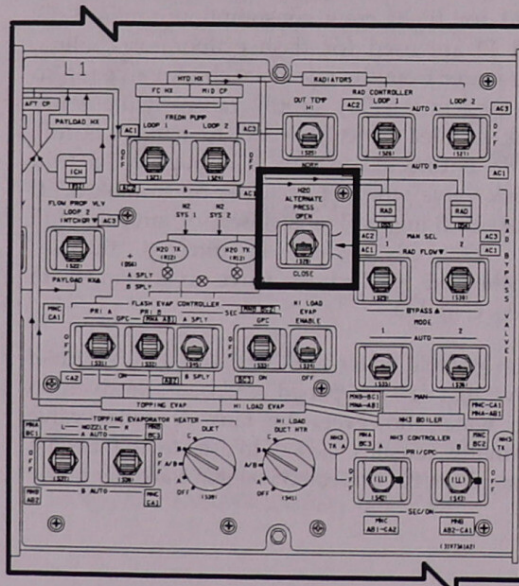
Alternate Water Pressurization

If neither nitrogen supply system 1 nor 2 can be used to pressurize the water tanks, the *H₂O ALTERNATE PRESS* switch on panel L1 can be positioned to *OPEN*, which would apply the crew cabin pressure to the water tanks.

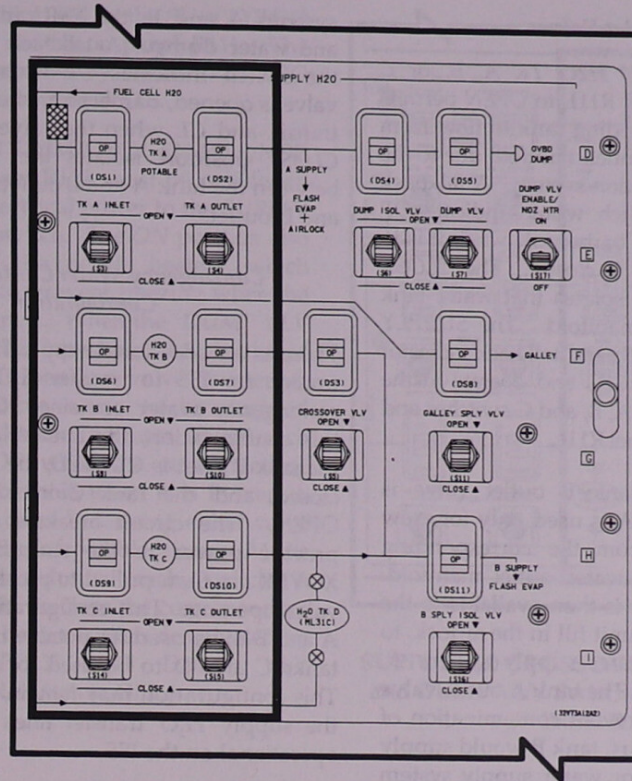
Normally, this switch is positioned to *CLOSE* to isolate the cabin pressurization system from the water tank pressurization system.

Supply Water Tank Inlet Valves

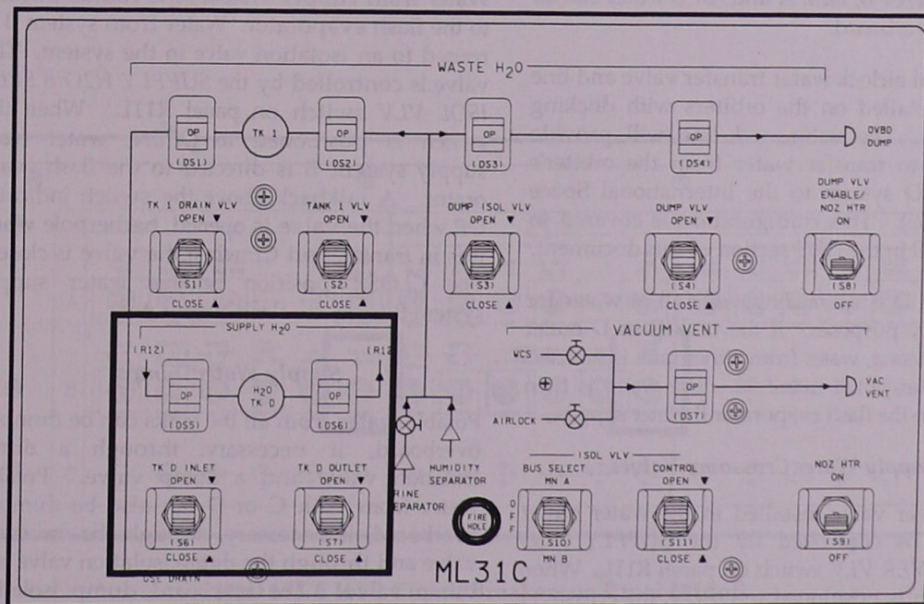
Potable water tank A, B, and C valves are controlled from panel R11L, and tank D valves are controlled from panel ML31C. When the *SUPPLY H₂O TK A INLET*, *TK B INLET*, or *TK C INLET* switch on panel R11L is positioned to *OPEN*, the inlet valve for the tank permits water into that tank. A talkback indicator above the corresponding switch indicates *OP* when the corresponding valve is open, barberpole when the valve is in transit, and *CL* when that valve is closed. When the switch is positioned to *CLOSE*, the water inlet to that tank is isolated from the inlet water supply. The *SUPPLY H₂O TK D INLET* switch and talkback indicator are located on panel ML31C and operate in the same manner as the switches and talkbacks for tanks A, B, and C.



H₂O ALTERNATE PRESS Switch on Panel L1



TKT and OUTLET Switches and Talkbacks on Panel R11L



TK INLET and OUTLET Switches and Talkbacks on Panel ML31C

Tank Outlet Valves

Positioning the *SUPPLY H₂O TK A, B, or C OUTLET* switch on panel R11L to *OPEN* permits water from the corresponding tank to flow from the tank into the water outlet manifold due to the tank nitrogen pressurization system. A talkback indicator above the switch would indicate *OP* when that valve is open, barberpole when it is in transit, and *CL* when it is closed. The *CLOSE* position of each switch isolates that water tank from the water outlet manifold. The *SUPPLY H₂O TK D OUTLET* switch and talkback indicator are located on panel ML31C and operate in the same manner as the tank A, B, and C switches and talkback indicators on panel R11L.

If the potable water tank B outlet valve is opened (normally tank A is used only for crew consumption), water from the corresponding tank is directed to the water outlet manifold. The tank A and B water is then available to the extravehicular mobility unit fill in the airlock, to the flash evaporator water supply system A, and to the water dump. The tank A outlet valve is normally closed to prevent contamination of the water in tank A. Thus, tank B would supply water to flash evaporator water supply system A and to the EMU fill in the airlock. If it is necessary to provide space for storing water in tank A and/or B, tank A and/or B water can be dumped overboard.

An external airlock water transfer valve and line will be installed on the orbiters with docking capability. The valve and line will provide capability to transfer water from the orbiter's supply H₂O system to the International Space Station (ISS). This configuration is covered in more detail in the ODS section of this document.

Tank C or D is normally saved full of water for contingency purposes. If the tank C or D outlet valve is opened, water from either tank is directed to the water outlet manifold. The water is then available to the flash evaporator B water supply.

Supply Water Crossover Valves

A crossover valve installed in the water outlet manifold is controlled by the *SUPPLY H₂O CROSSOVER VLV* switch on panel R11L. When the switch is positioned to *OPEN*, the crossover valve opens and allows tank A or B (also C or D) to supply flash evaporator water supply

systems A and B, the EMU fill in the airlock, and water dump. A talkback indicator above the switch indicates *OP* when the crossover valve is opened, barberpole when the valve is in transit, and *CL* when the valve is closed. The *CLOSE* position isolates the water manifold between the tank A and B outlets and the tank C and D outlets.

Contingency Water Container Fill Configuration

There is an additional supply H₂O tank configuration for ISS to transfer H₂O to the ISS via contingency water container (CWC) bags. In this configuration, the tank A outlet is *OPEN*, the tank B inlet is *CLOSED*, the *XOVER* valve is closed, and the tank C inlet and outlet are *OPEN*. The circuit breakers on ML86B that provide power to the tank B inlet and the *XOVER* are then pulled to preclude inadvertent valve opening. This configuration allows tanks A and B to be used for potable H₂O transfer and tanks C and D to be used for FES operations. This configuration may remain an option when the supply H₂O transfer lines are completely operational on the ISS.

Supply Isolation Valve

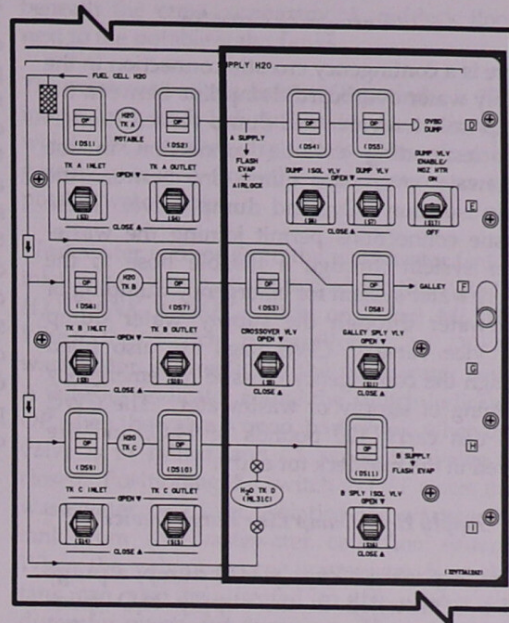
Water from supply system A is routed directly to the flash evaporator. Water from system B is routed to an isolation valve in the system. The valve is controlled by the *SUPPLY H₂O B SPLY ISOL VLV* switch on panel R11L. When the switch is positioned to *OPEN*, water from supply system B is directed to the flash evaporator. A talkback above the switch indicates *OP* when the valve is opened, barberpole when it is in transit, and *CL* when the valve is closed. The *CLOSE* position isolates water supply system B from the flash evaporator.

Supply Water Dumps

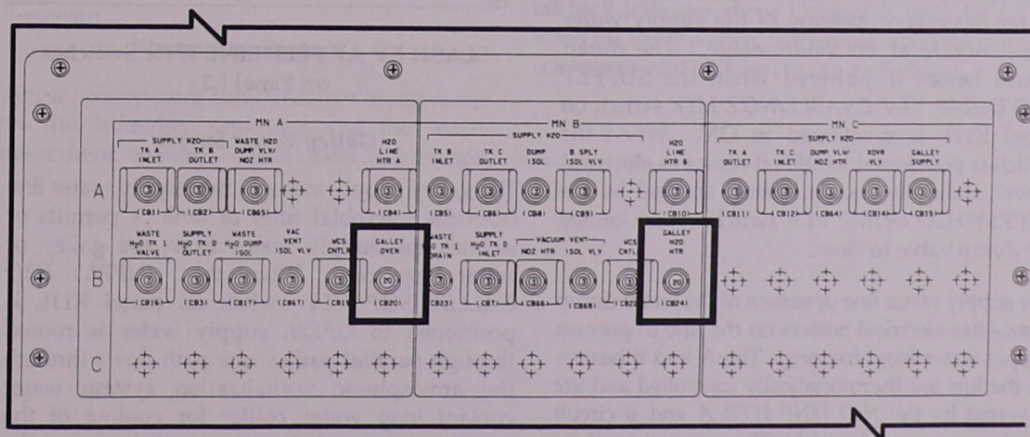
Potable water from all the tanks can be dumped overboard, if necessary, through a dump isolation valve and a dump valve. Potable water from tank C or D can also be dumped overboard, if necessary, through the crossover valve and through the dump isolation valve and dump valve. The overboard dump isolation valve is located in the crew cabin, and the dump valve is located in the midfuselage. The dump

isolation valve is controlled by the *SUPPLY H2O DUMP ISOL VLV* switch on panel R11L. The dump valve is controlled by the *SUPPLY H2O DUMP VLV* switch on panel R11L.

The *SUPPLY H2O DUMP VLV ENABLE/NOZ HTR* switch on panel R11L must be positioned to *ON* to supply electrical power to the *SUPPLY H2O DUMP VLV* switch. The *ON* position also applies power to the nozzle heaters, which warm the nozzles to prevent freezing when the dump valve is opened. When the *DUMP VLV* and *DUMP ISOL VLV* switches are positioned to *OPEN*, the corresponding valve is opened, which allows potable water to be dumped overboard. A talkback indicator above each switch indicates *OP* when the corresponding valve is open, *barberpole* when it is in transit, and *CL* when it is closed. Closing either valve inhibits the dumping of potable water. At the completion of the dump, each switch is positioned to *CLOSE* to close the corresponding valve. The nozzle heater is then deactivated by placing the *SUPPLY H2O DUMP VLV ENABLE/NOZ HTR* switch to *OFF*.



SUPPLY H2O CROSSOVER VLV, ISOL VLV, and DUMP VLV Switches and Talkback on Panel R11L



H2O LINE HTR Circuit Breakers on Panel ML86B

Contingency Crosstie

There is a contingency crosstie connection in the supply water overboard dump line between the dump isolation valve and dump valve. There is a corresponding crosstie connection in the wastewater overboard dump line between the dump isolation valve and dump valve. These crosstie connections permit joining the wastewater system through a flexible hose to the supply water system for emergency dumping of wastewater through the supply water dump (and vice versa). CWC bags are also filled through the contingency crosstie for emergency dumping of supply or wastewater. The CWC bags can carry 120 pounds of H₂O, and are stored in the middeck for entry.

Supply H₂O Dump Line Purge Device

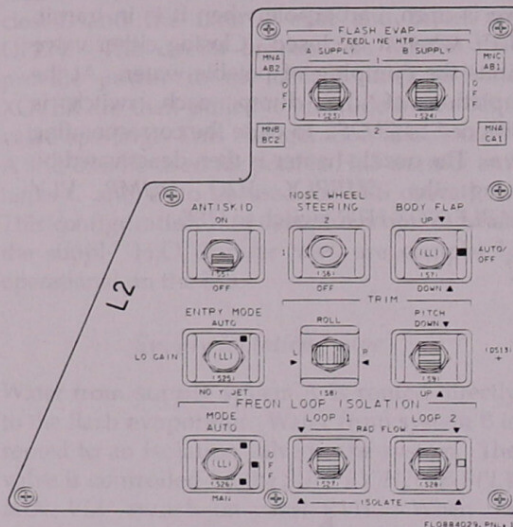
Before beginning a supply H₂O dump, a purge device is installed in the supply H₂O quick disconnect of the contingency crosstie. The purge device allows cabin air at ~3 lb/hr to purge the supply H₂O dump valve of any remaining water droplets to preclude a condition known as "burping" of the dump valve. When the water droplets freeze under the dump valve, they expand and could cause the dump valve to open. Purging the valve post dump alleviates this problem.

Dump Nozzle Heaters

The supply water dump nozzle employs a heater to prevent freezing of the supply water dump nozzle at the midfuselage. The dump nozzle heater is powered when the *SUPPLY H₂O DUMP VLV ENABLE/NOZ HTR* switch on panel R11L is positioned to ON. When the switch is positioned to OFF, it removes electrical power from the nozzle heater, as well as the *SUPPLY H₂O DUMP VLV* switch, which causes the dump valve to close.

The supply water line upstream of the water dump nozzle has electrical heaters on the line to prevent supply water from freezing. The A and B heaters on the line are thermostatically controlled and are powered by the *H₂O LINE HTR A* and *B* circuit breakers on panel ML86B. (These circuit breakers also provide power to thermostatically controlled heaters on the wastewater line and the waste collection system vacuum vent line.)

The supply water feed lines to the flash evaporators are approximately 100 feet long. To prevent the water in the lines from freezing, redundant heaters are installed along the length of the water lines. The heaters are controlled by the *FLASH EVAP FEEDLINE HTR A SUPPLY* and *B SUPPLY* switches on panel L2. When a switch is positioned to 1, it enables the thermostatically controlled heaters on the corresponding supply line to automatically control the temperature on that line. When a switch is positioned to 2, it enables the redundant thermostatically controlled heater system on the corresponding supply line. The OFF position of each switch inhibits heater operation on the corresponding supply line.

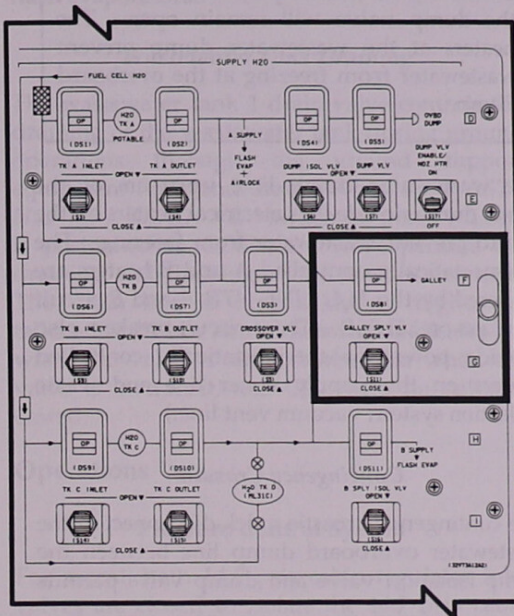


FLASH EV AP FEEDLINE HTR Switches
on Panel L2

Galley Water Supply

The galley supply valve in the supply water line from the microbial filter of tank A permits or isolates the supply water from the galley or water dispenser. When the *SUPPLY H₂O GALLEY SUP VLV* switch on panel R11L is positioned to OPEN, supply water is routed through parallel paths: one path flows through the atmospheric revitalization system water coolant loop water chiller for cooling of the supply water, and the other path bypasses the water chiller with ambient temperature water. A talkback indicator above the switch indicates OP when the valve is open, barberpole when the

valve is in transit, and *CL* when the valve is closed. The *CLOSE* position of the switch isolates the potable supply water from the middeck ECLSS supply water panel.



GALLEY Water Supply Switch and Talkback on Panel R11L

If the galley is not available/manifested for a flight, the chilled water and ambient water are connected to an Apollo water dispenser to dispense ambient and chilled water for drinking and food reconstitution.

Wastewater System

A single wastewater tank receives wastewater from the humidity separator and the waste management system. The tank is located

beneath the crew compartment middeck floor next to the potable water tanks.

The wastewater tank holds 168 pounds, is 35.5 inches long and 15.5 inches in diameter, and weighs 39.5 pounds dry. It is pressurized by gaseous nitrogen from the same source as the potable water tanks.

Wastewater is directed to the wastewater tank 1 inlet valve, which is controlled by the *WASTE H₂O TANK 1 VLV* switch on panel ML31C. When the switch is positioned to *OPEN*, wastewater is directed to the wastewater tank. A talkback indicator above the switch indicates *OP* when the valve is open, barberpole when the valve is in transit, and *CL* when the valve is closed. Positioning the switch to *OFF* closes the wastewater tank inlet, isolating the wastewater tank from the wastewater collection system. When the valve is open, wastewater from the tank can also be directed to the wastewater dump for overboard dumping. The waste tank outlet (or drain) is always closed, except for ground draining of the tank.

Wastewater Dumps

The wastewater dump isolation valve and wastewater dump valve in the wastewater dump line allow wastewater to be dumped overboard through the wastewater dump. The *WASTE H₂O DUMP ISOL VLV* switch on panel ML31C positioned to *OPEN* allows wastewater to be directed to the wastewater dump valve. A talkback indicator above the switch indicates *OP* when the valve is open, barberpole when the valve is in transit, and *CL* when the valve is closed.

For wastewater to be dumped overboard, the wastewater dump valve must be opened. It is controlled by the WASTE H₂O DUMP VLV ENABLE/NOZ HTR switch and WASTE H₂O DUMP VLV switches on panel ML31C. When the WASTE H₂O DUMP VLV ENABLE/NOZ HTR switch is positioned to ON, electrical power is supplied to the wastewater dump heaters and the WASTE H₂O DUMP VLV switch.

When the WASTE H₂O DUMP VLV switch is positioned to OPEN, the dump valve allows wastewater to be dumped overboard. A talkback indicator above the switch indicates OP when the valve is open, barberpole when the valve is in transit, and CL when the valve is closed. If wastewater is dumped overboard, the DUMP ISOL VLV switch is positioned to CL upon completion of the dump. The WASTE H₂O DUMP VLV is positioned to CLOSE, and the WASTE H₂O DUMP VLV ENABLE/NOZ HTR switch is set to OFF.

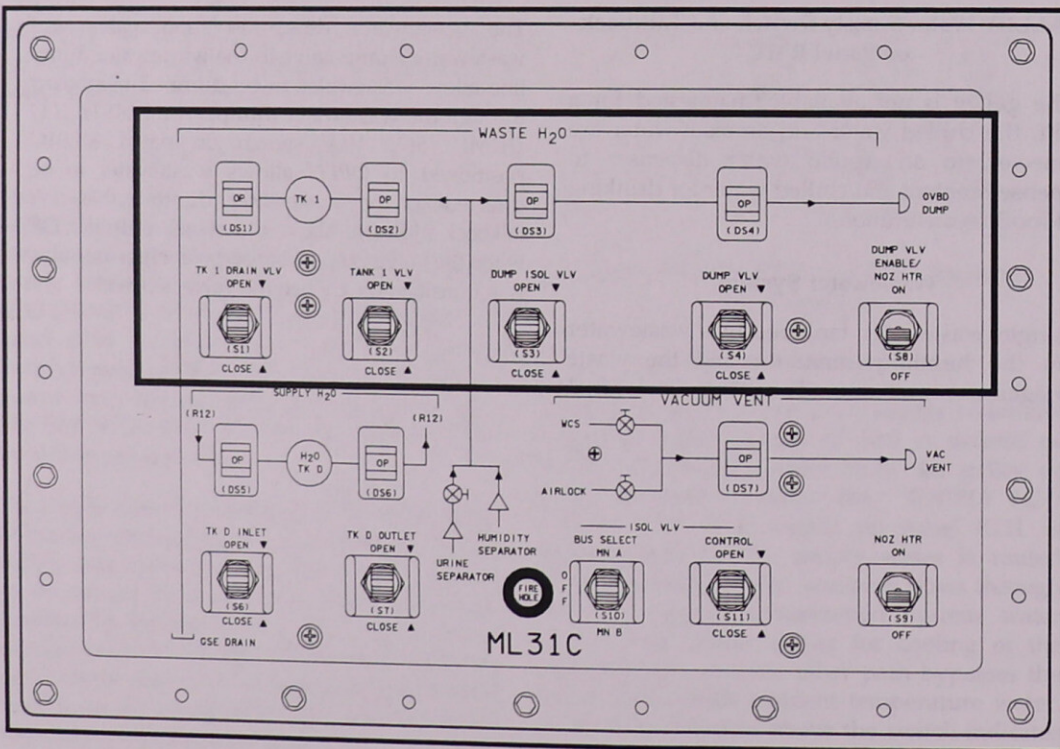
CAUTION

If the DUMP VLV ENABLE/NOZ HTR switch is positioned to OFF before the DUMP VLV switch is positioned to CLOSE, the dump valve will remain open. The heaters at the wastewater dump prevent wastewater from freezing at the overboard dump.

The wastewater dump line, upstream of the waste dump nozzle, has electrical heaters on the line to prevent wastewater from freezing. The thermostatically controlled A and B heaters are powered by the H₂O LINE HTR A and B circuit breakers on ML86B. (These circuit breakers also provide power to thermostatically controlled heaters on the supply water line and waste collection system vacuum vent line.)

Contingency Crosstie

The contingency crosstie quick disconnect in the wastewater overboard dump line between the dump isolation valve and dump valve permits



WASTE H₂O System Switches and Talkbacks on Panel ML31C

wastewater to be joined with the supply water system through a flexible hose for emergency dumping of supply water through the wastewater dump or using wastewater for the flash evaporators.

Wastewater Tank Draining

The wastewater tank 1 drain valve controls the draining of the wastewater tank during ground operations through the ground support equipment flush and drain. When the *WASTE H₂O TK 1 DRAIN VLV* switch on panel ML31C is positioned to *OPEN*, the valve permits the draining and flushing of the wastewater tank. The drain line is capped during flight. A talkback indicator above the switch indicates *OP* when the valve is open, barberpole when the valve is in transit, and *CL* when the valve is closed.

Operations

Pressure Control System

For ascent, both 14.7 psia cabin regulator inlet valves are closed to isolate the 14.7 psia cabin regulators. If a cabin leak develops, this configuration conserves nitrogen by not allowing any makeup flow into the cabin until the cabin pressure drops below 8 psia. The O₂ regulator inlet valves are closed, directing all the O₂ to the O₂ crossover manifold to supply the launch and entry suit helmets. The O₂/N₂ control valve on pressure control system 1 is open to allow N₂ to pressurize the O₂/N₂ manifold. The O₂/N₂ control valve on pressure control system 2 is closed. This would normally allow oxygen to flow to the O₂/N₂ manifold, but since the oxygen regulators are closed, nothing is configured to flow through the emergency 8 psia regulators on pressure control system 2. The crew will close the visors of their launch and entry suit helmets shortly before lift-off and breathe 100 percent O₂ until shortly after solid rocket booster separation.

The pressure control system remains in the ascent configuration until early in the flight plan when the orbit pressure control system configuration is performed. The pressure control system configuration to system 1 typically is called for in the flight day 1 EZ activities block. The 14.7 psia cabin regulator

inlet valve on the selected pressure control system is opened. This enables the cabin regulator to automatically maintain the cabin pressure at 14.7 psia. The O₂ regulator inlet valve is opened, and the selected system O₂/N₂ control valve is taken to *AUTO*. This enables the O₂/N₂ controller to control whether O₂ or N₂ flows into the O₂/N₂ manifold based on cabin PPO₂ level. During the postsleep activities on flight day 2, an O₂ bleed orifice is installed in launch and entry helmet QD-5. The O₂ bleed orifice is sized based on number of crew and compensates for the crew's metabolic O₂ usage by flowing O₂ directly into the cabin. This helps keep the PPO₂ level stable when the cabin pressure is greater than 14.7 psia and the cabin regulators are not flowing. A reconfiguration to pressure control system 2 is performed halfway through the mission.

A 10.2 psia cabin protocol was developed by the flight surgeons to minimize the risk of decompression sickness (bends) for crewmembers preparing for an EVA. The EVA crewmembers must prebreathe pure O₂ before they go EVA to help flush N₂ out of their body tissue. The following 10.2 cabin protocol options have been developed:

- Option 1
 - 60-minute initial prebreathe on launch and entry suit helmet
 - 12 hours at 10.2 psia cabin pressure
 - 75-minute final prebreathe in suit
- Option 2
 - 60-minute initial prebreathe on launch and entry suit helmet
 - 24 hours at 10.2 psia cabin pressure
 - 40-minute final prebreathe in suit
- Option 3
 - 4-hour prebreathe in suit

For scheduled EVAs, option 1 or 2 is chosen to minimize the in-suit prebreathe just prior to the EVA. The cabin is depressurized to 10.2 psia using the airlock depressurization valve located in the airlock. Because there is no 10.2 psia

cabin regulator, the cabin pressure and the PPO₂ levels must be manually managed during 10.2 psia cabin operations.

NOTE

If a 10.2 depress is scheduled early in the mission, the PCS 1 configuration may be delayed until 10.2 operations are no longer required. This saves consumables during consumable-critical missions, such as ISS docking missions, where orbiter O₂ and N₂ are used to repress and resupply the ISS.

The pressure control system configuration is the same for entry as it was for ascent.

Atmospheric Revitalization System

The atmospheric revitalization system is already configured for ascent at crew ingress. One cabin fan, one humidity separator, one inertial measurement unit fan, and one fan in each avionics bay are already operating. The cabin temperature control valve is positioned in the *FULL COOL* position by powering the controller and adjusting the rotary switch to the *COOL* position. Once the *FULL COOL* position is reached, cabin temperature controller 1 is unpowered. The humidity separators and the IMU fan signal conditioners are unpowered to protect against an ac to ac bus short, which could cause loss of a main engine controller. (The wire bundle that carries power to these signal conditioners did short on STS-6.) Water loop 2 is on, and water loop 1 is off during ascent. Both water bypass valves are positioned to flow approximately 950 lb/hr through the Freon/water interchanger.

If no failures occur during ascent, no actions are required to manage the atmospheric revitalization system in OV_s 103 and 104 (OV 102 and 105 if flown without the RCRS), with the exception of scheduled LiOH canister change-outs. During the post insertion period for RCRS configured vehicles, the crew will activate the system. Every 13 minutes, the RCRS will automatically switch chemical beds between regeneration and adsorption as part of a 26-minute full regeneration cycle with no further crew actions for nominal operations. Mid-mission (on 10+ day flights), the activated

charcoal canister will be changed out. The operating cabin fan(s) should be turned off for removal and installation of canisters.

The orbit fan and pump configuration is the same on orbit as for ascent, except water loop 1 is set to the *GPC* position and the *BYPASS* controller for water loop 2 is set to the *AUTO* position. While in SM OPS 2 (or SM OPS 4), the *GPC* position enables the inactive water loop to be cycled on periodically. This periodic cycling prevents the inactive water loop from freezing in the Freon/water interchanger. The cycling sequence is initiated any time an OPS transition is made into SM OPS 2 (or SM OPS 4). When an OPS transition is made, the pump will receive a 6-minute "ON" command, then remain off for 4 hours. The pump will cycle on for 6 minutes every 4 hours.

The pump on water loop 2 is powered by AC3 when its switch is in the *ON* position. The *GPC* position of the *WATER PUMP LOOP 2* switch provides an alternate power source for the pump during ascent and entry. When the backup flight system computer has control of the payload MDMs, the *GPC* position powers the loop 2 pump with AC1 power. Since water loop 2 has only one pump, this enables the pump to remain powered even if AC3 should fail. However, the circuit breakers that provide AC1 power to the *GPC* position of H₂O loop 2 and the A pump of H₂O loop 1 are pulled for the entire mission. This is because of the possibility of an AC1-to-AC3 short as a result of a relay failure or switch failure. If power is required for the pump to operate, these circuit breakers will need to be pushed in. The *GPC* position of the *WATER LOOP 1 PUMP* switch has no special function during ascent and entry; it acts just like the *OFF* position.

If the situation arises where no *PASS SM* or *BFS* computers are available, the water loop pumps can still be commanded on in the *GPC* position using real-time commands. The real-time commands can be issued by a ground uplink or crew inputs on *DPS UTILITY SPEC 1*. The real-time commands must be issued through the computer that has control of the payload MDMs. It would take a severe loss of system redundancy for the use of real-time commands to ever be required.

Cooling Management

Depending on the mission phase, the Freon cooling loops are cooled four different ways. Prior to launch, cooling is provided by the ground support equipment. After lift-off, there is no active means of cooling until after solid rocket booster separation. It takes the orbiter slightly more than 2 minutes to reach an altitude where water evaporation provides effective cooling. Until that time, sufficient "thermal inertia" is in the Freon loops to limit the temperature increase so that no active heat rejection is required.

At solid rocket booster separation, the flash evaporator system receives a GPC "ON" command from the BFS and begins providing active cooling. The flash evaporator system continues to be the primary cooling source through the ascent phase and on into the post insertion timeframe. During the Post Insertion checklist procedures, flow is initiated through the radiators, the payload bay doors are opened, and the radiators become the primary source of cooling. The topping flash evaporator system may be left on to provide supplemental cooling when necessary. If the orbiter is in a warm attitude, the radiator panels may not be effective enough to provide the desired cooling. The flash evaporator system can provide the additional cooling necessary to achieve the desired Freon loop temperatures.

During the deorbit prep procedures, the radiators are "cold soaked" for use later during entry. The radiator coldsoak process stores cool Freon in the radiator panels. This is accomplished by changing the radiator control temperature from 38° to 57° F. The flash evaporator system is reactivated to cool the Freon loops from 57° to 39° F. Since less cool Freon from the radiator panels is required to achieve the 57° F RAD OUT temperature, the Freon stays in the radiator panels longer and becomes even cooler. After being in this configuration for a little over an hour, the radiators are bypassed, and the flash

evaporator system begins providing all the cooling. The flash evaporator system provides the cooling during the rest of the deorbit, through entry interface, and on down to $V = 12k$ (approximately 175,000 ft). Additionally, during deorbit prep for RCRS configured vehicles, the crew will replace the LiOH canister, and deactivate the RCRS. The operating cabin fan(s) should be turned off during this procedure.

At $V = 12k$, the radiators are put through their auto startup sequence, and radiator flow is reinitiated. Below 100,000 ft, the atmospheric pressure is too high for the flash evaporator system to cool effectively. Normally, the radiator coldsoak is used as the primary source of cooling from this point through rollout.

Once radiator coldsoak is depleted, the ammonia boilers are used as the primary cooling source until the ground support equipment cooling cart hookup is complete. Then the ammonia cooling is deactivated, and ground support equipment cooling is initiated.

For ascent aborts, the thermal management of the Freon cooling is somewhat different. The flash evaporator system still provides the cooling after solid rocket booster separation. The cooling management during the entry portion changes. The ammonia boilers provide the cooling during the lower stages of the abort entry. The ammonia is used for cooling during the entry phase of an ascent abort because the orbiter lifts off without a radiator coldsoak, and the flash evaporator system functions normally only at low atmospheric pressure (above 100,000 ft).

For a transoceanic abort landing or an abort once around, the ammonia boiler receives a GPC "ON" command from the BFS at MM 304 and 120,000 ft. For a return to launch site abort, the ammonia boiler receives a GPC "ON" command from the BFS at external tank separation (MM 602). The ammonia boiler will provide the cooling from this point through landing. The ammonia boilers can provide cooling for approximately 1 hour.

ECLSS Caution and Warning Summary

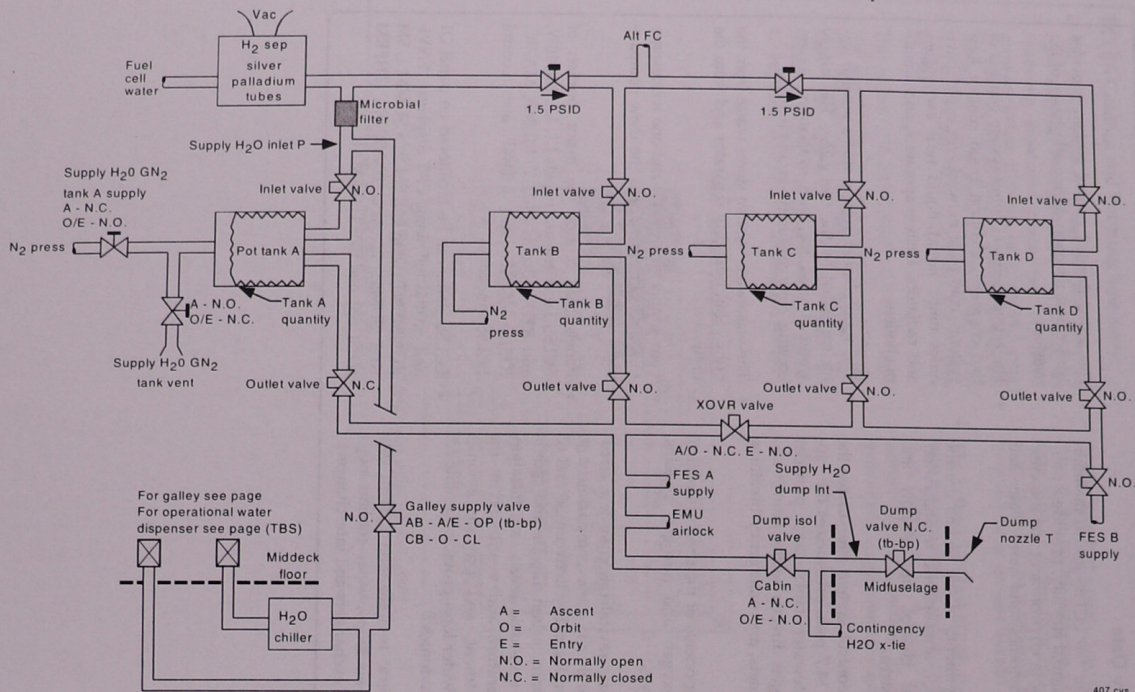
- The red *CABIN ATM* caution and warning light on panel F7 is illuminated for any of the following monitored parameters: (1) cabin pressure below 13.8 psia or above 15.2 psia, (2) PPO₂ below 2.7 psia or above 3.6 psia, (3) oxygen flow rate above 4.9 pounds per hour, and (4) nitrogen flow rate above 4.9 pounds per hour.
- The yellow *AV BAY/CABIN AIR C/W* light will illuminate for the following conditions: any avionics bay temperature higher than 130° F, the heat exchanger out temperature higher than 145° F, or cabin fan delta P below 4.2 inches of water or greater than 6.8 inches.
- The yellow *H₂O LOOP C/W* light will illuminate if the outlet pressure of water coolant loop pump 1 is less than 19.5 psia or greater than 79.5 psia, or if pump 2 pressure is less than 45 psia or greater than 81 psia.
- The yellow *FREON LOOP* light will illuminate if Freon flow in either coolant loop is less than 1200 pph, or if either loop's evap out temperature is less than 32.2° F or greater than 64.8° F (upper limit for ascent is 115° F.)

O ₂ PRESS	H ₂ PRESS	FUEL CELL REAC (R)	FUEL CELL STACK TEMP	FUEL CELL PUMP
CABIN ATM (R)	O ₂ HEATER TEMP	MAIN BUS UNDERVOLT	AC VOLTAGE	AC OVERLOAD
FREON LOOP	AV BAY/CABIN ATM	IMU	FWD RCS (R)	RCS JET
E ₂ O DOP	RGA/ACCEL	AIR DATA	LEFT RCS (R)	RIGHT RCS (R)
	LEFT RHC (R)	RIGHT/AFT RHC (R)	LEFT OMS (R)	RIGHT OMS (R)
PAYLOAD WARNING (R)	GPC	FCS SATURATION (R)	OMS KIT	OMS TVC (R)
PAYLOAD CAUTION	PRIMARY C/W	FCS CHANNEL	MPS (R)	
BACKUP C/W ALARM (R)	APU TEMP	APU OVERSPEED	APU UNDERSPEED	HYD PRESS

ECLSS Caution and Warning :Lights on Panel F7

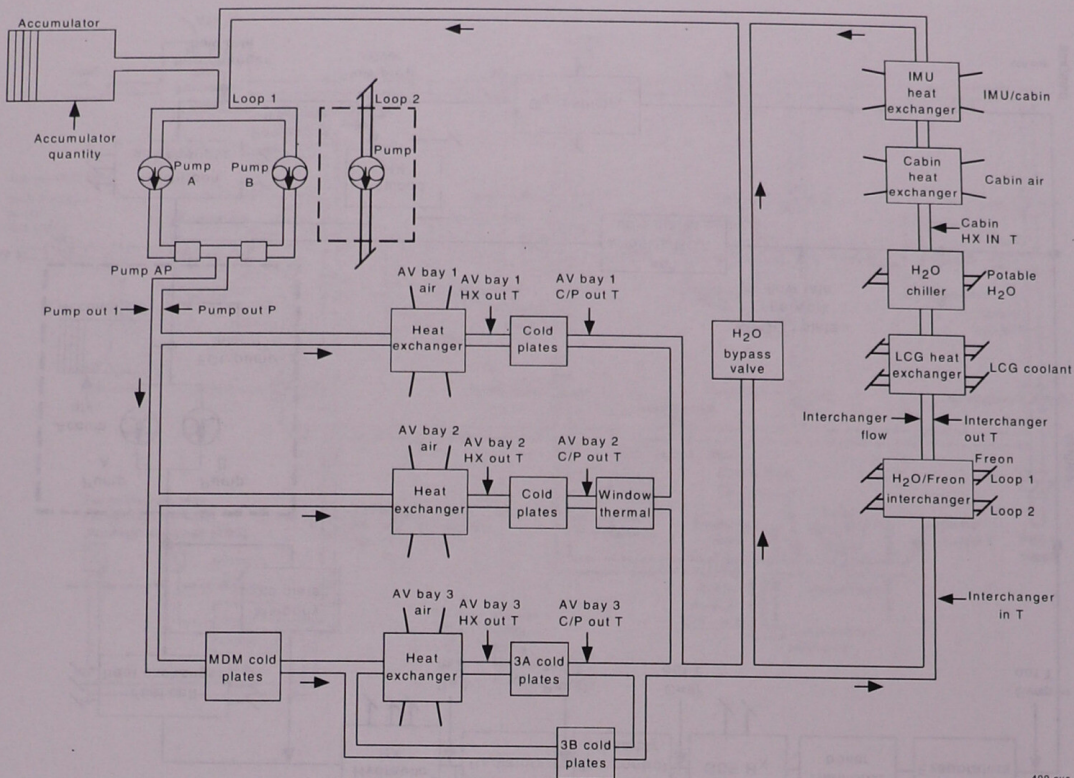
ECLSS Summary Data

- The functions of the ECLSS are to maintain the orbiter's thermal stability, provide a pressurized, habitable environment for the crew and onboard avionics, and store water and liquid waste.
- The four components of the ECLSS are the pressure control, atmospheric revitalization, active thermal control, and supply and wastewater systems.
- The pressure control system pressurizes the crew cabin at 14.7 psia, pressurizes the supply and wastewater tanks, and provides breathing oxygen directly to the launch and entry suit helmets, and emergency breathing masks.
- The main components of the pressure control system are oxygen and nitrogen systems, tanks, and valves.
- The atmospheric revitalization system circulates air through the crew compartment to control relative humidity between 30 and 65 percent, maintain carbon dioxide and carbon monoxide at non-toxic levels, air filtration, control temperature and ventilation in the crew compartment, and provide avionics cooling. The water loop provides cooling for the crew and avionics.
- The atmospheric revitalization system consists of cabin air loops, water coolant loops, fans, and heat exchangers and interchangers.
- The active thermal control system provides orbiter heat rejection during all phases of the mission.
- The active thermal control system consists of two complete, identical Freon coolant loop systems, cold plate networks for cooling avionics units, liquid/liquid heat exchangers, and radiators, flash evaporators, and ammonia boilers.
- The supply water system stores potable water generated by the fuel cells. The supply water is used for flash evaporator system cooling, crew consumption, and hygiene.
- The wastewater system stores waste from the crew cabin humidity separator and from the crew.
- Four supply water tanks and one wastewater tank are located beneath the crew compartment middeck floor.
- Panels that control the major portion of ECLSS functions are panels L1, L2, MO10W, and R11L. Panels ML31C, ML86B, MA73C, R13L, MO51F, and MD44F also control ECLSS functions.
- ECLSS status can be monitored on panel O1 and on the following CRT displays: ENVIRONMENT (DISP 66), SM SYS SUMM 1, SM SYS SUMM 2, APU/ENVIRON THERM (DISP 88), and BFS THERMAL.



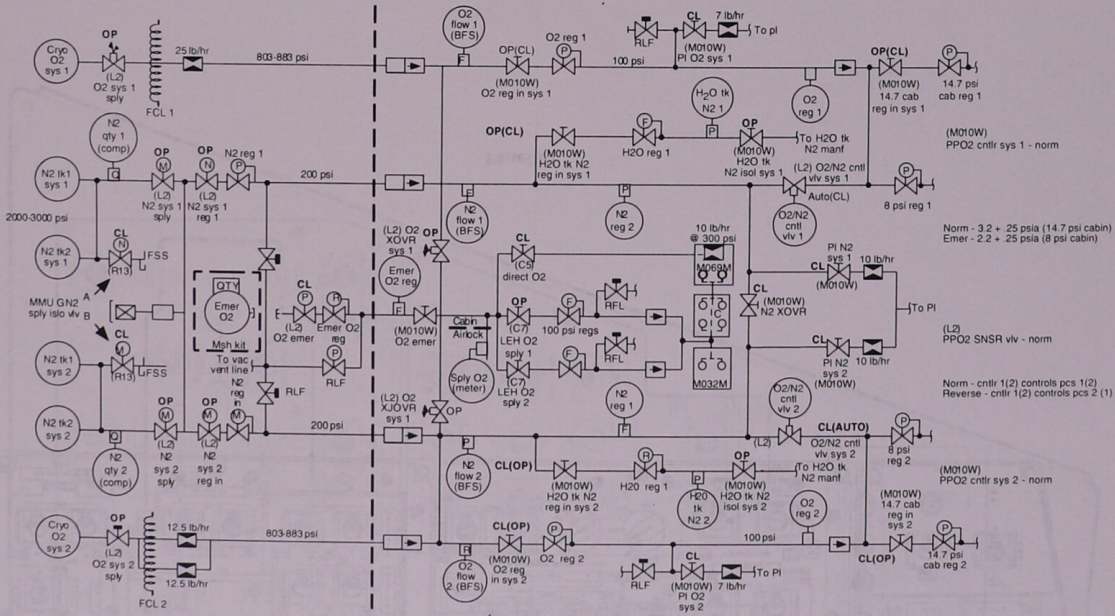
407 cvs

Supply Water Storage System



Water Loops

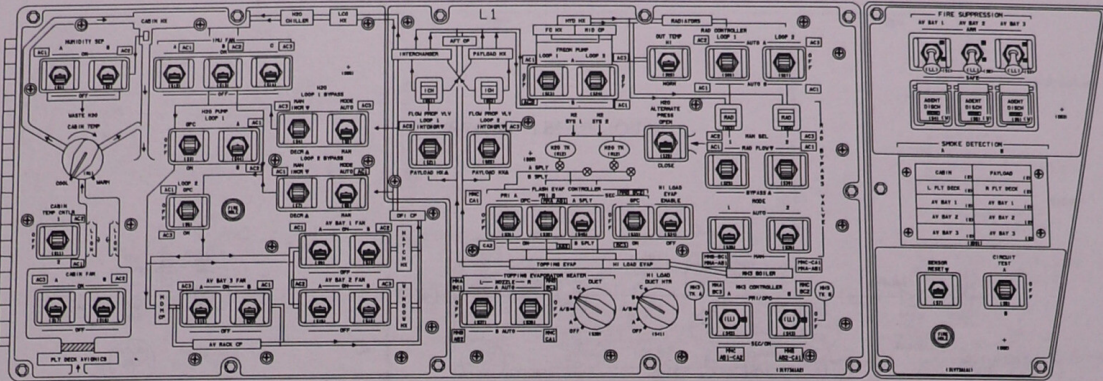
409.cvs



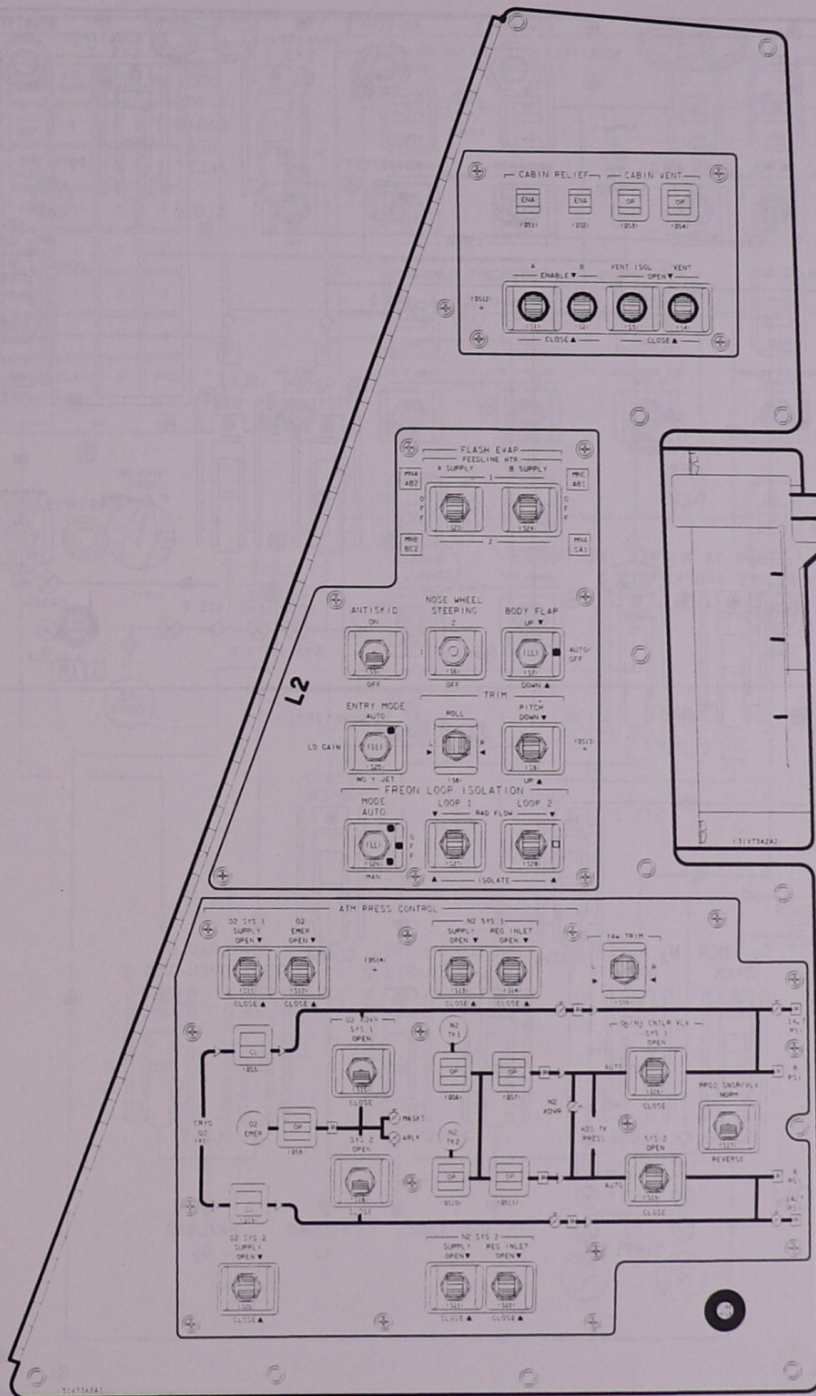
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Pressure Control System (Orbit)

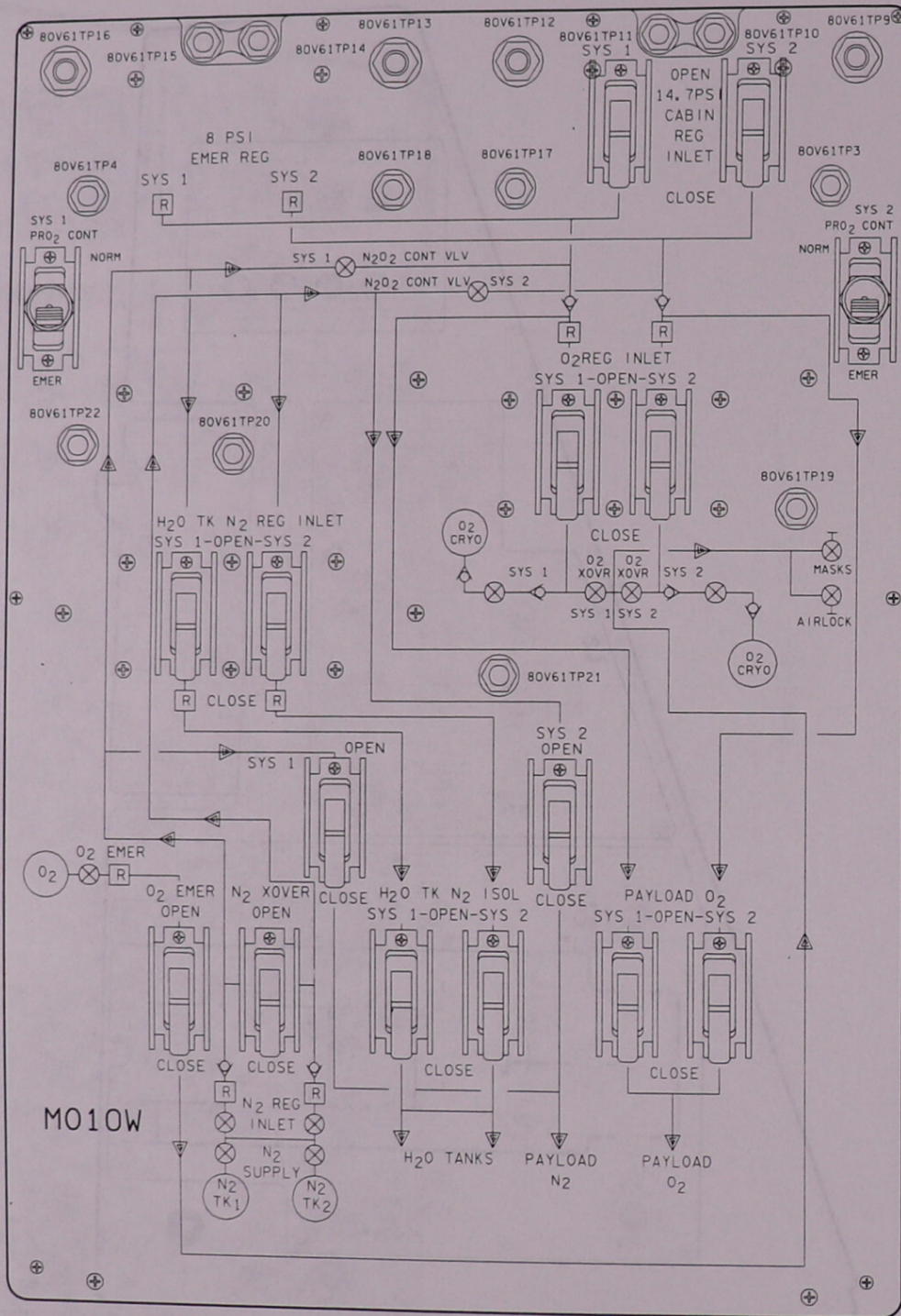
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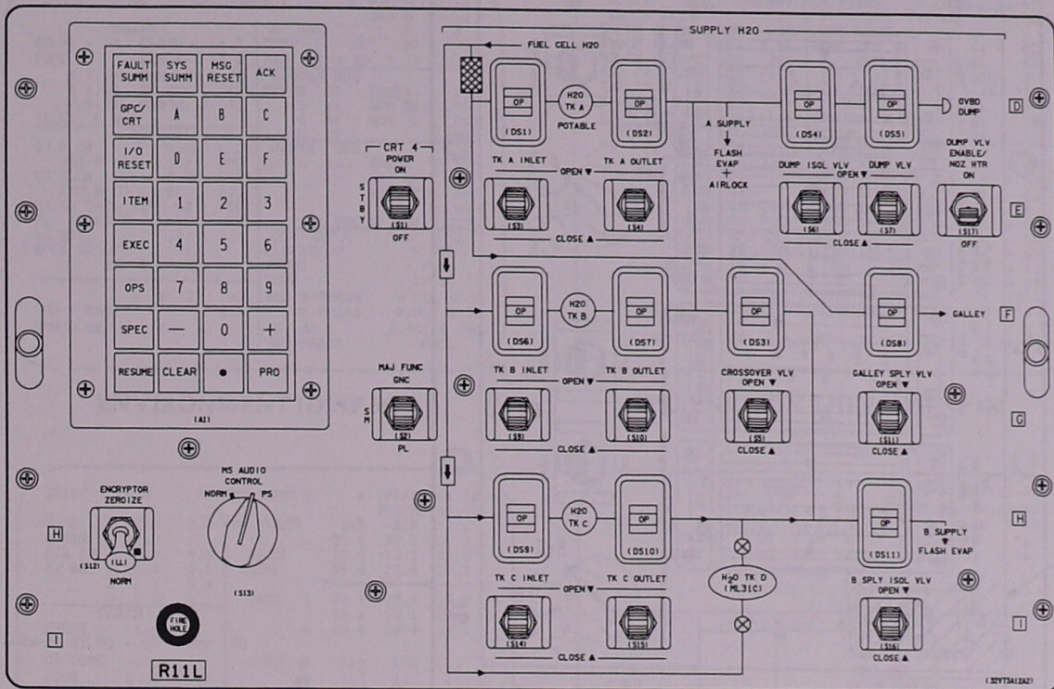
Panel L1



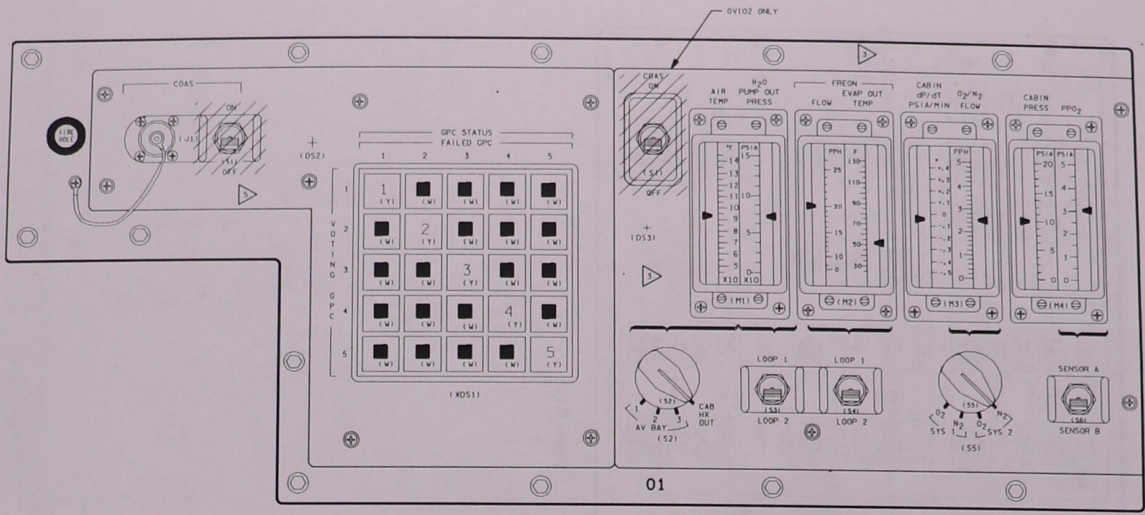
Panel L2



Panel MO10W



Panel R11L



Panel O1

2011/ /066 ENVIRONMENT				4 000/02:33:38			
				000/00:00:00			
CABIN				AV BAY			
dP/dT +.01	CABIN P	14.7		1	2	3	
PPO2	AIRLK P	14.8		90	90	78	
	AIRLK P	14.8		FAN ΔP	3.80	3.77	3.92
A 3.04	FAN ΔP	5.55		SUPPLY H2O			
B 3.04	HX OUT T	45L		QTY A	67	PRESS	32
C 3.04	CABIN T	71		B 18	DMP LN T	77	
PPO2 1.9				C 94	NOZ T A	64	
				D 94	B T A	64	
O2 FLOW	0.0L	0.0L		WASTE H2O			
REG P	100	100		QTY 1	15	PRESS	17
N2 FLOW	0.0L	0.0L				DMP LN T	58
REG P	202	202				NOZ T A	82
O2/N2 CNTL VLV	N2	O2				B	82
H2O TK N2 P	17	17		VAC VT NOZ T 224			
N2 QTY	131	131		CO2 CNTLR			
EMER O2	QTY	1				1	2
	REG P	4L		FILTER P			
						0.00L	
				PPO2			
						-0.0L	
				TEMP			
						32.0L	
				BED A PRESS			
						0.0L	0.0L
				B PRESS			
						0.0L	0.0L
				ΔP			
						0.00L	0.00L
				VAC PRESS			
						0.0L	

093

ENVIRONMENT (DISP 66)

2011/ /088 APU/ENVIRON THERM				4 000/02:36:51			
				000/00:00:00			
FREON LOOP				H2O LOOP			
ACCUM QTY	27	27		1	2		
FREON FLOW	2193	2190		PUMP OUT P			
PL HX FLOW	290	286				64	62
AFT CF FLOW	279	278		OUT T			
RAD IN T	97	96		ICH FLOW			
RAD OUT T	38	38		OUT T			
EVAP OUT T	38	38		CAB HX IN T			
EVAP TEMP	DUCT	NOZ		ACCUM QTY			
						45	55
HI LOAD INBD	259			APU FUEL T			
OUTBD	259	312				1	2
TOPPING FWD	257			TK SURF			
AFT	257					+69	+68
L 162	50			TK HTR			
R 162	50					+70	+68
EVAP FDLN T	A	B		TEST LN 1			
FWD	80	80				+62	+62
MID 1	80	80		TEST LN 2			
MID 2	79	75				+62	+63
AFT	75	79		FEED LN			
TOPPING	75	79				+57	+58
ACCUM	75	79		PUMP IN			
HI LOAD	75	79				+57	+58
				DRN LN 1			
						+62	+62
				DRN LN 2			
						+62	+62
				OUT			
						+92	+90
				BYP LN			
						+108	+102
				GG SPLY LN			
						113	111
				H2O LN INJ			
						+71	+72

078

APU/ENVIRON THERM (DISP 88)

2011/ /078 SM SYS SUMM 1				4 000/14:44:12			
				000/00:00:00			
SMOKE				DC VOLTS			
1/A	2/B			1/A	2/B	3/C	
CABIN	0.0			FC	30.6	30.1	31.0
L/R FD	0.0	0.0		MAIN	30.6	30.1	31.0
AV BAY 1	0.3	0.3		ESS	29.6	29.6	29.3
2	0.3	0.4		CNTL			
3	0.3	0.3		A	29.4	29.4	29.6
				B	29.4	29.4	29.4
				C	29.4	29.4	29.4
				A			
				B			
				C			
				A			
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ECLSS Rules of Thumb**NOTE**

Numbers presented here are for typical orbit power and heat loads and may vary significantly, depending on attitude and power loading.

- Supply water tanks fill at about 1.5 percent per hour depending on fuel cell load (.8 lb/kW hr ÷ 16 lb over 1%; 14 kW typical orbit power load).
- Water tanks empty at about 100 percent per hour for a water dump, about 50 percent per hour when using the FES high load evaporator for cooling with payload bay doors closed, and about 16 percent per hour when using the FES topping evaporator for supply water dumps on orbit with the doors open.
- On-orbit cold soak is good for 20 to 30 minutes of cooling. Prelaunch Freon conditioning is good for 2 to 3 minutes of cooling.
- NH₃ boiler supply is good for 25 minutes of ground cooling.
- A single cryo O₂ tank is good for about 2 to 3 days of orbit usage depending on crew size and power level. H₂ tanks are sized to match O₂ usage.
- A single LiOH canister is usable for about 48 man-hours.

2.10 ESCAPE SYSTEMS

CONTENTS

Description	2.10-1
Launch Pad Egress Systems	2.10-1
Launch and Entry Suits	2.10-4
Personal Parachute Assembly	2.10-8
Crew Escape System Pyrotechnics	2.10-11
Egress Pole System	2.10-12
Emergency Egress Slide	2.10-12
Secondary Emergency Egress	2.10-16
Procedures for Bailout, Water Survival, and Rescue	2.10-17
Escape Systems Summary Data	2.10-18

Description

Escape systems refer to equipment and systems intended to facilitate emergency and contingency egress of the flight crew. Escape systems include equipment worn by the crewmembers, hardware built into the orbiter, and external systems located on the launch pad. Types of escape or emergency egress from the orbiter depend upon the mission phase (basically prelaunch, in-flight, and post-landing). The prelaunch phase implies the crew must perform an emergency egress while the orbiter is still positioned on the launch pad.

The in-flight phase requires that the crew can safely bail out of the orbiter during controlled gliding flight at altitudes of 30,000 feet and below. A special in-flight crew escape system is devised for this phase. It includes pressure suits, oxygen bottles, parachutes, life rafts, pyrotechnics to vent the cabin and jettison the orbiter side hatch, and an escape pole to allow the crewmembers to clear the vehicle. The most likely uses of the system would be during a return-to-launch-site (RTL) abort, transatlantic abort landing (TAL), or abort once-around (AOA) when the orbiter has insufficient energy to achieve a runway landing or after an emergency deorbit made regardless of landing site opportunities.

During the post-landing phase, the crew exits the orbiter following an emergency landing or landing at a contingency site. The orbiter will

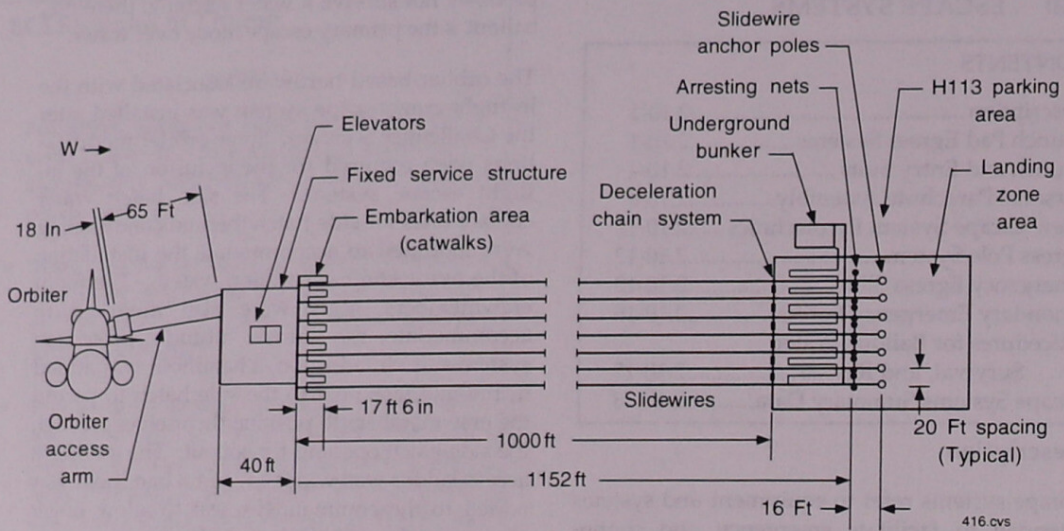
probably not survive a water ditching; therefore, bailout is the primary escape mode over water.

The orbiter-based hardware associated with the in-flight crew escape system was installed after the Challenger accident. Some orbiter modifications were required for the inclusion of the in-flight escape system. The side hatch water coolant lines for side hatch thermal conditioning were modified to accommodate the installation of the pyrotechnic separation system. The flight crewmembers' seats were also modified to accommodate the crew's altitude protection system suit. In addition, a handhold was added in the middeck next to the side hatch to permit the crewmembers to position themselves through the side hatch opening for bailout. The interdeck access ladder was widened, and a handhold was added to the commander's seat to allow easier movement through the interdeck access.

Software adjustments were also required to accommodate the in-flight escape system. Software changes applied to the primary avionics software system for OPS 3 and 6. The changes enable an automatic flight control mode of the orbiter with input by crewmembers by using the ATO abort position on the abort rotary switch in MM 603/305. The automatic mode stabilizes the orbiter by controlling the velocity and angle of attack to the desired bailout conditions, thus allowing the commander to escape.

Launch Pad Egress Systems

In the event of a potential catastrophe on the launch pad, escape by the flight crew is facilitated by descending to a safe area via slidewire baskets. The emergency egress/escape system uses seven separate slidewires and seven multi-person basket assemblies to effect rapid escape of personnel from the 195-foot level of the fixed service structure to a landing zone. The landing zone is approximately 1,200 feet west of the fixed service structure. The flight crew leaves the slidewire baskets and proceeds to the bunker, which is provided with breathing air, first aid supplies, and communications equipment. The flight crew will only leave the bunker upon instructions by the NASA Test Director.



Launch Pad Emergency Egress System

An M-113 is positioned near the slidewire termination area. The M-113 is a military personnel carrier designed to provide protected evacuation from the launch pad area.

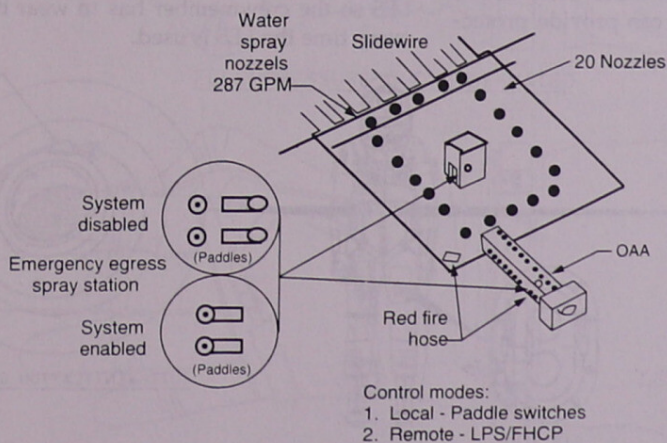
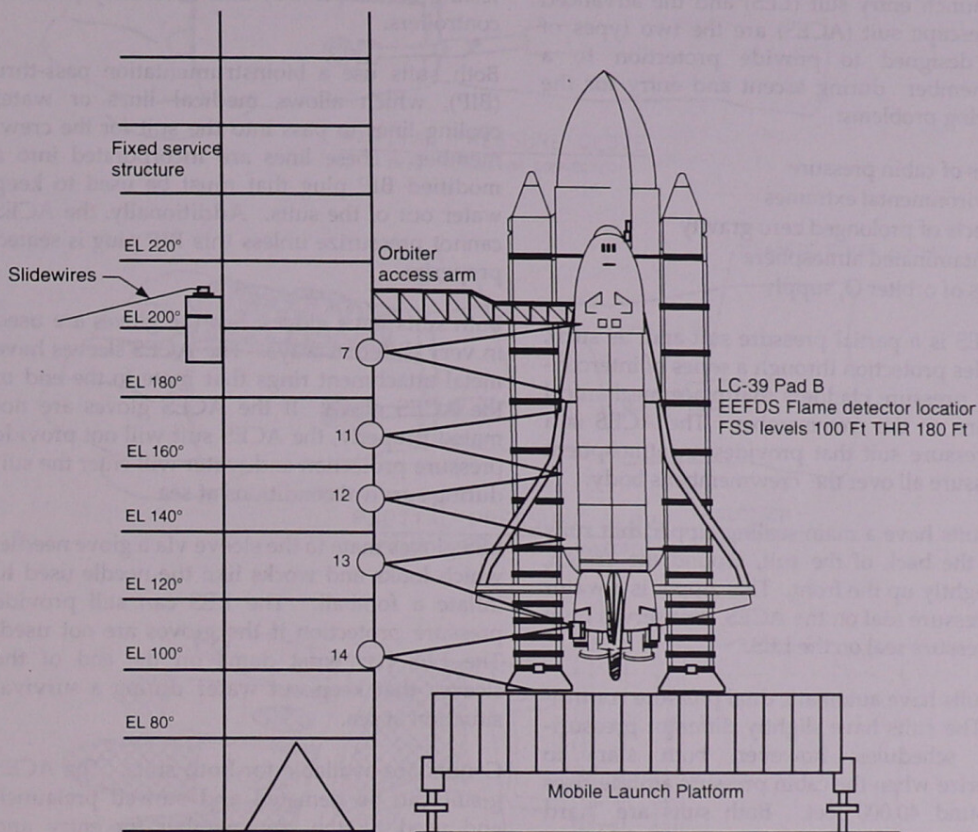
There are four modes of escape from the launch pad area, varying in degrees of egress aid to the crew by the closeout crew or pad fire/rescue crew. In the case of an aided escape, support crews are responsible for opening the side hatch using an emergency hatch opening tool.

The launch pad structure also includes an escape temperature and hydrogen fire-hazard monitoring system, consisting of 10 temperature sensors and 14 ultraviolet (UV) hydrogen fire detectors. Nine UV fire detectors are located in the area of the environmental chamber, the truss, and the fixed service structure both above and below the fire barrier. Five UV fire detectors are also spaced vertically down the fixed service structure from the 175-foot level to the 95-foot level to view a profile of the orbiter.

The 10 temperature sensors are located along the egress path, from the environmental chamber to the slidewire basket embarkation area. The sensors are placed both above and below the fire barrier. The signals from these sensors are displayed on firing room console C-7 in the launch control center.

The Firex spray system provides a water shower to the orbiter access arm and the fixed service structure in the event of a fire. There are 20 water spray nozzles located on the orbiter access arm, approximately 4 feet above the walkway, and 20 on the fixed service structure, 7 to 10 feet overhead. Each nozzle emits 287 gallons of water per minute. Two control modes, local and remote, operate the Firex spray system. The local mode consists of paddle switches located either outside the white room on the orbiter access arm or on the east side of the elevators directly facing the orbiter access arm. The remote mode is a hard-wire backup control panel located in the launch control center.

FLAME DETECTION (EEFDS)



Emergency Egress Water Spray Control Panels

Launch and Entry Suits

The launch entry suit (LES) and the advanced crew escape suit (ACES) are the two types of suits designed to provide protection to a crewmember during ascent and entry for the following problems:

- Loss of cabin pressure
- Environmental extremes
- Effects of prolonged zero gravity
- Contaminated atmosphere
- Loss of orbiter O₂ supply

The LES is a partial pressure suit and, as such, provides protection through a series of interconnected pressure bladders that place mechanical pressure on the crewmember. The ACES is a full pressure suit that provides an atmosphere of pressure all over the crewmember's body.

Both suits have a main sealing zipper that runs down the back of the suit, around the crotch, and slightly up the front. This zipper is a water and pressure seal on the ACES, but serves only as a pressure seal on the LES.

Both suits have automatic dual pressure controllers. The suits have slightly different pressurization schedules; however, both start to pressurize when the cabin pressure altitude rises to around 40,000 feet. Both suits are "hard pressed" above 60,000 feet. The ACES can provide pressure protection indefinitely above 100,000 feet, while the LES can provide protec-

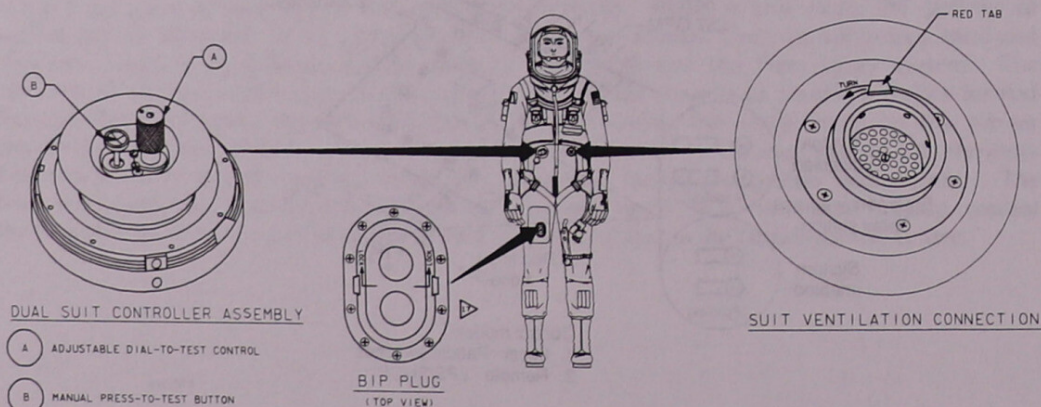
tion above 100,000 feet for 30 minutes. The suits have manual controls that are used for ground testing of the primary and secondary pressure controllers.

Both suits use a bioinstrumentation pass-thru (BIP), which allows medical lines or water cooling lines to pass into the suit for the crewmember. These lines are incorporated into a modified BIP plug that must be used to keep water out of the suits. Additionally, the ACES cannot pressurize unless this BIP plug is seated properly.

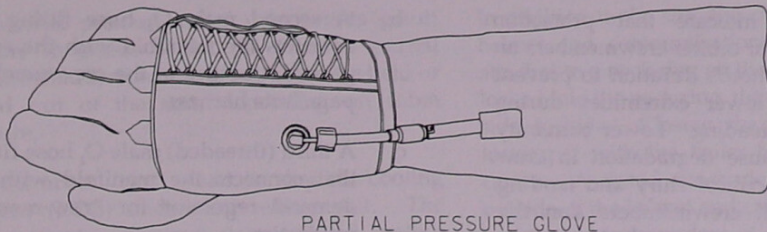
Both suits have gloves, but the gloves are used in very different ways. The ACES sleeves have metal attachment rings that mate to the end of the ACES glove. If the ACES gloves are not mated properly, the ACES suit will not provide pressure protection and water will enter the suit during survival conditions at sea.

LES gloves mate to the sleeve via a glove needle, which looks and works like the needle used to inflate a football. The LES can still provide pressure protection if the gloves are not used. The LES has wrist dams on the end of the sleeves that keep out water during a survival situation at sea.

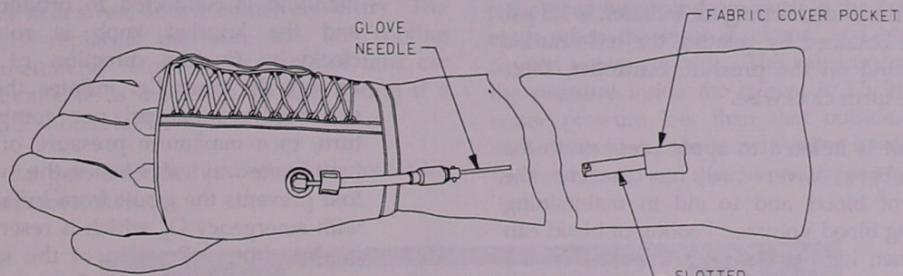
G-suits are available for both suits. The ACES g-suit can be demated and stowed prelaunch and used by the crewmember for entry and landing. The LES g-suit is integrated into the LES so the crewmember has to wear this g-suit every time the LES is used.



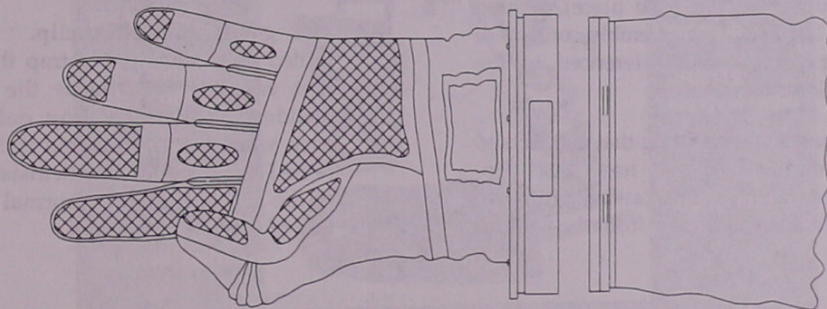
Bioinstrumentation Pass-Thru (BIP)



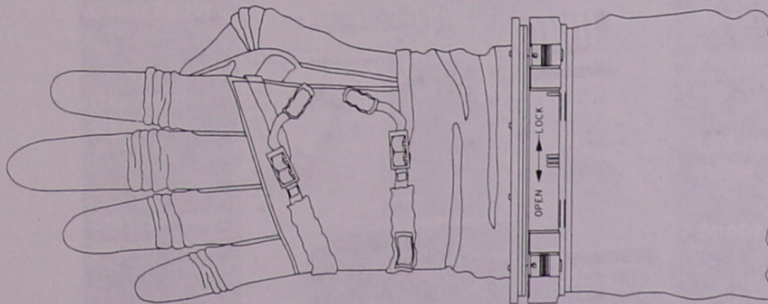
PARTIAL PRESSURE GLOVE
TWIST CONNECTOR CONNECTED



PARTIAL PRESSURE GLOVE
TWIST CONNECTOR DISCONNECTED



FULL PRESSURE GLOVE-DE-MATED



FULL PRESSURE GLOVE-MATED

Launch and Entry Suit Gloves

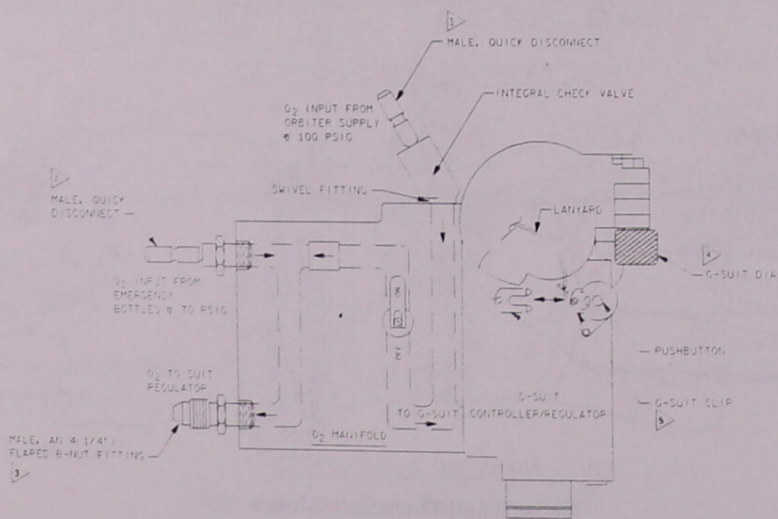
Physiological data indicate that protection should be provided for orbiter crewmembers on flights exceeding 12 hours duration to prevent fluid shifts to the lower extremities during exposure to entry g-loading. Lower extremity fluid shifts could cause degradation in crew performance during critical entry and landing mission phases. All crewmembers don the LES/ACES before entry, and, if needed, inflate the g-suit, sometimes referred to as an anti-g suit, prior to reaching a 400,000-foot altitude. The recommended setting for inflation is 1.5 psi, which is obtained by rotating the red knurled knob, found on the pressure controller, three complete turns clockwise.

The g-suit is inflated to apply pressure to the crewmember's lower body to prevent the pooling of blood and to aid in maintaining circulating blood volume. Pooling of blood can occur when high g-loads are imposed on the body and is particularly noticeable after the crewmember has had 3 days or more of zero-g.

Inflation of the g-suit is controlled at the O₂ manifold/g-suit controller (one piece), located on the upper left leg. This assembly consists of the following components, referenced to the illustration below:

- a. A male O₂ hose fitting that connects to the orbiter O₂ supply hose. It is provided with a breakaway fitting to facilitate rapid egress from the vehicle.

- b. A second male O₂ hose fitting that connects the manifold with the emergency O₂ bottles in the crewmember's parachute harness.
- c. A third (threaded) male O₂ hose fitting that connects the manifold with the demand regulator for crew-member respiration.
- d. **The g-suit controller.** When the manifold is connected to orbiter O₂, and the knurled knob is rotated clockwise (in the direction of the arrow), the controller inflates the g-suit bladders 0.5 psi per complete turn, to a maximum pressure of 2.5 psi. A one-way valve inside the manifold prevents the g-suit from inflating with emergency O₂, which is reserved for breathing. Rotation of the knob counterclockwise will deflate the g-suit bladders 0.5 psi per complete turn. Each complete revolution of the knob is indicated by a slight detent.
- e. **The g-suit controller clip.** When pulled free, the clip will trap the current volume of O₂ inside the g-suit bladders and prevent any deflation, even when the O₂ manifold is disconnected from orbiter O₂. Reinstallation of the clip will allow a normal deflation of the g-suit bladders.



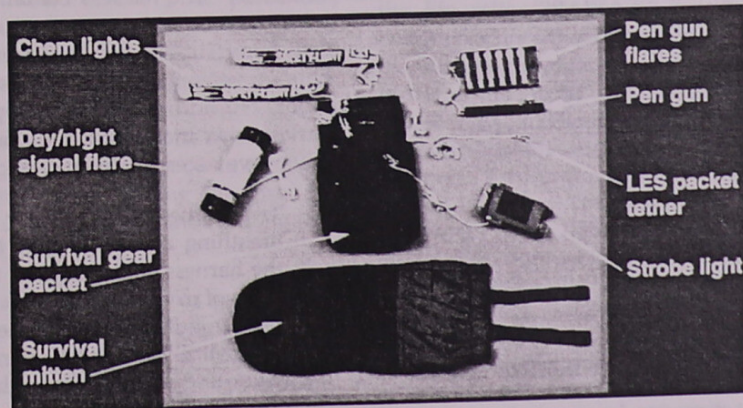
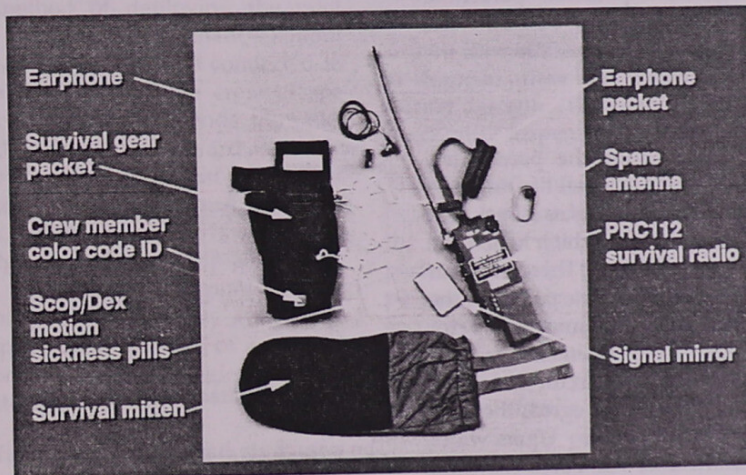
O₂ Manifold/G-Suit Controller

An internal pressure relief valve vents g-suit pressure in excess of 3.2 psi into the partial pressure bladders, where it will either be held or vented out of the suit, depending on cabin pressure.

Crewmembers can wear a liquid cooling garment (LCG) underneath either suit. The LCG mates to a thermal electric liquid cooling unit (TELCU) mounted on the crewmember's seat. The LCG and the TELCU combine to reduce heat stress during launch and entry. The TELCU replaced the suit fan for cooling crewmembers. However, spare suit fans are still available as a backup cooling option if a TELCU should fail before launch.

Survival gear is located in both of the lower leg pockets for either suit.

In addition to the suit, the crewmember wears a helmet and communications cap. The helmet attaches to a neck ring on the pressure suit. Once locked into the neck ring, the helmet swivels from side to side. Closing the pressure visor and locking it with the bailer bar seals the helmet cavity. A tinted sunshade is mounted to the outside of the helmet and can be manually raised or lowered independent of the clear visor. The helmet also contains an antisuffocation valve, located at the lower right rear of the helmet. It permits ambient air from outside the helmet to enter when the visor is closed, and breathing oxygen is not available. The valve opens when the pressure inside the helmet is 1.5 inches of water pressure less than that outside, which occurs whenever the crewmember inhales with the visor closed and there is no oxygen supply.



Survival Gear

The communications cap contains all necessary equipment for voice communication. The microphones and earphones are included in the cap. The communications cap has dual/redundant microphones and one set of dual/redundant earphones. There is a pigtail on the back of the cap that attaches to the inside of the helmet via a connector. From there, the cable passes through the helmet and connects to a standard headset interface unit, which in turn connects to the orbiter communications system via a cable. There are dual/redundant microswitches in the helmet that deactivate the microphones in the communications cap during oxygen flow to the helmet (inhalation, open visor, or leaking neck seal).

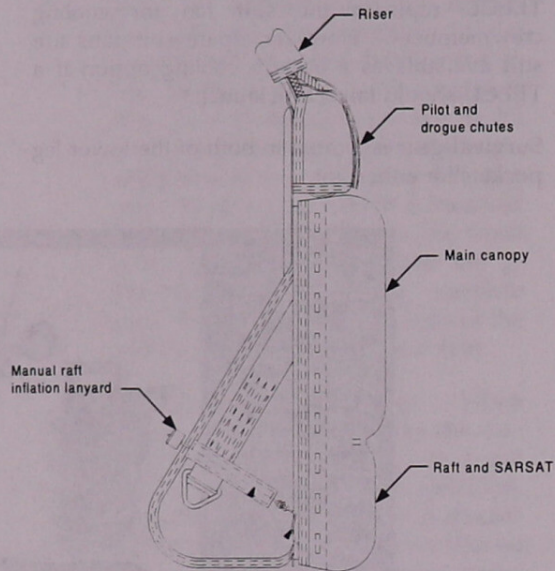
Personal Parachute Assembly

Crewmembers wear the personal parachute assembly (PPA) in the event of bailout. The PPA is designed to work automatically with the crew egress pole system or with manual backups as needed.

The parachute pack contains the parachutes, risers and associated items, a small life raft, and a radio beacon. The pack doubles as a back seat cushion and is already in the orbiter when the crew ingresses prior to launch. There are four connections between the parachute pack and the harness; two riser attach fittings and two ejector snaps. During a bailout, the crewmember needs only to rotate the lap belt connector to release the shoulder harness/lap belt to egress the seat, taking the parachute with him. Upon water landing, two standard U.S. Air Force seawater activated release system (SEAWARS) units, one for each riser, are used to release the risers and canopy from the harness. For a ground egress, the crewmember releases the four parachute attach points and leaves the parachute pack in the seat. The parachute pack contains the following items:

- Automatic and manual pilot chute deployment system
- Drogue chute release knob
- An 18-inch-diameter pilot chute
- A 4.5-foot-diameter drogue chute

- A 26-foot-diameter main canopy
- Deployment sleeve
- Automatic actuation device (AAD)
- Life raft compartment
- Life raft
- SARSAT personnel locator beacon



Parachute Pack (Side)

The parachute harness is a modified U.S. Navy MA-2 harness. The harness contains an interwoven system of nylon straps, providing complete body support for crewmembers during bailout, emergency egress, and rescue operations. In addition to the support straps, the harness also includes the following items that may prove necessary in an emergency:

1. Two bottles of oxygen for emergency breathing are woven into the back of the harness, and contain a total of 401 liters of oxygen at 14.7 psi. At 38 liters per minute of moderate use, the oxygen will last for 10 minutes at sea level and several times that at high altitudes.

2. A carabiner, attached to the left side of the harness, is an oval aluminum ring for attaching descent devices. The carabiner is used during emergency egress and rescue from the orbiter when it is on the ground.
3. A life preserver unit (LPU) encircles the crewmember's upper torso. It inflates automatically via a CO₂ cartridge when submersed in water. It may also be inflated manually. The unit is designed to keep an unconscious crewmember's head out of the water.
4. Sixteen individual packages contain two liters of emergency drinking water.

The primary method of deploying the pilot chute is by using the automatic bailout sequence. The extraction bridle is connected to a bailout lanyard located on the crew escape pole. As the crewmember descends the pole, the loads placed on the bridle/lanyard assembly activate two pyrotechnic systems. The first system separates the bridle/lanyard from the parachute pack, while the second system cuts the cord holding the pilot chute flap closed. As the flap opens, the spring-loaded pilot chute is allowed to deploy. The secondary system for deploying the pilot chute consists of a manual parachute ripcord handle and a single light duty pyrotechnic cutter.

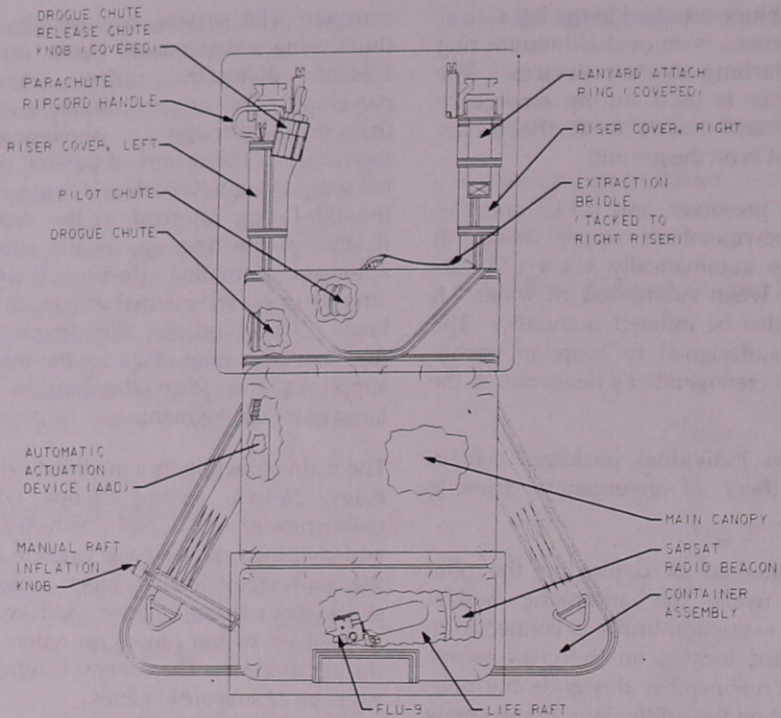
The function of the pilot parachute is to deploy the drogue parachute. The pilot parachute, located in the upper section of the pack, is a spring-loaded, internally vaned, flat circular parachute. Upon activation either through the automatic sequence or manual function, the pilot parachute is released from its closure. The pilot parachute then moves into clean air away from the crewmember providing the force for deploying the drogue chute and arming the automatic actuation device.

The drogue parachute functions as a stabilizing device to orient the crewmember in a preferred attitude in order to reduce injury during freefall, and reduce parachute opening deployment

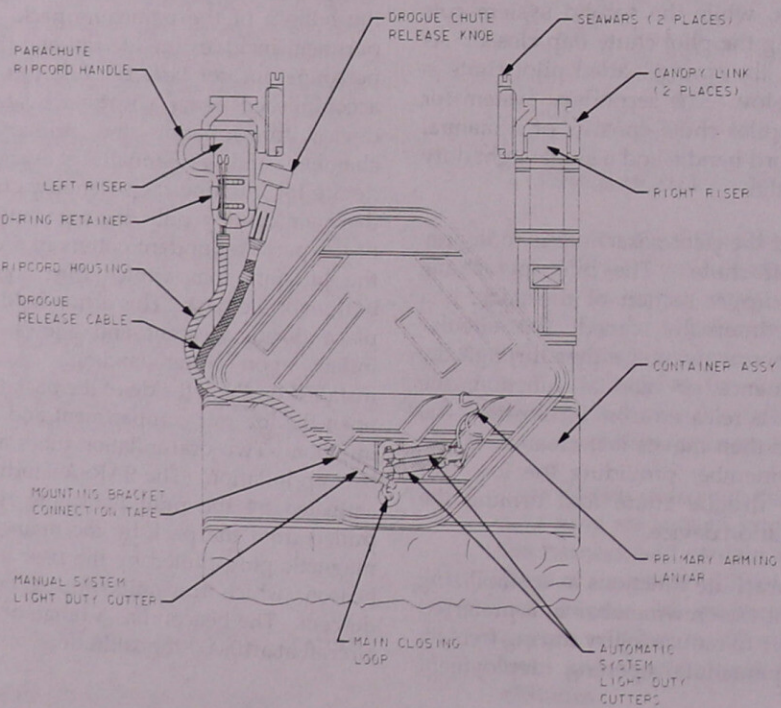
damage. The system, deployed by the pilot chute using a deployment sleeve, consists of a 4.5-foot diameter, ribless, guide-surface parachute. The drogue parachute connects to the pack through a three-ring release mechanism. The release of the first ring allows the second ring to unlock, which in turn unlocks the third ring attached to the drogue riser. Release of the first ring occurs either by the automatic actuation device at 14,000 feet altitude or by the manual drogue chute release knob. Upon release, the drogue parachute functions as a pilot chute for the main canopy, supplying the force through an extraction lanyard for deployment.

The main parachute is a modified version of the Navy, 26-foot, conical canopy with Kevlar reinforcement. A discard line reefing system is added to increase the basic strength and reduce the load to the crewmember during opening shock. Four anti-oscillation windows are added at the base of the canopy to reduce oscillation during descent. The canopy is attached to the risers by 22 suspension lines.

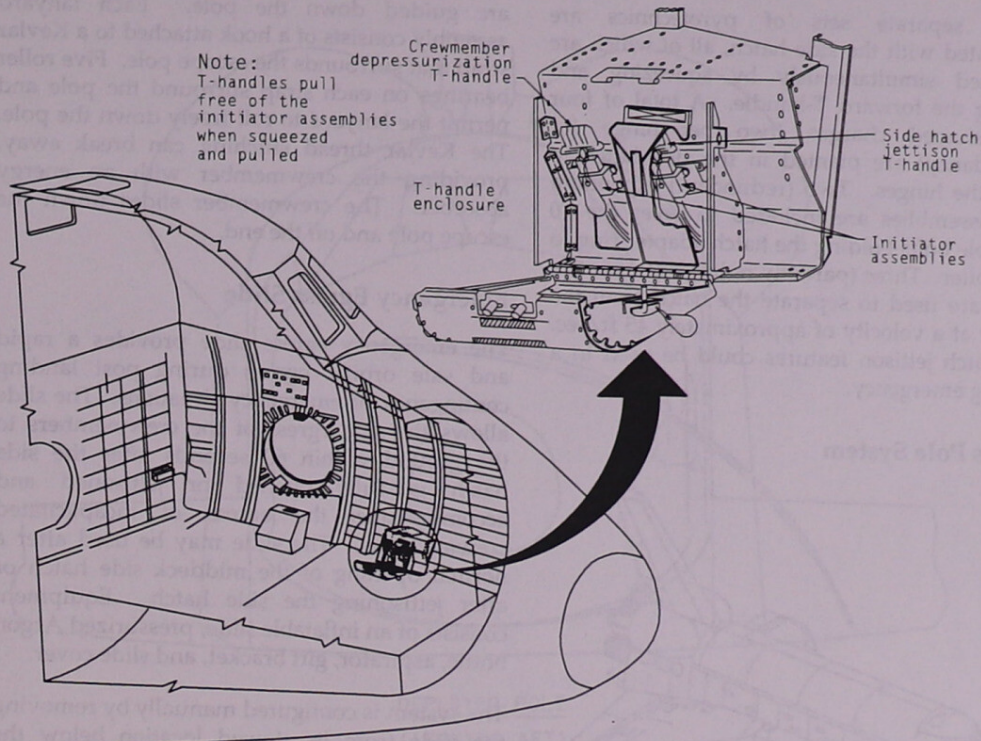
The life raft, made of polyurethane coated nylon, is contained in a separate compartment at the bottom of the parachute pack. This compartment includes the life raft and the SARSAT personnel locator beacon. Life raft inflation is accomplished using a water-activated inflation device for inflating the primary life raft chamber, and a manually activated inflation device for inflating the secondary chamber. As the main canopy pulls the parachute risers out of the pack, redundant cutters in the bottom of the life raft compartment fire, loosening the bottom of the pack. This action holds the raft in place during descent and allows the raft to inflate upon water landing. A lanyard is installed on the left side of the pack to manually open the life raft compartment and for manual inflation. Two oral inflation tubes are used for backup inflation. The SARSAT radio beacon is activated by the right parachute riser as it is pulled from the pack by the main canopy. A magnetic plug pulled by the riser activates the beacon, which transmits during crewmember descent. The beacon has a range of 60 miles to aircraft at a 10,000-foot altitude.



Parachute Pack (Back)



Parachute Pack (Back)



Emergency Crew Module Depressurization and Side Hatch Jettison T-Handles

Each crewmember is also armed with additional signalling devices, including a PRC-112 survival radio, a strobe light, a pen-gun flare kit, a hand-held flare, a signal mirror, two 12-hour stick chem-lights, and two packs of sea dye marker. Other survival gear includes drinking water, a knife, and motion-sickness pills.

Crew Escape System Pyrotechnics

The hardware associated with in-flight crew escape consists of several types of pyrotechnics plus the egress pole. The crew escape system pyrotechnics consist of a box with T-handle initiators, a pyro vent valve, and hatch pyrotechnics.

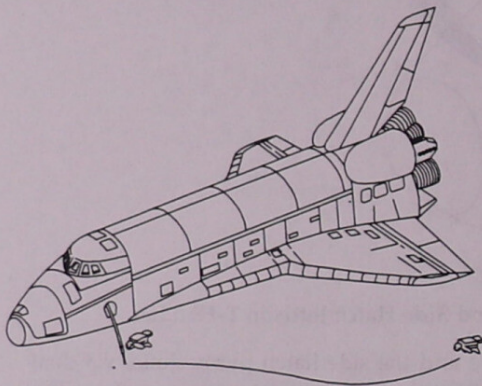
The T-handle box, containing two T-handles, is located on the port forward middeck floor. The aft T-handle activates the pyro vent valve to depressurize the cabin. The forward T-handle jettisons the side hatch. Both T-handles have safing pins through them that must be removed before the handles can be squeezed and pulled. The handles are connected to the pyro vent

valve and the side hatch pyrotechnics via dual lengths of shielded detonating cord. The handles, pyrotechnics, and detonating cord do not require orbiter power.

The pyro vent valve is located behind the waste management compartment, on the port side of the aft bulkhead of the middeck. The purpose of the valve is to depressurize the cabin at a controlled rate prior to jettisoning the side hatch in flight. This is necessary to prevent severe buckling of the middeck floor, which would occur if the side hatch were jettisoned without any attempt to equalize the inside and outside pressure. When activated by squeezing and pulling the aft T-handle, the pyro vent valve opens a 15-square-inch hole between the crew compartment and the payload bay. If it is opened at an altitude of 40,000 feet, approximately 75 seconds are required to lower the pressure in the cabin to that of the ambient air outside the orbiter. Equalization would occur at approximately 31,000 feet. The cabin vent pyros are an ignition source in the payload bay and should not be used for post landing egress.

Three separate sets of pyrotechnics are associated with the side hatch, all of which are activated simultaneously by squeezing and pulling the forward T-handle. A total of four linear-shaped charges (two per hinge for redundancy) are planted in the side hatch to sever the hinges. Two (redundant) expanding tube assemblies are included to sever the 70 frangible bolts holding the hatch adapter ring to the orbiter. Three (partially redundant) thruster packs are used to separate the hatch from the orbiter at a velocity of approximately 45 ft/sec. The hatch jettison features could be used in a landing emergency.

Egress Pole System



Crew Egress/Wing Clearance

The crew escape system orbiter-based hardware also includes the egress pole - a curved, spring-loaded, telescoping, steel and aluminum cylinder. The purpose of the egress pole is to guide escaping crewmembers on a trajectory that will clear the orbiter's left wing. The pole, extending downward 9.8 feet from the side hatch, is contained within an aluminum housing attached to the middeck ceiling (above the airlock hatch) and at the side hatch 2-o'clock position. The pole is removed from its launch position during orbit procedures and reinstalled for entry. The egress pole weighs about 240 pounds. A magazine holding eight lanyards is attached to the hatch end of the pole. The lanyards are the means by which crewmembers

are guided down the pole. Each lanyard assembly consists of a hook attached to a Kevlar strap that surrounds the escape pole. Five roller bearings on each strap surround the pole and permit the lanyard to roll freely down the pole. The Kevlar thread stitching can break away, providing the crewmember with an energy absorber. The crewmember slides down the escape pole and off the end.

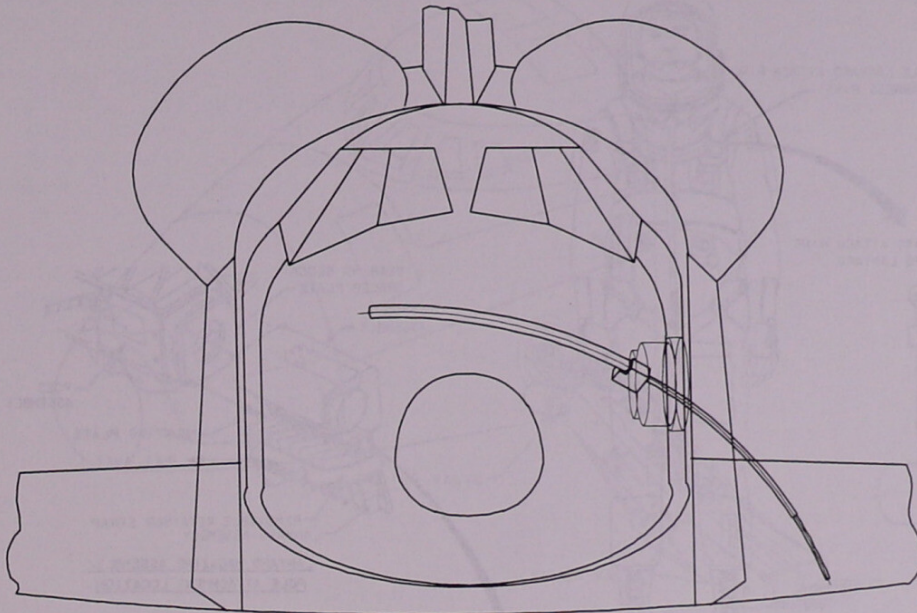
Emergency Egress Slide

The emergency egress slide provides a rapid and safe orbiter egress during post landing contingency or emergency situations. The slide allows the safe egress of the crewmembers to the ground within 60 seconds after the side hatch is fully opened or jettisoned and accommodates the egress of incapacitated crewmembers. The slide may be used after a normal opening of the middeck side hatch or after jettisoning the side hatch. Equipment consists of an inflatable slide, pressurized Argon bottle, aspirator, girt bracket, and slide cover.

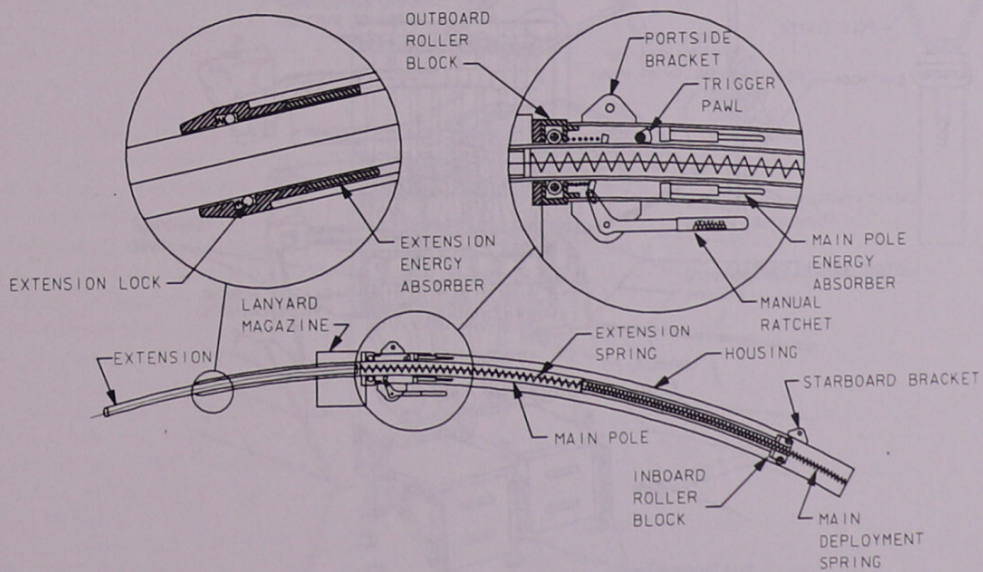
The system is configured manually by removing the slide from its stowed location below the middeck and attaching it to the side hatch if the hatch has not been jettisoned, or rotating the slide into the opening if the hatch has been jettisoned. The slide is inflated by pulling a lanyard that activates an Argon bottle pressurized to 3,000 psi. The slide inflates to approximately 2.75 psig. A relief valve bleeds off pressures greater than 3.0 psig.

The flight crewmembers egress wearing their launch entry suit. The slide remains functional in the egress environment for a minimum of 6 minutes after deployment and can be released from the side hatch to permit fire truck access.

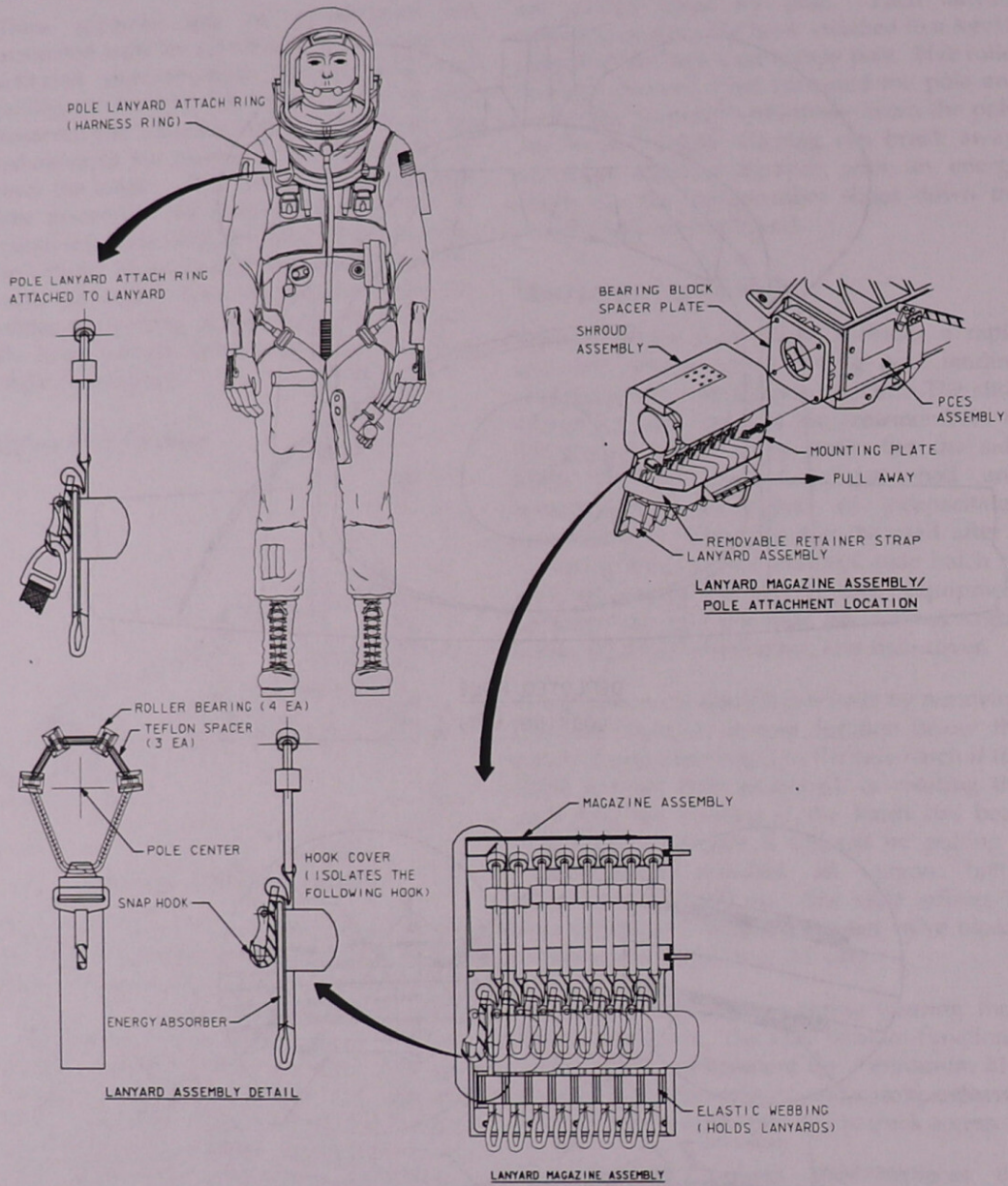
The emergency egress slide replaces the emergency egress side hatch bar, which required the flight crewmembers to drop approximately 10.5 feet to the ground. This drop could cause injury to the flight crew and prevent an injured crewmember from moving to a safe distance from the orbiter.



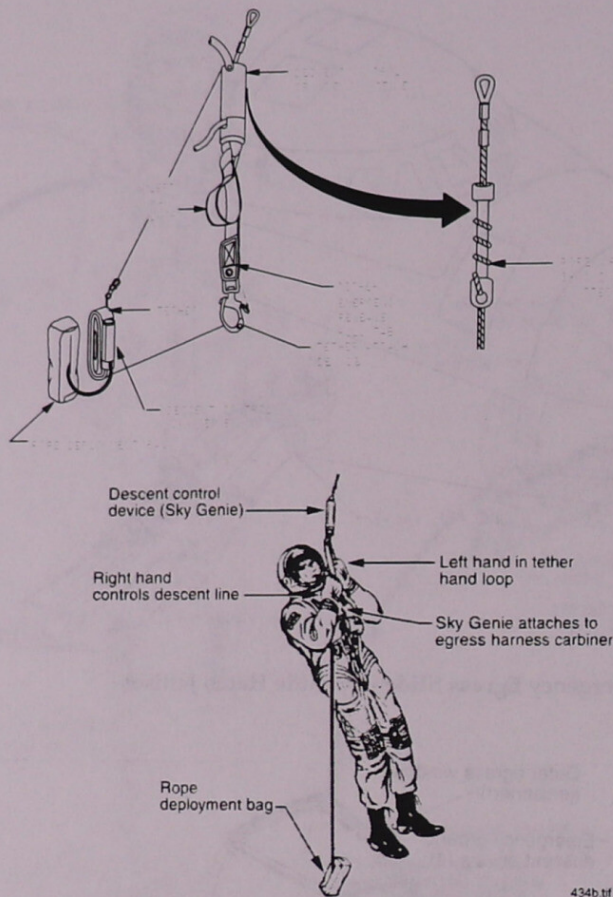
DEPLOYED POLE
(LOOKING AFT)



Deployed Pole Assembly



Lanyard Magazine Assembly



Descent Control Device

Secondary Emergency Egress

In the event that egress through the side hatch is not possible, the port side flight deck overhead window (window 8) provides the flight crew with a secondary emergency egress route. This overhead window consists of three panes of glass, two panes attached to the crew compartment and one attached to the upper forward fuselage. The overhead window jettison system consists primarily of expanding tube assemblies, mild detonating fuses, frangible bolts, and associated initiators.

Pulling the T-handle located forward of the flight deck center console (C3) activates the overhead window jettison system. When initiated, the outer pane is jettisoned upward and aft. A time delay in the pyrotechnic firing circuit delays the initiation of the jettisoning of

the inner pane 0.3 second after the outer pane is jettisoned. The inner window pane rotates downward and aft into the crew compartment aft flight deck on hinges located at the aft portion of the window frame. A capture device attenuates the opening rate and holds the window in position. This overhead window jettison system can also be initiated from the outside of the orbiter on the starboard side of the forward fuselage by ground personnel.

Crewmembers use the MS2 seat (seat 4) to climb up through the window. Seven emergency ground descent devices (Sky Genies) are stowed on the overhead aft flight deck outboard of each overhead window, one for each flight crewmember. The emergency ground descent device enables crewmembers to lower themselves to the ground over the starboard side of the orbiter.

Procedures for Bailout, Water Survival, and Rescue

The final decision to initiate a bailout rests with the commander. When the commander determines that a bailout is necessary (normally, when the range-to-go exceeds about 50 n. mi. at an altitude of 55,000 feet), the commander places the orbiter in a minimum-sink-rate attitude and engages the autopilot. At 40,000 feet, the commander directs the crew to close their visors and activate emergency oxygen, and for MS 3 (seated in the forward left seat in the middeck) to open the pyro vent valve. At an altitude of 31,000 feet the cabin pressure is about equalized with the outside atmosphere. Shortly thereafter, the commander directs MS3 to jettison the side hatch. As soon as the hatch is jettisoned, all crewmembers unstrap from their seats and break their oxygen, cooling, and communication connections.

MS3 deploys the egress pole by pulling the safing pin and arming pin and rotating the handle counterclockwise. Should the pole fail to deploy fully, the manual ratchet is used to manually extend the pole. The exit involves each crewmember attaching the lanyard hook assembly to the parachute harness and egressing through the side hatch opening. It takes approximately 2 minutes for a maximum crew of eight to bailout. After the first crewmember bails out from the middeck, the remaining crewmembers follow until all are out.

As each crewmember exits the orbiter, the force exerted by entering the windstream activates the automatic bailout sequence. Once the crewmember is off the pole and away from the orbiter (1.5 second delay), a pyrotechnic cutter separates the bridle and lanyard. The 18-inch pilot chute is deployed 1.5 seconds later, and immediately deploys the 4.5-foot drogue chute. The drogue chute stabilizes the crewmember down to an altitude of 14,000 feet, then deploys the main canopy.

Prior to a water landing, the crewmember pulls the manual inflation tab for the life preserver unit. The unit is designed to inflate automatically upon immersion in any type of water, but should be activated manually as an additional safeguard. Upon landing in saltwater, the SEAWARS automatically releases the crewmember from the parachute risers. At the same time, the life raft automatically deploys and

inflates. The crewmember's first task is to deploy the sea anchor and get into the life raft. Next, the crewmember pulls the activation tab on the upper CO₂ cylinder to inflate the upper chamber. Raft bailing proceeds by either using the spray shield, the bailing cup, or the bailing pump.

The crewmember's next task is to unpack the signaling equipment. The SARSAT personnel locator beacon is the primary signaling device. It is located on the raft spray shield. The telescoping antenna is extended, and the flexible antenna is removed. The PRC-112 is used to monitor 282.8 MHz and establish voice contact with search and rescue forces.

The arrival time of the search and rescue forces depends on where the bailout occurred. The first rescue force to arrive will probably be a C-130 transport aircraft, specially equipped for search and rescue. Two teams are dropped, each consisting of three rescue jumpers in a motorized rescue boat. One team drops to each end of the line of orbiter crewmembers. The C-130 may also drop two 20-person rafts for the assembled crewmembers and rescue personnel to wait in until rescue helicopters arrive.

Although no formal requirements exist for crewmembers to bail out of the orbiter during uncontrolled flight, they may be able to do so under certain circumstances. The pyro vent and hatch jettison pyrotechnics do not require orbiter power to function and can be activated even if orbiter power is lost. Each crewmember is wearing his or her own emergency oxygen bottles and parachute, and if the crew cabin were not spinning rapidly, at least some crewmembers should be able to get to the side hatch and get out.

In the case involving loss of orbiter control, the crewmembers should activate their emergency oxygen as soon as possible and then evaluate the situation. If the crew module is lofting to altitudes above 40,000 feet, the crew should remain within it until it passes through 40,000 feet on the way back down. If the cabin is depressurized, the LES/ACES can be used to judge the bailout altitude of 40,000 feet.

The escape pole is intended for use only during controlled gliding flight, and its use should not be attempted during an uncontrolled bailout. Once out of the orbiter, crewmembers should pull their parachute ripcord handle to activate the automatic opening sequence for their parachutes.

Escape Systems Summary Data

- Escape systems refer to equipment and systems intended to facilitate emergency egress of the flight crew. Escape systems include equipment worn by the crewmembers, hardware built into the orbiter, and external systems located on the launch pad.
- Escape by the flight crew on the launch pad is facilitated by descending to a safe area via slidewire baskets. The launch pad structure also includes an escape temperature and hydrogen fire-hazard monitoring system and a Firex spray system for water shower.
- The LES or ACES are designed to protect crewmembers from (1) loss of cabin pressure and/or orbiter oxygen at altitudes of up to 100,000 feet, (2) cold atmospheric and/or water temperatures after bailing out, (3) pooling of blood in the lower body, and (4) contaminated atmosphere during flight or post-landing procedures.
- The personal parachute assembly is worn by the crew in the event of bailout. It is designed to work automatically with the crew egress pole system or with manual backups as needed.
- The hardware associated with the orbiter for purposes of in-flight crew escape consists of several types of pyrotechnics plus the egress pole.
- Three separate sets of pyrotechnics are associated with jettisoning the side hatch, all of which are activated simultaneously by squeezing and pulling a T-handle.
- The purpose of the egress pole is to guide escaping crewmembers on a trajectory that will clear the orbiter's left wing.
- The emergency egress slide is intended for use after a normal opening of the middeck side hatch or after jettisoning of the side hatch at the nominal end-of-mission landing site or at a remote or emergency landing site.
- In the event that egress through the side hatch is not possible, the port side flight deck overhead window (W8) provides the flight crew with a secondary emergency egress route.
- The commander may decide a bailout is necessary, if the range-to-go exceeds about 50 n. mi. at an altitude of 55,000 feet. The orbiter is placed in a minimum-sink-rate attitude on autopilot.
- Bailout includes using the escape pole to leave the orbiter, deploying the parachute for descent, and inflating the life raft for a water recovery. Special survival gear and procedures are provided in the case of a bailout.

2.11 EXTRAVEHICULAR ACTIVITY (EVA)

CONTENTS

Description	2.11-1
Extravehicular Mobility Unit	2.11-2
Airlock	2.11-11
EVA Support Equipment	2.11-15
Simplified Aid for EVA Rescue	2.11-17
Operations	2.11-19
EVA Summary Data	2.11-22
EVA Rules of Thumb	2.11-22

Description

An EVA occurs when a crewmember leaves the protective environment of a spacecraft's pressurized cabin and ventures out into the vacuum of space wearing a space suit. An EVA is commonly referred to as a spacewalk. The current space suit, designed for a total maximum duration of 7 hours, provides environmental protection, mobility, life support, and communications. Two suits are included in each baseline

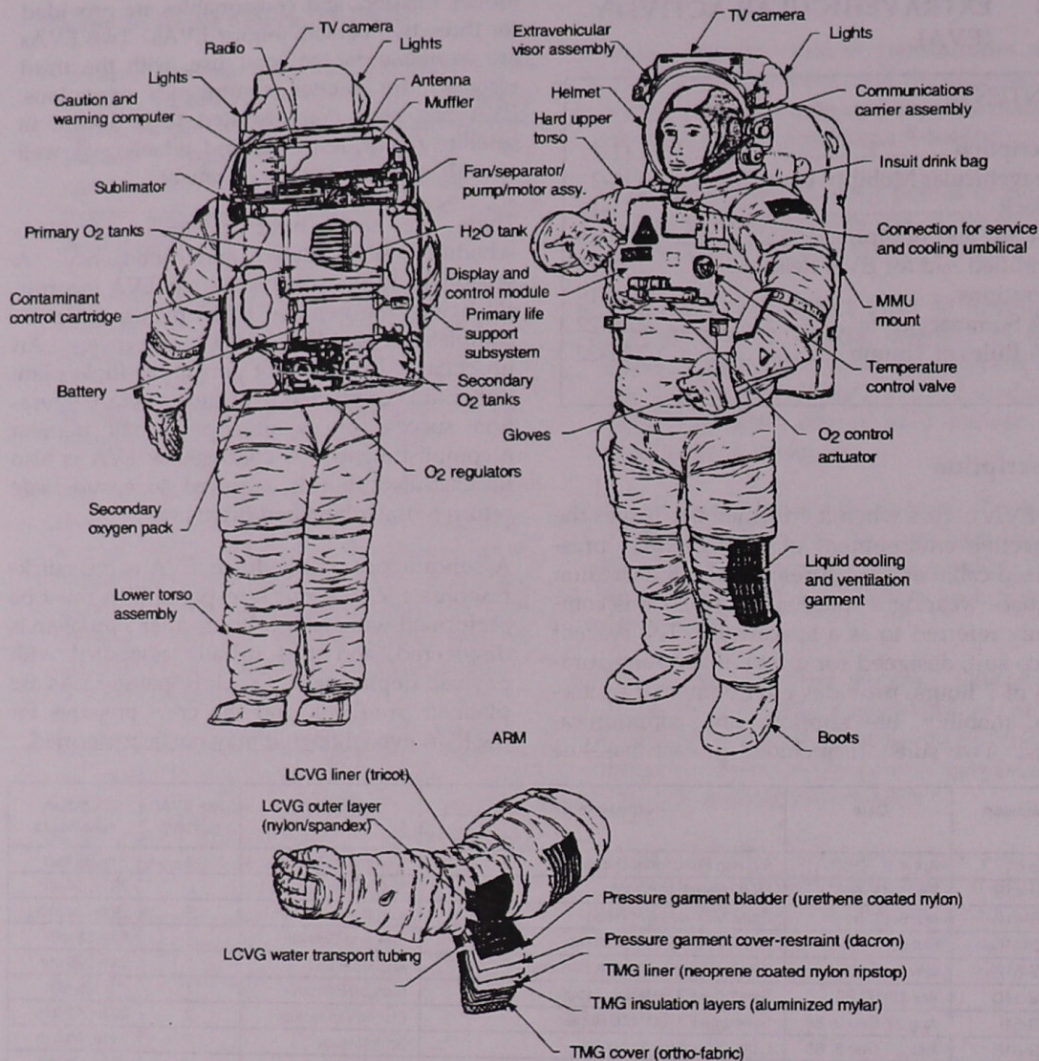
orbiter mission, and consumables are provided for three two-person, 6-hour EVAs. Two EVAs are available for payload use, with the third reserved for orbiter contingency operations. EVA has been demonstrated to be useful in satellite repair, retrieval, and refueling as well as with space station development.

There are three basic categories of EVA: scheduled, unscheduled, and contingency. A scheduled EVA is defined as any EVA incorporated into the nominal flight plan in order to complete a specific mission objective. An unscheduled EVA is not part of the flight plan; rather, it is conducted to achieve payload operation success or to advance overall mission accomplishments. A contingency EVA is also unscheduled, but is required to ensure safe return of the orbiter and flight crew.

A subcategory of scheduled EVA is the quick-response EVA. A quick-response EVA must be performed within a few hours after a problem is discovered, and it is usually associated with payload deployment. Quick-response EVAs are planned pre-flight, and the crew prepares for the EVA even though it may not be performed.

Mission	Date	Purpose of EVA	EVA crew	No. EVA/mission	Duration, man-hours
STS-6	Apr 4-9, 83	System Functional Demo	Musgrave/Peterson	1	8 hr, 34 min
STS-41B	Feb 3-11, 84	MMU Capability Demo	NcCandless/Stewart	2	23 hr, 14 min
STS-41C	Apr 6-13, 84	Solar Max Satellite Repair	Van Hoften/Nelson	2	20 hr, 12 min
STS-41G	Oct 5-13, 84	Orbiter Fuel Transfer Demo	Leestma/Sullivan	1	6 hr, 58 min
STS-51A	Nov 8-16, 84	Westar/Palapa Satellite Retrieval	Allen/Gardner	2	24 hr, 28 min
STS-51D	Apr 12-19, 85	Syncome F3 Satellite Repair	Griggs/Hoffman	1	6 hr, 20 min
STS-51I	Aug 27-Sep 3, 85	Syncome F3 Satellite Repair	Fisher/Van Hoften	2	23 hr, 42 min
STS-61B	Nov 26-Dec 3, 85	Large Structure Assembly	Spring/Ross	2	24 hr, 40 min
STS-37	Apr 5-10, 91	GRO Satellite Repair/Locomotion Studies	Ross/Apt	2	20 hr, 58 min
STS-49	May 10-14, 92	Intelsat Repair and Assembly of Station by EVA Methods (ASEM)	Thuot, Hieb, Akers, Thornton	4	59 hr, 51 min
STS-54	Jan 17, 93	First EVA Detailed Test Objective (DTO 1210)	Harbaugh, Runco	1	8 hr, 56 min
STS-57	Jun 25, 93	EURECA Antenna Stow and Second EVA DTO (1210)	Low, Wisoff	1	11 hr, 40 min
STS-51	Sep 16, 93	Third EVA DTO (1210)	Walz, Newman	1	14 hr, 10 min
STS-61	Dec 4-8, 93	Hubble Space Telescope Repair Mission	Musgrave, Hoffman, Akers, Thornton	5	70 hr, 58 min
STS-64	Sep 16, 94	SAFER First Flight	Lee, Meade	1	13 hr, 42 min
STS-63	Feb 9, 95	First EVA Development Flight Test (EDFT) (Spartan Mass Handling)	Foale, Harris	1	13 hr, 18 min
STS-69	Sept 16, 95	Second EDFT (Task board with station EVA interfaces)	Voss, Gernhardt	1	13 hr, 32 min
STS-72	Jan 14-16, 95	Third EDFT (Station assembly and maintenance hardware)	Chiao, Barry, Scott	2	26 hr, 4 min
STS-76	Mar 27, 96	Fourth EDFT (MEEP - Mir Environmental Effects Payload)	Godwin, Clifford	1	12 hr, 4 min

Space Shuttle EVA Chronology



435.cvs

Extravehicular Mobility Unit

Extravehicular activities are classified according to level of complexity: simple, intermediate, or complex. A simple payload EVA requires minimal unique tools, mockups, or mobility aids. Existing procedures and techniques may be adapted to particular EVA needs, thus requiring minimal crew training. An intermediate payload EVA requires development of new tools and equipment. Some procedure and technique development is required, with more extensive training necessary. A complex payload EVA requires the design and development of complex or elaborate tools and equipment. The tasks require extension of basic capabilities and

may pose difficulty in access or restraint. Procedure and technique development is extensive, as are crew training requirements.

Extravehicular Mobility Unit

The extravehicular mobility unit (EMU) is an independent anthropomorphic system that provides environmental protection, mobility, life support, and communications for the crewmember to perform EVA in Earth orbit. For EMU design considerations, an EVA is defined as any time the EMU external environmental pressure is below 4.0 psia. The EMU is designed to

accommodate an EVA mission with a total maximum duration of 7 hours, consisting of 15 minutes for egress, 6 hours for useful EVA tasks, 15 minutes for ingress, and a 30-minute reserve. The EMU also accommodates specific metabolic rate limits, including (1) an average metabolic rate not exceeding 1600 Btu/hr in any given EVA hour and not exceeding 1000 Btu/hr for the entire duration, (2) a peak metabolic rate not exceeding 2000 Btu/hr for a period of 15 minutes, and (3) a minimum metabolic rate not less than 400 Btu/hr for a period of 30 minutes. The EMU is an integrated assembly, primarily composed of the space suit assembly, life support system, and numerous items of associated support and ancillary equipment.

Space Suit Assembly

The space suit assembly (SSA) is the anthropomorphic pressure vessel that encloses the crewmember's torso, limbs, and head. The SSA provides a variety of functions while the crewmember performs an EVA, including suit pressure retention, crewmember mobility, crewmember liquid cooling distribution, oxygen ventilation gas circulation, downlink of crewmember's electrocardiogram data via EMU radio, crewmember interface with EMU radio, crewmember in-suit drinking water, and urine containment. The SSA operates under specific pressure requirements and leakage criteria.

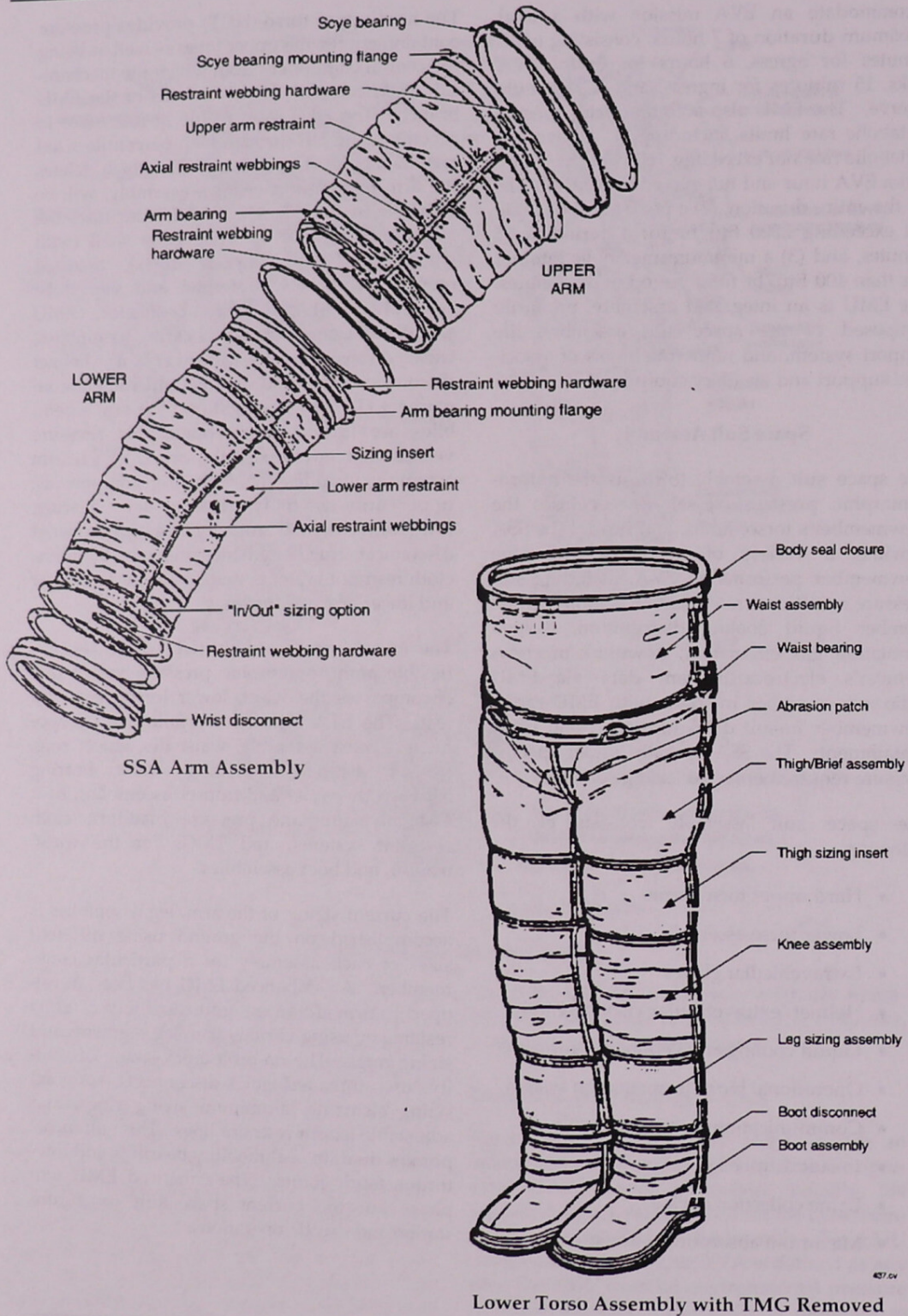
The space suit assembly consists of the following:

- Hard upper torso/arms
- Lower torso assembly
- Extravehicular gloves
- Helmet/extravehicular visor assembly
- Liquid cooling and ventilation garment
- Operational bioinstrumentation system
- Communications carrier assembly
- In-suit drink bag
- Urine collection device
- Maximum absorption garment.

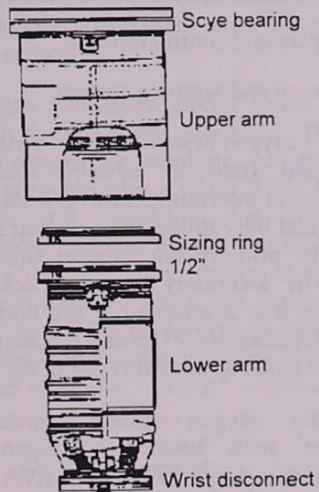
The hard upper torso (HUT) provides pressure containment for the upper torso as well as being the central component from which the mechanical, electrical, and fluid interfaces of the EMU branch. The HUT is available in four sizes to accommodate 5th through 95th percentile-sized crewmembers. The planar HUT, which deletes the arm gimbal and bellows assembly, will be available in two sizes. The HUT includes the following components: fiberglass shell (with water tubes and oxygen ducts), assorted mounting brackets, waterline and vent tube assembly, multiple water connector, EMU electrical harness, shoulder bearing assemblies, waist disconnect ring (passive half), helmet disconnect ring, and thermal micrometeoroid garment (TMG). The right and left arm assemblies are flexible, anthropomorphic pressure vessels that encompass the arms. Each arm assembly includes the following components: upper arm assembly, rotating scye bearing, lower arm assembly, rotating arm bearing, wrist disconnect ring, urethane pressure bladders, cloth restraint systems, and TMGs for the upper and lower arm assemblies.

The lower torso assembly (LTA) consists of a flexible anthropomorphic pressure vessel that encompasses the waist, lower torso, legs, and feet. The LTA includes the following components: waist assembly, waist disconnect ring, trouser assembly, rotating waist bearing between the waist and trouser assemblies, boot assembly, urethane pressure bladders, cloth restraint systems, and TMGs for the waist, trouser, and boot assemblies.

The current sizing of the arm/leg assemblies is accomplished on the ground using different sizes of each assembly for a particular crewmember. An enhanced EMU has been developed to provide an on-orbit capability of EMU resizing by using various arm/leg segments and sizing rings. The on-orbit quick-sizing capability, uses threaded quick-disconnects, softgood sizing elements, aluminum sizing rings, and adjustable-length restraint lines. This suit incorporates dual lip seal mobility bearings and low-torque fabric joints. The enhanced EMU will phase out the current space suit for future station and shuttle operations.



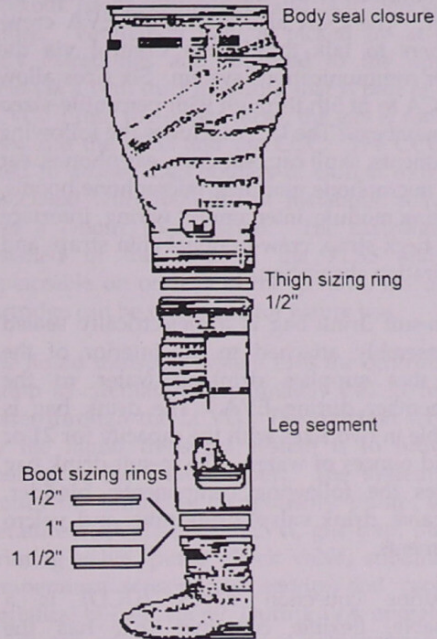
The extravehicular gloves consist of a detachable, flexible pressure vessel, encompassing each hand for use during EVA. The extravehicular gloves include the following components: urethane pressure bladder and cloth restraint system, wrist disconnect ring with rotating wrist bearing, wrist gimbal ring, adjustable palm restraint bar/strap, wrist tether strap, and TMG with palm restraint bar. The current 4000 series gloves incorporate a standard nine-size system to size the gloves for a comfortable fit. The glove fingers use a sizing feature that consists of a pair of polyester dacron cords to provide finger length adjustments. Customized gloves can be manufactured for the crewmember if a proper fit cannot be obtained from the standard size glove.



Enhanced Arm Assembly

The helmet, a "one-size-fits-all" model, consists of a detachable, transparent, hard pressure vessel encompassing the head. The helmet includes the following components: hard transparent bubble, helmet disconnect ring, helmet purge valve, and vent pad. Two crew optional items are also available for the helmet. One of these items is the Fresnel lens, which is mounted to the lower front inside of the helmet to improve display control module visibility for the crewmember. The other item is the valsalva device, attached to the inside of the bubble, which allows the crewmember to clear his or her ears during pressure changes. The extravehicular visor assembly (EVVA) attaches to the helmet to provide the crewmember with visual,

thermal, impact, and micrometeoroid protection. The EVVA includes the following components: clear protective visor, sun visor, center and side eyeshades, fiberglass shell, and latch mechanisms and supporting structure for the visor and eyeshades.



Enhanced Lower Torso Assembly

The liquid cooling and ventilation garment (LCVG) is a form-fitting elastic garment worn against the crewmember's body. The LCVG includes the following components: outer restraint fabric, inner liner assembly, crew optional comfort pads, biomed pocket, dosimeter pocket, water tubing network, paramanifold assembly, ventilation ducting network, vent plenum assembly, multiple water connector, and full torso zipper. The garment supports a network of tubing that circulates water over the body to provide cooling to the crewmember. It also supports a network of ducting that draws ventilation gas from the suit extremities and routes it back to the primary life support system to complete the suit ventilation loop. Connections to the ducting in the HUT for both cooling water and ventilation flow are made at the LCVG half of the multiple water connector. The LCVG is sized to fit the crewmember based on a sizing system with six size ranges.

The communications carrier assembly (CCA) is a cloth aviator-type cap that positions and supports the electronics for interface with the EMU radio for crewmember communications. The CCA contains the microphones and earphones necessary for the EVA crewmembers to communicate with each other or with the orbiter. The CCA also allows the EVA crewmembers to talk to Mission Control via the orbiter communications system. Six sizes allow the CCA to fit 5th through 95th percentile-sized crewmembers. The CCA includes the following components: skull cap, ear cups, ear phones, ear seals, microphone modules, microphone booms, summing module, interconnect wiring, interface cable, neck strap, crew-optional chin strap, and perspiration absorption strap.

The in-suit drink bag is a dielectrically sealed bag assembly attached to the interior of the HUT that supplies drinking water to the crewmember during EVA. The drink bag is available in two sizes with the capacity for 21 or 32 fluid ounces of water. The in-suit drink bag includes the following components: bladder, inlet valve, drink valve, drink tube, and velcro attachments.

The urine collection device (UCD) is a disposable, flexible container that has the capacity to hold up to 32 fluid ounces of urine. The UCD is worn under the LCVG by male crewmembers during EVA. It is designed for one-time use, then disposed of as wet trash. The UCD includes the following components: collection bag, attachment straps, one-way check valve, and disposable roll-on cuff.

The maximum absorption garment (MAG) consists of multiple layers of material designed to rapidly absorb and store urine. The MAG is designed to be worn under the LCVG by male or female crewmembers during EVA. It has the capacity to hold 32 fluid ounces of urine and is disposable after use. The MAG includes the following components, multilayer absorbent material and tape attachment straps.

Life Support System

The life support system (LSS) provides a safe living environment inside the EMU. The LSS provides a variety of functions while the crewmember performs an EVA, including provision

of breathing oxygen, suit pressurization, crewmember cooling, crewmember communications, displays and controls for crewmember operation of the EMU, and monitoring of EMU consumables and operational integrity. The life support system consists of the following:

- Primary oxygen system
- Secondary oxygen pack
- Oxygen ventilation circuit
- Liquid transport system
- Feedwater circuit
- Electrical interfaces
- Extravehicular communicator (EMU radio)
- Display and control module
- Caution and warning system.

The primary oxygen system, oxygen ventilation circuit, liquid transport system, feedwater circuit, electrical interfaces, extravehicular communicator, and the caution and warning system make up the primary life support subsystem (PLSS). The secondary oxygen pack is a separate unit that is attached to the bottom of the PLSS. Together, the PLSS and the secondary oxygen pack make up the backpack of the EMU.

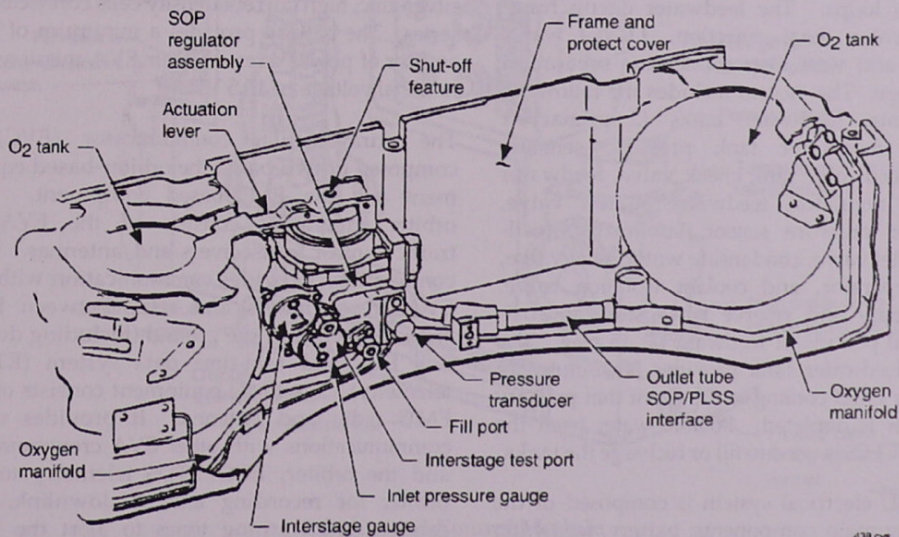
The primary oxygen system provides a crewmember with breathing oxygen and satisfies pressure requirements for EVA. The system stores 1.217 pounds of oxygen at 850 psia and 90° F. It delivers oxygen during EVA at 4.3 ± 0.1 psid, and maintains a metabolic use rate range of 0.02 to 0.33 lb/hr. The system is charged through a common multiple connection to the orbiter environmental control and life support system. Charging pressure is 850 ± 50 psig. The minimum usable pressure is 60 psi. The system performs various functions, including suit pressurization, provision of breathing oxygen, and water pressurization. The primary oxygen system includes the following components: oxygen tanks, oxygen tank pressure sensor, flow limiter, oxygen shutoff valve, oxygen actuator, suit pressure regulator, water pressure regulator, high mode relief valve, and low mode relief valve.

The secondary oxygen system, also known as the secondary oxygen pack (SOP), is the backup assembly to the primary oxygen system. This backup system provides a minimum of 30 minutes of emergency oxygen in the purge mode. The SOP functions include suit pressurization, provision of breathing oxygen, and some degree of cooling in the purge mode. There is no required crewmember interface to activate the SOP; it automatically activates whenever the oxygen actuator is in the EVA position and suit pressure is less than 3.9 psid. The SOP includes two oxygen tanks, containing a total of 2.65 pounds of oxygen at 5800 psia and 70° F. The system includes the following components: oxygen tanks, SOP inlet pressure gauge, first-stage regulator, interstage gauge, second-stage regulator/shutoff valve/flow restrictor, PLSS/SOP interface connector, and oxygen tank pressure sensor.

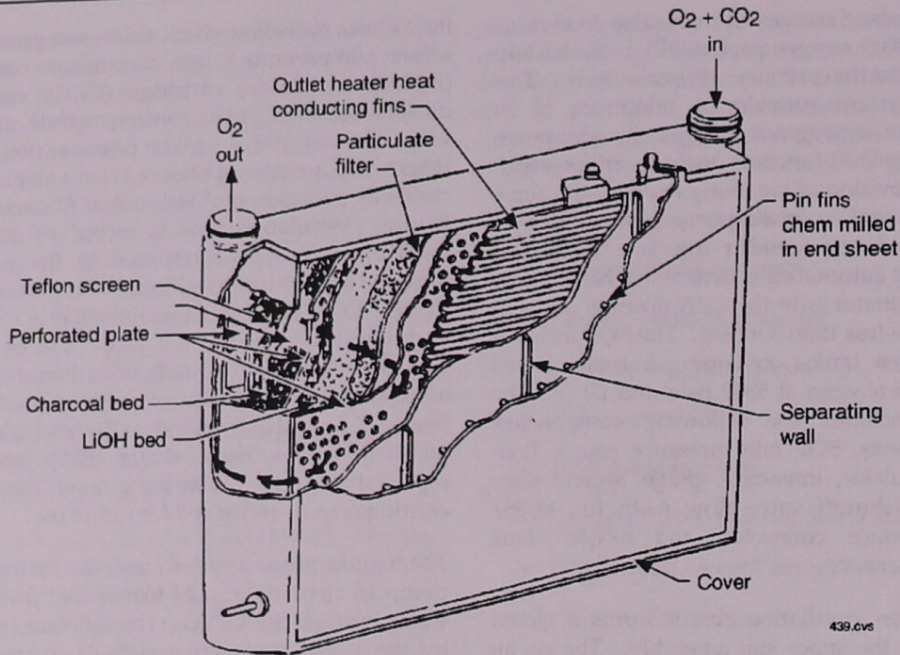
The oxygen ventilation circuit forms a closed loop with the space suit assembly. The circuit provides oxygen for breathing, suit pressurization for intravehicular activity (IVA) and EVA operation, and ventilation for cooling and elimination of exhaled gases. The oxygen flow picks up heat, humidity, carbon dioxide, and other contaminants, which are removed from the EMU by the ventilation circuit components. The system includes the following components: fan/water separator, slurper/ sublimator, vent

flow sensor/backflow check valve, suit pressure sensor, suit pressure gauge, contaminant control (lithium hydroxide) cartridge (CCC), carbon dioxide sensor, display control module purge valve, helmet purge valve, positive pressure relief valve, negative pressure relief valve, SOP checkout package, muffler, and SOP checkout fixture. Ventilation flow is picked up at the body extremities and returned to the upper torso via a vent duct manifold that is part of the LCVG. From the upper torso, the gas is routed back into the PLSS and the CCC. The CCC is sized to absorb 1.48 pounds of carbon dioxide associated with 7000 Btu of metabolic activity over a 7-hour EVA period. The cartridge is installed in the back of the PLSS and is replaceable on orbit. On the ground, the used cartridge can be recharged for future use.

The liquid transport system uses the centrifugal pump to circulate approximately 240 lb/hr of water through the LCVG. The function served by the liquid transport system is to provide cooling to the crewmember. The system includes the following components: pump, temperature control valve, LCVG, gas trap, pump priming valve, pump check valve, sublimator temperature sensor, and service and cooling umbilical bypass valve. During IVA operation, the pump circulates water not only through the EMU, but also through the service and cooling umbilical to the orbiter heat exchanger.



Secondary Oxygen Pack



LiOH Cartridge

The feedwater circuit contains the equipment and water to dissipate heat loads imposed on the system by the crewmember, the PLSS, and the environment. It also contains equipment to remove moisture from the ventilation circuit and gas from the transport circuit, to separate the water and gas, and to put them back in their respective loops. The feedwater circuit functions involve heat rejection, LCVG water makeup, and vent loop condensate separation and storage. The system includes the following components: feedwater tanks (2 primary/1 reserve), feedwater tank pressure sensors, reserve feedwater tank check valve, feedwater pressure regulator, feedwater shutoff valve, feedwater pressure sensor, sublimator, feedwater relief valve, condensate water relief valve, water separator, and coolant isolation valve. The primary and reserve tanks store approximately 10 pounds of feedwater at 15 psig. The reserve feedwater tank provides 30 minutes of water for EMU cooling in the event that primary feedwater is depleted. Potable water from the orbiter ECLSS is used to fill or recharge the tanks.

The EMU electrical system is composed of the following main components: battery, feedwater shutoff valve, coolant isolation valve, motor, instrumentation, extravehicular communicator,

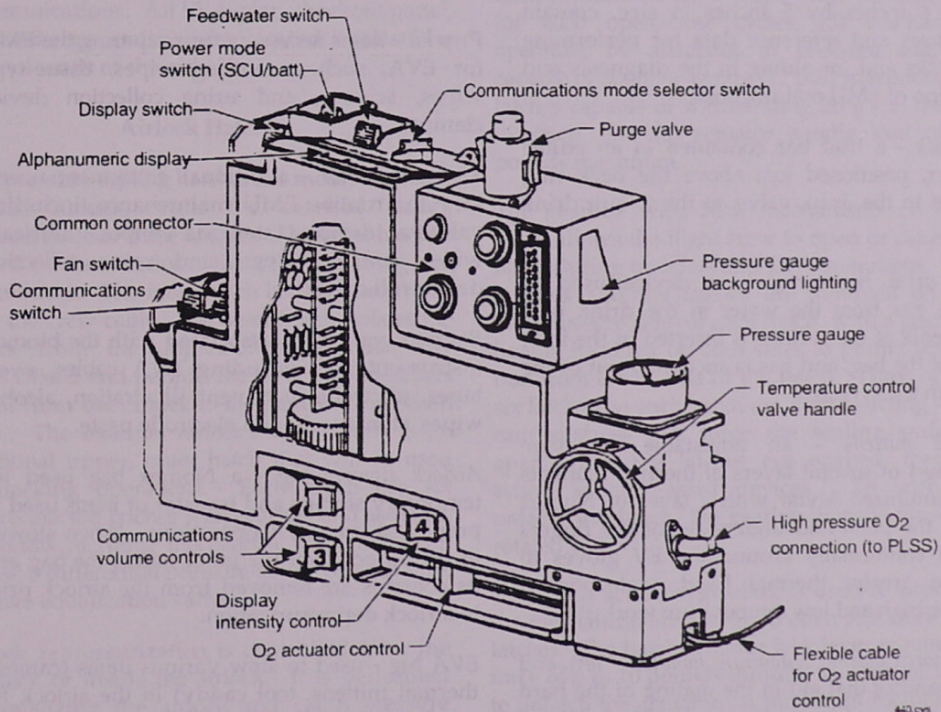
display and control module, and caution and warning system. Electrical interfaces exist between the display and control module and parts of the PLSS, SOP, and C/W. The power supply for operation of all electrical components of the EMU is a battery installed in the back of the PLSS. The EMU battery consists of eleven sealed, silver-zinc, high current density cells connected in series. The battery provides a minimum of 26.6 amp-hr of power over a 7-hour EVA mission at a nominal voltage of 16.5 V dc.

The extravehicular communicator (EVC) is composed of two parts, the orbiter-based equipment and the EMU-based equipment. The orbiter equipment consists of the EVA/air traffic control transceivers and antennas. This configuration provides communication with the EVA crewmembers and relay between EVA crewmembers and the ground (including downlink ECG and real-time data system (RTDS) telemetry). The EMU equipment consists of the EMU radio and antenna. It provides voice communications with other EVA crewmembers and the orbiter, ECG/RTDS telemetry to the orbiter for recording and/or downlink, and caution and warning tones to alert the EVA crewmember of anomalies or other significant events. The EVC includes the following compo-

nents: orbiter UHF system, EMU radio, EMU electrical harness, communications carrier assembly, biomed sensors, COMM MODE selector switch, COMM switch, volume controls, and real-time data system. Orbiter panels O6, A1R, and R10 are the crew communication interfaces. The panels control UHF operation, air-to-air or ground transmission, and biomed data down-link/recording respectively.

The display and control module (DCM) contains all controls and displays necessary for nominal operation and monitoring of EMU systems. The DCM includes the following components: POWER mode switch, DISPL switch, FAN switch, COMM switch, communications volume controls, display intensity control, oxygen actuator, temperature control valve, pressure gauge, DCM purge valve, alphanumeric display COMM mode selector, and WATER switch. The DCM is installed on the hard upper torso, with the surfaces covered with a TMG. This TMG contains the labels for the controls and displays.

The EMU caution and warning system (CWS) consists of instrumentation and a microprocessor to obtain, process, and visually display information for use by the EVA crewmember in the operation and management of the EMU. The system contains built-in test equipment (BITE), consisting of software and hardware that verify proper CWS operation. CWS serial data are also routed to the ground by the real-time data system. The CWS functions involve displaying EMU leak check procedures, monitoring and displaying EMU consumables status, monitoring EMU operational integrity, and alerting crewmembers to EMU anomalies. The system includes the following components: alphanumeric display with BITE indicator, display (DISPL) switch, alert/status/warning tones, sensors, and "black box" processor. The CWS receives inputs from EMU sensors and from the DISPL switch located on the DCM. Sensors gather information throughout the EMU system and relay it to the CWS. Information is provided on pressures, temperatures, currents, and voltages.



Display and Control Module

EMU Ancillary Equipment

The EMU ancillary equipment consists of hardware necessary to support the EMU during all phases of EVA (prep/post/operation). The following list itemizes the components with a brief description of their functions.

EMU helmet lights - attach to the helmet EVVA and provide two functionally independent sets of lights for portable lighting during an EVA task.

EMU scissors - steel cutters with one serrated edge capable of cutting anything from fabric bags and straps to lightweight steel cable and Kevlar cord.

EMU wrist mirror - attaches to the wrist of the EVA glove to allow the EVA crewmember to view the controls and displays on the front of the EMU.

EVA cuff checklist - a set of reference cards bound by an aluminum alloy bracket attached to a wrist band. The reference cards, approximately 4 inches by 5 inches in size, contain procedures and reference data for performing EVA tasks and for aiding in the diagnosis and resolution of EMU malfunctions.

Food stick - a fruit bar contained in an edible wrapper, positioned just above the neck ring adjacent to the drink valve on the in-suit drink bag.

In-suit drink bag syringe - a device used to remove gas from the water in the drink bag. The needle of the syringe is inserted in the inlet valve of the bag, and gas is suctioned out of the bag with the syringe.

Thermal mittens - an adjustable enclosure composed of several layers of thermal blankets and aluminized Mylar with a layer of Nomex felt on the palm and undersides of the fingers that fit conformally around the EV gloves to provide greater thermal hand protection at extreme high and low temperature worksites.

Lower torso assembly donning handles - left and right handles that aid in the mating of the hard upper torso and lower torso assembly halves of the waist ring.

Contingency tool - a pry bar used to disconnect the LTA and HUT halves of the waist ring in the event that the latching mechanism becomes jammed. Operation of the pry bar may damage the latching mechanism; therefore, it should be used only if the waist ring becomes jammed and the crewmember is entrapped in the space suit.

Bends treatment adapter (BTA) - an emergency device that may be used on-orbit in the event an EVA crewmember contracts decompression sickness (bends). The BTA converts the EMU into a hyperbaric treatment chamber, pressurizing the EMU to 8.0 psid over ambient cabin pressure.

SOP checkout fixture - a flight support test item installed on the HUT half of the neck ring during pre-EVA operations.

DCM plug - a cover that attaches to the multiple connector on the DCM in the event that water begins leaking from the connector after the service and cooling umbilical multiple connector is removed.

Prep kit - items necessary for preparing the EMU for EVA, such as antifog wipes, tissue-type wipes, scissors, and urine collection device clamps.

Maintenance kit - additional equipment necessary for routine EMU maintenance, including valsalva devices, stericide wipes, lubricant wipes, antifog wipes, and urine collection device roll-on cuffs.

Bio kit - equipment associated with the biomed instrumentation, including EVA cables, over-tapes, electrode placement illustration, alcohol wipes, stoma seals, and electrode paste.

Airlock stowage bag - a Nomex bag used for temporary storage and transfer of items used in prep- and post-EVA operations. When stowed in the airlock over the inner hatch, the bag and its contents are removed from the airlock prior to airlock depressurization.

EVA bag - used to stow various items (camera, thermal mittens, tool caddy) in the airlock for possible use during EVA. The EVA bag remains in the airlock during the EVA.

Airlock

An airlock on the orbiter accommodates astronaut EVA operations. The airlock permits EVA crewmembers to transfer from the mid-deck crew compartment into the payload bay in EMUs, without depressuring the orbiter crew cabin. The internal airlock provides launch and entry stowage of up to four EMUs, while the external airlock can stow two EMUs. Both types of airlock contain the interfaces and associated displays and controls for the orbiter systems that support EMU operation and servicing. Sized to accommodate a two-person EVA, the internal airlock dimensions have a diameter of 63 inches, a length of 83 inches, and two D-shaped 40-inch-diameter openings (three for external airlock). The internal airlock's volume measures 150 cubic feet, while the external airlock has a volume of 185 cubic feet. Support functions performed in the airlock include depressurization and repressurization, EVA equipment recharge, LCVG water cooling, and EVA equipment checkout, donning, and communications. All EVA gear, checkout panel, and recharge stations are located against the internal walls of the airlock.

Airlock Hatches

Two pressure-sealing hatches are mounted on the internal airlock, while the external airlock contains three of these hatches. The inner hatch is located on the exterior of the airlock opening into the middeck. The inner hatch isolates the airlock from the crew cabin. The outer hatch isolates the airlock from the unpressurized payload bay when closed and permits the EVA crewmembers to exit from the airlock to the payload bay when open. The external airlock's third hatch is an additional upper, outer hatch that will be used for docking operations. Each hatch has six interconnected latches with gearbox and actuator, a window, a hinge mechanism with hold-open device, a differential pressure gauge on each side, and two equalization valves.

Airlock repressurization is controlled from the middeck or inside the airlock. It is performed by equalizing the airlock and cabin pressure with airlock-hatch-mounted equalization valves on the inner hatch. Depressurization of the airlock is controlled from inside the airlock. The airlock is depressurized by venting the airlock

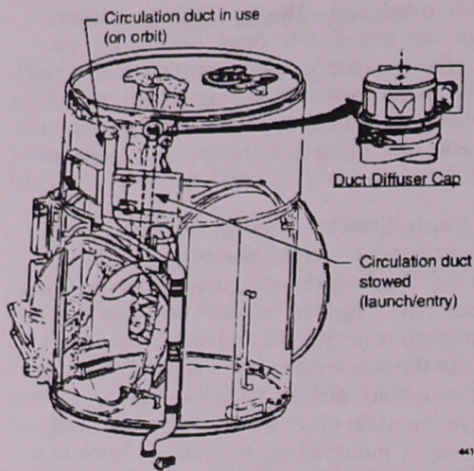
pressure overboard. The two D-shaped airlock hatches are installed to open toward the primary pressure source, the orbiter crew cabin, to achieve pressure-assist sealing when closed. Each hatch opening is 40 inches in diameter, yet with one side being flat, the minimum dimension is 36 inches.

The 4-inch-diameter window in each airlock hatch is used for crew observation from the cabin to the airlock and the airlock to the payload bay. The dual window panes are made of polycarbonate plastic and are mounted directly to the hatch using bolts fastened through the panes. Each airlock hatch has dual pressure seals to maintain the airlock's pressure integrity. One seal is mounted on the airlock hatch and the other on the airlock structure. A leak check quick disconnect is installed between the hatch and the airlock pressure seals to verify hatch pressure integrity before flight.

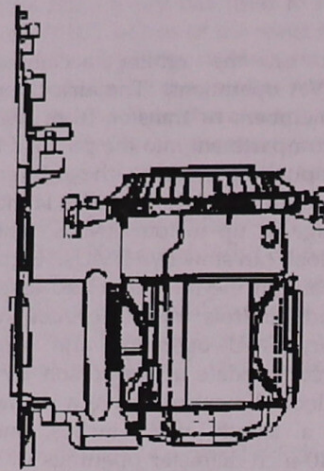
Each airlock hatch has the following design characteristics: (1) capable of being fully locked/unlocked from either side, (2) designed for 2000 open/close cycles, (3) one-handed operation by astronaut in pressure suit, (4) capable of opening against 0.2 psid maximum, (5) latches capable of withstanding 20 g's in the +X direction, and (6) actuator handle load of 30 pounds maximum.

The gearbox with latch mechanisms on each hatch allows the flight crew to open or close the hatch during transfers and EVA operations. The gearbox and the latches are mounted on the low-pressure side of each hatch, with a gearbox handle installed on both sides to permit operation from either side of the hatch. Three of the six latches on each hatch are double-acting with cam surfaces that force the sealing surfaces apart when the latches are opened, thereby acting as crew-assist devices. To latch or unlatch the hatch, the gearbox handle must be rotated 440°.

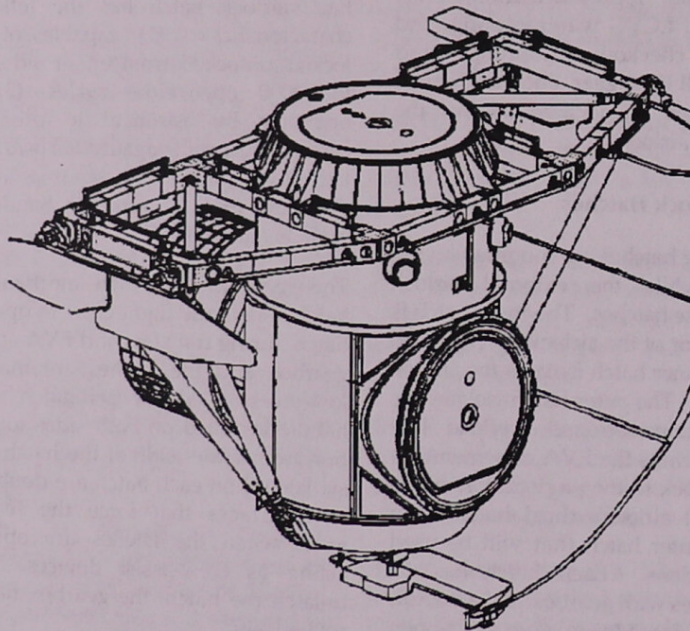
The hatch actuator/gearbox is used to provide the mechanical advantage to open and close the latches. The hatch actuator lock lever requires a force of 8 to 10 pounds through an angle of 180° to unlatch the actuator. A minimum rotation of 440° with a maximum force of 30 pounds applied to the actuator handle is required to operate the latches to their fully unlatched positions.



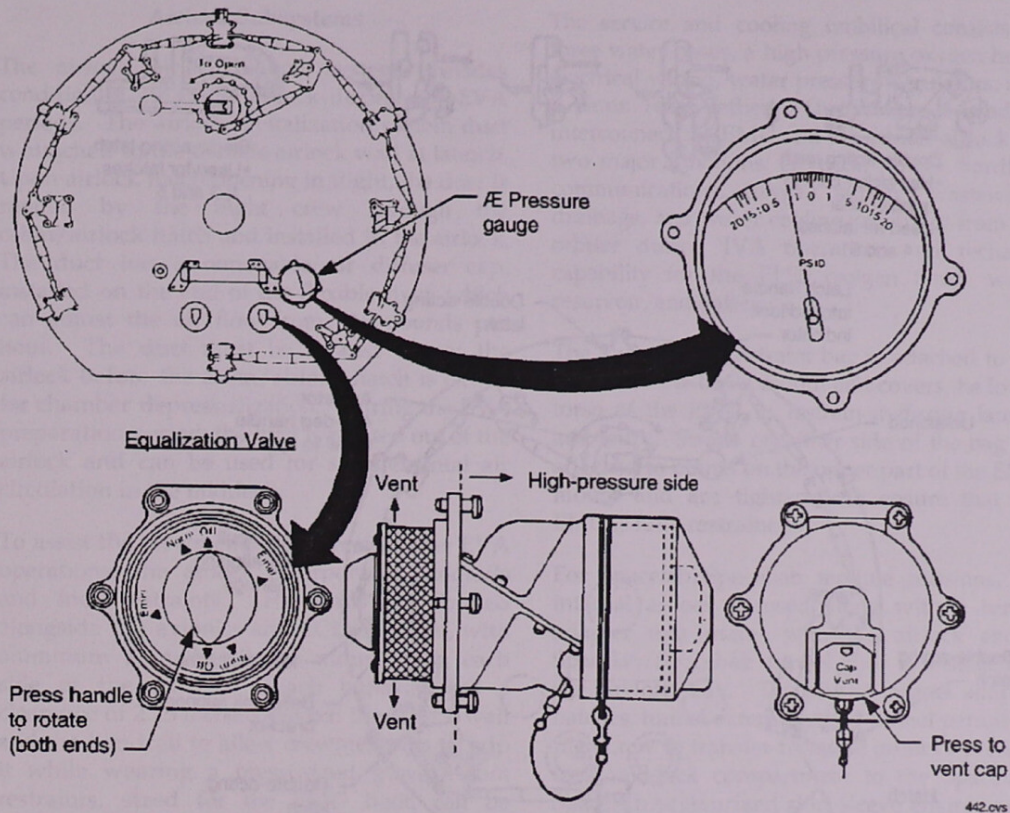
Airlock in Middeck



External Airlock
(port side view)



External Airlock ISS Configuration
(planned for OV-103, OV-104, OV-105)

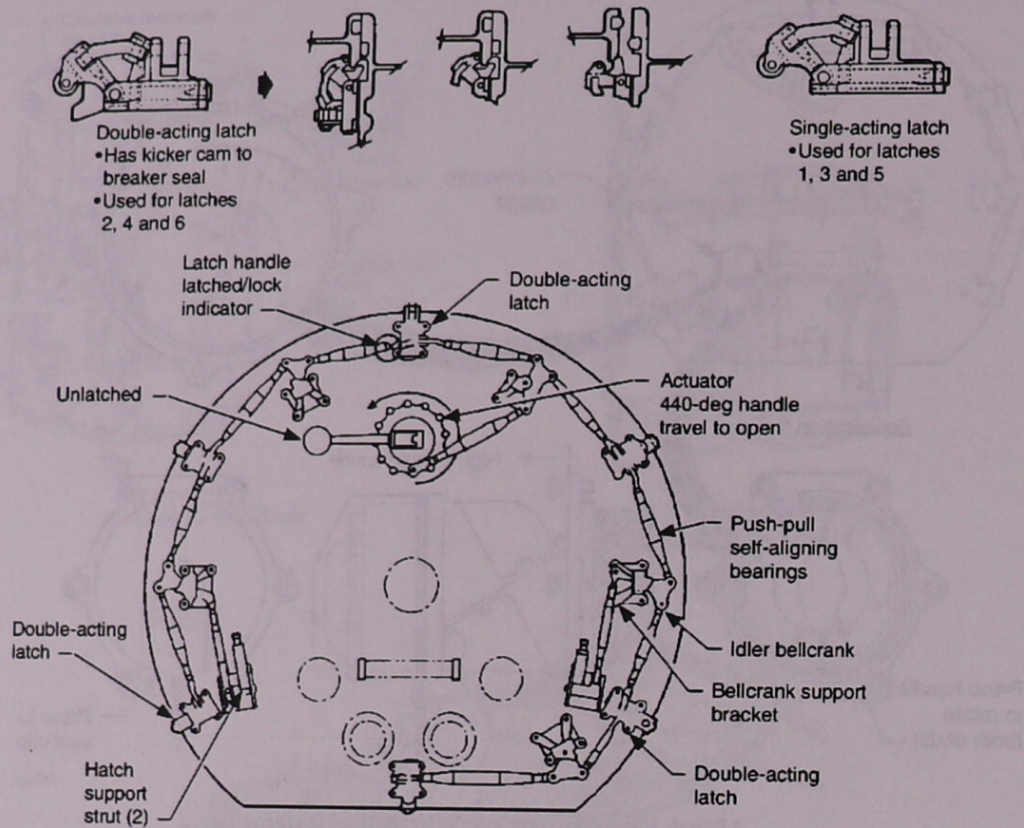


Airlock Repressurization, Schematic Diagram

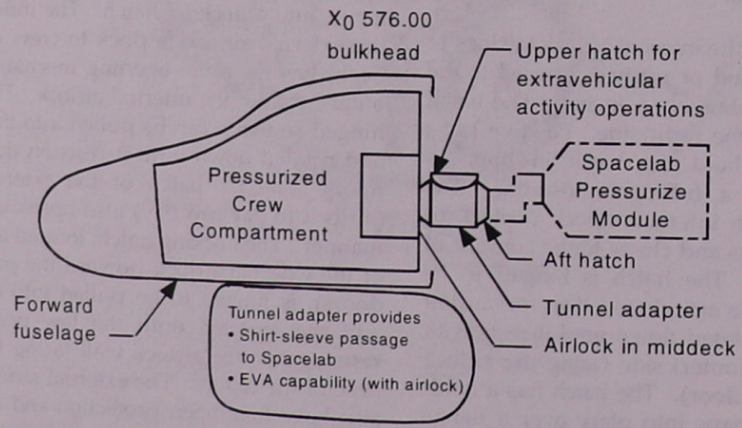
The hinge mechanism for each hatch permits a minimum opening sweep into the airlock or the crew cabin middeck.

The inner hatch of the internal airlock (airlock to crew cabin) is pulled or pushed forward to the crew cabin approximately 6 inches. The hatch pivots up and to the right side. Positive locks are provided to hold the hatch in both an intermediate and a full-open position. The outer hatch of the internal airlock (airlock to payload bay) opens and closes to the contour of the airlock wall. The hatch is hinged to be pulled first into the airlock and then forward at the bottom and rotated down until it rests with the low-pressure (outer) side facing the airlock ceiling (middeck floor). The hatch has a hold-open hook that snaps into place over a flange when the hatch is fully open. To support and protect the hatch against the airlock ceiling, the hatch incorporates two deployable struts.

The configuration of the external airlock, planned for International Space Station (ISS) operations, contains an inner hatch, an EV hatch, and a docking hatch. The inner hatch of the external airlock (airlock to crew cabin middeck) has the same opening mechanism as the outer hatch of the internal airlock. The hatch is hinged so that it can be pulled into the middeck and rotated down until it rests on the middeck floor. The EV hatch of the external airlock (airlock to payload bay) also opens in the same manner. The docking hatch, located on the floor of the external airlock (toward the payload bay doors), is hinged to be pulled into the airlock and then rotated until the low pressure side rests against the airlock wall facing toward the nose of the orbiter. The external airlock hatches also have hold-open protection and deployable struts for support against the airlock structure.



Airlock Hatch Latches, Schematic Diagram



Airlock/Tunnel Adapter

Airlock Subsystems

The airlock air circulation system provides conditioned air to the airlock during non-EVA periods. The airlock revitalization system duct is attached to the outside airlock wall at launch. Upon airlock hatch opening in flight, the duct is rotated by the flight crew through the cabin/airlock hatch and installed in the airlock. The duct has a removable air diffuser cap, installed on the end of the flexible duct, which can adjust the air flow from 216 pounds per hour. The duct must be rotated out of the airlock before the cabin/airlock hatch is closed for chamber depressurization. During the EVA preparation period, the duct is rotated out of the airlock and can be used for supplemental air circulation in the middeck.

To assist the crewmember before and after EVA operations, the airlock incorporates handrails and foot restraints. Handrails are located alongside the avionics and ECLSS panels, with aluminum alloy handholds mounted on each side of the hatches. Each handrail has a clearance of 2.25 inches between the airlock wall and the handrail to allow crewmembers to grip it while wearing a pressurized glove. Foot restraints, sized for the EMU boot, can be installed on the airlock floor nearer the payload bay side. The ceiling handhold is installed nearer the cabin side of the airlock. A rotation release knob on the foot restraint is designed for shirt-sleeve operation and, therefore, must be positioned before the suit is donned. The foot restraint is bolted to the floor and cannot be removed in flight.

Airlock-based EMU support components provide for EMU stowage, EMU operational support, and EMU recharge during intravehicular activity operations. These components include the EMU mount, the service and cooling umbilical, and the lower torso restraint bag. The EMU mount provides a mechanical interface between the EMU and airlock wall for EMU stowage. The mount attaches to the back side of the EMU and engages with three fixtures on the wall of the airlock. The mount is also used to maintain the EMU in a fixed position on orbit for EMU donning and doffing operations. If necessary, the EMU mount can be removed from the airlock wall while on orbit.

The service and cooling umbilical consists of three water hoses, a high pressure oxygen hose, electrical wiring, water pressure regulators, and a strain relief tether. The system is used to interconnect the EMU and the orbiter airlock for two major functions: electrical power, hardline communications, oxygen supply, wastewater drainage, and water cooling capability from the orbiter during IVA operation; and recharge capability for the PLSS oxygen tanks, water reservoir, and battery.

The lower torso restraint bag is attached to the bottom of the EMU mount and covers the lower torso of the EMU to restrain it during launch and entry. Straps on either side of the bag are attached to points on the upper part of the EMU mount and are tightened to ensure that the EMU is fully restrained.

For Spacelab/Spacehab module missions, the internal airlock is used along with a tunnel adapter that mates with the airlock and a Spacelab/Spacehab tunnel that is installed in the payload bay. The airlock tunnel adapter, hatches, tunnel extension, and tunnel permit the flightcrew to transfer from the orbiter's pressurized middeck compartment to the Spacelab/Spacehab pressurized shirt-sleeve environment. An upper hatch in the tunnel adapter provides egress/ingress for EVA operations. The external airlock is used in conjunction with the tunnel adapter during Spacelab/Spacehab missions when the orbiter is docked to Mir or the ISS. In the event of an EVA, the flightcrew is not present in the Spacelab/Spacehab.

EVA Support Equipment

A variety of equipment is available to support the EVA crewmember. Depending on the task to be performed, the proper tool is available outside the airlock. The general equipment functions include securing the crewmember to the orbiter/RMS, providing the crewmember with mechanical assistance, and assisting the crewmember in mobility. The following list itemizes the EVA support components with a brief description of their functions.

Crewmember safety tether - ensures the crewmember is positively tethered to the orbiter while providing access to all areas of the payload bay.

Before airlock egress, this 55-foot safety tether is attached to a waist tether and remains attached at all times during EVA, while the crewmember translates from one area of the payload bay to another.

Slidewires - facilitate the translation of a crewmember and equipment in the forward and aft directions of the payload bay. Two slide-wires are installed for all STS flights on either side of the payload bay for a length of approximately 46 feet.

Tethers - include waist and wrist tethers. Waist tethers are used to attach the crewmember to the orbiter safety tether system and to provide additional crewmember restraint at a worksite when required. Waist tethers use a large hook to be attached to various tether points (including the crewmember safety tether) and a small hook that attaches to an EMU waist tether ring. Wrist tethers are used to secure tools and hardware to the EVA crewmember and to tether points. Wrist tethers are both fixed and adjustable, attaching to loops on the EMU glove.

Handrails - aluminum tubing strategically located to aid in crewmember translation or restraint to accomplish a specific task. Handrails are located on the forward and aft bulkheads, the hingeline of the payload bay doors, and the RMS end effector. Handrails are designed with tether attach points.

Portable foot restraint - a working platform designed to restrain the EVA crewmember while performing contingency operations on various components of the payload bay systems. The portable foot restraint stabilizes the crewmember by using a system of toe guides and heel clips designed to interface with the EMU boots.

EVA Winch - allows the EVA crewmember to close the payload bay doors in the event of a payload bay door drive system failure. Prior to launch, the winch is mounted on both the forward and aft payload bay bulkheads. The winch consists of a reel, assisted by spring energy, housing 24 feet of 3/8-inch-diameter Kevlar rope with a hook attached to the free end.

Provisions stowage assembly (PSA) - an aluminum tool stowage container mounted under the cargo bay liner, flush with the bottom of the payload bay. Tool box tether protocol: when stowing the tools in the PSA, the tools/tool caddies are tethered before they are removed from the mini-workstation and untethered only after they are securely placed in their corresponding storage cavity. The tools listed below are contained within the PSA.

Mini-workstation - a mechanical device that mounts on the front of the EMU to stow tools and to provide a means of tether restraint for an EVA crewmember at a worksite.

Tube cutter - used for a contingency door-closing operation. The tool consists of spring-loaded retention rollers, a cutter wheel mounted on a slide, a blade ratchet handle, a rotating body, a control lever, and a tube-cutter ratchet handle. It is designed to cut drive door linkages.

Payload bay doors disconnect tools - used to disengage the payload bay doors power drive unit(s) (two) from the power-drive-unit torque shaft, allowing manual closing of the doors. The tool is approximately 6-3/4 inches long from the tip of the tether ring to the end of the 3/8-inch steel square drive extension. Additional tools for disconnecting the door drive linkage system include vise-grip, ratcheting box-end wrench, adjustable wrench, loop pin extractor, Velcro/tape caddy, bolt puller, and trash bag.

Three-point latch tool - used to compensate for failed bulkhead latches. The tool consists of a stowable ratchet handle, two interchangeable tool handles, a ratchet control selection lever, a spring-loaded compensator, and two fixed-load pickup points.

Centerline latch tool - used to compensate for a failed payload bay door centerline latch. The tool consists of a fixed-load and a spring-loaded pickup point, plus a reversible ratchet with a stowable handle and a pair of trigger release buttons with a safety that prevents an accidental release.

Airlock latch disconnect tool - a common, EVA-modified, crescent wrench used to force open a jammed latch and/or latches disconnected from the rotary actuator. The other contingency airlock disconnect tool is a drive ratchet with a 7/16-inch hex socket and 4-inch extension.

RMS rope reel - used in conjunction with the snatch blocks in the event of an RMS joint failure. The reel consists of a rope spool, spool bracket, rope guide, and cam cleats. The rope reel contains approximately 80 feet of 5/16-inch-diameter Kexlon rope.

Snatch block - a common marine device used, in the event of an RMS failure, in conjunction with the RMS rope reel and EVA winch to backdrive the RMS to a stowed position.

Payload retention device (PRD) - used as an on-orbit temporary tiedown tool so that the article or payload being secured can be repositioned as necessary to prevent damage. It consists of a housing that encloses a 15-foot Kevlar webbing strap on a spring-loaded reel.

RMS manipulator positioning mechanism wrench (RMS MPM wrench) - a double-ended, open-end steel wrench used to deploy or stow the MPMs (in the event the MPM motors fail) by manually turning the drive shaft in the appropriate direction, thus allowing for payload deployment and/or payload bay door closing.

RMS shoulder brace release - a flat steel bar with an angled foot used to disengage the RMS shoulder brace locking mechanism, thus releasing the shoulder brace. If the lock is not released, the RMS is inoperative.

Grapple fixture release tools - used to remove a grapple fixture shaft should an end effector malfunction, failing to release a payload. The tools include a probe and 1/2-inch ratcheting box-end wrench.

Radiator actuator disconnect tools - A 3/8-inch drive ratchet and 1/4-inch allen wrench extension used to disconnect a failed radiator actuator and support stowage of the radiators.

External tank umbilical door tool - used to override a failed external tank door centerline latch and support ET door closure.

Generic jam removal tools - diagonal cutter, cable cutter, needle nose pliers, probe, hammer, pry-bar, forceps, trash bag. For use in disconnecting or dislodging jams in various orbiter mechanisms, such as PLBD hinges, latches, etc.

Portable foot restraint (PFR) bridge clamp - provides a PFR socket that mounts on the sill of the PLB in available locations on existing bridge rails.

Simplified Aid for EVA Rescue

The simplified aid for EVA rescue (SAFER) is a small, self-contained, propulsive backpack system used to provide a free-flying rescue capability for an EVA crewmember. SAFER is a "simplified," single-string system that fits on the bottom of the EMU PLSS and attaches to existing mounts on the sides of the PLSS. In essence, SAFER is a small simplified version of the manned maneuvering unit (MMU). Because it is intended for self rescue use only, SAFER does not have the propellant capacity and systems redundancy that was provided with the MMU.

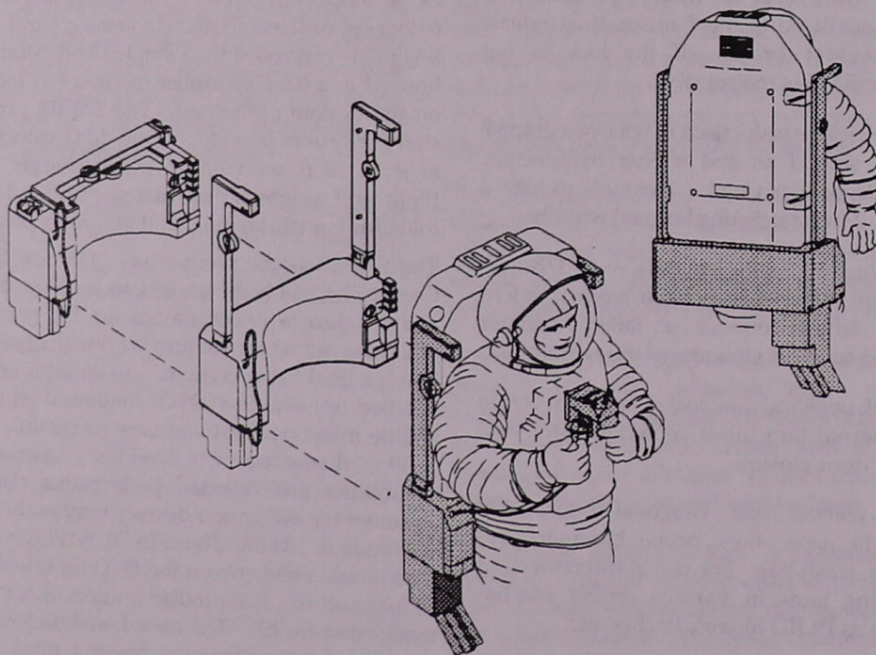
SAFER is designed to be used as a self-rescue device for a separated EVA crewmember in situations where the orbiter is unavailable to provide rescue capability. Such situations would include when the orbiter is docked to a large payload or structure, such as the Russian Mir Space Station or ISS. The SAFER will also be used during all future ISS EVA operations where the orbiter might not be present at the ISS during an EVA.

To provide self-rescue capability, the SAFER offers 13 minutes of propellant and control authority to stabilize and return a tumbling/separating EVA crewmember. The SAFER has 24 gaseous-nitrogen (GN₂) thrusters to provide 6 degrees-of-freedom maneuvering control. The SAFER is controlled by a single hand controller housed in a hand controller module box located on the bottom of the unit. The SAFER propulsion subsystem provides a total delta velocity of at least 10 ft/sec with an initial charge. The flight unit weighs approximately 85 pounds and folds for launch, landing, and on-orbit stowage.

The SAFER is the product of a Johnson Space Center (JSC) in-house project to develop, build, and produce a rescue device for the instances when the orbiter cannot provide rescue capability and for ISS EVA operations. An on-orbit SAFER detailed test objective (DTO) conducted on space shuttle mission STS-64 was very successful. This DTO demonstrated SAFER's operational capabilities and collected performance data to augment the design and development of the final operational SAFER. The STS-76 SAFER was a transitional unit between the DTO unit flown on STS-64 and the final production unit that will be manifested for ISS. The operational unit will be capable of being stationed on-orbit for 1 year; however, after use on orbit, the unit will be returned to Earth for refurbishing.



Simplified Aid for EVA
Rescue (SAFER)



Attachment of SAFER Unit to EMU

Operations

As previously discussed, there are three types of EVA: scheduled, unscheduled, and contingency. A scheduled EVA is defined as any EVA incorporated into the normal flight plan in order to complete a specific mission objective. An unscheduled EVA is not part of the flight plan; rather, it is conducted to achieve payload operation success or to advance overall mission accomplishments. A contingency EVA is also unscheduled, but is required to ensure safe return of the orbiter and flight crew.

Regardless of the EVA type, a series of procedures are required to initiate and terminate an EVA. These procedures cover an integrated timeline sequence from the EVA checklist. The detailed procedures are summarized for reference in the following steps:

1. *Quick don mask prebreathe* - Donning of the mask for prebreathe and cabin depressurization.
2. *Cabin depressurization to 10.2 psi* - Reducing the cabin pressure from 14.7 psi to 10.2 psi.
3. *EMU checkout* - Preliminary checkout of the EMU systems prior to EMU donning.
4. *Middeck preparation and preparation for donning* - Configuration of the EMU and its ancillary components for crewmember donning.
5. *Suit donning* - Crewmember donning of the EMU and ancillary components, approximately 40 minutes duration.
6. *EMU check* - Configuration and check-out of the EMU prior to EMU purge.
7. *EMU purge* - Nitrogen purge of the EMU prior to prebreathe.
8. *Prebreathe* - Crewmember acclimation to lower chamber pressure, over a period of 40 to 70 minutes.
9. *Preparation for depressurization* - Configuration of the airlock and

closing the inner hatch prior to airlock depressurization.

10. *Airlock depressurization* - Configuration and checkout of the EMU, airlock depressurization to vacuum, and opening of the outer hatch.
11. *Airlock repressurization* - Airlock repressurization and opening of the inner hatch.
12. *Post-EVA* - Shutdown of the EMU systems and doffing of the EMU and ancillary components.
13. *EMU maintenance/recharge* - Change-out or recharge of the EMU battery and lithium hydroxide cartridge and general cleaning of the EMU for subsequent EVA; recharge of the EMU water system.
14. *Post-EVA entry preparation* - Reconfiguration and restowage of the EMU and airlock equipment.

A set of procedures are followed when a crewmember has contracted the bends during an EVA. The crewmember discontinues the EVA and returns to the airlock to connect to the service and cooling umbilical. The airlock is repressed to 10.2 psia, and the cabin is repressed to 14.7 psia. The helmet is doffed, and the crewmember drinks a minimum of 32 ounces of fluids. After proper EMU reconfiguration, the bends treatment adapter is installed for bends recovery.

Scheduling an EVA is a very complex and involved task. The following list outlines the general mission constraints regarding EVA, but does not attempt to define the detailed specific activities.

- The maximum scheduled duration for an EVA is 6 hours.
- All scheduled and unscheduled EVAs require two crewmembers.
- No scheduled or unscheduled EVA shall occur on flight day 1 (~24 hours MET).

- No scheduled EVA shall be planned to occur prior to flight day 4 (~72 hours MET) unless:
 - i) A specific flight is dedicated to scheduled EVA activity, and
 - ii) That payload customer has specifically negotiated with NASA for the early scheduled EVA capability, and an exemption is processed.
 - The latest an EVA may be scheduled in preflight planning is EOM-2.
 - No unscheduled EVA shall be planned to occur prior to flight day 3 (~48 hours MET) unless:
 - i) A specific payload has no alternative but to utilize an EVA as its third level of redundancy for the purpose of a critical backup to deploy/operations that would prevent loss of the payload, and
 - ii) That payload customer has been made aware of the inherent risk that the EVA may not be able to be performed due to crew status, and the customer has agreed to accept the risk, and
 - iii) That payload customer has specifically negotiated with NASA for the early unscheduled EVA capability, and an exemption is processed.
 - The following are required response times prior to an unscheduled payload EVA:
 - i) Upon the discovery of a failure leading to an EVA, approximately 24 hours are allotted for EVA preparation prior to starting actual EVA maintenance on a failed component.
 - ii) If the case above occurs on launch day, then approximately 44 hours are allotted prior to starting EVA maintenance.
 - iii) If a payload requires a shorter EVA response time, then the requirement for that EVA must be negotiated with NASA, and an exemption must be processed.
 - Payload activities that could require an unscheduled EVA at the end of a mission may only be scheduled if there are sufficient consumables and landing opportunities to extend the mission to perform the EVA and preserve 2 wave-off days.
 - A minimum of 1 flight day must separate two scheduled EVAs, for any given EVA crewmember.
 - A contingency EVA will be scheduled in real time whenever it is necessary to restore the orbiter to a configuration for safe return.
- Contingency EVAs occur if orbiter hardware sustains a malfunction. Procedures, tools, and specified work locations are identified for practice on any STS mission. The recognized failures pertain to the following orbiter systems: radiator actuator, payload bay doors, bulkhead latches, centerline latches, airlock hatch, remote manipulator system (RMS), bulkhead camera, Ku-band antenna, and external tank doors. The corrective actions for each system failure are itemized in the following table.

FAILURE	CORRECTIVE ACTION
Radiator actuator	Radiator actuator disconnect
Payload bay door system	PDU Winch operations PLBD drive system linkage cut PLBD drive system disconnect Electrical crossover disconnect Jam removal
Bulkhead latch	3-point latch tool installation Jam removal
Centerline latch	Centerline latch tool installation Jam removal
Airlock hatch	Airlock latch disconnect Hinge disconnect
RMS	RMS joint alignment RMS tiedown MPM stow/deploy RMS shoulder brace release Grapple fixture release
Bulkhead camera	Disconnect and remove camera
Ku-band antenna fails to align for stowing	Ku-band antenna gimbal alignment
External tank door	ET door centerline latch release

System Failure Corrective Actions Table

EVA Summary Data

- EVA refers to operations performed outside the spacecraft crew compartment.
- For generic orbiter missions, two suits are included with consumables provided for three, two-person, 6-hour EVAs.
- There are three basic categories of EVA: scheduled, unscheduled, and contingency.
- The extravehicular mobility unit (EMU) is an independent anthropomorphic system that provides environmental protection, mobility, life support, and communications for the crewmember to perform EVA in Earth orbit. An EVA is defined, for EMU design considerations, as any time the EMU external environmental pressure is below 4.0.
- The EMU is an integrated assembly, primarily composed of the space suit assembly, life support system, and numerous items of associated support and ancillary equipment.
- The orbiter's airlock permits EVA flight crew members to transfer from the middeck crew compartment into the payload bay in EMUs without depressurizing the orbiter crew cabin. The airlock also provides launch and entry stowage of up to three EMUs.
- The airlock's support functions include airlock depressurization and repressurization, EVA equipment recharge, LCVG water cooling, EVA equipment checkout, donning, and communications.
- Depending on the task to be performed, the proper tool is available outside the airlock. The general EVA-support equipment functions include securing the crewmember to the orbiter/RMS, providing the crewmember with mechanical assistance, and assisting the crewmember in mobility.
- A standard series of procedures (pre and post operations) are required to initiate and terminate an EVA, regardless of the EVA type.

EVA Rules of Thumb

- Always use "make before break" tether protocol.
- Don't use the glove as a hammer.
- EVA crewmember and equipment must remain tethered at all times.
- Slow and deliberate motion provides much greater stability than quick, jerky motions.
- Body positioning is 90 percent of the task.
- Each EVA crewmember should check out his or her own EMU.

2.12 GALLEY/FOOD

CONTENTS

Description	2.12-1
Repackaged Galley	2.12-1
Volume A - Pantry	2.12-3

Description

The middeck of the orbiter is equipped with facilities for food stowage, preparation, and dining. The food supply is categorized as either menu food, pantry food, or fresh food. Meals are individually tailored, based on crewmember preference. Menu food consists of three daily meals per crewmember and provides an average energy intake of approximately 2,700 calories per crewmember per day. The pantry food is a 2-day contingency food supply that also contains food for snacks and beverages between meals and for individual menu changes. Pantry food provides an average energy intake of 2,100 calories per crewmember per day. Fresh food items consist of perishable items such as fruits and tortillas. The types of food include fresh, thermostabilized, rehydratable, irradiated, intermediate-moisture, and natural-form food and beverages.

Three 1-hour meal periods are scheduled for each day of the mission. This hour includes actual eating time and the time required to clean up. Breakfast, lunch, and dinner are scheduled as close to the usual hours as possible. Dinner is scheduled at least 2 to 3 hours before crewmembers begin preparations for their sleep period.

If a payload or the middeck accommodation rack is installed in the middeck, the repackaged galley will be manifested. The primary components (galley oven, rehydration station, hot water tank) are taken from the existing galley inventory, and have been repackaged to occupy less space. These operate in the same manner as on the larger galley. The repackaged galley was first manifested on STS-49, and has permanently replaced the larger galley. The menu trays are housed in a middeck locker.

Repackaged Galley

The repacked galley (hereafter referred to as the galley) is a multipurpose facility that provides a centralized location for one individual to handle all food preparation activities for a meal. The galley has facilities for heating food, rehydrating food, and stowing food system accessories. The galley consists of a rehydration station, oven, hot water tank, and associated controls.

Oven

The oven is divided into two principal compartments: an upper compartment designed for heating at least 14 rehydratable food containers inserted on tracks, and a lower compartment designed to accept up to 7 flexible packages. The *OVEN/RHS ON/OFF* switch provides power to the oven heaters and the control electronics assembly. The oven fan *ON/OFF* switch enables/disables power to three oven fans. These fans circulate warm air over a heat sink, thus providing forced convection heating for the rigid packages. The flexible packages are held against the heat sink by three spring-loaded plates, and warmed by conduction. The oven has a heating range of 160° to 185° F. The oven door is operated by "squeeze" latch requiring only 3 lb of pressure to open the door.

Rehydration Station Dispensing System

The galley rehydration station dispensing system interfaces directly with food and beverage packages to provide rehydration capability and drinking water for crewmembers.

When both *WATER HEATER* switches are turned on, 145° - 160° water is available for rehydration. The *VOLUME/OUNCES* switch selects the volume of water to be dispensed by the rehydration station in 0.5-ounce increments from 0.5 of an ounce to 8 ounces. The yellow *HOT* pushbutton indicator allows hot water to be dispensed when it is depressed and is illuminated when energized. When the selected volume of water has been dispensed, the pushbutton will begin to flash on and off. The light will be extinguished when the food package is retracted, releasing the rehydration station lever *ARM/LIMIT* switch.

The rehydration station lever ARM/LIMIT switch serves as an interlock so water can be dispensed only when a food package is connected to the needle. The food package makes contact with the rehydration station lever, which activates the LIMIT switch (note that the flight crew does not physically actuate the lever).

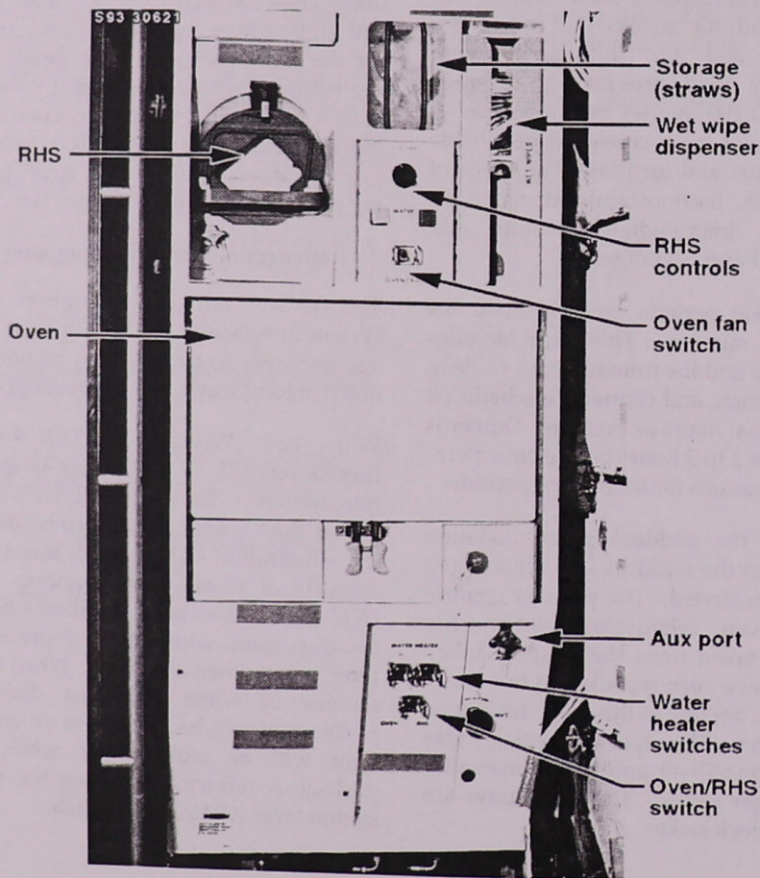
The blue COLD pushbutton indicator allows cold water to be dispensed when it is depressed and is illuminated when energized. When the selected volume of water has been dispensed, the pushbutton will begin to flash on and off. The light will be extinguished when the food package is retracted, releasing the rehydration station lever ARM/LIMIT switch.

Galley Controls

The galley controls consist of the OVEN/RHS switch, the two WATER HEATER switches, the

OVEN FAN switch, the rehydration station hot and cold pushbuttons and quantity selector dial, and the MV2 valve. Six water heater strips on the hot water tank are energized when the two WATER HEATER switches are turned on. The OVEN/RHS switch controls power to the oven heaters and rehydration pumps and associated electronics.

On the lower right-hand side of the galley (above the MV2) is an auxiliary port water quick disconnect (AUX PORT QD) that allows the crewmembers to access ambient to hot potable water when a 12-foot flex line and water dispensing valve are attached to the QD. The MV2 valve, located below the AUX PORT QD, allows the crew to control the temperature of water (hot to ambient) out of the AUX PORT. The galley also has a test port (under the rehydration station) and a canon plug (by the oven latch) that are used for ground operations.



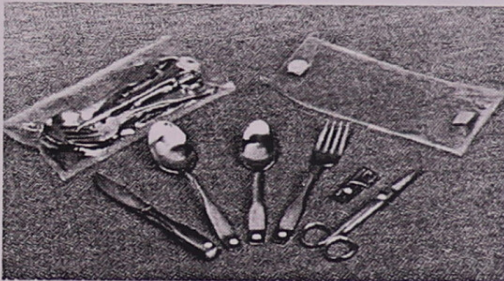
Shuttle Repackaged Galley

Volume A - Pantry

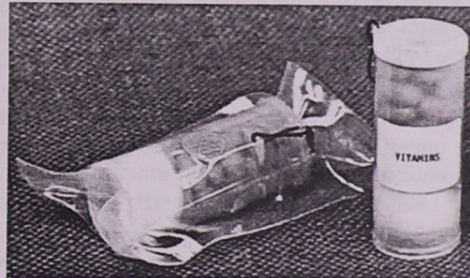
Volume A holds a hodgepodge of items in three half trays stowed upside down. Snack foods, such as almonds, dried apricots, butter cookies, candy-coated nuts, candies, granola bars, peanut butter, and dried beef, are stowed in the right-hand tray. This "free-for-all" food is available to anyone at any time and tends to be very popular. The second tray of volume A contains all the entry day weather wave-off entrees. Unlike the menu food that is packed by meals and itemized with labels, this food is stuffed into the tray in a jumble. Crewmembers are free to swap out their planned meals during the mission with items from this tray. The third tray holds reentry kits, extra drink bags, straws, and utensils. The reentry kits, also known as fluid loading kits, contain either empty drink bags and salt tablets, chicken consommé (drink packets, or Astroade packets (like Gatorade without sugar). Crewmembers must consume a certain amount of water and salt tablets, depending on their body weight, prior to entry

to aid in their readjustment to one-g. The extra drink bags are for drinking water. Drinking straws can be removed from this tray and temporarily stowed in the storage compartment of the galley for easy access. Each crewmember is provided with one set of utensils, which includes a knife, fork, tablespoon, and a small pair of scissors, for the entire flight.

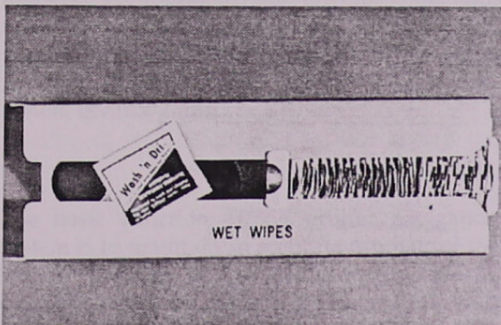
About 6 months before a flight, crewmembers attend a food tasting provided by the food systems group (SP4) to sample and rate every food and drink item, including reentry kits. Several weeks later, crewmembers individually meet with a dietitian to develop their personal menus for the flight. Choices are based on the crewmember's preferences from the tasting and on the dietitian's nutritional and caloric recommendation. Generally the food supply is more than adequate because about 30 to 50 percent of all the food manifested for flight returns unopened. The food systems people make a good effort to accommodate special requests for favorite and ethnic foods.



Utensils



Vitamins



Wet Wipes



Salt, Pepper, and Toothpicks

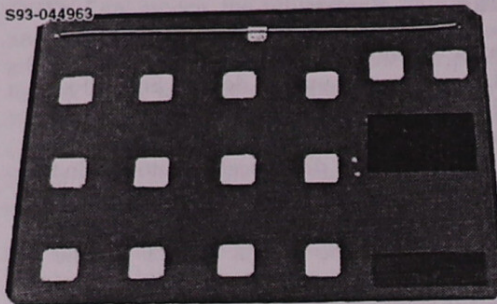
Accessories

Accessories consist of gum and candy, vitamins, wet wipes, and the galley adapter. The galley adapter is a removable piece of the galley slide/adapter mechanism. The wet wipes dispenser is launched in place in the galley as well. This spring-loaded dispenser initially contains 100 wet wipes. As they are used up, crewmembers can use the Consumables cue card (unofficial) or the Reference Data stowage list to locate more wet wipes for the dispenser.

Trays

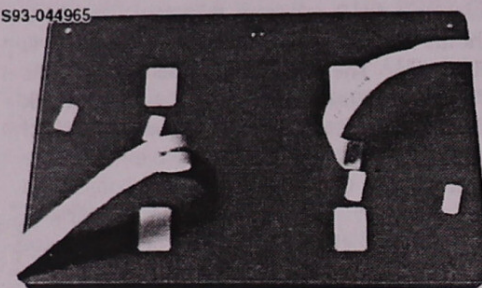
After the dehydrated foods were repackaged into nonrigid containers and after cans were demanifested, the old food trays lost their specific usefulness, and new trays were designed. The new tray consists of a flat piece of aluminum with magnets and Velcro patches for holding utensils, food, and drink packets. These trays are lighter than the old trays and generally are preferred by the crews. Crewmembers either can Velcro the trays to a wall (ceiling/floor) or can strap the trays to one of their legs for use. The strap on the underneath side has been modified so that it fits over the right or the left thigh (not both).

S93-044963



Top of Tray

S93-044965



Bottom of Tray

2.13 GUIDANCE, NAVIGATION, AND CONTROL (GNC)

CONTENTS

Description	2.13-1
Navigation Hardware.....	2.13-5
Flight Control System Hardware	2.13-26
Digital Autopilot.....	2.13-46
Operations	2.13-53
GNC Caution and Warning Summary.....	2.13-62
GNC Summary Data.....	2.13-63
GNC Rules of Thumb	2.13-70

Description

Guidance is the computation of corrective actions to change from the navigation-determined vehicle state to a required vehicle state. The required state depends on particular mission requirements. Mission requirements usually specify a required present state (e.g., a particular orbit) or an objective (e.g., rendezvous at a point in space) from which the present required state can be computed.

Navigation is the determination of the state of motion of the vehicle; i.e., position, velocity, and attitude. This state is determined with reference to some mission-dependent coordinates suitable for defining the motion of the vehicle.

Control is the application of corrective maneuvers to obtain the changes commanded by guidance. Flight control for the orbiter converts guidance computations into effector commands to point and translate the vehicle. Control software frequently uses navigation data to determine the effectors used and the appropriate system control gains.

State Vector

The basic function of the orbiter navigation system is to maintain an accurate estimate of the inertial position and velocity of the vehicle, called its state vector, with respect to time. In addition, during a rendezvous mission, the navigation system must also maintain an estimate of a target's position and velocity. This information is then used by the onboard guidance system to compute the commands required

to transfer the vehicle from one position and velocity to another, as well as to point the vehicle at a specified target (Earth, Sun, another orbiting vehicle, etc.). The state vector data are also used by the ground controllers for monitoring the health of the onboard navigation system. Information about the orbiter and target state vectors is displayed to the crew on the dedicated displays and GNC CRT displays.

The navigation system maintains its knowledge of the orbiter's position and velocity with a group of six parameters (X, Y, Z, V_x, V_y, V_z) defining the state vector. A time tag is also associated with this state vector. The X, Y, Z components are the orbiter's position in the Mean of 1950 (M50) coordinate system measured in feet from the center of the Earth. The velocity components are measured in feet per second, and are also in the M50 coordinate system. The time at which the state vector is applicable is based on Greenwich mean time (GMT).

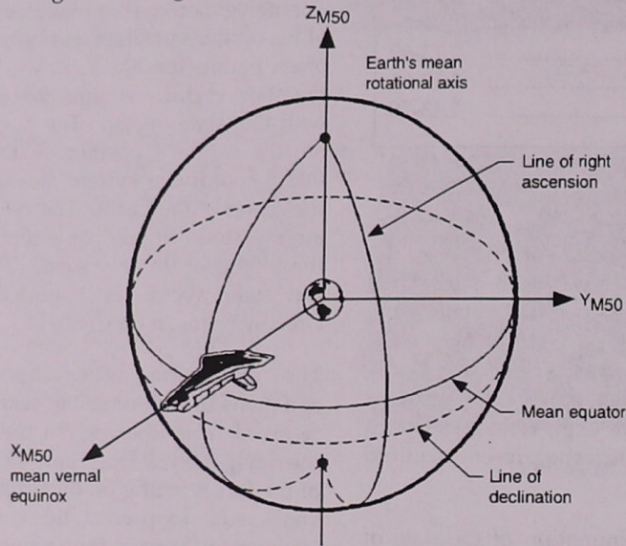
The navigation system uses the standard equations of motion along with the information received from the inertial measurement units, the navigation sensors, and the software models of the forces acting on the orbiter (gravity, drag, vents, etc.) to predict the components of the state vector at each time value. This process is called state vector propagation, a scheme in which errors are inherent. The equations of motion and the propagation technique are approximations, as are the gravity, drag, and vent models. In addition, the acceleration, position, and range rate information received from the inertial measurement units and the navigation sensors is also prone to error. To correct these errors, which increase with time, the ground controllers periodically uplink a new state vector or a delta to the current onboard state based upon the more accurate ground radar tracking data.

The release of OI-27 flight software (FSW) will begin the process of replacing the orbiter tactical air navigation (TACAN) system with a global positioning system (GPS). GPS is designed to provide the navigation system with an alternate source of orbiter state vector data throughout the orbit and entry phases of flight. GPS hardware installation onto each vehicle is determined by the orbiter maintenance down period (OMDP) schedule. As a result, a mixed

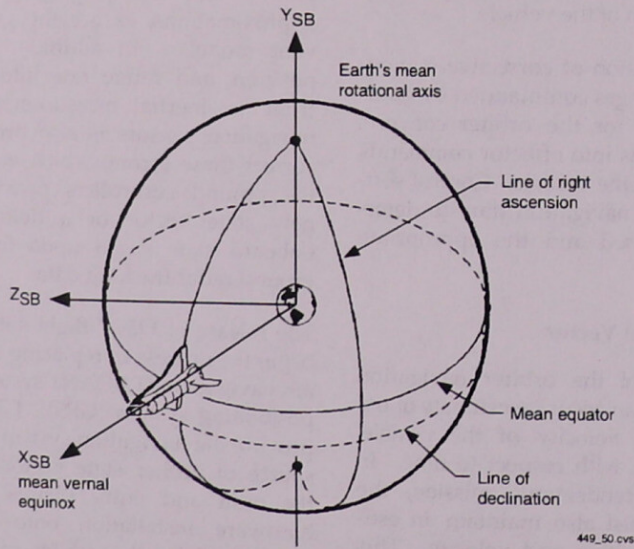
fleet operation of either triple-string TACAN or triple-string GPS will continue. Some orbiters may be equipped with a single GPS unit as part of the OI-26B development test objectives (DTOs). However, at this time there are no plans to operate the navigation software in other than a triple-string TACAN mode for these orbiters. The OI-27 FSW will support each option. This section addresses both triple-string TACAN and triple-string GPS configurations.

WARNING

Control software uses state vector information to select control effectors and set control gains, especially during entry. Large navigation errors can cause the orbiter to depart controlled flight.



M50 Coordinate System



Starball Coordinate System

449_50.cvs

Coordinate Systems

The position and velocity of the orbiter must be uniquely defined in terms of an inertial coordinate system - a reference frame that is neither rotating nor accelerating. Such a system ensures that the normal equations of motion are valid. The onboard navigation system uses the M50 inertial system. However, some computations are considerably simpler if performed in other coordinate systems. For example, when landing the orbiter, the position of the vehicle relative to the runway is more meaningful than its position in a coordinate system fixed in space. Therefore, the onboard navigation system uses a number of different coordinate systems to simplify the various inputs, outputs, and computations required. These inputs and outputs can be expressed in any coordinate system by using coordinate transformations resident in the navigation software.

All the coordinate systems referenced are right-handed Cartesian systems. These right-handed systems have three mutually perpendicular axes, sequentially ordered such that each axis satisfies the application of the right-hand rule to the other two axes (XYZ system: applying right-hand rule to X-Y yields Z, to Y-Z yields X, and to Z-X yields Y).

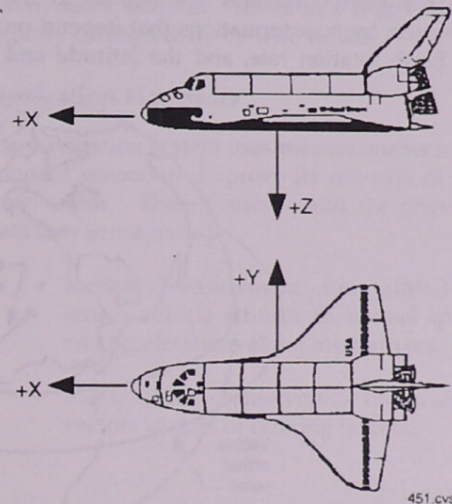
Body Axis Coordinate System

The body axis coordinate system maintains the origin at the orbiter's center of mass with the three axes stemming from that point. The X axis is parallel to the X_0 axis of the orbiter structural body (orbiter + external tank + solid rocket boosters) and lies in the orbiter plane of symmetry. The positive direction is toward the nose. The Z axis lies in the orbiter plane of symmetry and is perpendicular to the X axis. The positive direction is opposite the payload bay. The Y axis completes the right-handed orthogonal system and points out of the right wing. Note that vehicle pitch is a rotation about the Y body axis, roll is a rotation about the X body axis, and yaw is a rotation about the Z body axis.

M50 Coordinate System

The inertial coordinate system used by the onboard navigation system is the Aries Mean of 1950 Cartesian system, generally called the M50 system. The M50 system is used to establish and maintain the inertial position and velocity

of the orbiter during all flight phases. The X axis points toward the mean vernal equinox (the apparent point on the celestial sphere where the Sun crosses the Earth's equator on its northward journey) of the year 1950. The Z axis points along Earth's mean rotational axis of 1950 with the positive direction toward the North Pole. The Y axis completes the right-handed system, with the corresponding X-Y plane lying in the plane of the equator. Note that this is an inertial system and, although its origin is at the Earth's center, the M50 system is completely independent of the Earth's rotation.



Body Axis Coordinate System

Starball Coordinate System

The Starball coordinate system, a variation of the M50 system, is described by rotating the M50 system by 90° about the X axis. The Starball orientation makes the pitch angle equivalent to the right ascension and the yaw angle equivalent to declination, thus simplifying maneuvers to point at stars. This coordinate system is seldom, if ever, used.

Local Vertical/Local Horizontal Coordinate System

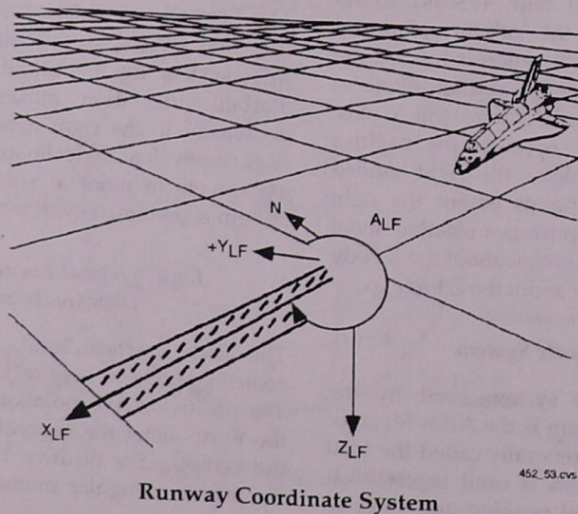
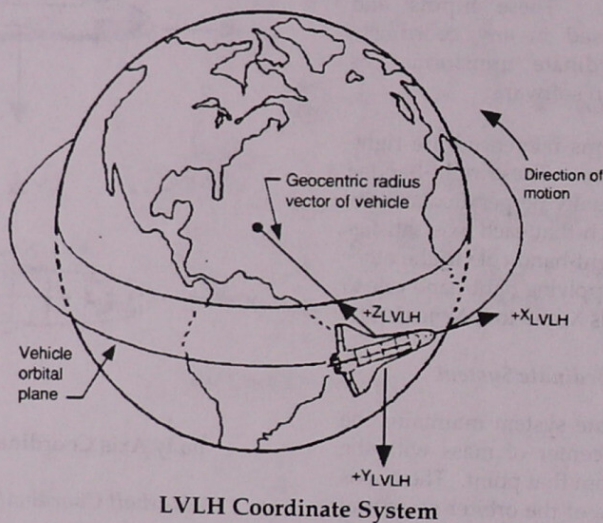
The local vertical/local horizontal (LVLH) coordinate system is an orbiter-centered system. The positive Z axis points toward the center of the Earth along the geocentric radius vector of the vehicle. The positive Y axis points toward the negative angular momentum vector of the

vehicle's orbit. The X axis completes the right-hand rule with positive X along the vehicle's direction of motion in the orbital plane. The LVLH system allows the crew to see the attitude of the orbiter in relation to the Earth's surface. It is not an inertial system, because it rotates at approximately 4°/minute with respect to the inertial frame.

Runway Coordinate System

For launch, landing, and Earth observation, it is advantageous to know the orbiter's position and velocity in coordinate systems fixed to the Earth. These non-inertial systems are related to the M50 system by transformations that depend on time, Earth rotation rate, and the latitude and

longitude of the point of interest. The runway coordinate system is a good example of an Earth-fixed reference frame. The origin of the system is placed at the runway center at the approach threshold. The Z axis is normal to the ellipsoid model through the runway centerline and positive toward the center of the Earth. The X axis is perpendicular to the Z axis and lies in a plane containing the Z axis and the runway centerline (positive in the direction of landing). The Y axis completes the right-hand rule. Note that A is the runway azimuth measured in the X-Y plane from true north to the positive X axis (positive clockwise). The runway coordinate system is used by navigation and the crew during ascent, entry, and landing phases of flight.



Guidance, Navigation, and Control Software

Guidance, navigation, and control (GNC) software commands the GNC system to effect vehicle control and to provide sensors and controllers with the data needed to compute these commands. The process involves three steps:

1. Navigation tracks the vehicle's actual location.
2. Guidance equipment and software compute the orbiter location required to satisfy mission requirements.
3. Flight control transports the orbiter to the required location.

During launch and ascent, most of the GNC commands are directed to gimbal the three SSMEs and two SRBs to maintain thrust vector control. The GNC software also controls SSME burns for maximum aerodynamic loading of the vehicle during ascent, referred to as max q. To circularize the orbit and perform on-orbit and deorbit maneuvers, the GNC software commands the orbital maneuvering system (OMS) engines. At external tank separation, on orbit, and during portions of entry, GNC controls commands to the reaction control system (RCS). In atmospheric flight, GNC controls the orbiter aerodynamic flight control surfaces.

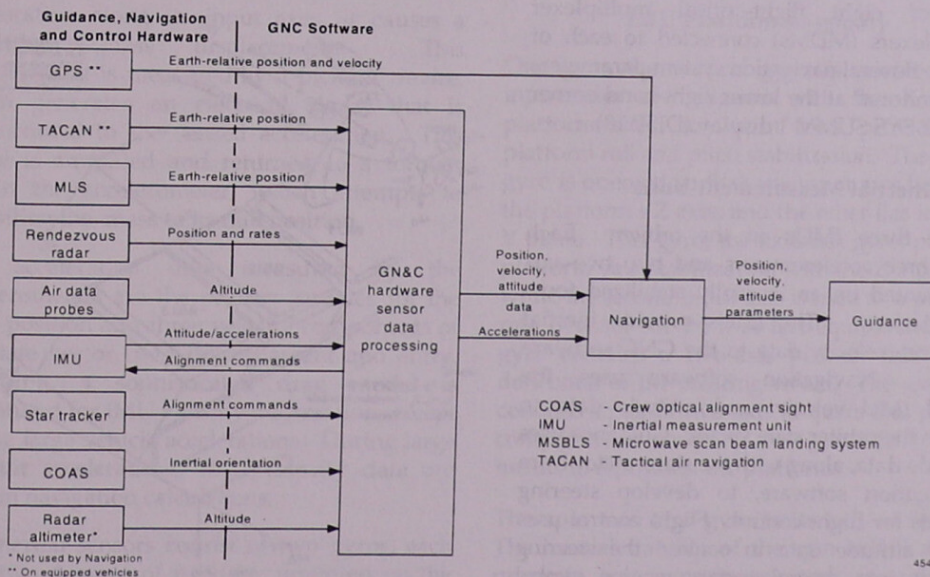
Control Modes

The GNC system consists of two operational modes: automatic and control stick steering. In the automatic mode, the primary avionics software system (PASS) essentially allows the GPCs to fly the vehicle. The flight crew may control the vehicle in the control stick steering mode using hand controls, such as the rotational hand controller. In the control stick steering mode, flight crew commands must still pass through and be issued by the GPCs. There are no direct mechanical links between the flight crew and the orbiter's various propulsion systems or aerodynamic surfaces. The orbiter is an entirely digitally controlled, fly-by-wire vehicle.

Navigation Hardware

The navigation system uses measurements from onboard sensors to improve its estimate of the state vector. These sensors and the physical data they sense include:

- Inertial measurement unit (IMU) -- senses vehicle attitude in inertial space and accelerations along inertial axes.
- Star trackers -- sense vehicle line of sight vectors to stars or orbiting targets.



Navigation Interfaces

- Crew optical alignment sight (COAS) -- allows the crew to visually align the vehicle line of sight to stars or orbiting targets. The head up display (HUD) test pattern also allows the crew to visually align the vehicle line of sight to the stars. The HUD serves as the backup to the star trackers.
- Tactical air navigation (TACAN) -- senses vehicle position with respect to a ground-based TACAN station.
- Air data system -- senses air temperature and pressure in free stream and air disturbed by vehicle.
- Microwave landing system (MLS) -- senses vehicle position with respect to ground stations alongside the landing runway.
- Radar altimeters (RA) -- sense vehicle altitude above the ground.
- GPS - senses satellite ranging signals to determine position and velocity.

NOTE:

Radar altimeter altitude is not used for navigation or guidance. The information is displayed for the crew to monitor.

Each piece of navigation hardware is hard-wired to one of eight flight-critical multiplexer /demultiplexers (MDMs) connected to each of five GPCs. Several navigation system parameters can be monitored at the lower right-hand corner of the GNC SYS SUMM 1 display (DISP 18).

Inertial Measurement Units

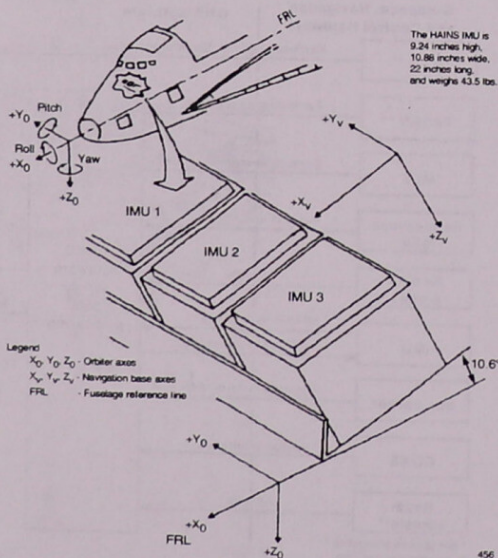
There are three IMUs on the orbiter. Each contains three accelerometers and two two-axis gyros mounted on an inertially stabilized four-gimbal platform. The IMUs provide inertial attitude and velocity data to the GNC software functions. Navigation software uses the processed IMU velocity and attitude data to propagate the orbiter state vector. Guidance uses the attitude data, along with the state vector from the navigation software, to develop steering commands for flight control. Flight control uses the IMU attitude data to convert the steering commands into control surface, engine gimbal (thrust vector control), and RCS jet fire commands.

RCS		JET	ISOL	GNC SYS SUMM 1			1 000/02:46:03 000/00:00:00				
MANF	FATH	VLV	SURF	POS	MCM	DPS	1	2	3	4	5
F1		OP	L OB			GPC					
2		OP	IB			MDM FF					
3		OP	R IB			FA					
4		OP	OB								
5		OP	AIL								
L1		OP	RUD			FCS CH	1	2	3	4	
2		OP	SPD BRK								
3		OP	BDY FLP								
4		OP									
5		OP				NAV	1	2	3	4	
R1		OP				IMU					
2		OP	CNTLR	1	2	3	ACC				
3		OP	RHC	L			RGA				
4		OP		R			TAC				
5		OP		A			MLS				
			THC	L			ADTA				
				A							
			SBTC	L							
				R							

**GNC SYS SUMM 1 Display
(Three-String TACAN Vehicles)**

RCS		JET	ISOL	GNC SYS SUMM 1			1 000/02:46:03 000/00:00:00				
MANF	FATH	VLV	SURF	POS	MCM	DPS	1	2	3	4	5
F1			L OB			GPC					
2			IB			MDM FF					
3			R IB			FA					
4			OB								
5			AIL								
L1			RUD			FCS CH	1	2	3	4	
2			SPD BRK								
3			BDY FLP								
4											
5						NAV	1	2	3	4	
R1						IMU					
2			CNTLR	1	2	3	ACC				
3			RHC	L			RGA				
4				R			GPS				
5				A			MLS				
			THC	L			ADTA				
				A							
			SBTC	L							
				R							

**GNC SYS SUMM 1 Display
(Three-String GPS Vehicles)**



Inertial Measurement Units

Although flight could be accomplished with only one IMU, three units are installed on the orbiter for redundancy. The IMUs are mounted on the navigation base, which is located inside the crew compartment flight deck forward of the flight deck control and display panels. The base provides a platform on which the IMUs can be repeatedly mounted with great accuracy, enabling the definition of transformations that relate IMU reference frame measurements to any other reference frame.

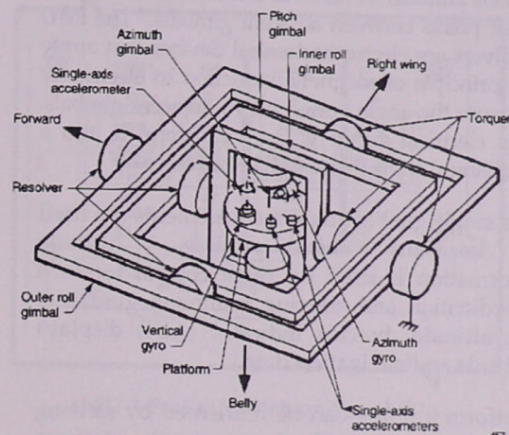
The IMU consists of a platform isolated from vehicle rotations by four gimbals. Since the platform does not rotate with the vehicle, its orientation remains fixed, or inertial, in space. The gimbal order from outermost to innermost is outer roll, pitch, inner roll, and azimuth. The platform is attached to the azimuth gimbal. The inner roll gimbal is a redundant gimbal used to provide an all-attitude IMU, while preventing the possibility of gimbal-lock (a condition that can occur with a three-gimbal system and can cause the inertial platform to lose its reference). The outer roll gimbal is driven from error signals generated by disturbances to the inner roll gimbal. Thus, the inner roll gimbal will remain at its null position, orthogonal to the pitch gimbal.

The IMUs have three accelerometers, one on each of the X, Y, and Z axes. The accelerometer is basically a force rebalance-type instrument. When the accelerometer experiences an acceleration along its input axes, it causes a pendulum mass displacement. This displacement is measured by a pick-off device, which generates an electrical signal that is proportional to the sensed acceleration. This signal is amplified and returned to a torquer within the accelerometer, which attempts to reposition the mass to its null position.

The acceleration data measured by the accelerometers are the primary sources for the three position and three velocity components of the state vector used during ascent and entry. On orbit, a sophisticated drag model is substituted for IMU velocity information, except during large vehicle accelerations. During large on-orbit accelerations, IMU velocity data are used in navigation calculations.

The inertial sensors consist of two gyros, each with two degrees of freedom, mounted on the cluster platform. Angular motion about any

axis perpendicular to the spin axis causes rotation about a third orthogonal axis, which is electrically sensed. In response to this sensed rotation, the appropriate gimbals are torqued to null the gyro rotation. This gimbal torquing in response to vehicle motion results in an inertially stabilized platform. In addition, the gyros may be pulse torqued (small angles) or slewed (large angles) by software, which results in gimbal torquing to position or reposition the platform. Each gimbal has a coarse (one-speed or 1X) resolver and a fine (eight-speed or 8X) resolver. The resolver readouts are sent to the data processing system, which determines the gimbal angles, which in turn determine the attitude of the orbiter.



IMU Platform Assembly

One gyro, the vertical gyro, is oriented so its input axes are aligned with the X and Y platform axes; its input axes provide IMU platform roll and pitch stabilization. The second gyro is oriented so that one input axis lies along the platform's Z axis, and the other lies in the X-Y plane. This gyro, the azimuth gyro, provides platform yaw stabilization with the Z input axis, while the second input axis is used as a platform rate detector for built-in test equipment. Each gyro contains a two-axis pick-off that senses deflection of the rotating wheel. The gyro also contains a pair of two-axis torquers that provide compensation torquing for gyro drift and a means to reposition the platform.

The spin axis of a gyro is its axis of rotation. The inertial stability of the spin axis is a basic property of gyroscopes and is used in stabilization loops, which consist of the gyro

pick-off, gimbals, and gimbal torquers. When the vehicle is rotated, the platform also tends to rotate due to friction at the gimbal pivot points. Because the gyro casing is rigidly mounted to the platform, it will also rotate. The gyro resists this rotation tendency to remain inertial, but the resistance is overcome by friction. This rotation is detected by the pick-offs as a deflection of the rotating gyro wheel. A signal proportional to this deflection is sent to the gimbal electronics, which route the signals to the appropriate torquers, which in turn rotate their gimbals to null the pick-off point. When the output is nulled, the loop is closed.

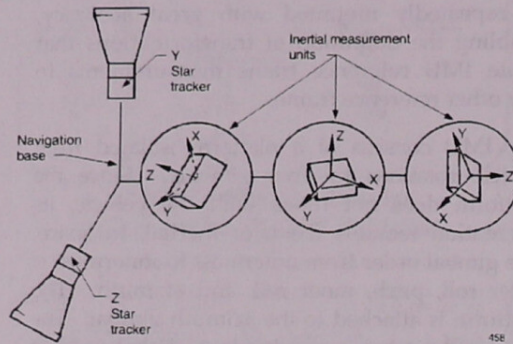
Four resolvers in an IMU are used to measure vehicle attitude. A resolver is located at one of two pivot points between adjacent gimbals. The IMU resolvers are electromechanical devices that apply the principle of magnetic induction to electrically measure the angle between two adjacent gimbals. This electrical signal is then transformed into a mechanical angle by the IMU electronics.

The single gimbal angle measurements are used to determine vehicle attitude. Attitude information is used by flight control for turn coordination and steering command guidance. An attitude director indicator (ADI) displays attitude and navigation data.

Platform attitude can be reoriented by slewing or pulse torquing. Slewing rotates the platform at a high rate (1.2° per second), and pulse torquing rotates it very slowly ($.007^\circ$ per second). Platform reorientation relies on another property of gyroscopes: precession. If a force is applied to a spinning gyroscope, the induced motion is 90° from the input force. In each IMU, a two-axis torquer is located along the input axes of both gyros. Commands are sent to the torquers from the GPC to apply a force along the input axes. The result is a deflection of the gyro spin axis that is detected and nulled by the stabilization loops. Because the gyro spin axis is forced to point in a new direction, the platform has to rotate to null the gyro outputs.

The three IMUs have skewed orientations: their axes are not co-aligned and not aligned with the vehicle axes. This is done for two reasons. First, gimballed platforms have problems at certain orientations. Skewing ensures that no more than one IMU will have an orientation problem for a

given attitude. Second, skew allows resolution of a single-axis failure on one IMU by multiple axes on another IMU since the possibility of multiple-axis failure is more remote. Skewing is also used by redundancy management to determine which IMUs have failures.



IMU Skew

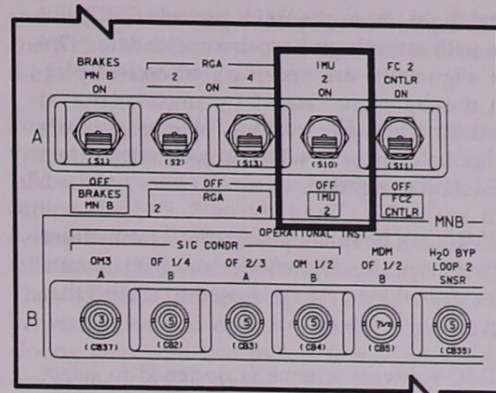
Each IMU contains heaters, temperature sensors, and built-in test equipment (BITE). Very precise thermal control must be maintained in order to meet IMU performance requirements. The IMU thermal control system consists of an internal heater system and a forced-air cooling system. The internal heater system is completely automatic and is activated when power is initially applied to the IMU. It continues to operate until the IMU is powered down. The forced-air cooling consists of three fans that serve all three IMUs. Each IMU fan is controlled by an individual IMU FAN switch located on panel L1. Only one fan is used at a time; three are provided for redundancy.

Each IMU is supplied with redundant 28-volt dc power through two separate remote power controllers. The IMU 1, 2, and 3 power switches are located on panels O14, O15, and O16. Loss of one control bus or one main bus will not cause the loss of an IMU.

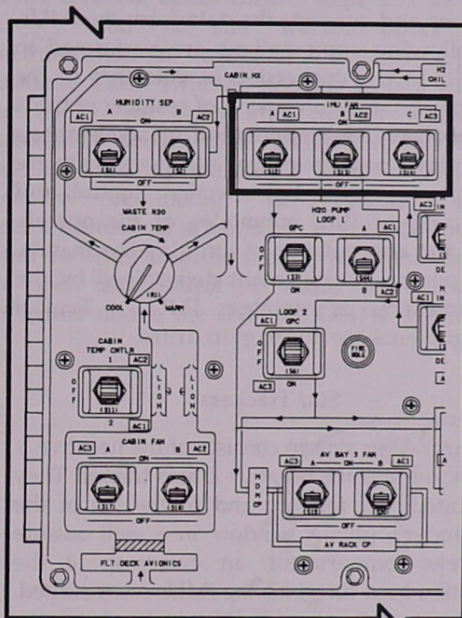
Each IMU has two modes of operation, a warmup/standby mode and an operate mode. When an IMU switch is positioned to ON, the IMU is powered in the warm-up/standby mode, which applies power only to the heater circuits. It takes approximately 8 hours from cold start for the IMU to reach its operating temperature range, at which time the IMU enters a standby mode. A software command in GNC OPS 2, 3, or 9

transitions the IMU to the operate mode. To mode the IMU to operate, the controlling GPC sends the operate discrete to the IMU through the flight forward MDM. The IMU, upon receiving this command, initiates its run-up sequence.

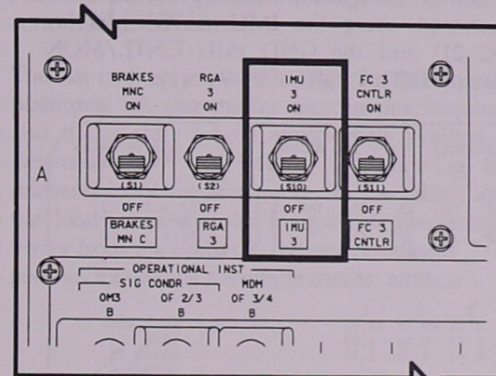
The run-up sequence first cages the IMU, a process of reorienting the IMU gimbals and then mechanically locking them into place so that the gyros may begin to spin. When the IMU is caged, its platform orientation is known when it becomes inertial. The caged orientation is defined as the point at which all resolver outputs are zero. Inner roll and azimuth must always be at 90° angles to each other.



IMU 2 Power Switch on Panel O15



IMU FAN ON/OFF Switches on Panel L1

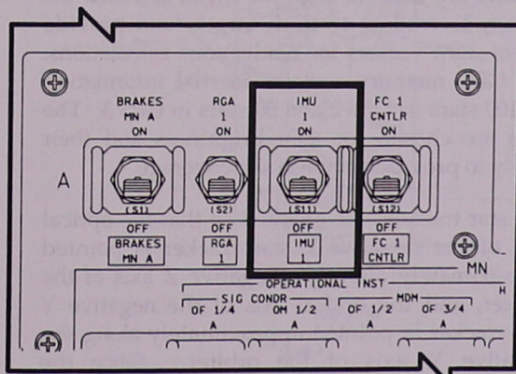


IMU 3 Power Switch on Panel O16

Once the IMU gimbals are caged, the gyros begin to spin, and power is applied to the remaining IMU components. When the gyros have reached the correct spin rate, the stabilization loops are powered, and the IMU becomes inertial. At this time, the IMU returns an in-operate-mode discrete to the GPC, indicating that the run-up sequence is complete. This process requires approximately 85 seconds.

The IMUs are in operate by the time the flight crew enters the vehicle before launch and remain in that state for the duration of the flight, unless powered down to minimize power consumption. While in the operate mode, the IMU maintains its inertial orientation and is used for calibration and preflight, on-orbit, and entry alignments.

During ascent, the IMUs provide accelerometer and resolver data to the GNC software to propagate the state vector, determine attitude, and display flight parameters. During the



IMU 1 Power Switch on Panel O14

orbital flight phase, the IMUs provide GNC software with attitude and accelerometer data. On-orbit alignments are necessary to correct platform misalignment caused by uncompensated gyro drift. During entry, IMU operation differs only in the manner in which accelerometer data are used by navigation.

The IMUs can be safely powered off from either the warmup/standby mode or the operate mode. A braking system is used to ensure that the gyros have slowed to a stop.

The IMU software scheme is designed to select the best data for GPC use and to detect system failures. This scheme is referred to as redundancy management. IMU parameters can be accessed using the IMU ALIGN display (SPEC 21) and the GND IMU CNTL/MON display (SPEC 104)(GNC OPS 9 only).

3011/021/			IMU ALIGN			1 006/09:34:09		
IMU						000/00:00:00		
STAT	1	2	3					
TEMP	OK	OK	OK	IMU	1 10	STAR ALIGN	13*	
STBY	21	22	23		2 11	14 IMU/IMU		
OPER	4*	5*	6*		3 12	MATRIX	15	
DES	7	8	9					
								EXEC 16
								TERM 17
ACC								
X	-0.03	+0.01	-0.03			IMU BITE MASK		
Y	-0.02	-0.01	+0.03			1 0000	24	
Z	-0.01	-0.02	-0.03			2 0000	25	
						3 0000	26	
ANG								
X	299.07	299.16	299.12					
Y	339.17	339.09	339.14			NAV ΔV THRESH		
Z	160.65	160.72	160.64			18	3840	
ΔX	+0.00	+0.00	+0.00					
ΔY	+0.00	+0.00	+0.00			MM READ	19	
ΔZ	+0.00	+0.00	+0.00					

IMU ALIGN Display (SPEC 21)

9011/104/			GND IMU CNTL/MON			2 150/12:20:13		
IMU						000/00:44:47		
X	1	0.00	4	0.00	7	0.00	SEL IMU	1 16*
Y	2	0.00	5	0.00	8	0.00		2 17*
Z	3	0.00	6	0.00	9	0.00		3 18*
O	83.62	192.88	297.47	AIT DET	19			
M	23.65	301.81	26.65	HNGR CAL A	20			
I	99.91	42.01	351.09		B 21			
IR	0.00	0.00	0.00		C 22			
DV X	-10.72	+ 9.50	+25.73	PREFLT CAL	23			
Y	+27.14	+ 6.88	- 9.28	GYROCOMP	24			
Z	-13.24	+29.74	-16.57					
DVRSS	32.04	31.96	31.98	INERTIAL	25*			
B HDW	8000	8000	8000	PLAT POS	26			
I S/W	00	00	00	TERM/IDLE	27			
STAT	3F	3F	3F	28 MM WRITE	1			
PWR ON	*	*	*	READ	29			
I/O				MM STATUS				
STBY	10	11	12	30 SITE SEL	7			
OPER	13*	14*	15*	ACTUAL	39B			

GND IMU CNTL/MON Display (SPEC 104)
(available in OPS 9 only)

In the event of an IMU dilemma, the IMU caution and warning light on panel F7 will be illuminated. (The light will not illuminate for a redundancy management fail.) If temperatures are out of limits or if BITE detects a failure, a fault message (IMU BITE/T X) and SM ALERT will be annunciated.

The accuracy of the IMU deteriorates with time. If the errors are known, they can be physically or mathematically corrected. Software based on preflight calibrations is used to compensate for most of the inaccuracy. The star trackers are used to determine and correct additional errors.

The IMU subsystem operating program (SOP) processes and converts the data from the IMUs. The following computations are performed in the IMU SOP: conversion of velocities to the M50 coordinates; conversion of resolver outputs to gimbal angles; computation of accelerations for displays; performance of additional software BITE checks; support of selection, control, and monitoring of IMU submodes of the operate mode; and computation of torquing commands, based on the misalignment determined by the star trackers or another IMU. Typical misalignments are due to gyro drifts.

Star Trackers

The star tracker system consists of the negative Y axis tracker and the negative Z axis tracker. They are located just forward and to the left of the commander's plus X window in a well outside the crew compartment, an extension of the navigation base on which the IMUs are mounted. The star trackers are slightly inclined off the vehicle axes for which they are named. The star trackers are used to align the IMUs onboard the orbiter, as well as to track targets and provide line-of-sight vectors for rendezvous calculations. The GPC memory contains inertial information for 100 stars in OPS 2 and 50 stars in OPS 3. The stars are chosen for their brightness and their ability to provide complete sky coverage.

The star trackers are oriented so that the optical axis of the negative Z star tracker is pointed approximately along the negative Z axis of the orbiter, and the optical axis of the negative Y star tracker is pointed approximately along the negative Y axis of the orbiter. Since the navigation base provides the mount for the

IMUs and star trackers, the star tracker line of sight is referenced to the navigation base and the orbiter coordinate system; thus, the GPC knows the star tracker's pointing direction and its orientation with respect to the IMUs.

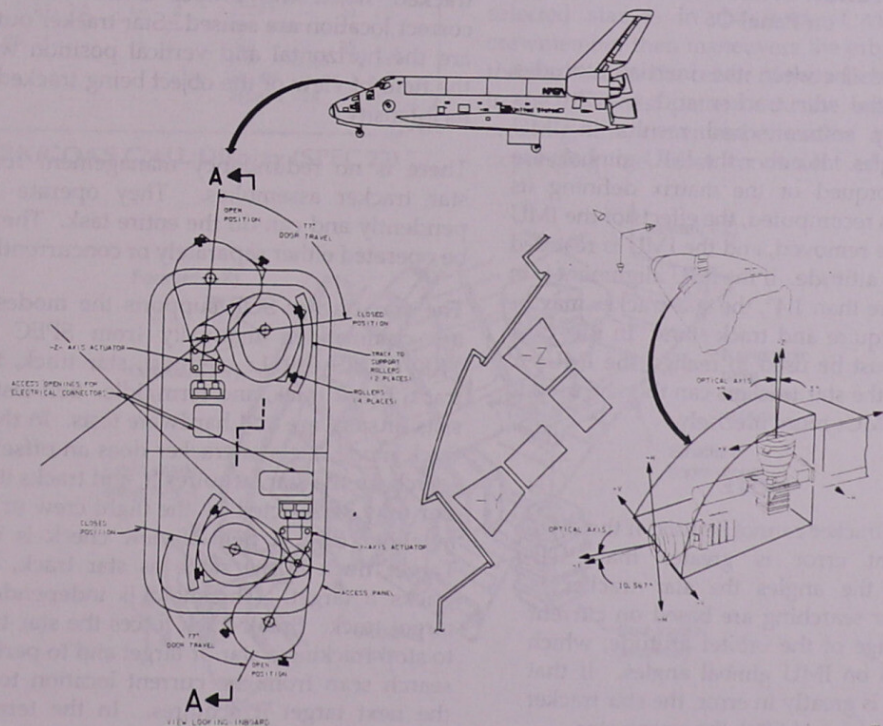
Each star tracker has a door to protect it during ascent and entry. The doors are opened on orbit to permit use of the star trackers. To enable the star tracker doors to open, the STAR TRACKER POWER -Y and -Z switches on panel O6 must be positioned to ON. The STAR TRACKER DOOR CONTROL SYS 1 and SYS 2 switches on panel O6 control two three-phase ac motors on each door. Positioning the SYS 1 switch to OPEN controls motor control logic and drives the -Y and -Z star tracker doors by electromechanical actuators to the open position. Limit switches stop the motors when the doors are open and control talkback indicators above the DOOR CONTROL switches. Setting the SYS 2 switch to OPEN controls redundant ac motors and electromechanical actuators to open both doors. Limit switches stop the motors when the doors are open and control the same two talkback indicators above the DOOR CONTROL SYS 1

and SYS 2 switches. Normally, both the SYS 1 and SYS 2 switches are used together to actuate the star tracker doors.

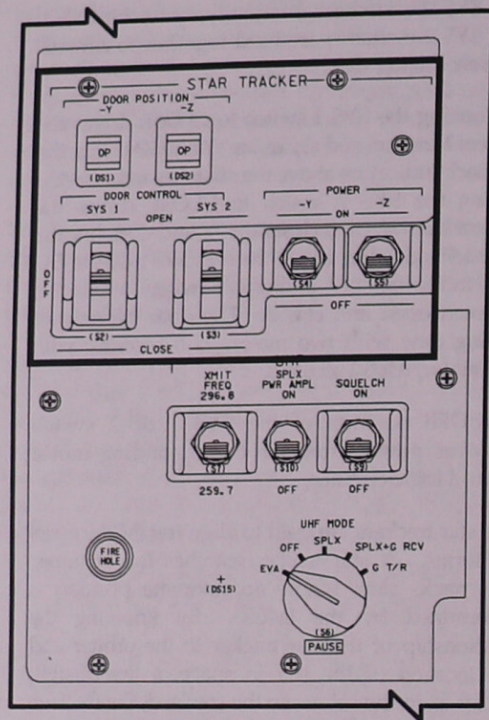
Positioning the SYS 1 switch to CLOSE drives the system 1 motors and closes the -Y and -Z doors; the talkback indicators above the switches indicate CL. Setting the SYS 2 switch to CLOSE drives the system 2 motors and closes the -Y and -Z doors; the talkback indicators above the switches indicate CL. The indicators are barberpole when a door is between open and closed. The door opening or closing time with two motors is 6 seconds; with one motor, it is 12 seconds.

The OFF position of the SYS 1 or 2 switch removes power from the corresponding motor control logic circuitry.

The star trackers are used to align the IMU inertial platforms. A star tracker searches for, acquires, and tracks stars whose approximate position is determined by the IMUs. By knowing the relationship of the star tracker to the orbiter and the location of the star in space, a line-of-sight vector from the orbiter to the star is defined. Two such vectors define the orbiter inertial attitude.



Star Trackers



**STAR TRACKER Controls and Talkbacks
on Panel O6**

The difference between the inertial attitudes defined by the star tracker and the IMU is processed by software and results in IMU torquing angles. If either the IMU gimbals are physically torqued or the matrix defining its orientation is recomputed, the effects of the IMU gyro drift are removed, and the IMU is restored to its inertial attitude. If the IMU alignment is in error by more than 1.4° , the star tracker may be unable to acquire and track stars. In this case, the HUD must be used to realign the IMUs to within 1.4° ; the star trackers can then be used to realign the IMUs more precisely.

NOTE

The star tracker cannot be used if the IMU alignment error is greater than 1.4° because the angles the star tracker is given for searching are based on current knowledge of the orbiter attitude, which is based on IMU gimbal angles. If that attitude is greatly in error, the star tracker may acquire and track the wrong star.

In addition to aligning the IMUs, the star trackers can be used to provide angular data from the orbiter to a target. This capability can be used during rendezvous or proximity operations.

The star tracker includes a light shade assembly and an electronics assembly mounted on top of the navigation base. The light shade assembly defines the tracker field of view (10° square). Its shutter mechanism may be opened manually by the crew using an entry on the S TRK/COAS CNTL display, or it can be opened and closed automatically by a bright object sensor or target suppress software. The bright object sensor reacts to close the shutter before a bright object, such as the Sun or Moon, can damage the star tracker (the sensor has a larger field of view than the star tracker shutter).

The electronics assembly contains an image dissector tube mounted on the underside of the navigation base. The star tracker itself does not move; the field of view is scanned electronically. The star tracker may be commanded to scan the entire field of view or a smaller offset field of view (1° square) about a point defined by horizontal and vertical offsets. An object is tracked when the proper intensity and the correct location are sensed. Star tracker outputs are the horizontal and vertical position within the field of view of the object being tracked and its intensity.

There is no redundancy management for the star tracker assemblies. They operate independently and can do the entire task. They can be operated either separately or concurrently.

The star tracker SOP supports the modes that are commanded manually from SPEC 22 S TRK/COAS CNTL: self-test, star track, target track, break track, and term/idle. Self-test consists of software and hardware tests. In the star track mode, the star tracker does an offset scan search for the star, acquires it, and tracks it. The star may be selected by the flight crew or GPC; in either case, a field-of-view check is made. Target track is the same as star track, but it tracks a target. Threshold is independent of target track. Break track forces the star tracker to stop tracking a star or target and to perform a search scan from the current location to track the next target it acquires. In the term/idle mode, the star tracker hardware continues

operation, but star tracker software processing ceases. In addition, the star tracker SOP maintains the star table. When a star tracker has acquired and tracked a star, and the data have passed software checks, the star identification, time tag, and line-of-sight vector are stored. The identification and time elapsed since time tag are displayed in the star table. When two or three stars are in the table, the angular difference between their line-of-sight vectors is displayed. The difference between the star tracker and star catalog angular differences is displayed as an error. The star tracker SOP selects line-of-sight vectors of two stars in the star table for IMU alignment and outputs an ALIGN ENA discrete. The software selects the star pair whose angular difference is closest to 90° .

3011/022/		S TRK/COAS CNTL		1 006/09:35:06	
				000/00:00:00	
S TRK CNTL	-Y	-Z	S TABLE	1	2
SELF-TEST	1	2	TRK ID	15	43
STAR TRK	3	4	Δ MIN	1	1
TGT TRK	5	6	ANG DIF	84.1	0.0
BREAK TRK	7	8	ERR	0.02	0.00
TERM/IDLE	9*	10*	SEL	17*	18*
				S TABLE CLR 20	
				COAS	
S TRK	-Y	-Z	REQD ID	21	0
REQD ID	11	0	ADEG X	-0.2	
TRK ID	0	0	Y	+0.3	
S PRES			SIGHT MODE	22	
Δ ANG	+0.00	+0.00	ACCEPT	23	
THOLD	13	0	CAL MODE	24	
SHUTTER	CL	CL	DES	25	
MAN OP	15	16	POS	+X 26	-Z 27*
STATUS			ABIAS	0.00	0.00
				UPDATE	28
					29

S TRK/COAS CNTL Display (SPEC 22)

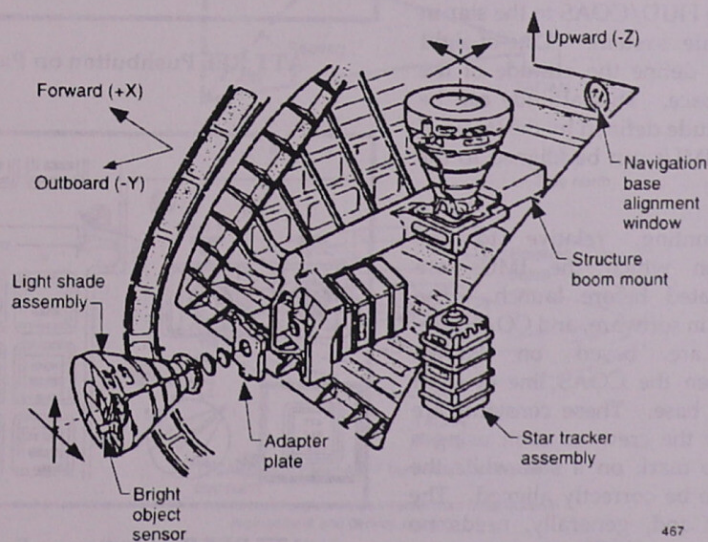
The flight crew may manually override the SOP selection or clear the table if desired. The SOP also determines and displays star tracker status. Star tracker parameters are accessible to the crew on the S TRK/COAS CNTL display (SPEC 22).

Crew Optical Alignment Sight

The COAS is an optical device with a reticle focused at infinity projected on a combining glass. The reticle consists of a 10° -wide circle with 1° marks. A light bulb with variable brightness illuminates the reticle. The COAS requires 115-volt ac power for reticle illumination. The COAS is 9.5 by 6 by 4.3 inches and weighs 2.5 pounds.

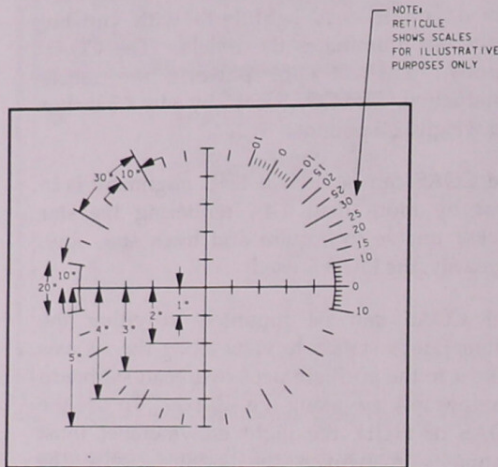
The COAS can be used if IMU alignment is in error by more than 1.4° , rendering the star tracker unable to acquire and track stars, but, primarily, the HUD is used.

The COAS can be mounted at either the commander's station to view along the +X axis or next to the aft flight deck overhead starboard window to view along the -Z axis. To use the COAS or HUD, the flight crewmember must manually maneuver the orbiter until the selected star is in the field of view. The crewmember then maneuvers the orbiter so that the star crosses the center of the reticle or the "P" in the HUD test pattern. At the instant of the crossing, the crewmember enters a mark by depressing the most convenient of the three



View into Star Tracker Cavity

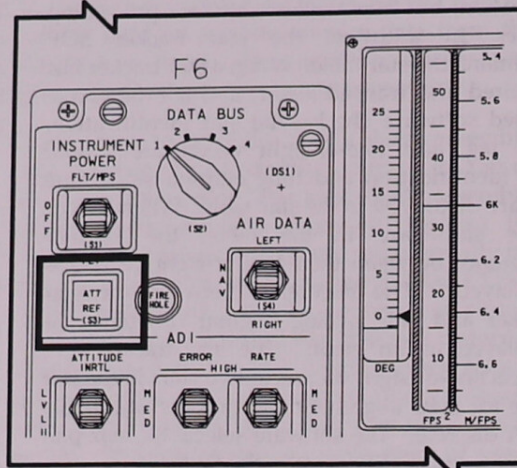
ATT REF pushbuttons located on panels F6, F8, and A6U. At the time of the mark, software stores the gimbal angles of the three IMUs. This process can be repeated if the accuracy of the star's centering is in doubt. When the crewmember feels a good mark has been taken, the software is notified to accept it. Good marks for two stars are required for an IMU alignment. The separation between the two stars should be between 60° and 120°.



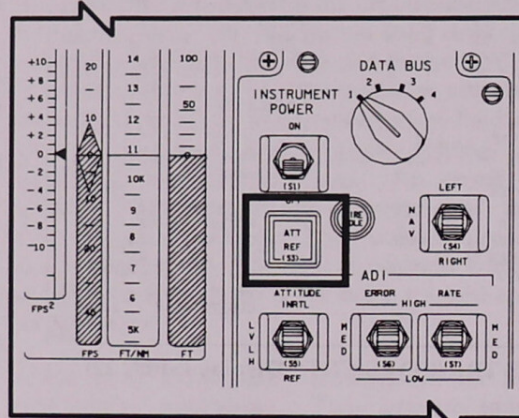
RETICAL PATTERN
COAS Reticle Pattern

By knowing the star being sighted and the HUD or COAS's location and mounting relationship in the orbiter, software can determine a line-of-sight vector from the HUD/COAS to the star in an inertial coordinate system. Line-of-sight vectors to two stars define the attitude of the orbiter in inertial space. This attitude can be compared to the attitude defined by the IMUs; if an error exists, the IMUs can be aligned to the correct orientation.

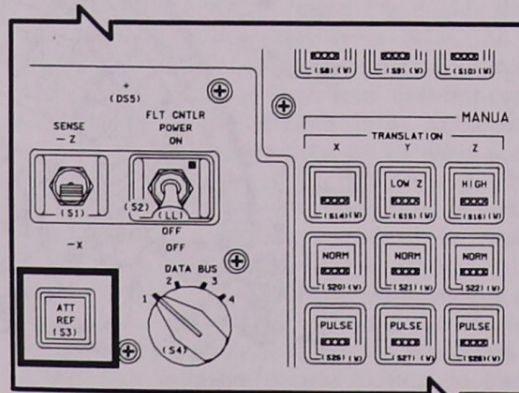
The COAS's mounting, relative to the navigation base on which the IMUs are mounted, is calibrated before launch. The constants are stored in software, and COAS line-of-sight vectors are based on known relationships between the COAS line of sight and the navigation base. These constants are usually updated by the crew on orbit using a calibration mode to mark on a star while the IMUs are known to be correctly aligned. The HUD is consistent and, generally, needs no calibration.



ATT REF Pushbutton on Panel F6



ATT REF Pushbutton on Panel F8



ATT REF Pushbutton on Panel AU6

The COAS can also be used to visually track targets during proximity operations or to visually verify tracking of the correct star by the -Z star tracker.

COAS data processing is accomplished in the star tracker SOP. This SOP accepts and stores crew inputs on COAS location, star identification, or calibration mode, accepts marks, computes and stores the line-of-sight vectors, enables IMU alignment when two marks have been accepted, and computes, updates, and provides display data. COAS parameters may be accessed using the S TRK/COAS CNTL (SPEC 22) display (lower right).

Tactical Air Navigation

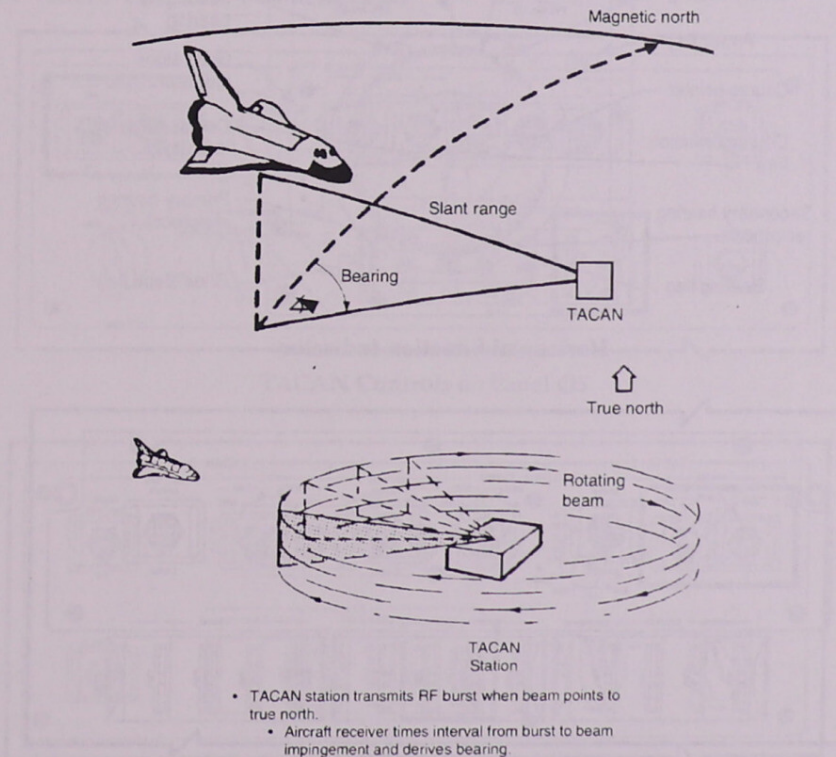
The onboard TACAN units determine slant range and magnetic bearing of the orbiter to a TACAN or VHF omnirange tactical air navigation (VORTAC) ground station.

The ground-based TACAN and VORTAC stations constitute a global navigation system for military and civilian aircraft operating at L-band frequencies (1 GHz). The TACAN unit includes a

transmitter, a receiver, and a data processor. The data processor decodes the selected channel and sends the frequency to the receiver.

Vehicles without the GPS upgrade are equipped with three TACANs that operate redundantly. Each TACAN has two antennas, one on the orbiter's lower forward fuselage and one on the orbiter's upper forward fuselage. The antennas are covered with thermal protection system tiles. The three convection-cooled TACANs are located in the orbiter crew compartment middeck avionics bays. The onboard TACANs are used to obtain orbiter position data from an external source during entry. TACAN's maximum range is 400 nautical miles (n. mi.). Each set is 7.62 inches high, 7.62 inches wide, and 12.53 inches long and weighs 30 pounds.

Each ground station has an assigned frequency (L-band) and a three-letter Morse code identification. The ground station transmits on one of 252 (126X, 126Y) preselected frequencies (channels) that correspond to the frequencies the onboard TACAN sets are capable of receiving. These frequencies are spaced at 63-MHz intervals.



473 74 cvs

TACAN Operation

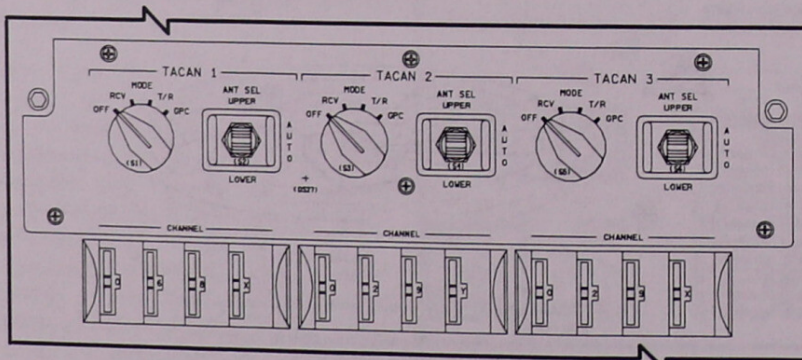
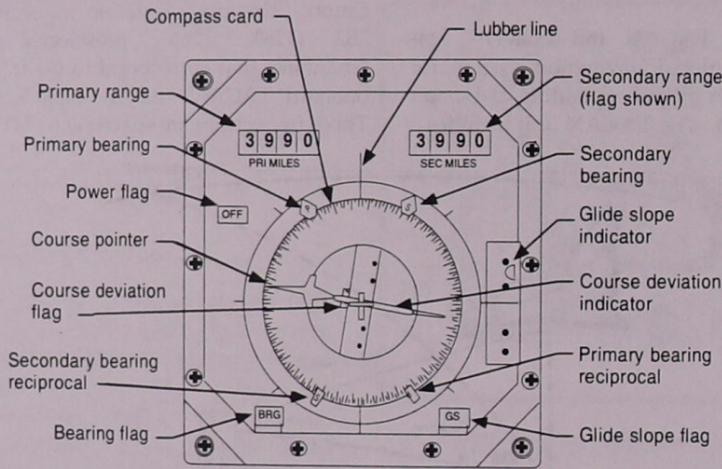
The TACAN ground station beacon continuously transmits pulse pairs on its assigned frequency. The orbiter TACAN receivers pick up these pulse pairs, and the TACAN data processors decode them to compute bearing. The onboard TACAN sets detect the phase angle between magnetic north and the position of the orbiter with respect to the ground station. The ground beacon is omnidirectional. When the orbiter is over the ground station, or nearly so, it is in a cone of confusion. Within this cone, bearing is unusable.

Periodically, the onboard TACAN sets emit an interrogation pulse that causes the selected TACAN ground station to respond with distance-measuring equipment pulses. The slant range (orbiter to ground station) is computed by the onboard TACAN sets by measuring the elapsed time from interrogation

to valid reply and subtracting known system delays. As the orbiter approaches a ground TACAN station, the range decreases. After a course has been selected, the onboard TACAN sets derive concise deviation data.

The TACAN range and bearing data are used to update the state vector position components during entry. Range and bearing data are also displayed on the horizontal situation indicators on panels F6 and F8, as well as on the GNC SPEC 50 HORIZ SIT display.

TACAN controls are located at the top of panel O7. The TACAN 1,2,3 ANT SEL switches control antenna selection. In the AUTO position, the onboard GPCs automatically select the best antenna for that TACAN. The UPPER and LOWER positions of the switches allow the



TACAN Switches and Thumbwheels on Panel O7
(Three-string TACAN Vehicles)

flight crew to manually select the upper or lower L-band antenna.

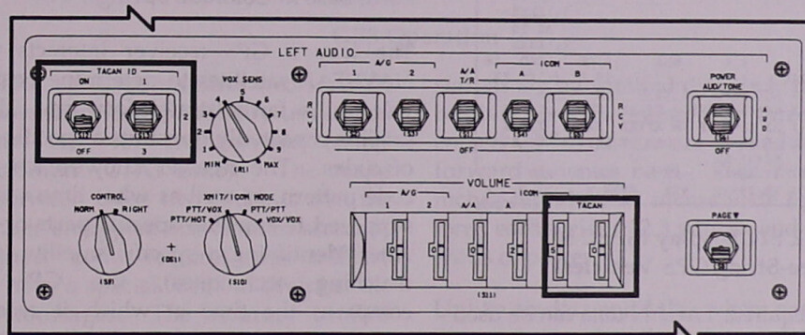
Each TACAN also has a MODE rotary switch on panel O7. The modes are OFF, receive (RCV), transmit and receive (T/R), and GPC. In the GPC mode, the onboard GPCs control TACAN ground station channel selection automatically, and both bearing and range are processed by hardware and software. In the T/R mode, both bearing and range are processed by hardware and software, but TACAN ground station channels are selected manually using the four CHANNEL thumbwheels for that TACAN on panel O7. The first three thumbwheels (left to right) select the channel (frequency), and the fourth selects the X or Y. In the RCV mode, only bearing is received and processed by the hardware; the thumbwheels for that TACAN are used to select the channel.

Approximately every 37 seconds, the selected TACAN ground station transmits its three-letter identification to the onboard TACAN. In order for the Morse code identification to be verified by the commander and pilot, TACAN ID audio controls are located on panel O5 (designated

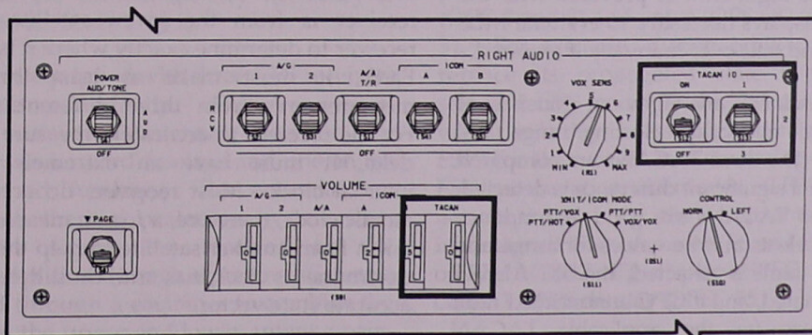
LEFT AUDIO) for the commander and panel O9 (designated RIGHT AUDIO) for the pilot. The TACAN ID ON/OFF switch is positioned to ON to receive the TACAN identification. The TACAN ID 1, 2, 3 switch selects the onboard TACAN that will transmit the TACAN identification code. VOLUME TACAN thumbwheels on panels O5 and O9 control the volume setting of the TACAN identification code to the commander and pilot.

During entry, when at least two TACANs lock on, TACAN range and bearing data are used by navigation software to update the state vector until microwave landing system (MLS) acquisition at approximately 18,000 feet.

TACAN azimuth and range (TAC AZ, RNG) are provided on the lower left side of the HORIZ SIT display (SPEC 50). TACAN range and bearing data cannot be used to produce a good estimate of the altitude position component, so navigation uses barometric altitude derived from the air data system probes, which are deployed by the flight crew at approximately Mach 5.

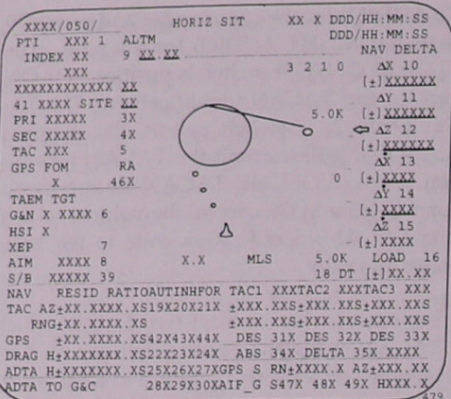


TACAN Controls on Panel O5

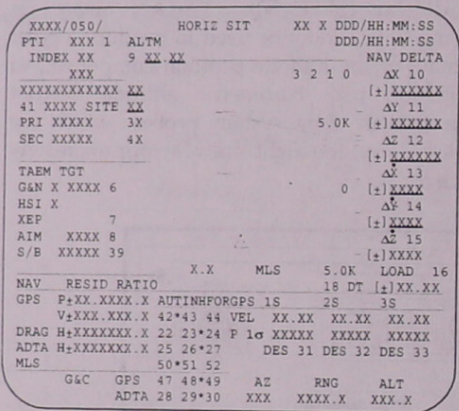


TACAN Controls on Panel O9

Global Positioning System



**HORIZ SIT Display (SPEC 50)
(TACAN Azimuth and Range
Three-String TACAN Vehicles)**



**HORIZ SIT Display (SPEC 50)
(Three-String GPS Vehicles)**

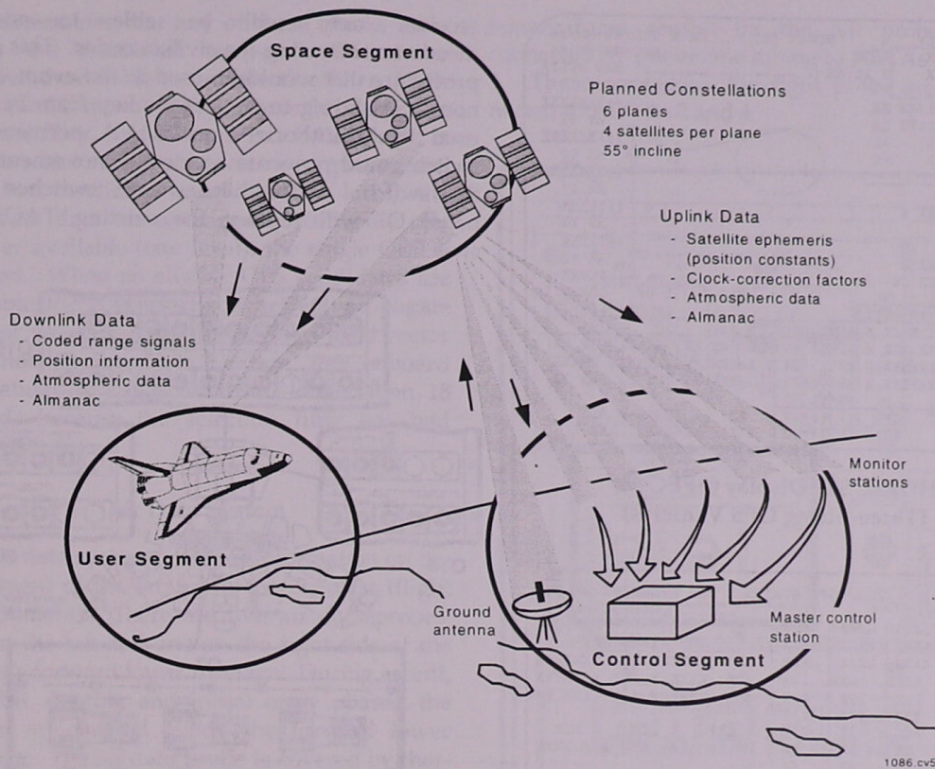
If MLS is not acquired, TACAN data can be used until an altitude of 1,500 feet. When runways with MLS are acquired, MLS operation is automatic. The flight crew is provided with the controls and displays necessary to evaluate MLS performance and take over manually if required.

TACAN redundancy management consists of processing and mid-value-selecting range and bearing data. The three TACANs are compared to determine if a significant difference is detected. When all three TACANs are good, redundancy management selects middle values for range and bearing. If a fault is detected, the SM ALERT light is illuminated, and a GPC annunciated fault message occurs for the applicable TACAN parameter.

The GPS is a relatively new navigation tool to the shuttle. Because of the anticipated decommissioning of TACAN stations by the Department of Defense (DOD), shuttle program officials decided to use GPS as the replacement for TACANs, which had been a primary navigational tool for entry.

The NAVSTAR GPS is a space-based radio positioning navigation system that provides three-dimensional position, velocity, and time information to suitably equipped users anywhere on or near the surface of the Earth. The GPS constellation consists of 24 NAVSTAR satellites, including 3 active on-orbit spares. The satellites travel in 10,980 n. mi. orbits at velocities of 14,500 km/hr for periods of 12 hours. These satellites are in six planes, each at an inclination of 55° with respect to the equator. NAVSTAR satellites and their support equipment are financed by the DoD, but their navigation signals are available free of charge to anyone. The NAVSTAR satellite constellation control center facility is located at Falcon Air Force Base in Colorado Springs, CO.

The way a GPS receiver interacts with the NAVSTAR satellites to determine position and velocity is fairly straightforward. Each GPS satellite repeatedly transmits a specific sequence of codes. The receiver knows each satellite's code pattern, as well as what time a satellite is supposed to transmit specific parts of the code. After identifying a specific satellite (via code-matching techniques), the GPS receiver compares the time at which it received the specific part of the code to the time at which the satellite was supposed to have sent it. This time delta directly corresponds to how far the receiver is from the given satellite. For a receiver to determine exactly where it is near the Earth, it must make at least three such measurements from three different satellites. For the receiver to accurately measure the time delta, it must have an extremely accurate internal clock. Most receivers do not have an atomic clock; therefore, a fourth measurement is taken from another satellite to help the receiver determine its clock bias and, thus, determine an accurate state vector.



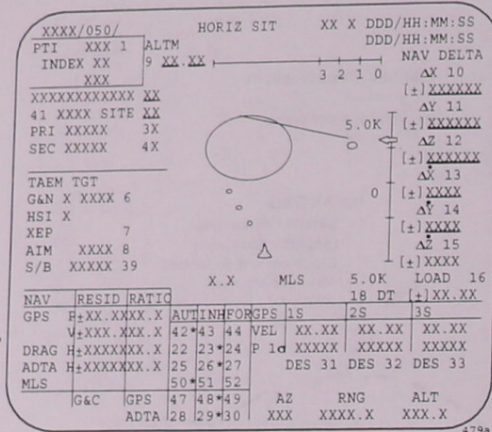
GPS Operation

The NAVSTAR satellites transmit two separate codes, one intended for U.S. military use (called Y-code) and one for civilian use (called coarse/acquisition (C/A) code). The major difference between these two codes is that the military code is encrypted and is more accurate. The encrypted code requires the military receivers to have a special "key" to decipher the transmitted messages. The accuracy of GPS using Y-code is expected to be better than 110 ft, and better than 170 ft using C/A code. The orbiter receivers contain the key necessary to use the more accurate Y-code.

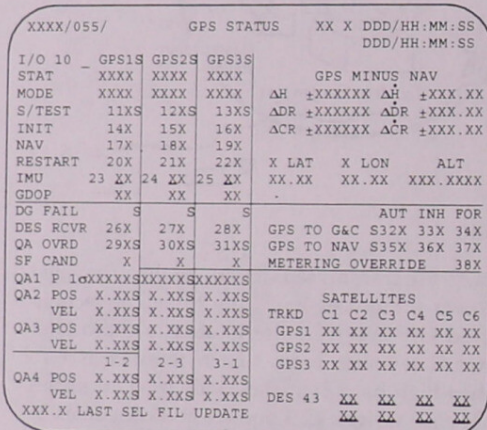
The orbiter is equipped with three GPS receivers that operate redundantly. Each receiver is equipped with two antennas, one on the orbiter's lower forward fuselage and one on the upper forward fuselage. The antennas are covered with thermal protection system tiles. The satellite signals are received by the antennas, amplified through a preamplifier, and then routed through a combiner to combine the signals from the upper and lower antenna pairs into a single stream of data. From there, the

signals are transmitted directly to the associated receiver for processing. The three convection-cooled GPS receivers are located in the orbiter forward avionics bays. Each receiver is 6.78 inches high by 3.21 inches wide by 12.0 inches long; each weighs 12.3 pounds and consumes 26 watts of power.

Unlike air data and MLS, where navigation data are used to update the onboard state vector, the selected GPS vector completely replaces the propagated vectors periodically during orbit (OPS 2 and 8) and entry (OPS 602/603 and OPS 3). For example, during orbit, the FSW will replace its propagated state vector with a selected GPS vector every 90 minutes. This vector will then be propagated forward by the FSW for the next 90 minutes, using the nominal FSW propagation techniques. GPS information is displayed on the horizontal situation indicators (HSIs) on panels F6 and F8, as well as on the HORIZ SIT display (SPEC 50) and the GPS STATUS display (SPEC 55).



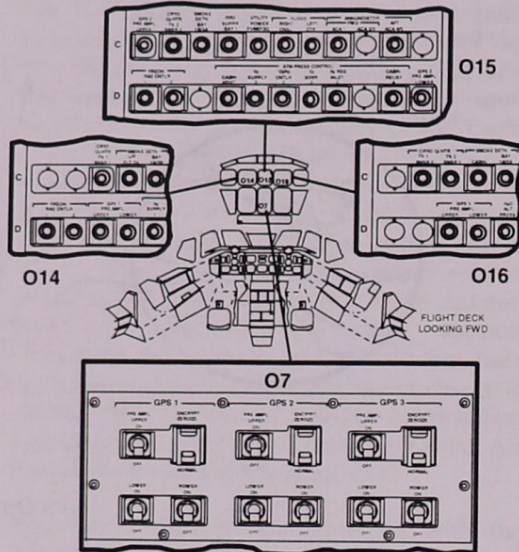
**HORIZ SIT Display (SPEC 50)
 (Three-String GPS Vehicles)**



GPS STATUS Display (SPEC 55)

GPS hardware controls are located at the top of panel O7. GPS 1,2,3 PRE AMPL UPPER (LOWER) switches provide power to each of the antenna preamplifiers, with circuit breakers located on panels O14, O15, and O16. Each receiver has a POWER switch on panel O7 and is powered through a single energy storage system (ESS) bus/forward power controller (FPC) combination. The ENCRYPT switches located on panel O7 control the integrity of the Y-code key within each receiver. In NORM, the key is kept intact such that it can be used to decode the more accurate Y-code signals being sent by the NAVSTAR satellites. If this switch is moved to the ZEROIZE position, the key will be erased from the memory of the receiver and the

receiver only will be able to make measurements using the civilian codes. This is a procedure that would be used in the event of a non-U.S. landing to protect the key from being used by unauthorized users. A permanent switch guard prevents accidental movement of this switch. All of the new GPS switches on panel O7 will replace the existing TACAN switches.



**GPS Controls
 (Three-String GPS Vehicles)**

Unlike the classical redundancy management (RM) schemes applied to other shuttle sensors, the GPS uses a cyclic quality assessment (QA) process that is more conducive to its performance. Because of the nature of its operation, whereby poor satellite coverage may result in short periods of invalid data, it would not be prudent to "permanently" remove a unit from availability because of these questionable periods.

There are four separate QA checks the software will perform to determine the status of the data from each receiver. These four checks include each receiver's estimate of the error in its own navigation state (QA1), the difference between each receiver's state and the FSW's computed state (QA2), the difference between each receiver's current state and its previous state (QA3), and the differences between each receiver and the other receivers (QA4). If the

FSW determines that any of these checks have failed, the associated receiver will not be considered available to the selection filter. With three candidates available (three level) to the selection filter, mid-value select (MVS) logic is used to select a unit's state vector for processing. With two candidates available (two level), the candidate data are averaged. With only one receiver available (one level), the single GPS is selected. When no eligible GPS candidates are available, the GPS selection filter will propagate the last valid data for processing. This vector will not be used to update the onboard navigation state if it has been longer than 18 seconds because the selection filter has had valid GPS data.

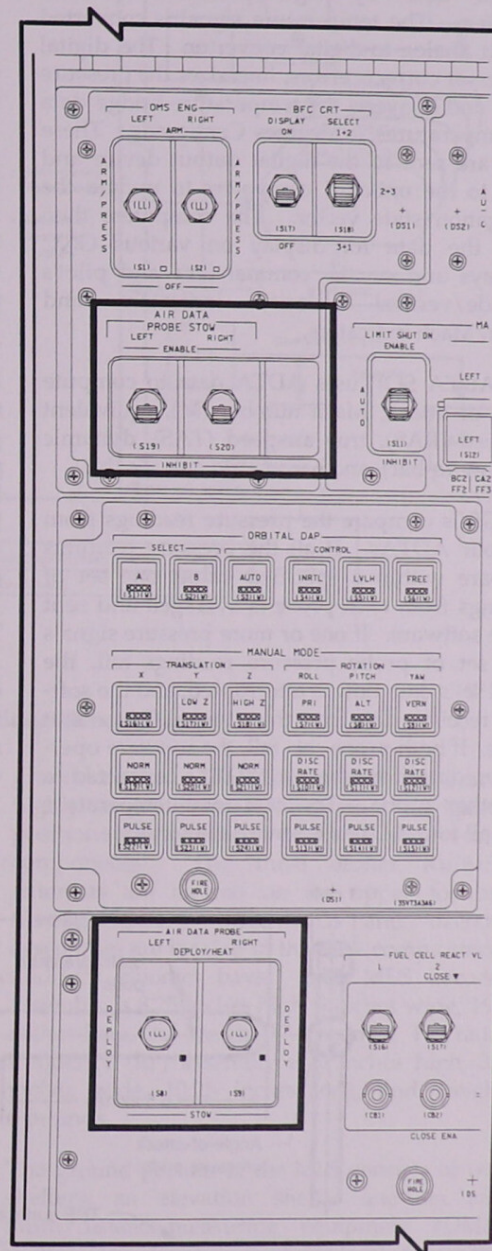
Air Data System

The air data system provides information on the movement of the orbiter in the air mass (flight environment). There are two air data probes, one on the left and one on the right side of the orbiter's forward lower fuselage. During ascent, on orbit, deorbit, and initial entry phases, the probes are stowed inside the forward lower fuselage. The air data probe is covered by thermal protection system tiles while in the stowed position. At Mach 5, depending on mission requirements, the air data probes are deployed. Each probe is 4.87 inches high, 21.25 inches long, 4.37 inches wide, and weighs 19.2 pounds.

The air data system senses air pressures related to spacecraft movement through the atmosphere to update the navigation state vector in altitude, provide guidance in calculating steering and speed brake commands, update flight control law computations, and provide display data for the commander's and pilot's alpha/Mach indicators (AMIs), altitude/vertical velocity indicators (AVVIs), and various GNC displays. (The AMI and AVVI are detailed in Section 2.7.)

Each air data probe has four pressure-port sensors and two temperature sensors. The pressures sensed include static pressure and angle-of-attack upper, center, and lower pressure. The four pressures are sensed at ports on each probe. The probe-sensed pressures are connected by a set of pneumatic lines to two air data transducer assemblies (ADTAs). The two temperature sensors are installed on each probe and wired to an ADTA. The pressures and

temperatures sensed by the left probe are connected by pneumatic tubing to ADTAs 1 and 3. Those sensed by the right probe are connected to ADTAs 2 and 4.



AIR DATA PROBE Switches on Panel C3

Within each ADTA, the pressure signals are directed to four transducers, and the temperature signal is directed to a bridge. The pressure transducer analogs are converted to digital data by digital-processor-controlled counters. The temperature signal is converted by an analog-to-digital converter. The digital processor corrects errors, linearizes the pressure data, and converts the temperature bridge data to temperatures in degrees Centigrade. These data are sent to the digital output device and then to the onboard computers to update the navigation state vector. The computers then send the data for display on various GNC displays and on the commander's and pilot's altitude/vertical velocity indicators and alpha/Mach indicators.

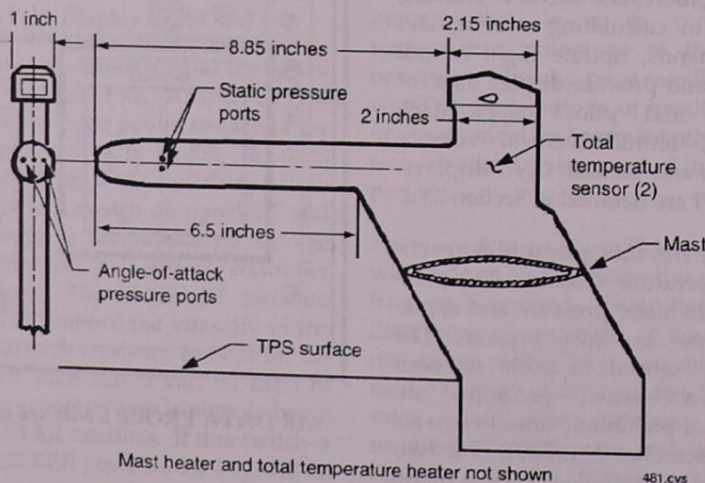
The ADTA SOP uses ADTA data to compute angle of attack, Mach number (M), equivalent airspeed (EAS), true airspeed (TAS), dynamic pressure (q-bar), and barometric altitude (h).

The GPCs compare the pressure readings from the four ADTAs. If all the pressure readings compare within a specified value, one set of readings from each probe is averaged and sent to the software. If one or more pressure signals of a set of probe pressure readings fail, the failed set's data flow is interrupted, and the software receives data from the other ADTA on that probe. If both probe sets fail, the software operates on data from the two ADTAs connected to the other probe. The best total temperature from all four ADTAs is sent to the software.

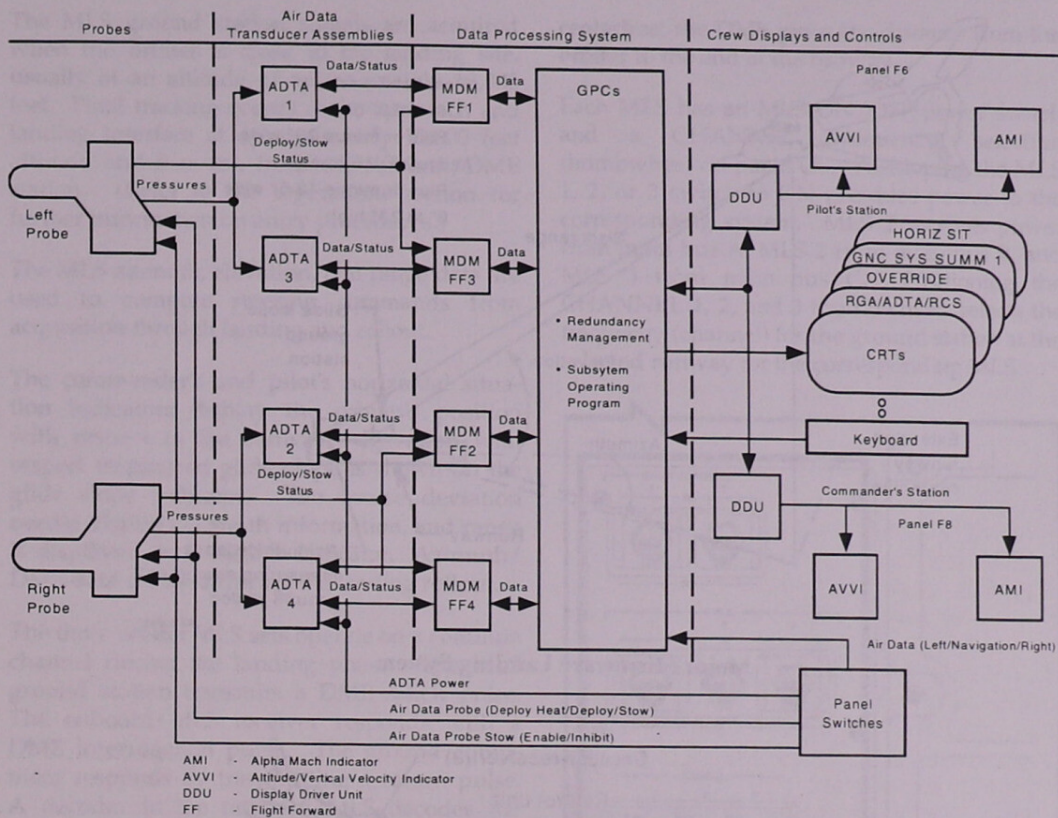
Each probe is independently deployed by an actuator consisting of two ac motors connected to a rotary electromechanical actuator. Each probe is controlled by its AIR DATA PROBE switch on panel C3. To deploy the air data probes, the LEFT and RIGHT switches are positioned to DEPLOY. The redundant motors for each probe drive the probe to the deployed position. When the probe is fully deployed, limit switches remove electrical power from the motors. Deployment time is 15 seconds for two-motor operation and 30 seconds for single-motor operation. The DEPLOY position deploys the probe without electrical heaters; the DEPLOY/HEAT position deploys the air data probes with heaters powered.

The AIR DATA PROBE STOW LEFT and RIGHT switches on panel C3 are used to stow the probes. The stow procedure includes positioning the switches to ENABLE and positioning the corresponding AIR DATA PROBE switch to STOW. The AIR DATA PROBE STOW INHIBIT position opens the ac motor circuits, disables the stow, and protects the microswitches.

The fault detection system illuminates the red AIR DATA and BACKUP C/W ALARM lights on panel F7, and illuminates the MASTER ALARM. A fault also sounds the audible tone and generates a fault message. A communication fault illuminates the SM ALERT light.



Air Data Probe



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Air Data System Functional Block Diagram

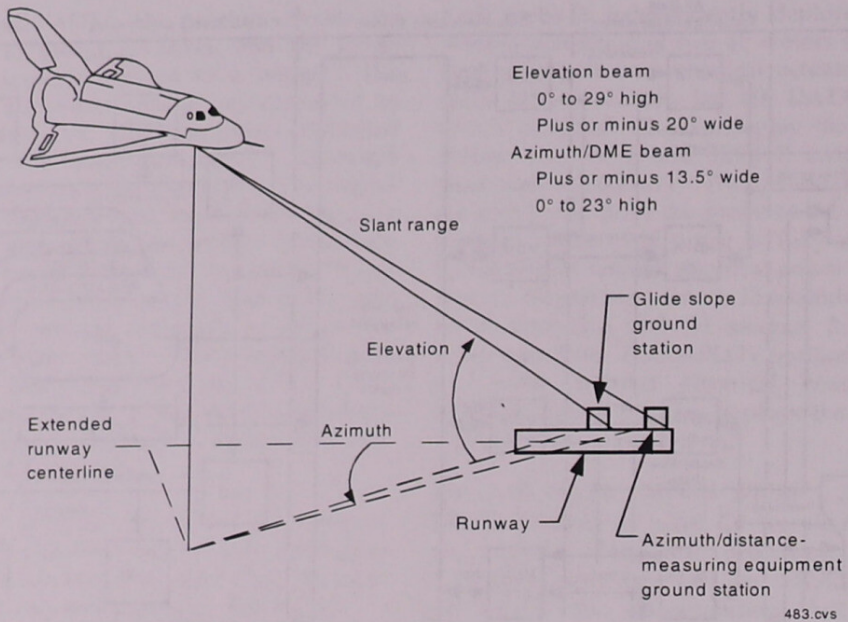
Microwave Landing System

The three onboard MLS units are airborne navigation and landing aids with decoding and computational capabilities. The MLS units determine slant range, azimuth, and elevation to the ground stations alongside the landing runway. MLS is used during the approach and landing flight phases. When the channel (specific frequency) associated with the target runway approach is selected, the orbiter's MLS units receive elevation from the glide slope ground station and azimuth and slant range from the azimuth/distance-measuring equipment ground station.

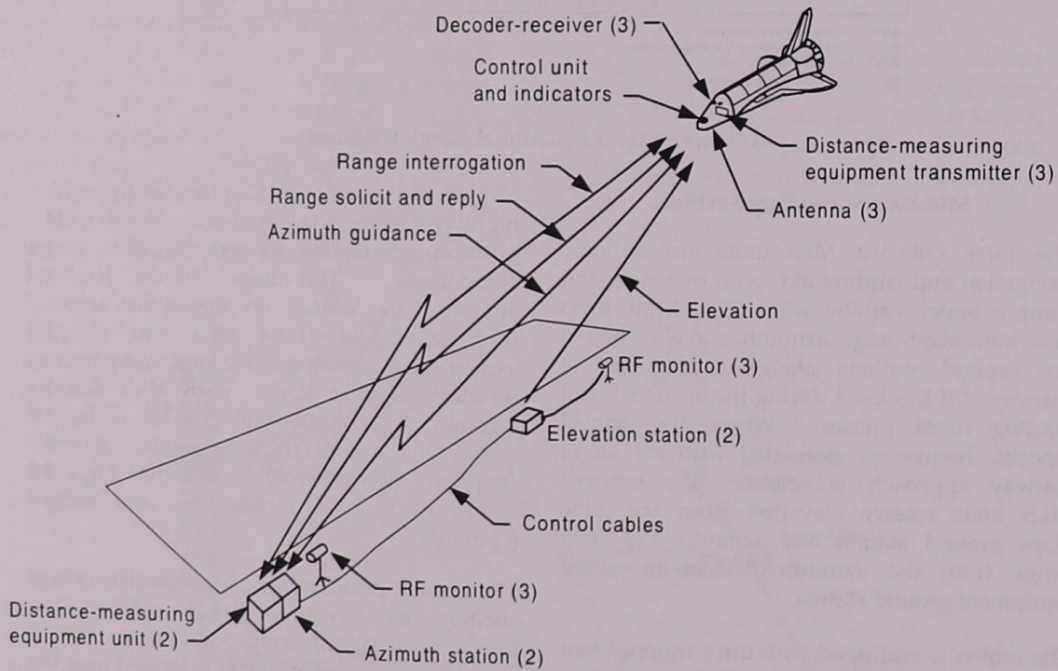
The orbiter is equipped with three independent MLS sets, each consisting of a Ku-band receiver transmitter and decoder. Data computation capabilities determine elevation angle, azimuth angle, and orbiter range with respect to the MLS

ground station. The MLS provides the orbiter highly accurate three-dimensional navigation position information to compute state vector components. The three orbiter Ku-band antennas are located on the upper forward fuselage. The three MLS and decoder assemblies are located in the crew compartment middeck avionics bays. Each MLS decoder assembly is 8.25 inches high, 5 inches wide, 16.6 inches long, and weighs 17.5 pounds. The radio frequency (RF) assembly is 7 inches high, 3.5 inches wide, 10.25 inches long, and weighs 6 pounds.

The ground portion of the MLS consists of two shelters: an elevation shelter and an azimuth/distance-measuring equipment (DME) shelter. The elevation shelter is located near the projected touchdown point, and the azimuth/DME shelter is located at the far end of the runway.



Major Microwave Landing System



Major Microwave Landing System Components and Radio Frequency Links

The MLS ground station signals are acquired when the orbiter is close to the landing site, usually at an altitude of approximately 18,000 feet. Final tracking occurs at the approach and landing interface at approximately 10,000 feet altitude and 8 n. mi. from the azimuth/DME station. (Refer to the Operations section for further information on entry procedures.)

The MLS azimuth, elevation, and range data are used to compute steering commands from acquisition through landing and rollout.

The commander's and pilot's horizontal situation indicators display the orbiter's position with respect to the runway. Elevation with respect to planned glide slope is shown on the glide slope indicator. The course deviation needle displays azimuth information, and range is displayed on a mileage indicator. Azimuth/DME data are used during the landing rollout.

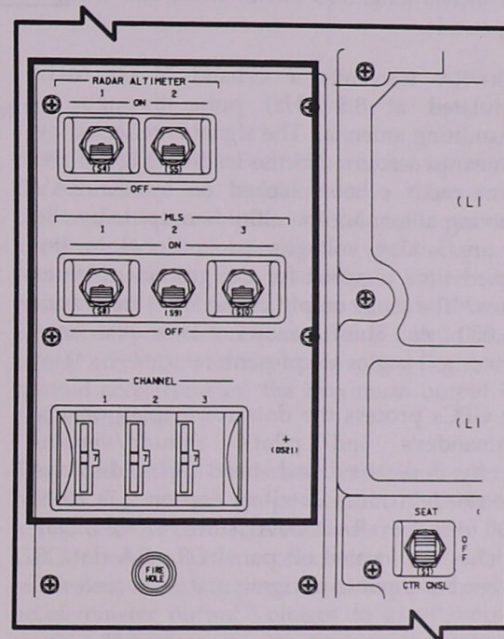
The three orbiter MLS sets operate on a common channel during the landing phase. The MLS ground station transmits a DME solicit pulse. The onboard MLS receiver responds with a DME interrogation pulse. The ground equipment responds by transmitting a return pulse. A decoder in the onboard MLS decodes the pulses to determine range, azimuth, and elevation. Range is a function of the elapsed time between interrogation pulse transmission and signal return. Azimuth pulses are returned in pairs. The spacing between the two pulses in a pair identifies the pair as azimuth and indicates on which side of the runway the orbiter is situated. Spacing between pulse pairs defines the angular position from the runway centerline. The spacing between the two pulses in a pair identifies the pair as elevation, while the spacing between pulse pairs defines the angular position of the orbiter above the runway.

Each RF assembly routes range, azimuth, and elevation information in RF form to its decoder assembly. The decoder assembly processes the information and converts it to digital data for transmission to the onboard GNC software via the MDMs.

Because the azimuth/DME shelters are at the far ends of the runway, the MLS provides useful data until the orbiter stops. Azimuth data provide position in relation to the runway

centerline; the DME gives the distance from the orbiter to the end of the runway.

Each MLS has an MLS ON/OFF power switch and a CHANNEL (frequency) selection thumbwheel on panel O8. Positioning the MLS 1, 2, or 3 switch to ON provides power to the corresponding system. MLS 1 receives power from main bus A, MLS 2 from main bus B, and MLS 3 from main bus C. Positioning the CHANNEL 1, 2, and 3 thumbwheels selects the frequency (channel) for the ground station at the selected runway for the corresponding MLS.



RADAR ALTIMETER Switches and MLS Switches and Thumbwheels on Panel O8

Redundancy management selects range, azimuth and elevation angles for processing navigation data. The three MLS sets are compared to identify any significant differences among them. When data from all three MLS sets are valid, redundancy management selects middle values from three ranges, azimuths, and elevations. In the event that only two MLS sets are valid, the two ranges, azimuths, and elevations are averaged. If only one MLS set is valid, its range, azimuth, and elevation are passed for display. During fault detection, the SM ALERT light is illuminated, and a GPC annunciated fault message is shown.

Radar Altimeters

The two RAs onboard the orbiter measure absolute altitude from the orbiter to the nearest terrain within the beam width of the orbiter's antennas. The two independent RAs consist of a transmitter and receiver antenna. The systems can operate simultaneously without affecting each other. The four C-band antennas are located on the lower forward fuselage. The two receiver/transmitters are located in the middeck forward avionics bays. Each radar altimeter receiver/transmitter measures 3.13 inches high, 7.41 inches long, 3.83 inches wide, and weighs 4.5 pounds.

Each RA transmits a C-band (4,300 MHz modulated at 8.5 kHz) pulse through its transmitting antenna. The signal is reflected by the nearest terrain, and the leading edge of the return radar echo is locked on by the RA's receiving antenna. The altitude outputs by the RA are analog voltages, proportional to the elapsed time required for the ground pulse to return. The range output of the RA is from zero to 5,000 feet. The RA may not lock on if large pitch or roll angles are present.

The GPCs process the data for display on the commander's and pilot's altitude/vertical velocity indicators and head up displays (described in more detail in Section 2.7) from 5,000 feet. Two RADAR ALTIMETER ON/OFF switches are located on panel O8. RA data is not used as input to navigation; it is for crew use only.

Flight Control System Hardware

The flight control system (FCS) ascent and entry hardware provides manual guidance commands to GNC software and responds to effector commands from GNC software in order to effect vehicle and trajectory control.

The following hardware includes sensors responsible for flight control data:

- Accelerometer assembly (AA) -- senses vehicle accelerations along two body axes.
- Rate gyro assembly (RGA) -- senses vehicle rotation rates about three body axes.

- SRB rate gyro assembly (SRB RGA) -- senses vehicle rotation rates about two body axes during first stage ascent before SRB separation.

The following hardware provides manual guidance commands:

- Rotational hand controller (RHC) -- commands acceleration about a body axis.
- Translational hand controller (THC) -- commands vehicle motion along a body axis.
- Rudder pedal transducer assembly (RPTA) -- commands an acceleration about the yaw body axis in atmospheric flight.
- Speed brake/thrust controller (SBTC) -- commands changes in vehicle aerodynamic drag or change in main engine throttle level (specific function is flight-phase dependent).
- Switches (body flap and trim) -- command the flight control system or aerosurface trim.

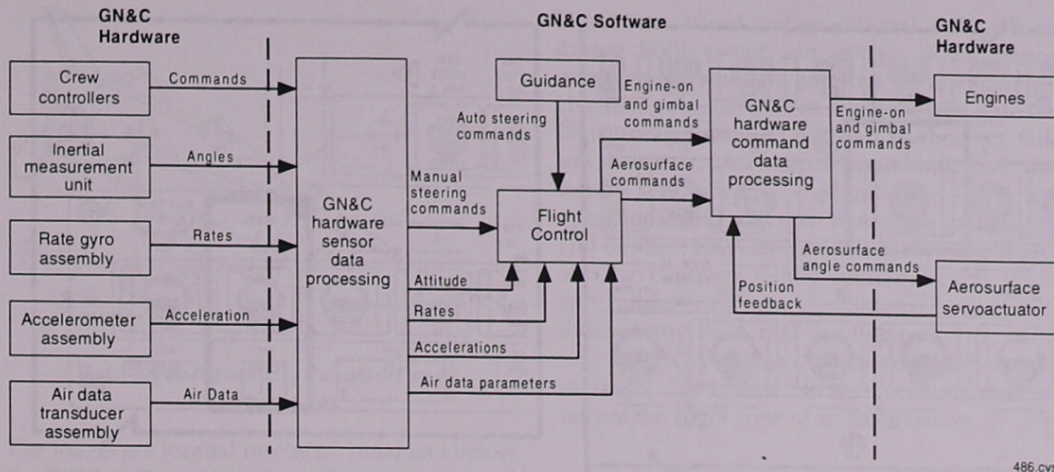
The following hardware responds to software commands:

- Aerosurface servoamplifier (ASA) -- responsible for aerosurface actuator positioning.
- Ascent thrust vector control (ATVC) -- responsible for main engine and SRB actuator positioning.

Each piece of flight control system hardware is hardwired to one of eight flight-critical MDMs connected to each of the five GPCs by data buses. Each GPC is assigned to command one or more data buses.

Accelerometer Assemblies

There are four AAs onboard the orbiter, each containing two identical single-axis accelerometers. One senses vehicle acceleration along the lateral (left and right) vehicle Y axis; the other senses vehicle acceleration along the normal (vertical) Z axis. The four AAs are located in the crew compartment middeck forward avionics bays 1 and 2. The AAs are convection cooled and require a 5-minute warmup period.



Flight Control Interfaces

The AAs provide acceleration feedback to the FCS. These accelerations are 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.

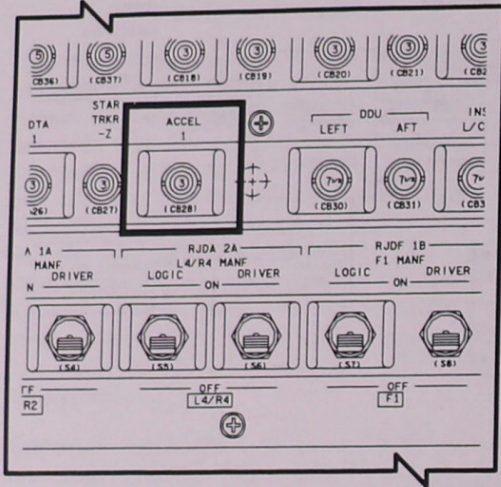
The lateral acceleration readings enable the FCS to null side forces during both ascent and entry. The normal acceleration readings augment pitch control and indicate the need to relieve normal loads. During the latter stages of entry, the normal acceleration measurements provide feedback for guidance to control pitch. (In contrast, the accelerometers within the IMUs measure three accelerations used in navigation to calculate state vector changes.)

Each accelerometer consists of a pendulum suspended so that its base is in a permanent magnetic field between two torquer magnets. A light beam passes through an opening in one of the torquer magnets; photodiodes are located on both sides of the other torquer magnet. When acceleration deflects the pendulum toward one photodiode, the resulting light imbalance on the two photodiodes causes a differential voltage. This voltage increases the magnetic field on one of the torquer magnets to rebalance the pendulum at an offset position representing the sensed acceleration. The magnitude of the current required to accomplish this is proportional to the acceleration. The polarity of the differential voltage depends on the direction

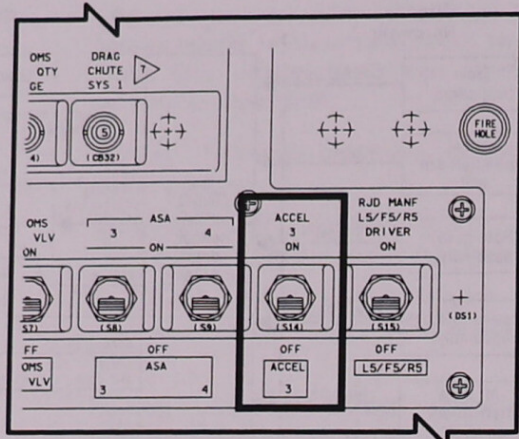
of the pendulum's movement, which is opposite the direction of acceleration. The only difference between the lateral and normal accelerometers is the position in which they are mounted within the assembly. When the acceleration is removed, the pendulum returns to the null position. The maximum output for a lateral accelerometer is plus or minus 1 g; for a normal accelerometer, the maximum output is plus or minus 4 g's.

The accelerations transmitted to the forward MDMs are voltages proportional to the sensed acceleration. These accelerations are sent to the GPCs, where an accelerometer assembly subsystem operating program converts the eight accelerometer output voltages to gravitational units. This data is also sent to the MEDS displays and attitude director indicator during entry.

The accelerometer assemblies provide fail-operational redundancy during both ascent and entry. The four assemblies employ an interchangeable mid-value software scheme to select the best data for redundancy management and a reasonableness limit check for failure detection. Software fault detection will operate when all four AAs are operational and will then detect the first failure and deselect that accelerometer assembly. A caution and warning message "RM FAIL AA" is generated to inform the flight crew of an accelerometer failure. The RGA/ ACCEL caution and warning light on panel F7 is not supported.

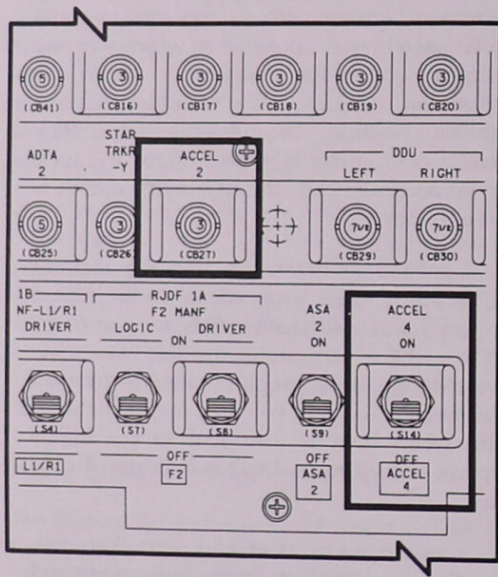


Accelerometer 1 Power Control on Panel O14



Accelerometer 3 Power Control on Panel O16

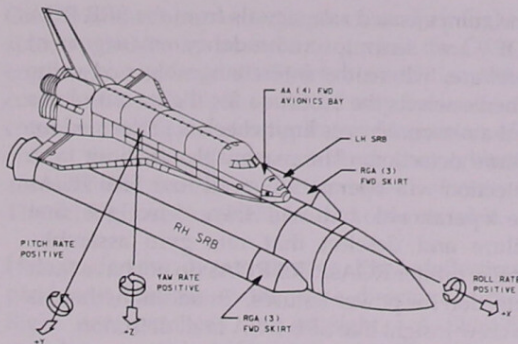
Accelerometer 1 is powered from main bus A through the ACCEL 1 circuit breaker on panel O14. Accelerometer 2 is powered from main bus B through the ACCEL 2 circuit breaker on panel O15. Accelerometer 3 is redundantly powered through the ACCEL 3 ON/OFF switch on panel O16. Accelerometer 4 is redundantly powered through the ACCEL 4 ON/OFF switch on panel O15. The accelerometers are turned off once on orbit and on again before entry.



Accelerometer 2 and 4 Power Controls on Panel O15

Orbiter Rate Gyro Assemblies

The orbiter has four RGAs, referred to as RGAs 1, 2, 3, and 4. Each RGA contains three identical single-degree-of-freedom rate gyros so that each gyro senses rotation about one of the vehicle axes. Thus, each RGA includes one gyro sensing roll rate (about the X axis), one gyro sensing pitch rate (about the Y axis), and one gyro sensing yaw rate (about the Z axis). These rates are the primary feedback to the FCS during ascent, entry, insertion, and deorbit. The FCS must have good rate feedback in all three axes to maintain control.



Rate Gyro Assembly Location and Rotation Axes

The RGAs are located on the aft bulkhead below the floor of the payload bay. They are mounted on cold plates for cooling by the Freon coolant loops and require a 5-minute warm-up time.

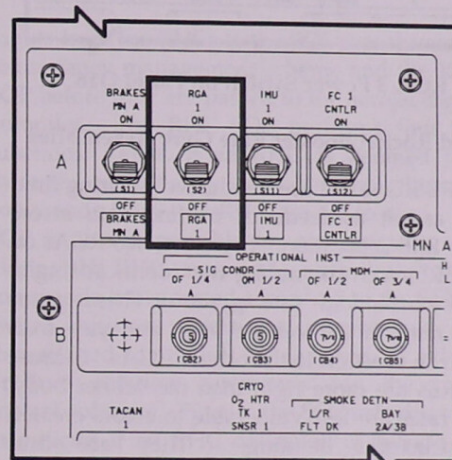
Each gyro has three axes. A motor forces the gyro to rotate about its spin axis. When the vehicle rotates about the gyro input axis, a torque results in a rotation about the output axis. An electrical voltage proportional to the angular deflection about the output axis, representing vehicle rate about the input axis, is generated and transmitted through the flight aft MDMs to the GPCs and RGA SOP. This same voltage is used within the RGA to generate a counteracting torque that prevents excessive gimbal movement about the output axis. The maximum output for roll rate gyros is plus or minus 40° per second; for the pitch and yaw gyros, the maximum output is plus or minus 20° per second.

The RGA 1, 2, 3, and 4 power switches are located on panels O14, O15, O16, and O15 respectively. The redundant power supplies for RGAs 1 and 4 prevent the loss of more than one rate gyro assembly if main bus power is lost. The RGAs are turned off on orbit, except during flight control system checkout, to conserve power. RGAs are reactivated during deorbit prep, and prior to any transition to OPS 3, when they are required for the transition DAP to control vehicle attitude.

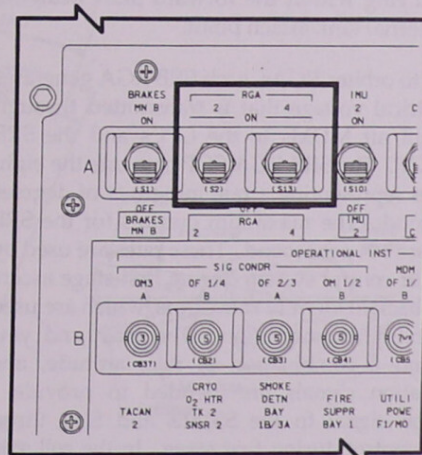
WARNING

A transition to OPS 3 with RGAs off can result in loss of control.

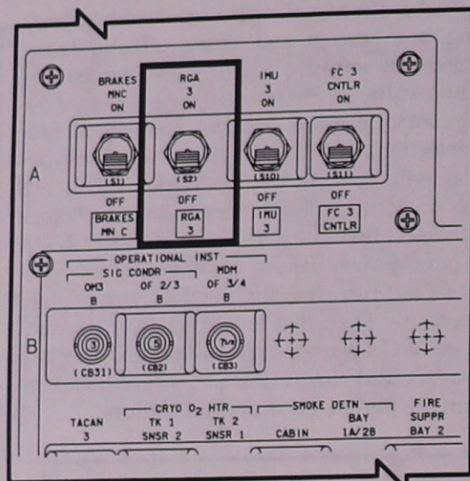
The RGAs afford fail-operational redundancy during both ascent and entry. Redundancy management software employs an interchangeable mid-value scheme to select the best data for flight control use and has two methods of failure detection. A reasonableness limit fault detection will operate when all four RGAs are operational and will then detect the first failure and deselect that rate gyro assembly. The RGAs also have power failure fault detection via a spin motor run detector (SMRD), which will deselect any RGA that has lost power up until only one RGA remains. A caution and warning message, "RM FAIL RGA," is generated to inform the flight crew of an RGA failure.



RGA 1 Power Switch on Panel O14



RGA 2 and 4 Power Switches on Panel O15



RGA 3 Power Switch on Panel O16

Solid Rocket Booster Rate Gyro Assemblies

The SRB RGAs are used exclusively during first-stage ascent as feedback to find rate errors before SRB separation. There are two RGAs on each SRB, each containing two identical single-degree-of-freedom rate gyros. These gyros sense rates in the vehicle pitch and yaw axes similar in function to the orbiter RGAs. Because the SRBs are more rigid than the orbiter body, these rates are less vulnerable to errors created by structural bending. They are thus particularly useful in thrust vector control. The two RGAs in each SRB are mounted on the forward ring within the forward skirt near the SRB-external tank attach point.

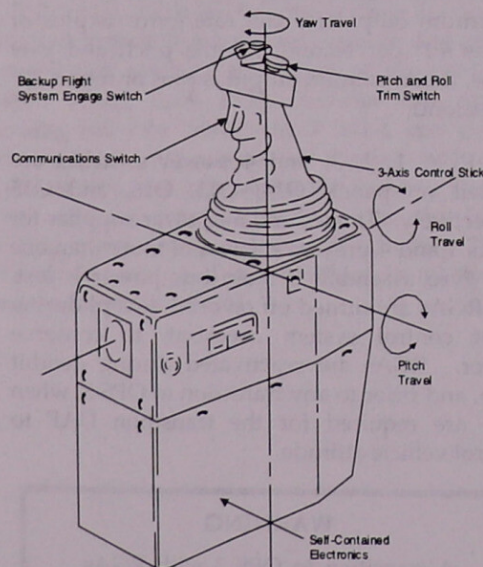
Similar to orbiter RGAs, each SRB RGA generates an electrical voltage that is transmitted through the flight aft MDMs to the GPCs and the SRB RGA SOP. The SRB RGA SOP converts the eight voltages representing a rate into units of degrees per second. The maximum outputs for the SRB RGAs are 10° per second. These rates are used by the flight control system during first-stage ascent as feedback to identify rate errors, which are used for stability augmentation. The pitch and yaw axes and a combination of rate, attitude, and acceleration signals are blended to provide a common signal to the SSMEs and SRB thrust vector control during first stage. In the roll axis, rate and attitude are summed to provide a common signal to the engines and SRB thrust vector control.

The compensated rate signals from the SRB RGA SOP are sent to redundancy management software, where the interchangeable mid-value scheme selects the best data for flight control use and a reasonableness limit check is performed for failure detection. The reasonableness limit fault detection will operate when all four SRB RGAs are operational and will then detect the first failure and deselect that rate gyro assembly. Unlike orbiter RGAs, SRB RGAs do not have fault detection for power failures. In addition, there is no crew insight into SRB RGA fault detection.

The SRB RGAs are commanded to null and released from the flight control system 2 to 3 seconds before SRB separation; SRB yaw and pitch rate data are then replaced with orbiter RGA pitch and yaw data.

Rotational Hand Controller

There are three RHCs on the orbiter flight deck: one at the commander's station, one at the pilot's station, and one at the aft flight deck station. Each RHC controls vehicle rotation about the roll, pitch, and yaw axes. During ascent, the commander's and pilot's RHCs may be used to gimbal the SSMEs and SRBs. For insertion and deorbit, the commander's and pilot's RHCs may be used to gimbal the OMS engines or to command the RCS jets.



Rotational Hand Controller

On orbit, the commander's, pilot's, and aft flight station RHCs may be used to gimbal the OMS engines and command RCS jets. In addition, the commander's and pilot's RHCs may be used to command RCS jets during the early portion of entry, as well as to command the orbiter aerosurfaces during the latter portion of entry. The aft flight station RHC is used only on orbit.

Human factors dictate that an RHC deflection produce a rotation in the same direction as the flight crewmember's line of sight. A SENSE switch on panel A6U selects the line-of-sight reference, either -Z or -X, for the aft station RHC.

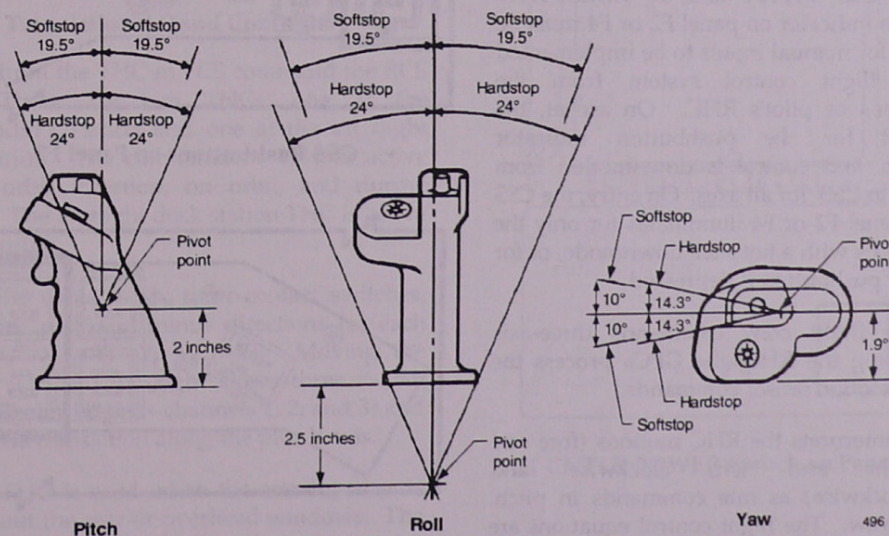
Several switches are located on the RHC. Depressing the backup flight system (BFS) mode button on the commander's and pilot's RHCs engages the BFS. The commander's, pilot's, and aft flight station RHCs have a two-contact trim switch. This switch, when pushed forward or aft, adds a trim rate to the RHC pitch command, or adds a roll trim rate when pushed left or right. The aft RHC's trim switch is inactive. The communications switch on each RHC is a push-to-talk switch that enables voice transmission.

Each RHC contains nine transducers: three transducers sense pitch deflection, three sense roll deflection, and three sense yaw deflection. The transducers produce an electrical signal proportional to the deflection of the RHC. The three transducers are called channels 1, 2, and 3.

Each channel is powered by a separate power supply in its associated display driver unit. Each controller is triply redundant; thus, only one good signal from a controller is required for the controller to operate.

Each RHC has an initial dead band of 0.25° in all three axes. To move the RHC beyond the dead band, an additional force is required. When the amount of deflection reaches a certain level, called the soft stop, a step increase in the force required for further deflection occurs. The soft stop occurs at 19.5° in the roll and pitch axes, and 9.5° to 10.5° in the yaw axis. The mechanical hard stop is 24.3° in the roll and pitch axes and 14.3° in the yaw axis.

Inputs from the RHCs to the FCS pass through a redundancy management scheme and the RHC SOP before they are passed to the aerojet digital autopilot. The RHC SOP performs four key functions. First, if an RHC is deemed bad, through redundancy management, then all commands from that RHC are set to zero. The SOP is also responsible for compensating and biasing the RHC commands, with the aft RHC commands transformed according to the SENSE switch position. Next the compensated and transformed commands are summed, by axis, to produce rotation commands for the flight control software. Finally, the SOP sets discretets to indicate if an RHC deflection is outside the software detent or beyond the software softstop.



Rotational Hand Controller Mechanical Limits

RHC Use	Forward RHC Use- Commander and Pilot	Aft Line-of-Sight Reference Aft RHC Use Sense Switch -X	Overhead Line-of-Sight Reference, Aft RHC Use Sense Switch -Z
	+ Pitch 	- Pitch 	- Pitch
	+ Roll 	- Roll 	- Yaw
	+ Yaw 	+ Yaw 	- Roll Visualize RHC mounted on same plane as -X windows

495

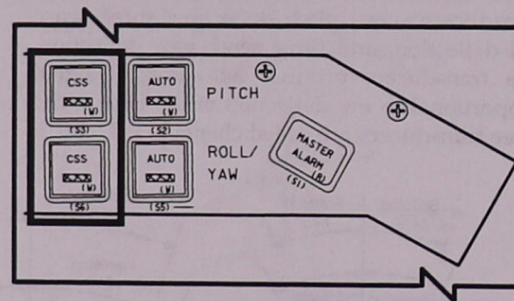
Positive Deflections of the Rotational Hand Controller by Axis

In a nominal mission, the flight crew can make manual inputs using the RHC during every major mode except terminal countdown. During all phases except ascent, when an RHC deflection exceeds the detent in an axis, the RHC SOP generates a discrete signal that converts the flight control system from the automatic mode to control stick steering (CSS), or hot stick, in the axis of deflection. During ascent, a CSS PITCH and/or ROLL/YAW pushbutton indicator on panel F2 or F4 must be depressed for manual inputs to be implemented into the flight control system from the commander's or pilot's RHC. On ascent, the CSS light for the pushbutton indicator illuminates, and control is downmoded from automatic to CSS for all axes. On entry, the CSS light on panel F2 or F4 illuminates for only the deflected axis with a hot stick downmode, or for whichever pushbutton is depressed.

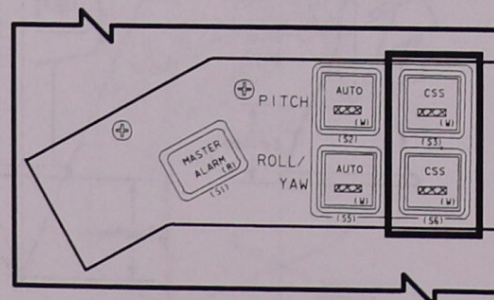
When the flight crew commands three-axis motion using the RHC, the GPCs process the RHC and motion sensor commands.

The FCS interprets the RHC motions (fore and aft, right and left, clockwise and counterclockwise) as rate commands in pitch, roll, and yaw. The flight control equations are subsequently processed to provide control

response and stability. If conflicting commands are given from more than one RHC, no commands result.



CSS Pushbuttons on Panel F2



CSS Pushbuttons on Panel F4

During orbital flight, any one of the three stations can input three-axis control commands to the flight control system. During entry and landing, the commander and pilot have two-axis (bank and pitch only) capability. Aerosurface deflection trim, in all three axes, is controlled by the panel trim switches on panels L2 and C3, while bank and pitch vehicle rate trim is controlled with the trim switches on the RHC. For a return-to-launch-site abort, both the commander's and pilot's RHC have three-axis capability during powered flight and two-axis capability during gliding flight.

The commander's RHC is powered when the FLT CNTLR POWER switch on panel F7 is positioned to ON. Similarly, the pilot's RHC and the aft RHC are powered when the FLT CNTLR POWER switches on panels F8 and A6U are positioned to ON.

RHC software redundancy management detects malfunctions in roll, pitch, or yaw axes for all three channels. The first malfunction detected will deselect all axes in that channel. For a second malfunction between the remaining two channels, the RHC is put in dilemma and the RHC SOP will no longer accept inputs from that RHC. For any detected malfunction, caution and warning generates an "RHC L," "RHC R," or "RHC A" message and illuminates the corresponding LEFT RHC or R/AFT RHC light on panel F7.

Translational Hand Controller

Signals from the THC in FCS command the RCS jets. There are two THCs, one at the commander's station and one at the aft flight deck station. The commander's THC is active during orbit insertion, on orbit, and during deorbit. The aft flight deck station THC is active only on orbit.

Each THC contains six three-contact switches, one in the plus and minus directions for each axis (+X, -X, +Y, -Y, +Z, -Z). Moving the forward THC to the right closes three switch contacts (referred to as channels 1, 2, and 3) and commands translation along the plus Y axis.

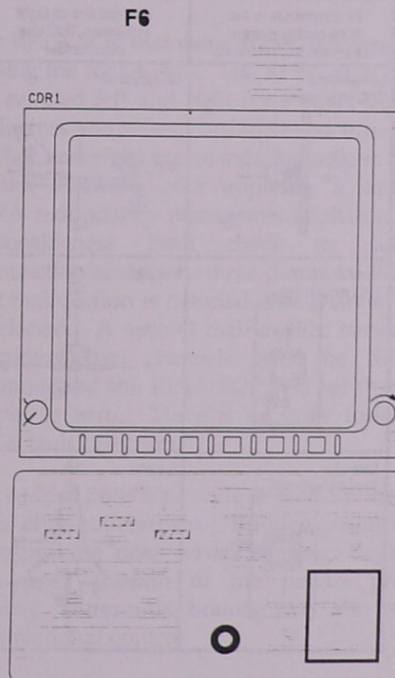
The aft THC is used when the crewmember is looking out the rear or overhead windows. The SENSE switch on panel A6U selects the line-of-

sight reference along the -X or -Z axis of the orbiter for the aft THC. The SENSE switch must be in the -X position for aft windows and -Z for the overhead windows for the aft THC commands to be correctly transformed to give the desired orbiter movement.

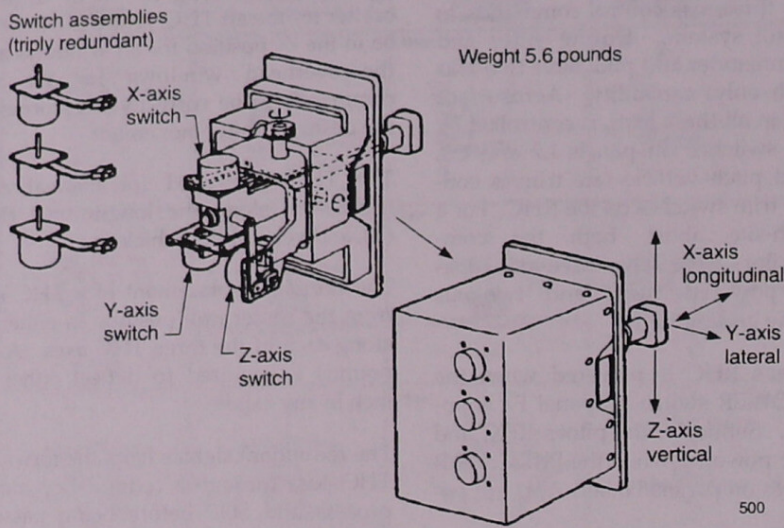
The THCs are used for manual control of translation along the longitudinal (X), lateral (Y), and vertical (Z) vehicle axes.

The normal displacement of a THC is 0.5-inch from the center null position in either direction along each of the three THC axes. A force of 2 pounds is required to deflect either THC 0.5 inch in any axis.

The redundant signals from the forward and aft THC pass through a redundancy management process and SOP before being passed to the flight control system. If the forward and aft THCs generate conflicting translation commands, no output translation command is issued.



FLT CNTLR POWER Switch on Panel F6

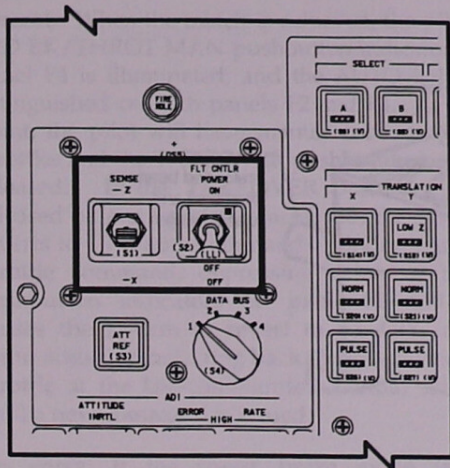


Translational Hand Controller

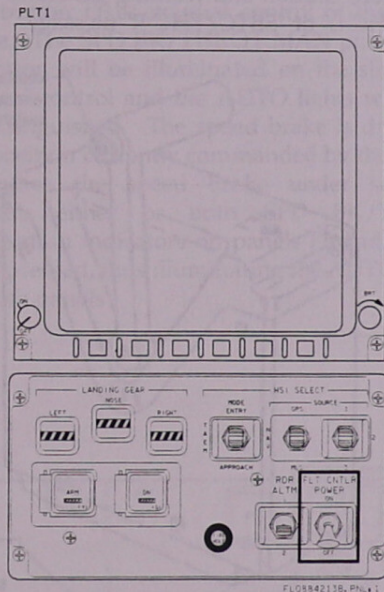
All commands to the flight control system are sent in this reference	Forward line-of-sight Reference THC use commander	Aft line-of-sight reference; Aft THC use sense switch-X	Overhead line-of-sight Reference; Aft THC use sense switch-Z
<p>Longitudinal THC movement</p>	<p>Longitudinal</p>	<p>Longitudinal</p>	<p>Vertical orbiter movement</p>
<p>Vertical THC movement</p>	<p>Vertical</p>	<p>Vertical</p>	<p>Longitudinal orbiter movement</p>
<p>Lateral THC movement</p>	<p>Lateral</p>	<p>Lateral</p>	<p>Lateral orbiter movement</p>

501

Positive Deflections of the Translational Hand Controller



FLT CNTRL POWER and SENSE Switches
on Panel A6U



FLT CNTRL POWER Switches on Panel F8

THC software redundancy management detects miscompares between the three channels for all six directions of movement. The first miscompare detected deselects only that channel for that direction. A second miscompare between the remaining two channels puts that THC direction in dilemma, so its commands are no longer noted by flight control. For any detected miscompare, caution and warning generates an "SBTC/THC L" or "SBTC/THC A" message.

The commander's THC is powered when the FLT CNTRL POWER switch on panel F6 is positioned to ON. The aft THC is powered when the FLT CNTRL POWER switch on panel A6U is positioned to ON.

Rudder Pedal Transducer Assembly

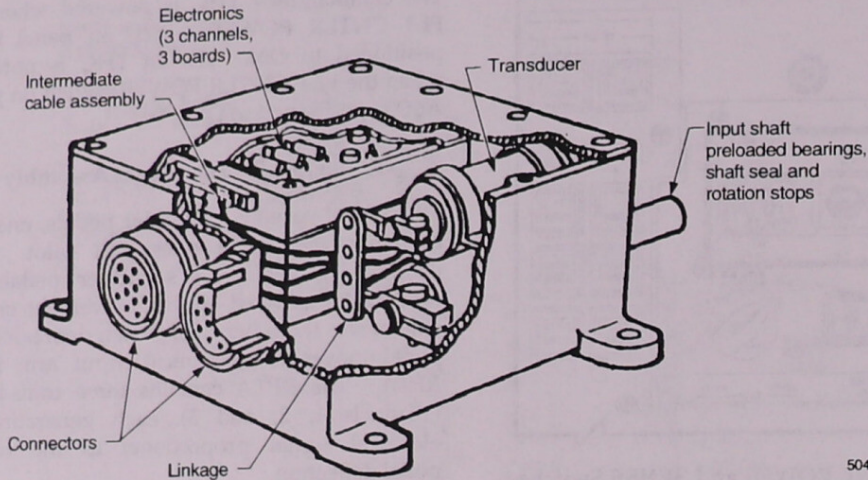
There are two pairs of rudder pedals, one pair each for the commander and pilot. The commander's and pilot's rudder pedals are mechanically linked so that movement on one side moves the other side. When depressed, the pedal moves a mechanical input arm in an RPTA. The RPTA contains three transducers (channels 1, 2, and 3), each generating an electrical signal proportional to the rudder pedal deflection.

The rudder pedals command orbiter acceleration about the yaw axis by positioning the rudder during atmospheric flight. Because the flight control software performs automatic turn coordination, the rudder pedals are not used for nose wheel steering until after touchdown.

The RPTA SOP maintains many functions in processing the RPTA data. The RPTA SOP converts the selected left and right commands from volts to degrees and selects the larger absolute value of the left and right commands for output to flight control software after applying a deadband. RPTA redundancy management software uses a reasonableness limit check to detect a malfunction among the three channels. When the first malfunction is detected, that channel will be deselected. A second malfunction between the remaining two channels puts the RPTA in dilemma and the RPTA SOP will set that RPTA output to zero. There is no crew insight into RPTA fault detection.

The rudder pedals provide two additional functions after touchdown. Rudder pedal deflections provide nose wheel steering; depressing the upper portion of the pedals provides braking. Differential braking may also be used for directional control.

The rudder pedals can be adjusted 3.25 inches forward or aft from the neutral position in 0.81-inch increments (nine positions). A pedal force of 70 pounds is required to depress a pedal to its maximum forward or aft position.



Rudder Pedal Transducer Assembly

The commander's RPTA is powered when the FLT CNTLR POWER switch on panel F7 is positioned to ON. The pilot's RPTA is powered when the FLT CNTLR POWER switch on panel F8 is positioned to ON.

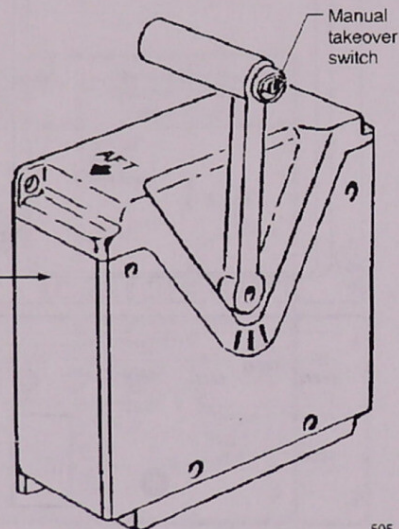
malfunction, caution and warning generates an "SBTC/THC L" or "SBTC/THC R" message.

Speed Brake/Thrust Controller

There are two SBTCs, one on the commander's left-hand side of the flight deck forward on panel L2 and one on the pilot's left-hand side on the center console on panel C3. The SBTCs serve two distinct functions. During ascent, the pilot's SBTC may be used to throttle the engines. During entry, the commander's or pilot's SBTC may be used to control aerodynamic drag (hence airspeed) by opening or closing the speed brake.

At the forward setting, the SSME thrust level is the greatest, or the speed brake is closed. Rotating the SBTC back decreases the SSME thrust level or opens the speed brake.

Each SBTC contains three transducers (channels 1, 2, and 3) that produce a voltage proportional to the deflection. Redundancy management uses a mid-value select scheme to determine output. It also uses a reasonableness limit check between the channels to detect failures. When the first malfunction is detected, that channel will be deselected. A second malfunction between the remaining two channels puts the SBTC in dilemma and inputs from that SBTC will no longer be accepted. For any detected



Speed Brake/Thrust Controller

In the case of the engine thrust-level setting, the top half (AUTO) of both SPD BK/THROT pushbutton indicators on panels F2 and F4 are illuminated nominally. Only the pilot's SBTC can be enabled for manual throttle control. The pilot depresses the TAKEOVER pushbutton on the SBTC, causing the GPC throttle command to be frozen at its current value. While depressing the TAKEOVER button, the pilot moves the SBTC to match the frozen GPC command. Manual control is established when the match is within 4

percent. When the match is achieved, the pilot's SPD BK/THROT MAN pushbutton indicator on panel F4 is illuminated, and the AUTO light is extinguished on both panels F2 and F4. At this point, the pilot will have manual control of the throttles and the TAKEOVER pushbutton is then released. If the TAKEOVER pushbutton is released before a match is achieved, the system reverts to GPC auto commands. Under manual throttle command, depressing either or both pushbutton indicators on panel F2 and F4 causes the system to revert to the GPC auto commands. Transferring back to auto leaves the throttle at the last-commanded manual setting until a new command is issued.

On entry, if the speed brake mode is in automatic, and the commander or pilot wishes to control the speed brake manually, momentarily depressing the TAKEOVER pushbutton takes manual control of the speed brake. The SPD BK/THROT MAN pushbutton indicator will be illuminated on the side with manual control and the AUTO lights will both be extinguished. The speed brake is driven to the position currently commanded by the SBTC. To place the speed brake under software control, either or both SPD BK/THROT pushbutton indicators on panels F2 and F4 can be depressed, thus illuminating the AUTO lights on both panels.

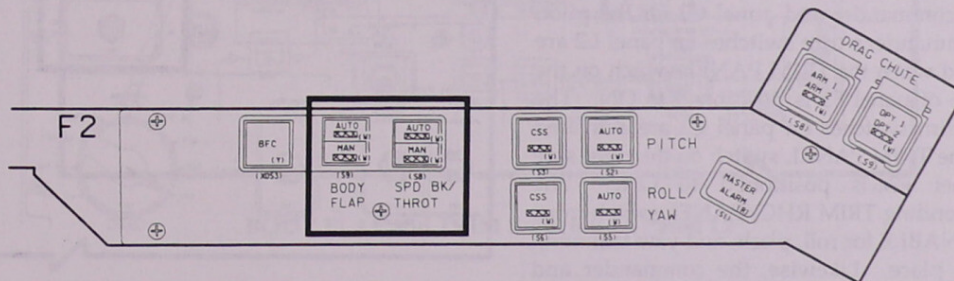
The SBTC SOP converts the selected SSME throttle command to a setting in percent and the selected speed brake command from volts to degrees. In addition, the SBTC SOP selects the speed brake command from the SBTC whose TAKEOVER button was depressed last. If both TAKEOVER buttons are depressed simultaneously, the commander's SBTC is given control. If redundancy management declares an SBTC bad, the command is frozen.

The commander's SBTC is powered by the FLT CNTLR POWER switch on panel F7 when positioned to ON. The pilot's SBTC is powered by the FLT CNTLR POWER switch on panel F8.

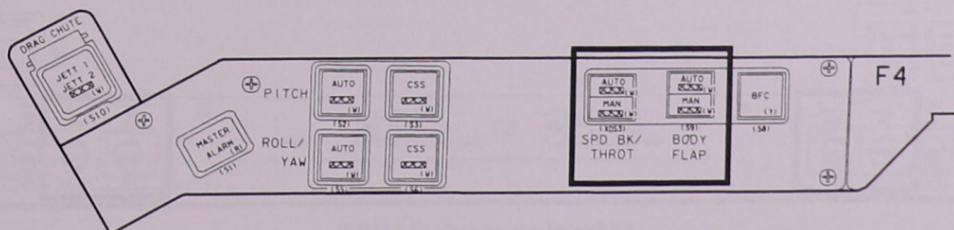
Body Flap Switches

There are two BODY FLAP switches, one on panel L2 for the commander and one on panel C3 for the pilot. Each switch is lever-locked and spring-loaded to the AUTO/OFF position. The UP and DOWN positions of each switch have two power supplies from separate control buses. In addition, each contact status is sent to the data processing system via an MDM. The switches provide manual control for positioning the body flap for main engine thermal protection and for pitch trim to reduce elevon deflections during the entry phase.

Body flap control is initialized in its automatic mode with both BODY FLAP AUTO pushbutton



BODY FLAP and SPD DK/THROT Pushbuttons on Panel F2



SPD BK/THROT and BODY FLAP Pushbuttons on Panel F4

indicators illuminated on panels F2 and F4. The body flap can be switched to its manual mode by depressing either BODY FLAP pushbutton. The white BODY FLAP MAN pushbutton indicators will then illuminate, indicating manual control of the body flap. To regain automatic control, the BODY FLAP pushbutton indicator on panel F2 or F4 is again depressed, extinguishing the MAN light and illuminating the AUTO light. The pushbutton indicator is triply redundant.

Trim Switches

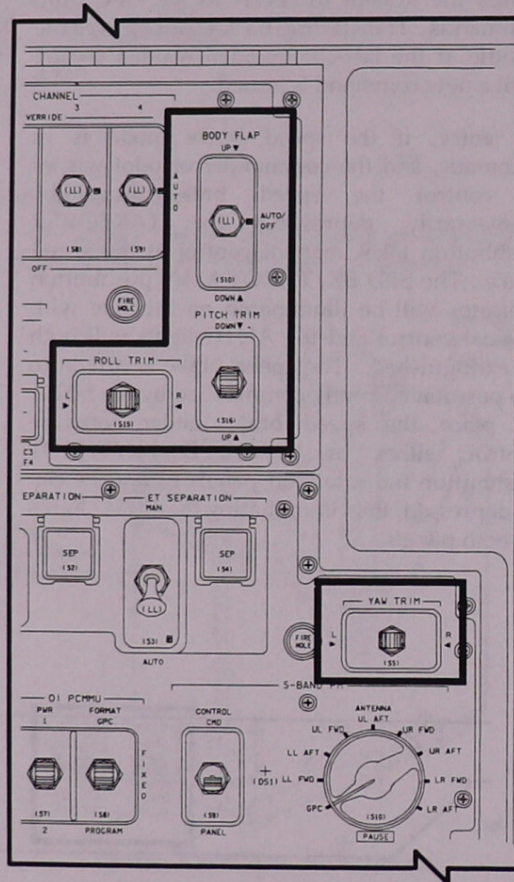
Roll and pitch panel trim switches allow the crew to actually move the aerosurfaces, whereas the RHC trim switches change the rate command. The yaw panel trim switch inputs an acceleration bias into the yaw channel.

The TRIM PANEL switches on panel F3 enable control bus power to a set of three panel trim switches. The dual-redundant TRIM RHC/PANEL switches on panel F3 provide signals to the GPCs, prohibiting software execution of the associated RHC and panel trim switch inputs while in the INHIBIT position. The ENABLE position permits the RHC and TRIM PANEL switch to be used for trimming.

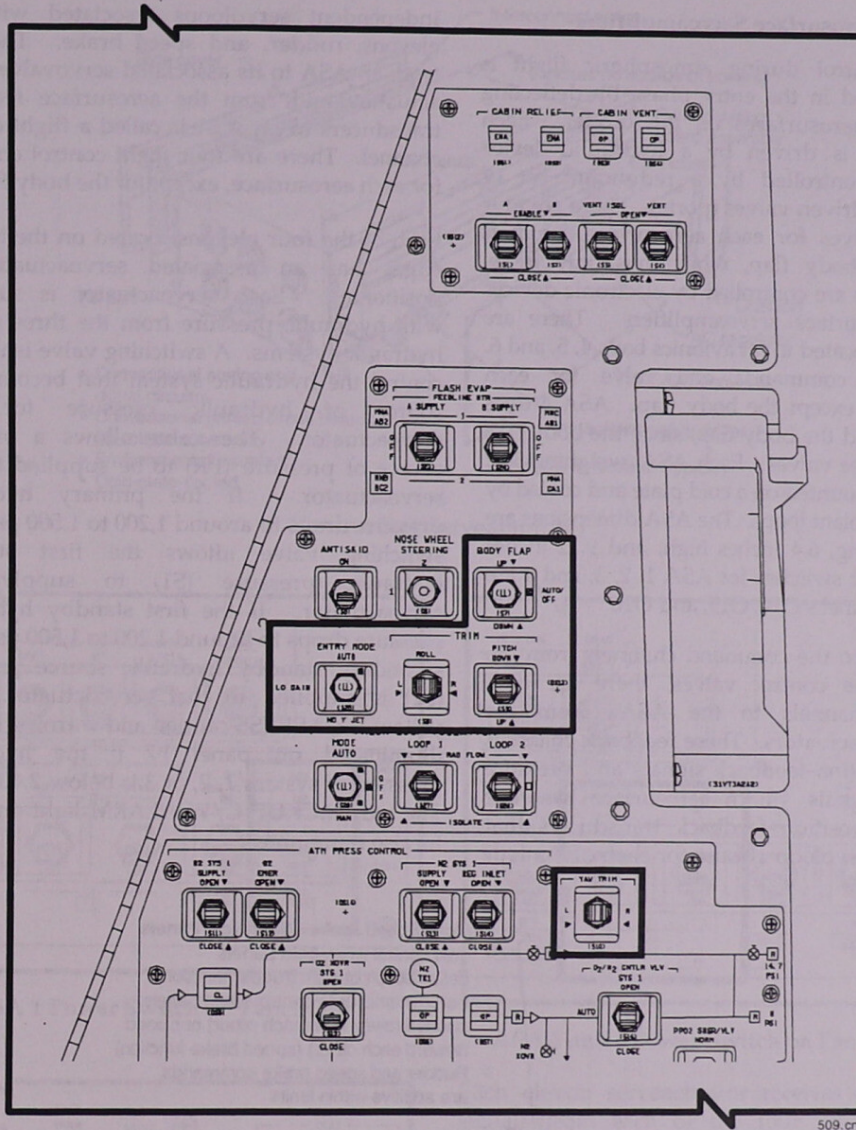
Six panel switches control roll, pitch, and yaw. The switches, labeled ROLL TRIM, PITCH TRIM, and YAW TRIM, are located on panel L2 for the commander and panel C3 for the pilot. The commander's trim switches on panel L2 are activated when the TRIM PANEL switch on the left side of panel F3 is positioned to ON. The pilot's trim switches on panel C3 are activated when the TRIM PANEL switch on the right side of panel F3 is positioned to ON. The corresponding TRIM RHC/PANEL switch must be in ENABLE for roll, pitch, and yaw trimming to take place. Likewise, the commander and pilot RHC trim is activated when the

corresponding FLT CNTRL POWER switch on panel F7 or F8 is ON and the corresponding TRIM RHC/PANEL switch on F3 is in ENABLE. All the trim switches on the RHC and on panels L2 and C3 are spring loaded to the OFF position.

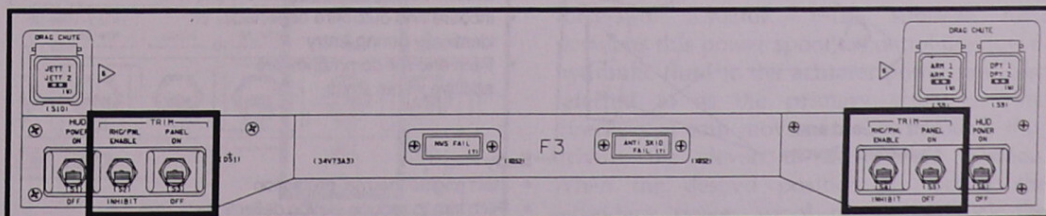
Redundancy management processes the two sets of TRIM switches. If two switches generate opposing commands, the resultant trim command in that axis is zero.



BODY FLAP and TRIM Switches on Panel C3



BODY FLAP and TRIM Switches on Panel L2



TRIM Switches on Panel F3

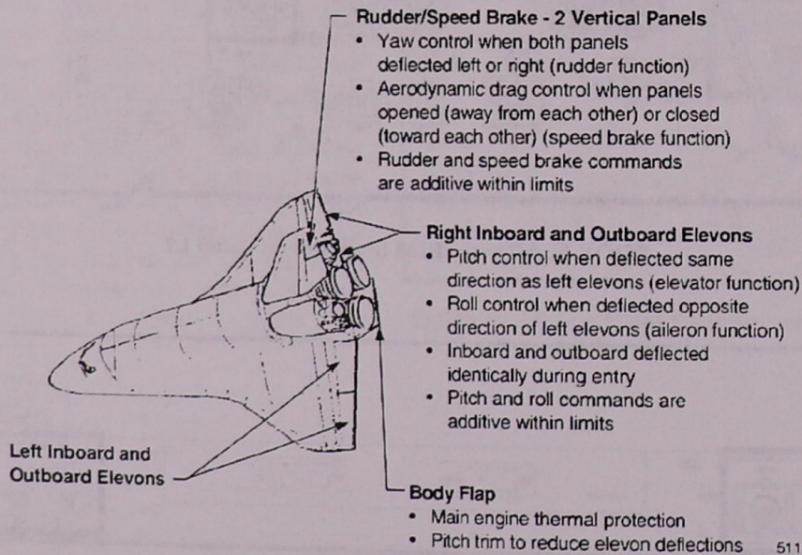
Aerosurface Servoamplifiers

Vehicle control during atmospheric flight is accomplished in the entry phase by deflecting the seven aerosurfaces on the orbiter. Each aerosurface is driven by a hydraulic device (actuator) controlled by a redundant set of electrically driven valves (ports). There are four of these valves for each aerosurface actuator, except the body flap, which has only three. These valves are controlled by electronic devices called aerosurface servoamplifiers. There are four ASAs located in aft avionics bays 4, 5, and 6. Each ASA commands one valve for each aerosurface, except the body flap. ASA 4 does not command the body flap, since the body flap has only three valves. Each ASA, weighing 30.2 pounds, is mounted on a cold plate and cooled by the Freon coolant loops. The ASA dimensions are 20 inches long, 6.4 inches high, and 9.12 inches wide. Power switches for ASA 1, 2, 3, and 4 are located on panels O14, O15, and O16.

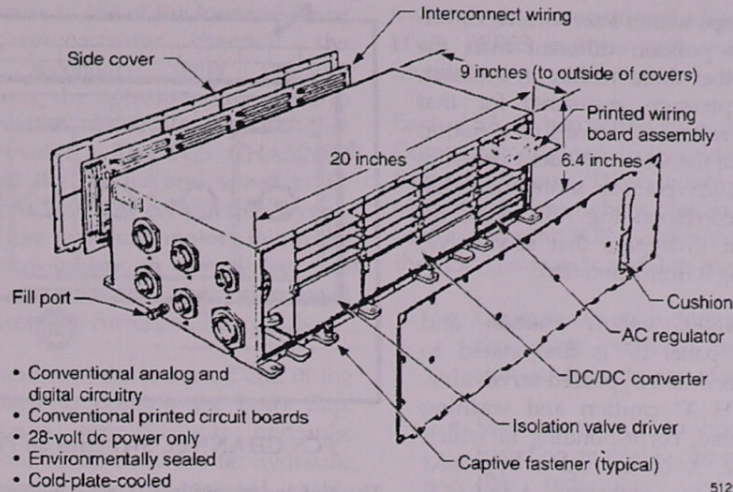
In addition to the command channels from the ASAs to the control valves, there are data feedback channels to the ASAs from the aerosurface actuators. These feedback channels include position feedback signals and pressure feedback signals. Each aerosurface has four associated position feedback transducers that provide a servoloop closure for each of the four

independent servoloops associated with the elevons, rudder, and speed brake. The path from an ASA to its associated servovalve in the actuators and from the aerosurface feedback transducers to an ASA is called a flight control channel. There are four flight control channels for each aerosurface, except for the body flap.

Each of the four elevons located on the trailing edges has an associated servoactuator for positioning. Each servoactuator is supplied with hydraulic pressure from the three orbiter hydraulic systems. A switching valve is used to control the hydraulic system that becomes the source of hydraulic pressure for that servoactuator. The valve allows a primary source of pressure (PR) to be supplied to that servoactuator. If the primary hydraulic pressure drops to around 1,200 to 1,500 psia, the switching valve allows the first standby hydraulic pressure (S1) to supply that servoactuator. If the first standby hydraulic pressure drops to around 1,200 to 1,500 psia, the secondary standby hydraulic source pressure (S2) is supplied to that servoactuator. The yellow HYD PRESS caution and warning light is illuminated on panel F7 if the hydraulic pressure of system 1, 2, or 3 is below 2,400 psia. The red BACKUP C/W ALARM light on panel F7 also illuminates.

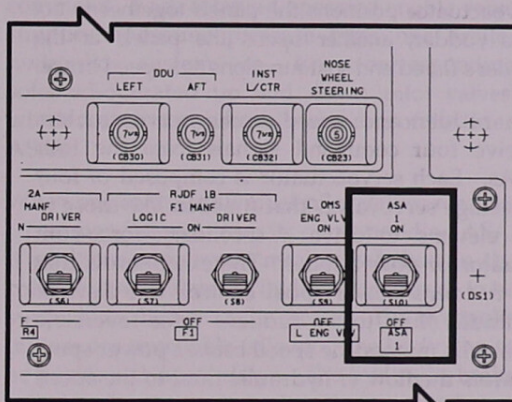


Aerodynamic Surfaces and Associated Control Axes

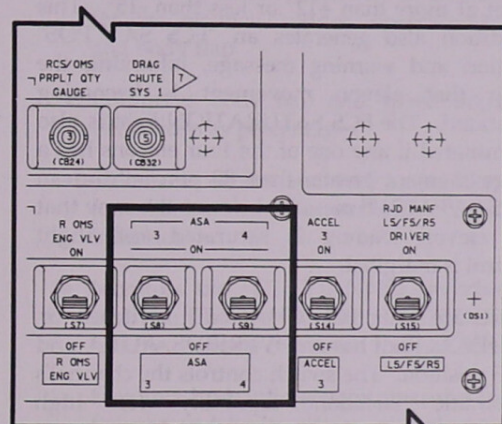


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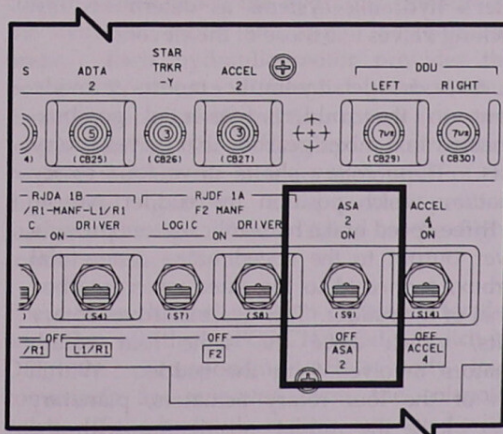
Aeosurface Servoamplifier



ASA 1 Power Switch on Panel O14



ASA 3 and 4 Power Switch on Panel O16



ASA 2 Power Switch on Panel O15

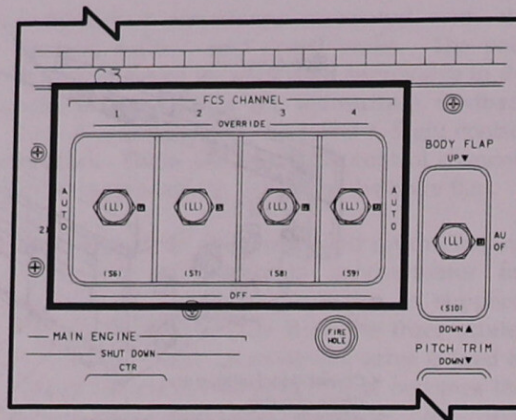
Each elevon servoactuator receives command signals from each of the four ASAs. Each actuator is composed of four two-stage servovalves that drive a modulating piston. Each piston is summed on a common mechanical shaft, referred to as the secondary force-sum actuator. The summed force positions this power spool to control the flow of hydraulic fluid to the actuator power ram, also referred to as the primary actuator. The direction of ram movement is controlled, thus driving the elevon to the desired position. When the desired position is reached, the secondary power spool moves to block the hydraulic pressure to the hydraulically operated ram, thus stopping the ram at that position.

If a problem develops within a servovalve, or it is commanded to a position different than the positions of the other three within an actuator, secondary delta pressure, measured for that servovalve off the secondary force-sum actuator, begins to rise. Once the secondary delta pressure is at or above 2,025 psi for more than 120 milliseconds, the corresponding ASA sends an isolation command to bypass that servovalve, effectively removing it from operation.

The FCS CHANNEL yellow caution and warning light on panel F7 is illuminated to inform the flight crew of a bypassed servovalve. Also, an "FCS CH X" caution and warning message is generated, corresponding to which FCS channel (1, 2, 3, or 4) had a bypassed servovalve on one of its actuators. A red FCS SATURATION caution and warning light on panel F7 is illuminated if one of the four elevons is set at more than +12° or less than -15°. This condition also generates an "FCS SAT POS" caution and warning message, informing the crew that elevon movement is becoming saturated. The FCS SATURATION light is also illuminated if any one of the four elevons has a hinge moment greater than 80 percent and an "FCS SAT MOM" message informs the crew that the elevon loading is saturated and flight control is marginal.

There are four FCS CHANNEL switches on panel C3. Each has an OVERRIDE, AUTO, and OFF position. The switch controls the channel's automatic isolation capability for high secondary delta pressure for the elevons, rudder, speed brake, and SRB and SSME actuators. When an FCS CHANNEL switch is in AUTO, the isolation capability discussed above can take place. Moving the switch to OVERRIDE and back to AUTO will reset any isolated servovalves on that channel. Leaving the switch in OVERRIDE will prevent the auto isolation from taking place. When the switch is positioned to OFF, that channel is bypassed on all actuators.

During ascent, the elevons are deflected to reduce wing loads caused by rapid acceleration through the lower atmosphere. In this scheme, the inboard and outboard elevons are deflected separately. By the time the vehicle reaches approximately Mach 2.5, the elevons have reached a null position, where they remain.



FCS CHANNEL Switches on Panel C3

The rudder/speed brake, which consists of upper and lower panels, is located on the trailing edge of the orbiter's vertical stabilizer. One servoactuator positions the panels together to act as a rudder; another opens the panels at the rudder's flared end so it functions as a speed brake.

The rudder and speed brake servoactuators receive four command signals from the four ASAs. Each servoactuator is composed of four two-stage servovalves that function like those of the elevons to drive a secondary force-sum actuator or power spool. The exception is that the rudder's power spool controls the flow of hydraulic fluid to the rudder's three reversible hydraulic motors; the speed brake's power spool controls the flow of hydraulic fluid to the speed brake's three reversible hydraulic motors. Each rudder and speed brake hydraulic motor receives hydraulic pressure from only one of the orbiter's hydraulic systems as determined by switching valves like those of the elevons.

The three rudder hydraulic motors provide output to the rudder differential gearbox, connected to a mixer gearbox that drives rotary shafts. These rotary shafts drive four rotary actuators, which position the rudder panels. The three speed brake hydraulic motors provide power output to the speed brake differential gearbox, connected to the same mixer gearbox as that of the rudder. This gearbox drives rotary shafts, which drive the same four rotary actuators involved with the rudder. Within each of the four rotary actuators, planetary gears blend the rudder positioning with the opening of the speed brake.

If a problem occurs in one of the four rudder or speed brake servoactuator channels, the corresponding secondary delta pressure transducer causes the corresponding ASA to signal an isolation valve to bypass that actuator's servovalve. The FCS CHANNEL switches control the rudder and speed brake channels the same way they control the elevons. If two of the three hydraulic motors fail in the rudder or speed brake, no servovalves are bypassed; however, about half the design speed output results from the corresponding gearbox.

Three servoactuators at the lower aft end of the fuselage are used to position the body flap. Each is separately supplied with hydraulic pressure from one of the three orbiter hydraulic system and has a solenoid-operated enable valve controlled by one of three ASAs. Note that the fourth ASA is not used for the body flap command. Each solenoid-operated enable valve supplies hydraulic pressure from one orbiter hydraulic system to two corresponding solenoid-operated up and down pilot valves, which are, in turn, controlled by one of the three ASAs.

When one of the individual pilot valves receives a command signal from its corresponding ASA, it positions a common mechanical shaft in the control valve, allowing hydraulic pressure to be supplied to the hydraulic motors. The hydraulic motors are reversible, allowing the body flap to be positioned up or down. The hydraulic brake associated with each hydraulic motor releases the hydraulic motor for rotation. When the desired body flap position is reached, the control valves block the hydraulic pressure to the hydraulic motor and apply the hydraulic brake. Each hydraulic motor provides the power output to a differential gearbox, thus driving a rotary shaft and four rotary actuators, which position the body flap. Four rotary position transducers measure the output of the differential gearbox to provide position feedback through all four ASAs to the flight control system software.

There is no channel isolation capability for the body flap. With the FCS CHANNEL switch in OFF, the corresponding ASA's body flap commands are removed from the solenoid valves. If the hydraulic system associated with the hydraulic motor fails, the remaining two

hydraulic motors position the body flap, and the HYD PRESS caution and warning light is illuminated.

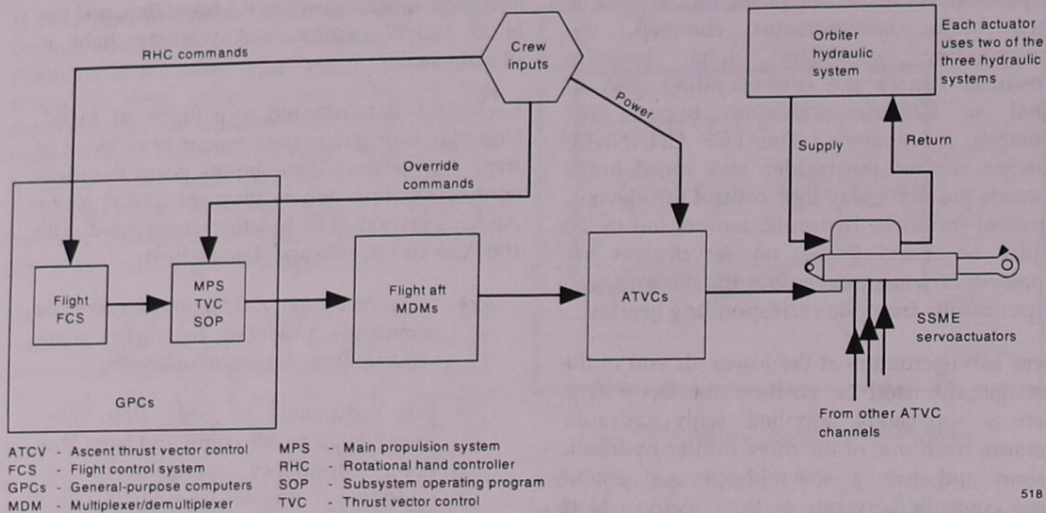
Each ASA is hardwired to a flight aft MDM. Commands originate from guidance software or from controllers. These inputs go to the flight control software, where they are routed to the ASAs. Several SOP functions associated with the ASA commands and data include:

- Converts elevon, rudder, and speed brake commands produced by flight control software from degrees to millivolts
- Sets commands to body flap valves based on an enable command from body flap redundancy management and up/down commands from flight control
- Converts position feedback to degrees for the elevons, rudder, speed brake, and body flap
- Computes body flap and speed brake deflections as percentages
- Calculates elevon and rudder positions for display on the surface position indicator
- Monitors the FCS CHANNEL switches and, if any are positioned to OVERRIDE, sets the override command for that ASA
- Monitors hydraulic system pressures for failures and limits aileron and elevator commands according to the number of failures.

Isolation status of the FCS CHANNEL servovalves is displayed on the GNC SYS SUMM 1 display under FCS CH for all actuators, and on the SPEC 55 CONTROLS display in more detail for each aerosurface and SSME actuator.

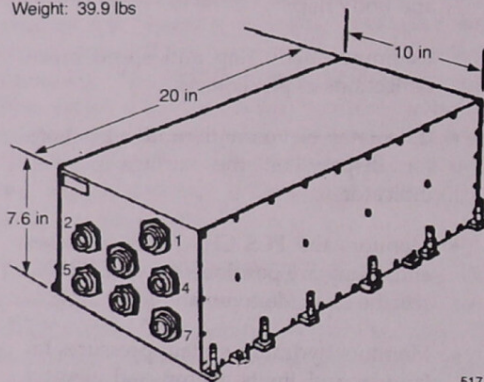
Ascent Thrust Vector Control

The orbiter ATVC portion of the FCS controls attitude and trajectory by directing the thrust of the three main engines and two solid rocket boosters during lift-off and first-stage ascent, and of the main engines only during second-stage ascent.



SSME Thrust Vector Control Interface Flow

Weight: 39.9 lbs



Ascent Thrust Vector Controller

ATVC is provided by four avionics hardware packages that supply gimbal commands and fault detection for each hydraulic gimbal actuator. The packages are located in the three aft avionics bays in the orbiter aft fuselage and are cooled by cold plates and the Freon system. The associated flight aft MDMs are also located in the aft avionics bays.

The main propulsion system (MPS) thrust vector control command flow starts in the GPCs, in which the flight control system generates the position commands, and terminates at the SSME servoactuators, where the actuators gimbal the SSMEs in response to the commands. All the position commands are issued to the MPS thrust

vector control command SOP. This program processes and transmits the commands to their corresponding flight aft MDMs. The commands are then separated and distributed to the four ascent thrust vector control channels, which generate equivalent command analog voltages for each command issued. These voltages are, in turn, sent to one of four servovalves on a servoactuator, commanding the SSME hydraulic actuators to extend or retract, thus gimbaling the main engines to which they are fastened.

Ten actuators respond to the command voltages issued by four ascent thrust vector control channels. Each FCS channel contains an ATVC that has six MPS drivers and four solid rocket booster drivers. Each actuator receives four identical command voltages from four different drivers, each located in one of the four ATVCs.

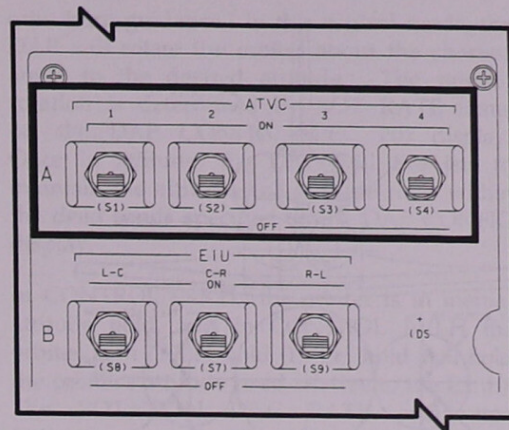
Both main engine and solid rocket booster servoactuators consist of four independent, two-stage servovalves that receive signals from the drivers. The force of these four servovalves is summed on a secondary force-sum actuator or power spool, which positions an actuator ram and thus the engine to control thrust direction.

The four servovalves in each actuator provide a force-summed majority voting arrangement to position the power spool. With four identical commands to the four servovalves, the actuator's force-sum action prevents a single

erroneous command from affecting power ram motion. If the erroneous command persists for more than a predetermined time, differential pressure measured off of the secondary force-sum actuator for that servovalve is sensed in the corresponding ATVC, which activates an isolation driver. This driver energizes an isolation valve that isolates the defective servovalve and removes hydraulic pressure, permitting the remaining channels and servovalves to control the actuator ram spool, provided the FCS CHANNEL 1, 2, 3, or 4 switch on panel C3 is in the AUTO position. A second failure would isolate the defective servovalve and remove hydraulic pressure in the same manner as the first failure, leaving only two channels remaining.

Failure monitors are provided for each channel on the GNC SYS SUMM 1 display and with the yellow FCS CHANNEL and red BACKUP C/W ALARM lights on panel F7 to indicate which channel has a bypassed servovalve for any of the MPS and/or solid rocket boosters. There is more detailed crew information on precisely which MPS actuator has a bypassed servovalve on the SPEC 53 CONTROLS display. If the FCS CHANNEL 1, 2, 3, or 4 switch on panel C3 is positioned to OFF, then that ATVC channel is isolated from its servovalves on all MPS and solid rocket booster actuators. The OVERRIDE position of the switch inhibits the corresponding ATVC from automatically bypassing servovalves on that channel due to high secondary delta pressure problems on the power spool and provides the capability to reset a bypassed servovalve on that channel.

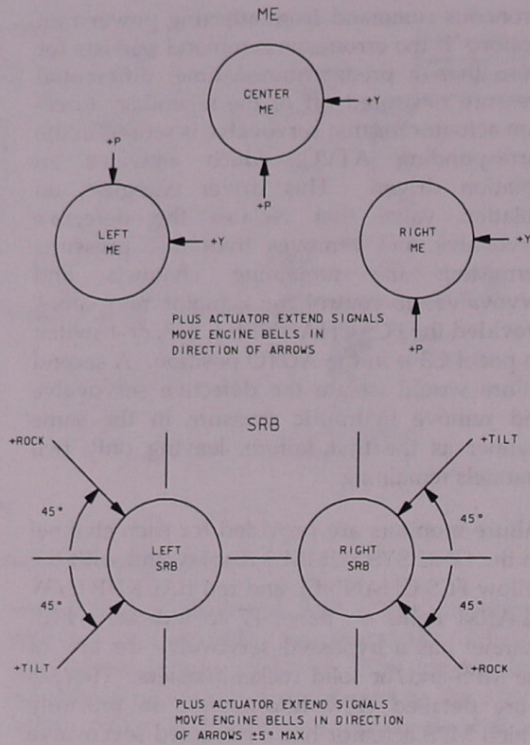
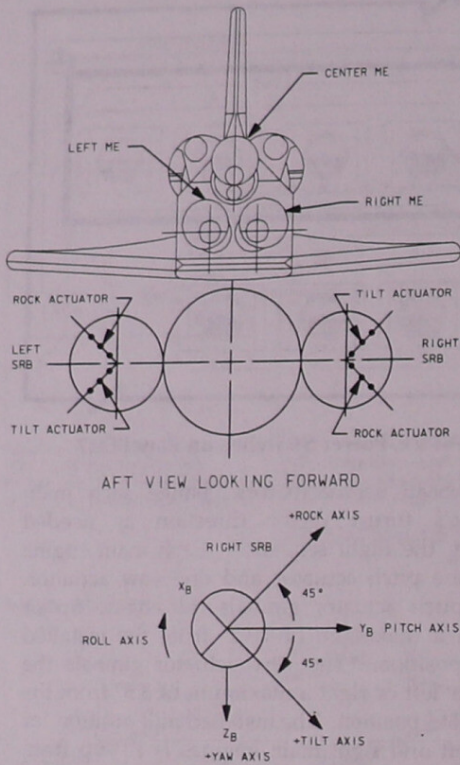
The ATVC 1, 2, 3, 4 power switches are located on panel O17. The ON position enables the ATVC channel selected; OFF disables the channel.



ATVC Power Switches on Panel O17

The SSME servactuators change each main engine's thrust vector direction as needed during the flight sequence. Each main engine has one pitch actuator and one yaw actuator. The pitch actuator gimbals the engine up or down a maximum of 10.5° from the installed null position. The yaw actuator gimbals the engine left or right a maximum of 8.5° from the installed position. The installed null position for the left and right main engines is 10° up from the X axis and 3.5° outboard from an engine centerline parallel to the X axis. The center engine's installed null position is 16° above the X axis centerline for pitch and on the X axis centerline for yaw. When any engine is installed in the null position, the other engines cannot collide with it.

Each SRB also has two thrust vector control actuators. However, the SRB TVC coordinate axes are called "rock" and "tilt" rather than pitch and yaw. The rock and tilt axes form a 45° angle with the pitch and yaw axes. This allows an equivalent $\pm 7^\circ$ movement range in pitch and yaw with a rock/tilt gimbal range of $\pm 5^\circ$.



SSME and SRB Thrust Vector Control

Digital Autopilot

The digital autopilot (DAP) is the heart of flight control software. It is composed of several software modules that interpret maneuver requests, compare them to what the vehicle is doing, and generate commands for the appropriate effectors. There are different DAPs for different flight phases, particularly insertion and orbit, and various modes and submodes within each.

The DAP controls the orbiter in response to automatic or manual commands during insertion and on orbit. The effectors used to produce control forces and moments on the orbiter are the two OMS engines and the 38 primary RCS jets. Six vernier RCS jets are also available on orbit for attitude control. The forward and aft RCS jets also provide attitude control and three-axis translation during external tank separation, insertion, and on-orbit maneuvers, as well as roll control for a single-OMS-engine operation. The OMS provides

propulsive control for orbit insertion, orbit circularization, orbit transfer, and rendezvous. Failure of a single OMS engine does not preclude a nominal orbit insertion.

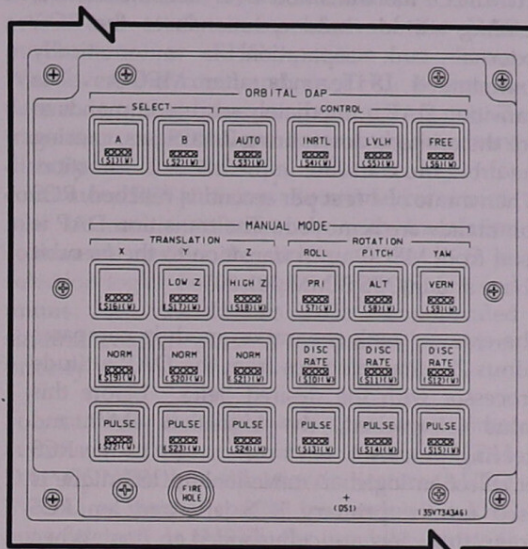
Orbital DAP Panel

There are 24 ORBITAL DAP pushbutton indicators on panels C3 and A6U. Assuming no electrical, computer, or hardware failures affect the operation of the indicators, inputs made to one panel are reflected in the configuration of the other panel. All the pushbuttons are active in the orbital DAP, whereas only a subset are operational in the transition DAP or when the backup flight system is engaged. None of the indicators are operational during ascent or entry. As with other aft flight-deck controls, aft panel A6U pushbutton indicators are only operational during the on-orbit phase.

The orbital DAP is somewhat similar to the transition DAP, but has many options and capabilities added. These added capabilities can

best be explained by a review of the ORBITAL DAP controls on panels C3 and A6U. Discussions of the various DAP modes follow.

The SELECT (A or B) pushbutton indicators toggle the DAP between one of two configurations. These configurations are changed and displayed on the DAP CONFIG display (SPEC 20).



**ORBITAL DAP Pushbuttons on Panel C3
(Panel A6U identical)**

2011/020/		DAP CONFIG		1 000/19:07:32	
PRI	1 DAP A08	2 DAP B08	PRI	DAP EDIT	000/00:00:00
ROT RATE	10 0.2000	30 0.2000	50 0.2000	3 DAP A08	
ATT DB	11 1.00	31 1.00	51 1.00	4 DAP B	
RATE DB	12 0.10	32 0.10	52 0.10	5 LOAD	
ROT PLS	13 0.10	33 0.10	53 0.10		
COMP	14 .000	34 .000	54 .000		
P OPTION	15 TAIL	35 TAIL	55 TAIL		
Y OPTION	16 TAIL	36 TAIL	56 TAIL	NOTCH FLTR	
TRAN PLS	17 0.05	37 0.01	57 0.05	ENA 6X	
ALT			ALT		
RATE DB	18 0.200	38 0.200	58 0.200	XJETS ROT	
JET OPT	19 ALL	39 ALL	59 ALL	ENA 7X	
# JETS	20 2	40 2	60 2		
ON TIME	21 0.08	41 0.08	61 0.08	REBOOST	
DELAY	22 0.00	42 0.00	62 0.00	8 CFG X	
VERN			VERN	9 INTVL	
ROT RATE	23 0.2000	43 0.2000	63 0.2000	XXX XY	
ATT DB	24 1.000	44 1.000	64 1.000		
RATE DB	25 .020	45 .020	65 .020		
ROT PLS	26 0.010	46 0.010	66 0.010		
COMP	27 .000	47 .000	67 .000		
CNTL ACC	28 0	48 0	68 0		

DAP CONFIG Display (SPEC 20)

The CONTROL pushbutton indicators toggle the DAP between AUTO, INRTL, LVLH, and FREE. In AUTO the orbiter's attitude is controlled by universal pointing (UNIV PTG) or

orbit burn guidance. In this control mode, the DAP will rotate the orbiter about the shortest angle to the desired attitude. The rate of rotation is determined by ROT RATE items on the DAP CONFIG (SPEC 20) display. Once in attitude, the DAP will fire jets to maintain the attitude and attitude rates within the dead bands specified on the DAP CONFIG display.

In CONTROL INRTL, the orbiter is in inertial attitude hold, and in CONTROL LVLH the orbiter is in LVLH hold (LVLH hold will hold the orbiter's attitude fixed relative to the Earth). The ROTATION DISC RATE pushbutton indicators must be illuminated for INRTL or LVLH to hold attitude.

The CONTROL FREE pushbutton indicator puts the DAP into free drift. In this mode, the ROTATION PULSE pushbutton indicators will illuminate, and RCS jets will not fire if the RHC and THC remain in detent.

The first row of the MANUAL MODE TRANSLATION pushbuttons control which of the +Z (up firing) jets will fire. Nominally, none of the pushbutton indicators are illuminated, and the "normal" number of up firing jets will be commanded to fire. If the LOW Z pushbutton indicator is depressed, DAP will never command an up firing jet to fire. This mode is used to protect a payload or crewmember that is operating close to the orbiter.

In HIGH Z, all the up firing jets will be commanded to fire if a +Z translation is commanded with the THC. All other DAP maneuvers will result in the "normal" number of up firing jets to fire. This mode is used to quickly separate the orbiter from a payload.

The second and third rows of MANUAL MODE TRANSLATION pushbuttons toggle the DAP between NORM and PULSE. In NORM, RCS jets will be continuously commanded to fire if the THC is moved out of detent. In PULSE, DAP will fire RCS jets to achieve the TRANSLATION PULSE rate specified on the DAP CONFIG display. The PULSE units are feet per second.

The first row of the MANUAL MODE ROTATION portion of the DAP panel toggles the DAP between primary (PRI), alternate

(ALT), and vernier (VERN). In PRI, one or more of the primary RCS jets will be continuously commanded to fire if either the attitude or attitude rate dead bands are exceeded. This mode will not be used for many different RMS and payload operations.

In ALT, the primary RCS jets are still used, but the number of jets, duration of firings, and time between firings can be controlled on the DAP CONFIG display. This extra control of jet firings greatly reduces the stress on a payload and the RMS. The ALT mode allows almost unrestricted payload and RMS operations if the vernier jets are not available. In ALT mode, the DAP also determines the best jet(s) to fire based on the combined orbiter/payload moments of inertias. These inertias are selected with CNTL ACCEL (item 14) on the DAP CONFIG display.

In VERN, the DAP uses the six vernier RCS jets for attitude control. Vernier control produces less stress on the RMS/payload, uses less propellant, and can achieve tighter dead bands than either PRI or ALT. Like the ALT mode, the best jet(s) to use are determined by the orbiter/payload moments of inertias.

The second and third rows of the ROTATION pushbutton indicators toggle the DAP between discrete rate (DISC RATE) and PULSE. For these rows to have any effect, the ORBITAL DAP CONTROL must not be in AUTO. In DISC RATE, if the RHC is taken out of detent, the DAP will fire RCS jets to achieve and maintain the rate specified by the ROT RATE in the DAP CONFIG display. If the RHC is in detent, the DAP will fire jets to maintain either inertial or LVLH attitude hold, depending on the selection of the ORBITAL DAP CONTROL pushbutton indicators.

In ROTATION PULSE, moving the RHC out of detent commands a pulse of jet firings to increase the rotation rate by the ROT PLS rate specified on the DAP CONFIG display. When the RHC is in detent, the DAP is in free drift for that axis. Pushing the CONTROL FREE pushbutton indicator is functionally equivalent to pushing all three ROTATION PULSE pushbutton indicators.

Continuous rotation RCS jet firings can be obtained by moving the RHC past the soft stop.

This continuous firing of jets can be obtained in either DISC RATE or PULSE. Even if CONTROL is in AUTO, moving the RHC out of detent will force the DAP to INRTL, and further movement past the soft stop will cause continuous jet firings.

Transition DAP

At MECO, the transition DAP becomes active, sending attitude hold commands to the RCS. External tank separation is automatically commanded 18 seconds after MECO. The transition DAP immediately sends commands to fire the orbiter's down firing Z RCS jets, causing the orbiter to translate in the minus Z direction. When a rate of 4 feet per second is reached, RCS commands are removed. The transition DAP is used from MECO until transition to the on-orbit phase and in OPS 3 MM 301-303.

The external tank separation module compares minus Z delta velocities from the DAP attitude processor with the desired delta. Before this value is reached, the transition DAP and steering processor send commands to the RCS jet selection logic. A table-lookup technique is used for the primary RCS jets, and ten RCS down firing jets are commanded to fire. When the desired minus Z-delta velocity is reached, the translation command is set to zero. Rotation commands are also permitted during the external tank separation sequence. The RCS jet driver forward and aft assemblies provide the turn-on/turn-off jet selection logic signals to the RCS jets. There is also an RCS redundancy management program that permits only "good" RCS jets to be activated.

Insertion flight control is also accomplished with the transition DAP. The transition DAP uses commands from the guidance software for automatic maneuvers to the OMS burn attitude using RCS jets. During OMS-1 and OMS-2 (or only OMS-2 in a direct insertion), the transition DAP uses the OMS engines thrust vector control and RCS jets, as required. The transition DAP also receives commands from the commander's THC and the commander's or pilot's RHC. The transition DAP then takes these commands and converts them into appropriate RCS or OMS TVC commands. The transition DAP monitors the resultant attitude and attitude rates and sends the necessary commands to achieve the

targeted attitude and attitude rate within premission-specified dead bands.

The flight crew interfaces directly with the transition DAP through the forward RHCs and THC and indirectly through entries to the OMS MNVR EXEC display and the ORBITAL DAP pushbuttons on panel C3.

In the transition DAP, the commander's THC is active and totally independent of the DAP pushbuttons or RHC position or status. Whenever the commander's THC is out of detent in either plus or minus X, Y, or Z, translation acceleration commands are sent directly to the RCS jet selection logic for continuous RCS jet firing. Rotational commands may be sent simultaneously with translation commands within the limits of the RCS jet selection logic. For example, if both plus X and minus Z translations are commanded simultaneously, plus X translation receives priority.

For rotations, the flight crew can select either automatic or manual control via the ORBITAL DAP CONTROL pushbutton indicators (AUTO, INRTL) or manual control by moving the RHC out of detent. In INRTL, the capability exists to rotate about any axis in one of two modes. When the ROTATION PULSE mode is selected, each RHC deflection results in a single burst of jet fire. In DISC RATE mode, RHC deflection results in a specified rate being commanded in that axis for the entire time the RHC is deflected. A free-drift mode (INRTL/PULSE) is also available in which no RCS jets are fired, or an attitude-hold mode, in which the DAP sends commands to maintain the current attitude with null rates within premission-specified dead bands. Also, if the RHC is deflected beyond the soft stop, continuous RCS jet firings result. In translation, movement of the THC results in continuous jet firings. Pulse translation mode is not available in the transition DAP.

The transition DAP also involves maintaining the OMS thrust vector control. The OMS processor generates OMS engine gimbal actuator thrust vector control commands to produce the desired spacecraft/engine relationship for the specified thrust direction.

For the OMS burn, the orbital state vector (position and velocity) is produced by navigation using inertial measurement unit delta velocities during powered and coasting flight. This state is sent to guidance, which uses target inputs through the CRT to compute thrust direction commands for flight control and burn parameters for CRT display. Flight control converts the commands into OMS engine gimbal angles (thrust vector control) for the OMS burn.

OMS thrust vector control for a normal two-engine burn is entered by depressing the ORBITAL DAP CONTROL AUTO pushbutton indicator with both RHCs within software detents. OMS manual thrust vector control for both OMS engines is entered by depressing the INRTL pushbutton indicator or by moving the commander's or pilot's RHC out of detent. The flight crew supplies the rate commands to the burn vector control system instead of guidance. The manual RHC rotation requests are proportional to RHC deflections and are converted into gimbal angles. OMS thrust in either case is applied through the spacecraft's center of gravity.

Orbital DAP

The orbital flight control software includes an RCS DAP, an OMS TVC DAP, and an attitude processor module to calculate vehicle attitude, as well as logic to govern the selection of a DAP. The attitudes calculated by the attitude processor are displayed on the attitude director indicator, as well as on the OPS 201 UNIV PTG display, which is available whenever orbit software is active. The vehicle attitude is used by the DAP to determine attitude and rate errors.

RCS DAP

The RCS DAP is used at all times in the on-orbit phase except during an OMS burn. This DAP controls vehicle attitudes and rates through RCS jet fire commands. Either the larger primary jets or the less powerful vernier jets can be used for rotational maneuvers, depending on whether PRI, ALT, or VERN is selected on the panel C3 (or A6U) ORBITAL DAP CONTROL panel. The choice of primary or vernier thrusters depends on fuel consumption considerations, how

quickly the vehicle needs to be maneuvered to satisfy a mission objective, and interaction with payloads. ALT mode uses primary jets with fewer jet firings of a small duration and selectable delay between firings to allow attitude control when vernier jet capability is lost.

The rotation rates and dead bands, translation rate, and additional DAP options can be changed by the flight crew during the orbit phase using the DAP CONFIG display. The flight crew loads the DAP with these options in two ways, one option set is accessed by depressing the A pushbutton on the ORBITAL DAP SELECT panel and the other by depressing the B pushbutton.

Each planned DAP configuration is given a reference number. Typically, the A configurations have smaller dead bands and lower rates than the B configurations. The wide dead bands are used to minimize fuel usage, while the tight dead bands allow greater precision in executing maneuvers or holding attitude.

The RCS DAP operates in an automatic or one of two (INRTL or LVLH) manual rotation modes, depending on whether the flight crew selects AUTO, INRTL, or LVLH on the ORBITAL DAP CONTROL panel. The INRTL mode is also accessed when the RHC is moved out of its detent position. In both the automatic and manual modes, the rotation rate is controlled by the selection of DAP A or B and the information loaded in the DAP CONFIG display. In addition, in automatic, the DAP determines the required attitude to be achieved from the UNIV PTG display and then computes the RCS jet-fire commands necessary to achieve these requirements within the current set of dead bands.

In the manual rotation mode, the RCS DAP converts flight crew inputs from any of the three RHCs to RCS jet-fire commands, depending on whether PULSE or DISC RATE is selected on the MANUAL MODE ROTATION ROLL, PITCH, and YAW pushbuttons on panel C3 or A6. Simply, when PULSE is selected, a single burst of jet fire is produced with each RHC deflection. The desired rotational rate is specified on the DAP CONFIG display (ROTATION). When DISC RATE is selected, jet

firings occur whenever the RHC is out of detent, but inside the soft stop, thus maintaining the rotational rate specified on the DAP CONFIG display. When the RHC is beyond the soft stop, continuous jet firings will result. When the RHC is returned to detent, the current M50 attitude will be maintained within the specified dead bands.

Another manual RCS DAP mode, local vertical/local horizontal (LVLH), is used to maintain the current attitude with respect to the rotating LVLH reference frame. It is selected through the LVLH pushbutton on panel C3 or A6U.

The RCS DAP includes only a manual translation capability, executed through the forward or aft THC. Only the primary RCS jets are used. If in VERN, DAP will automatically upmode to primary RCS (PRCS) when the THC is moved out of detent. The DAP will return to VERN or ALT when the desired rate is achieved or the THC is returned to detent. Deflections of the THC result in RCS jet firings based on the MANUAL MODE TRANSLATION pushbutton indicator selected on the ORBITAL DAP panel. PULSE mode results in a single burst of jet fire. NORM mode results in continuous jet firings as long as the THC is out of detent. Two additional submodes, HIGH Z and LOW Z, are available for special applications of +Z translations. NORM will fire three up-firing jets when a +Z translation is commanded and is the default. HIGH Z will fire all nine up-firing jets and would be used only for emergency escape from the vicinity of another orbiting body. LOW Z fires two aft-firing and two forward-firing jets for +Z maneuvers. LOW Z is used to maneuver near payloads that can be contaminated or damaged by the plume from an up-firing jet. Selection of NORM, HIGH Z, or LOW Z has no effect on choice of jets for $\pm X$, $\pm Y$, or $-Z$ translations. LOW Z will inhibit upfiring jets for rotations.

OMS TVC DAP

The OMS thrust vector control DAP is available when an OMS burn is executed through the ORBIT MNVR EXEC display. The TVC DAP uses the guidance-generated velocity requirements and converts these into the appropriate OMS gimbal commands, assuming AUTO is

selected on the ORBITAL DAP CONTROL panel. The TVC DAP also generates the OMS fire commands, the OMS shutdown commands, and, if necessary, due to OMS engine failure, the required RCS commands to maintain attitude control. Under INRTL selection, the TVC DAP takes inputs from the RHC to control attitude during the burn. When the RHC is in detent, the TVC DAP will maintain the current inertial attitude.

Before OMS ignition, the orbiter is automatically or manually maneuvered to the OMS ignition attitude using the RCS jets. Automatic TVC for one OMS engine is identical for two, except that the RCS processor is responsible for roll control. Single-OMS-engine burn is also through the orbiter's center of gravity, except when pitch or yaw rate commands are non-zero. If the left or right OMS engine fails during a burn, a red LEFT or RIGHT OMS light on panel F7 is illuminated. Since an OMS cutoff is based on time rather than velocity, a velocity residual may exist following the cutoff. The residual can be reduced to zero by the RCS through the THC.

Aerojet DAP

The aerojet DAP has the following characteristics: (1) flight adaptive (changes as a function of q-bar), (2) closed loop (compares feedback with command to generate an error signal), and (3) rate command (jets and aerosurfaces are commanded as necessary to achieve the desired rate). Once the desired rate is obtained, forward loop trim integrators maintain the desired rate. The aerojet DAP is activated by MM 304 transition, usually at EI-5, and runs through wheel stop on the runway. It slowly blends out the use of jets and blends in the use of aerosurfaces as the orbiter makes the transition from a spacecraft to hypersonic glider to subsonic glider to finally a high-speed 100-ton tricycle.

Pitch control is driven by either the auto system via alpha error (MM 304/602) or N_z error (MM 305/603), which is turned into a rate command, or by CSS via RHC input. This rate command is compared to the pitch RGA output to come up with a rate error that is turned into a jet command until q-bar 40, and/or elevator (elevons moving symmetrically) command after q-bar 2. The body flap is used as a trim device to

keep the elevons on or near schedule. This allows the elevons to be in the right position for maximum effectiveness, and to limit hinge moments and thermal effects. The speed brake is opened at $V_{REL} = 10$ k and is used supersonic as a lateral-directional stability device (speed brake opens causing a pitch-up moment that the elevons counteract by moving down, making the elevons more effective as an elevator and as ailerons). Subsonic, the speed brake is used first as an energy modulator, then as a q-bar modulator below 9,000 feet.

Other features of the pitch channel include:

- Pitch panel trim moves the elevons up or down. It requires trim be enabled and on, and either the CDR or PLT use the TRIM switches on panel L2 or C3. There is no current use for this feature, especially with the body flap in AUTO.
- RHC pitch rate trim biases the output of the RHC by inputting a rate command. It requires trim to be enabled and flight controller power on, and the CDR or PLT to use the "beep trim" switch on their RHC. Any input by the RHC rate trim will be zeroed if the pitch axis is returned to AUTO. This switch is used to perform the beep trim derotation during landing rollout.
- Nose-up turn compensation provides a pitch rate as a function of steady state turn yaw rate and bank angle during bank maneuvers in MM 305. This provides a constant flight path angle without the crew having to make a pitch adjustment during turns.
- At nose gear touchdown, the pitch axis will mode to AUTO and auto-load relief will move the elevons down to off-load the main gear. (This is the only entry phase auto flight control feature in the BFS.)

Because of the very high angles of attack (alpha) that the orbiter flies, there is a large difference in the velocity vector and the body X axis. For conventional airplanes that fly at small alpha, a body axis roll is very close to a velocity vector bank. (Bank refers to a rotation about the

velocity vector, or a stability axis rotation. Roll refers to a rotation about the X axis or a body axis rotation.) But at an alpha of 90° , a velocity vector bank is a body axis yaw. Therefore, at 40° alpha, normal alpha for the orbiter from MM 304 transition to $V_{REL} = 10.5$ k, a velocity vector bank requires a combination of a body axis roll and body axis yaw.

Another very important feature of the orbiter during early entry ($V_{REL} >$ approximately 4 k) is that the vehicle rolls and yaws due to beta or sideslip. Beta can be generated by either yaw jets or the adverse yaw caused by aileron displacement. (Adverse yaw means instead of rolling because of the increased lift caused by moving an aileron down, the vehicle will yaw because of the increased drag caused by moving an aileron down. This yaw produces beta.) Therefore, adverse yaw is purposely used during early entry to start a bank by using "reverse aileron" (left aileron up when initiating a bank to the right) along with yaw jets to develop a beta to get the vehicle banking. One of the two purposes of a gain called GALR is to determine whether the first output from the roll channel is reverse or proverse aileron, and how big the output should be. (Basically, no initial aileron is used until q-bar 10, reverse aileron is used from q-bar 10 until approximately $V_{REL} = 3.8$ k, and steadily increasing proverse aileron from $V_{REL} = 3.8$ k.) However, once a beta has been induced, it must be controlled. More precisely, beta dot must be made zero when the desired bank rate is achieved. Proverse aileron, used in the proper relationship to compensated body axis yaw and alpha, is introduced after the bank has been started to control beta and maintain the bank rate. This is called beta dot damping, and GALR controls how much aileron is used for damping and when it is terminated. Beta damping is used from q-bar 2 until Mach 0.9, although it starts ramping down at approximately $V_{REL} = 3.8$ k.

Roll channel is driven by either the auto system via bank angle error, which is turned into a bank rate command, or by CSS via RHC input. This bank rate command is multiplied by (1-GALR) to determine if the initial command should be reverse or proverse ailerons (ailerons refer to the use of elevons asymmetrically). It is converted into a roll rate command and is summed with beta dot damping (which is

multiplied by GALR to determine magnitude) and compared with the output from the roll axis RGAs after compensation for roll rates from the steady-state turn. This is the rate error that is turned into jet commands until q-bar 10 and/or aileron commands after q-bar 2.

The Entry Mode Switch, also known as the Roll Mode Switch, on the CDR L2 panel, allows the crew to select one of three aerojet DAP flight control modes. The switch positions are Auto, Low Gain, and No Yaw Jet. Auto allows selection, via Override SPEC 51, of either the baseline or Wraparound DAP roll modes. Wraparound DAP provides the same GALR terms as the No Yaw Jet mode, which are seven times that of the baseline GALR term for Mach >4 . Wraparound DAP is the nominal entry roll mode. With increased GALR, Wraparound DAP decreases RCS propellant usage by using the ailerons as the primary control effectors and the RCS jets as supplemental control effectors.

The No Yaw Jet entry mode eliminates all yaw jet commands. Bank Maneuvers are accomplished only with aileron commands. This flight mode is certified for q-bar >20 (or very soon after the first non-zero bank) to landing. No Yaw Jet will be used in case of low (<10 percent) aft RCS propellant critical entries or loss of aft RCS yaw jets.

The Low Gain position cuts the GALR terms in half, using both yaw jets and ailerons for control. This mode may be selected in off-nominal situations because of airframe vibrations or oscillations.

Other features of the roll channel are:

- Roll channel trim is automatic in AUTO until rollout. Because auto trim in CSS is terminated at Mach 1.25, if CSS is taken at Mach >1 , the CDR may experience a roll rate on final that must be compensated for by displacing the RHC slightly to the right or left. That is because the trim required on final is different from the trim required when CSS was taken. The RHC roll trim may be used to trim the RHC.
- RHC roll rate trim is exactly the same as pitch rate trim.

- At main gear touchdown, auto load balance keeps the wings level during rollout and prevents the downwind tire from experiencing excessive loads with crosswinds. After nose gear touchdown, load balance is faded out over 100 seconds.
- Any yaw jet firing causes the ailerons to trim in the proper direction to reduce the number of jet firings (right yaw jet firings will cause left aileron to trim up).

Except during bank maneuvers, DAP attempts to keep beta small throughout entry. Until Mach 0.6, the yaw channel is driven by bank angle error, which is turned into a bank rate command. After Mach 0.6, the yaw channel is driven by the roll rate compensated for steady state turn so rudder pedal inputs are not required to maintain coordinated flight. The bank rate command or the compensated roll rate is converted to a body yaw command and summed with a beta compensation term until q-bar 20. That is compared with the output from the yaw axis RGAs after compensation for yaw rates from the steady state turn. This yaw rate error is then summed with lateral acceleration (N_y), RPTA input, and yaw panel trim inputs. This is the rate that is turned into jet commands until Mach 1 and/or rudder commands after Mach 5. This causes the beta during early entry to cause the orbiter to bank, or during late entry ($M < 0.6$), coordinates the bank.

Other features of the yaw channel are:

- The RPTA does not directly control the rudder, but commands lateral acceleration, and the rudder moves as necessary to maintain that lateral acceleration. Yaw panel trim performs exactly the same function. There is no operational reason to command a non-zero lateral acceleration.
- At GSENBLS set (WOW set for 2 sec, $\theta < 0$ deg, WONG), if in AUTO R/Y, the yaw channel will provide nose wheel steering commands to maintain runway centerline.

Operations

Ascent

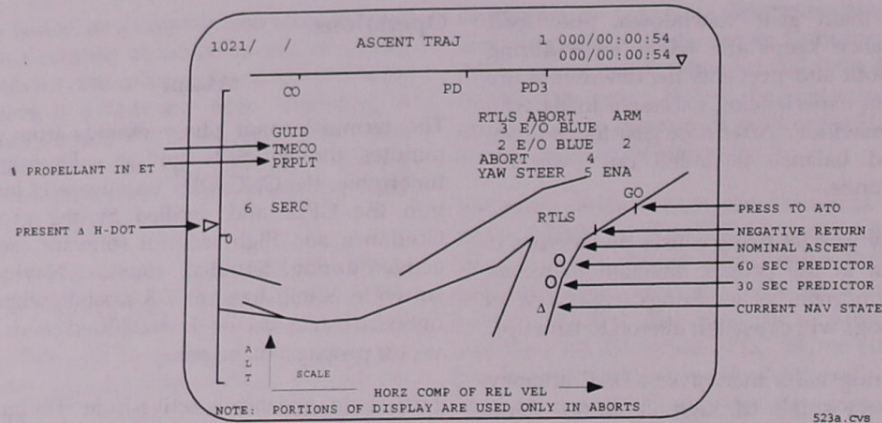
The terminal count phase extends from T-20 minutes through SRB ignition. During this timeframe, the GNC OPS 1 software is loaded into the GPCs and verified by the ground. Guidance and flight control software are not active during terminal count. Navigation software is initialized at T-8 seconds when the onboard state vector is initialized and state vector propagation begins.

First-stage guidance is active from SRB ignition through SRB separation command. In this stage, guidance uses a preflight planned ("canned") table of roll, pitch, and yaw attitudes referenced to relative velocity. In addition to sending commands to flight control to obtain proper attitudes, the guidance software also sends commands to the MPS throttle per a preflight defined throttle schedule. Steering of the vehicle during first stage is accomplished by gimbaling the SSME bells and SRB nozzles. First-stage guidance also attempts to relieve vehicle aerodynamic loads based on sensed accelerations.

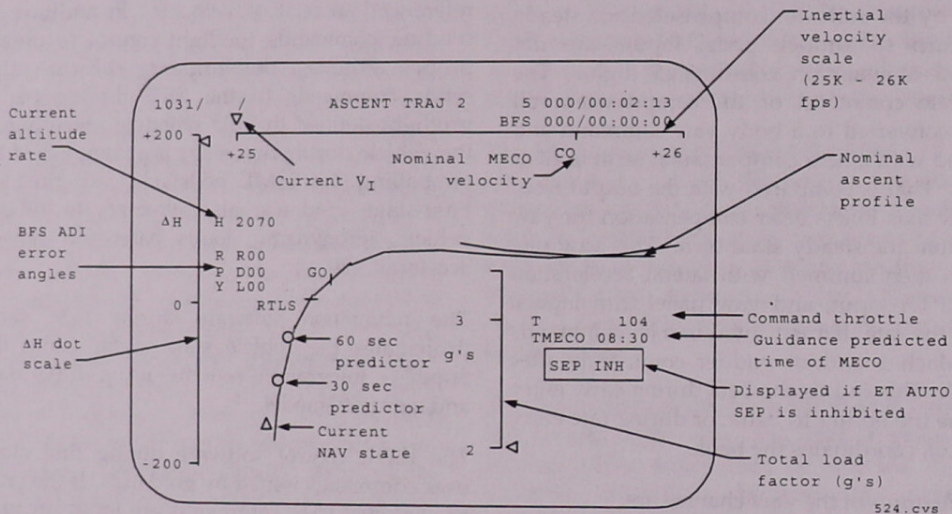
The navigation software during first stage propagates the vehicle state vector using the Super-G integration scheme using IMU data and a gravity model.

The flight control software during first stage uses commands issued by guidance. If the crew has selected CSS, commands are input through the RHC. Feedback from rate gyro assemblies and accelerometers is used to generate commands to reposition the SRB nozzles and main engine bells. The current vehicle attitude rates and the errors between current and desired attitudes are sent to the attitude director indicator for display to the crew. If the crew does CSS, the resultant control mode is discrete rate/attitude hold. In this mode, when the rotational hand controller is moved, a specified attitude rate is commanded as long as the RHC is out of its neutral position. When the RHC is in detent, attitude hold commands are generated by flight control.

During first stage, no GNC-related crew actions are planned unless a failure occurs. Following



PASS ASCENT TRAJ Display



BFS ASCENT TRAJ 2 Display

launch, the crew uses the Ascent Flip Book for general procedures. To ensure that the auto flight control system is maintaining the expected ascent profile, the crew can scan the cue cards placed next to the dedicated displays.

Second-stage ascent begins at SRB separation and extends through MECO and external tank separation. The second stage guidance software uses a cyclic, closed loop scheme to calculate the necessary commands to take the mated vehicle to a specified set of target MECO conditions. These conditions include cutoff velocity, radius from the Earth, flight path angle, orbital inclination, and longitude of the ascending

node. The name of the targeting scheme is PEG (powered explicit guidance) 1. Guidance software also governs the main engine throttle commands such that 3 g's are not exceeded. The predicted time of MECO (TMECO) is calculated and displayed to the crew on the PASS ASCENT TRAJ display. Following SRB separation, it may take the PEG 1 guidance algorithm several cycles to converge and for TMECO to become stable. Forty seconds prior to MECO, guidance begins targeting only for the desired cutoff velocity.

Second-stage navigation software continues as it did during first stage; i.e., it propagates a state vector using the Super-G integration scheme.

Second-stage flight control software continues through MECO as it did during first stage, with the exception of gimbaling the main engines versus the SRBs. After separation, attitude hold is commanded until guidance converges. At MECO, the transition (or TRANS) DAP, becomes active. Initially it sends attitude hold commands. External tank separation is automatically commanded 18 seconds after MECO. The DAP immediately sets commands to fire the orbiter -Z RCS jets resulting in the orbiter translating in the -Z direction (away from the external tank). When -4 fps delta velocity is reached, the fire commands are removed.

During second stage, the crew monitors the onboard systems to ensure that the major GNC events occur correctly. These events include closed loop guidance convergence, 3-g throttling, MECO, external tank separation, and -Z translation.

The crew can monitor for guidance convergence by noting if the guidance-computed time of MECO is stabilized on the ASCENT TRAJ display. If not, the crew is required to take manual control of the vehicle. They can also ensure that 3 g's are not exceeded by monitoring the BFS ASCENT TRAJ 2 display or the accel tape AMI. The ASCENT TRAJ 2 display also can be used to monitor the MECO velocity. MECO is indicated by the illumination of three red MAIN ENGINE STATUS lights on panel F7 and the sudden decrease in acceleration. MECO confirm is also indicated by the illumination of the ORBITAL DAP pushbutton lights.

Orbit Insertion

During the orbit insertion phase, the guidance software is used to target the OMS 1 and OMS 2 burns. The primary targeting scheme used is called PEG 4. This is a cyclic, closed loop scheme that computes the required delta velocity to achieve a target specified by a time of ignition. In addition, the guidance software is constrained to optimize fuel usage. For the OMS 1 burn, it also must ensure that the burn attitude at ignition is near the MECO attitude. The PEG 4 targeting scheme can compensate for the loss of one OMS engine or an RCS downmode during the burn if it detects the OMS loss. Prior to and during the burn, guidance computes the remaining burn time and total remaining delta velocity.

Navigation during the orbit insertion phase is identical in processing to that used in the mainstage whenever the IMU-sensed acceleration is greater than the noise threshold. If the IMU-sensed acceleration drops below the threshold, navigation ignores the IMU data and propagates the state vector using an atmospheric drag model of the orbiter.

Insertion flight control is accomplished using the transition DAP. The transition DAP uses commands from guidance for automatic maneuvers to burn attitude using the RCS jets. During the OMS 1 and 2 burns, it uses the OMS engines and RCS jets as required. It can also receive commands from the crew via the forward THC and RHC. The transition DAP takes these commands and converts them into the appropriate RCS commands. It then monitors the resultant attitude and attitude rates. The necessary commands are sent to achieve the targeted attitude and attitude rate within the pre-mission specified deadbands.

For rotations, the crew selects either AUTO or INRTL control on the ORBITAL DAP panel or by moving the RHC. In translation, movement of the THC results in continuous jet firings.

Orbit GNC

The major GNC-related orbit tasks include achieving the proper position, velocity, and attitude necessary to accomplish the mission's objectives. To do this, the GNC software maintains an accurate state vector, maneuvers to specified attitudes and positions, and points a specified orbiter body vector at a selected target. These activities are planned with several constraints in mind, including fuel consumption, vehicle thermal limits, payload requirements, and rendezvous/proximity operations considerations. The GNC displays for the majority of on-orbit operations are OPS 201 UNIV PTG and MNVR EXEC. Both are available in OPS 2, and MNVR EXEC is available for the orbit portion of OPS 1 and 3.

The navigation software has several important features. As before, it propagates the orbiter state vector using the Super-G integration scheme. During coasting flight, the software uses a model of atmospheric drag acceleration to propagate the state vector. If translational

thrusters are anticipated, the crew can set a flag for navigation to use inertial measurement unit-sensed acceleration if above a noise threshold value. When this flag is set, the crew can monitor the thrust on the REL NAV display (SPEC 33) through an item called AVG G.

Another navigation option that is available on-orbit is called rendezvous navigation. When this option is enabled by a crew input on the REL NAV display, the software maintains a target state vector, as well as the orbiter state vector. In this mode, navigation can use external sensor data from the star tracker, COAS, or rendezvous radar in computing the orbiter target state vector.

For vehicles equipped with three-string GPS hardware, the navigation software will replace its propagated vector with a selected GPS vector every 90 minutes. This will happen only if the selected GPS state vector falls within the navigation software's expected error. After the orbiter vector is updated, it will then be propagated for the next 90 minutes using the same techniques as described above (i.e., Super-G, drag model, etc.). This automatic GPS state vector update will be inhibited during rendezvous operations to avoid interfering with the current rendezvous navigation sensor processes.

Because there is no method onboard to independently compute corrections to the state vector for non-GPS orbiters, periodic updates are sent from Mission Control to correct any errors that develop with the onboard nav state.

The on-orbit guidance software has several features. Universal pointing is used to compute attitude changes required to "point" a specified orbiter body axis at a specified target, to maneuver to a predetermined attitude, to rotate the orbiter about a specified body axis, or to maintain attitude hold. The crew interacts with this software via the UNIV PTG display.

Another guidance feature is PEG 7, or external delta-V, targeting for OMS or RCS burns. In this mode, guidance sends the commands to flight control to execute a burn specified by an ignition time (TIG) and delta velocities in the local vertical coordinate system at ignition.

XXXX/055/			GPS STATUS			XX X DDD/HH:MM:SS				
			DDD/HH:MM:SS							
I/O 10	GPS1S	GPS2S	GPS3S	GPS MINUS NAV						
STAT	XXXX	XXXX	XXXX	ΔH	±XXXXXX	ΔH	±XXX.XX			
MODE	XXXX	XXXX	XXXX	ADR	±XXXXXX	ADR	±XXX.XX			
S/TEST	11XS	12XS	13XS	ΔCR	±XXXXXX	ΔCR	±XXX.XX			
INIT	14X	15X	16X	X LAT	X LON	ALT				
NAV	17X	18X	19X	XX.XX	XX.XX	XXX.XXXX				
RESTART	20X	21X	22X							
IMU	23 XX	24 XX	25 XX							
GDOP	XX	XX	XX							
DG FAIL	S	S	S	AUT INH FOR						
DES RCVR	26X	27X	28X	GPS TO G&C S32X 33X 34X						
QA OVRD	29XS	30XS	31XS	GPS TO NAV S35X 36X 37X						
SF CAND	X	X	X	METERING OVERRIDE 38X						
QA1 P 1	XXXXXX	XXXXXXXX	XXXXXXXX	SATELLITES						
QA2 POS	X.XXS	X.XXS	X.XXS	TRKD	C1	C2	C3	C4	C5	C6
VEL	X.XXS	X.XXS	X.XXS	GPS1	XX	XX	XX	XX	XX	XX
QA3 POS	X.XXS	X.XXS	X.XXS	GPS2	XX	XX	XX	XX	XX	XX
VEL	X.XXS	X.XXS	X.XXS	GPS3	XX	XX	XX	XX	XX	XX
	1-2	2-3	3-1							
QA4 POS	X.XXS	X.XXS	X.XXS	DES 43	XX	XX	XX	XX	XX	XX
VEL	X.XXS	X.XXS	X.XXS		XX	XX	XX	XX	XX	XX
XXX.X	LAST	SEL	FIL	UPDATE						

GPS STATUS Display (SPEC 55)

2011/ /	UNIV PTG	2 000/02:44:58
CUR MNVR COMPL	02:55:29	000/00:00:00
1 START TIME	0/000:00:00	
MNVR OPTION	START MNVR	CUR FUT
5 R 0.00	18	RBST 25 .X X
6 P 0.00	19 *	CNCL 26
7 Y 0.00	20	DURATION 27
	21	XX.XX.XX.XX
TRK/ROT OPTIONS	ATT MON	
8 TGT ID 2	22 MON AXIS 1 +X	
	ERR TOT 23 *	
	ERR DAP 24	
9 RA 0.000	ROLL	PITCH
10 DEC [] 0.000	CUR 163.59	40.77 338.38
11 LAT [] 0.000	REQD 304.04	139.80 342.99
12 LON [] 0.000	ERR + 74.86	- 62.92 + 86.93
13 ALT [] 0.0	14 BODY VECTOR 3	RATE - 0.266 - 0.367 + 0.443
15 P 90.00		
16 Y 0.00		
17 OM 270.00		

UNIV PTG Display

1041/	OMS 1 MNVR EXEC	1 000/00:40:23
OMS BOTH 1*		000/00:15:37
L 2	BURN ATT	AVTOT 0
R 3	24 R 083	TGO 0:00
RCS SEL 4	25 P 195	
S TV ROLL 180	26 Y 300	VGO X +
TRIM LOAD	MNVR 27*	Y +
6 P [-10.1]	REI 4366	Z +
7 LY [-15.7]	TFP 24:40	
8 RY [-15.7]	GMBL	HA HP
9 WT 217047	L R	TGT 130 +129
10 TIG	P +0.4 +0.4	CUR 130 + 9
TGT PEG 4	Y +5.8 +5.8	
14 C1	PRI 28* 29*	35 ABORT TGT
15 C2 [-]	SEC 30 31	
16 HT	OFF 32 33	FWD RCS
17 OT	GMBL CK 34	ARM 36
18 PRPLT [-]		DUMP 37
TGT PEG 7		OFF 38*
19 AVX [-]		SURF DRIVE
20 AVY [+]		ON 39
21 AVZ [-]		OFF 40*
LOAD 22/TIMER 23		

MNVR Display

described above for the next 42 seconds, at which time they will be replaced with a new selected GPS vector and then the process will repeat.

Guidance during the deorbit phase is similar to that used in the orbit insertion phase. The PEG 4 scheme is used again to target the deorbit burn and guide the vehicle during the burn although the required conditions are different. The deorbit burn targets ensure the proper conditions for entry interface, including altitude, position with respect to the Earth (and landing site), and velocity/flight path angle constraints. These deorbit burn targets are specified preflight for a nominal mission, although it is also possible for the ground to uplink changes or for the crew to recompute them onboard. It is also possible to specify OMS fuel "wasted" (burned out of plane) during the deorbit burn in order to establish an acceptable orbiter center of gravity (c.g.) for entry. The crew is responsible for loading these targets on the DEORB MNVR EXEC display.

The display is used to set up and target the OMS burn, to specify fuel to be wasted, to display the required burn attitude, to initiate an automatic attitude maneuver, and to monitor the progress of the burn. The crew's task for deorbit guidance includes ensuring the correct burn targets are entered on the DEORB MNVR EXEC display, "loading" this target for PEG 4 deorbit burn guidance software, and maneuvering to calculated and displayed burn attitude either in AUTO or manually using the RHC. The burn itself is typically executed in AUTO such that the crew's task is to monitor the burn progress in terms of velocities and OMS performance.

Flight control during the deorbit phase is similar to the procedures used during orbit insertion - the transition DAP is again in effect.

Entry

The entry phase of flight is subdivided into three separate subphases because the software requirements for each are different:

- The ENTRY subphase extends from EI-5 to the point at which the vehicle is traveling at 2500 fps (83,000 ft altitude).
- The terminal area energy management (TAEM) subphase begins at 2500 fps and

extends to the approach/landing capture zone, defined when the vehicle is on glide-slope, on airspeed, and on runway centerline (below 10,000 ft altitude).

- The approach/landing (A/L) subphase begins at the approach/landing capture zone and extends through wheel stop after touchdown.

The guidance software during the entry portion of flight performs different tasks during each of the ENTRY, TAEM, and A/L subphases. During the ENTRY subphase, guidance attempts to keep the vehicle on a trajectory that provides protection against excessive temperature, dynamic pressure, and normal acceleration (Nz) limits. To do this, the software sends commands to flight control to fly a drag/acceleration determined profile, which guides the vehicle through a tight corridor limited on one side by altitude and velocity requirements for ranging (in order to make the runway), and on the other side by the thermal, q-bar, and Nz constraints. Ranging is accomplished by adjusting drag acceleration to velocity such that the vehicle stays in that corridor. Drag acceleration can be adjusted by modifying the angle of attack, which changes the vehicle's cross sectional area with respect to the airstream, or by adjusting the vehicle bank angle, which affects lift and thus the vehicle's sink rate into denser atmosphere. The vehicle's angle of attack is maintained at a high value (40°) during most of this phase to protect the upper surfaces from extreme heat. It is ramped down to a lower value at the end of this phase for vehicle controllability. Using bank angle to adjust drag acceleration results in the vehicle turning off course. Therefore, at certain times, the vehicle must be rolled back toward the runway. This is called a roll reversal and is commanded as a function of azimuth error from the runway. The ground track during this phase, then, looks like a series of S-turns.

During the entry phase of flight, the crew uses CRT displays, dedicated displays, certain panel switches (such as TRIM switches), the RHC, and the SBTC to control the vehicle. Between the ENTRY interface and the TAEM interface, five ENTRY TRAJ displays sequentially become available. These displays are used to monitor autoguidance and the vehicle's trajectory

compared to the planned entry profile. The five displays are identical with the exception of the central plot, which shows vehicle velocity versus range or energy/weight versus range with a changing scale as the vehicle approaches the landing site. Two trajectory displays are shown on the next page as examples. This central plot also includes static background lines that allow the crew to monitor the vehicle's progression compared to planned entry profiles.

Once TAEM interface is reached, the VERT SIT 1 display becomes available. This display includes a central plot of vehicle altitude with respect to range. The plot has three background lines that represent the nominal altitude versus range profile, a dynamic pressure limit profile, and a maximum lift-over-drag profile. At 30,000 feet altitude, the scale and titles on the display change to VERT SIT 2. This second display is used through landing. When the A/L interface conditions are met, a flashing A/L is displayed on the VERT SIT 2 display.

Guidance software during TAEM generates the necessary commands to enable the vehicle to achieve the proper A/L conditions by following an energy/weight versus range profile. During TAEM, as the name implies, the goal is to manage the vehicle's energy while the orbiter travels around an imaginary arc called the heading alignment cone (HAC). An HAC is an imaginary cone that when projected on the Earth, lies tangent to the extended runway centerline. The guidance software performs the TAEM function as follows:

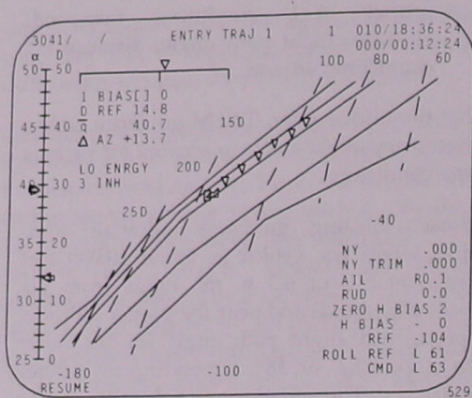
- S-Turns: If the vehicle is high on energy, it dissipates the excess by turning away from the HAC until the proper energy conditions are met.
- HAC Acquisition: Turns the vehicle toward the targeted tangent point on the HAC and flies to this point.
- Heading Alignment: Flies the vehicle around the HAC to the point at which the HAC is tangent to the runway centerline, called the nominal energy point (NEP).
- Prefinal: From the NEP, flies the vehicle down the runway centerline until the

proper A/L conditions (airspeed, altitude, flight path angle, distance off centerline) are met.

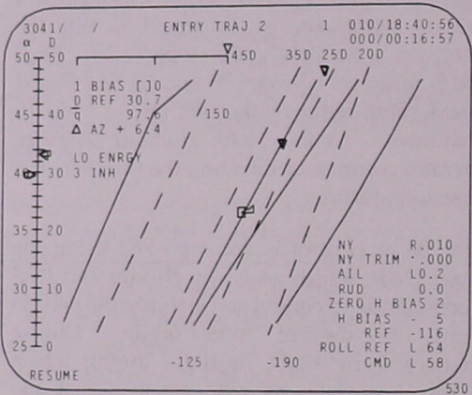
Within the above steps, TAEM guidance makes the necessary adjustments to account for various energy conditions.

Approach/landing guidance software commences when the vehicle is about 10,000 feet altitude (at 5.8 or 6.3 n. mi. range from the runway threshold) and near the proper altitude, airspeed, and flight path angle for the outer glide slope (20° or 18°, depending on orbiter weight). The guidance software sends commands to keep the vehicle tracking the runway centerline and on the steep glide slope until approximately 2000 feet, at which point a pre-flare maneuver is performed to put the orbiter on a shallow glide slope (1.5°). Final flare is initiated between 30 and 80 feet (based on sink rate), reducing the sink rate to 3 fps for touchdown. At this point, guidance software generates commands directing the vehicle to the runway centerline.

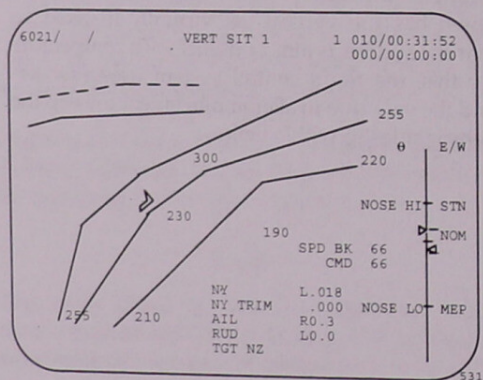
Entry flight control is accomplished using the aerojet DAP, which generates effector and RCS jet commands to control and stabilize the vehicle during its descent from orbit. During exoatmospheric flight, or flight during which certain aerosurfaces are rendered inefficient due to adverse aerodynamics, a combination of aerosurface and RCS jet commands are used. For example, at Mach > 5, the angle of attack profile flown has the vertical tail virtually blanked so that the rudder is almost useless. To compensate for this, the flight control system uses yaw jets and the yaw due to aileron movement to keep the vehicle sideslip within limits.



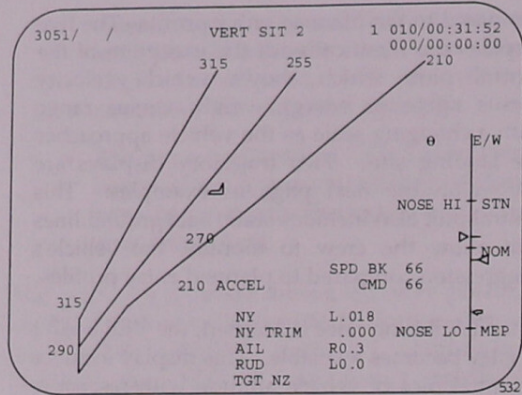
ENTRY TRAJ 1 Display



ENTRY TRAJ 2 Display



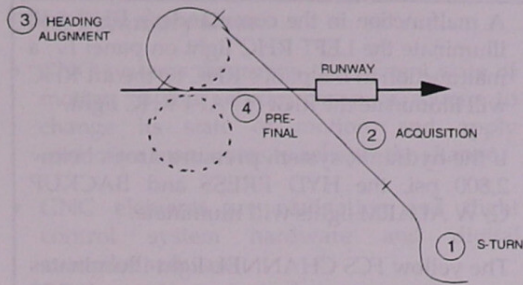
VERT SIT 1



VERT SIT 2

In the entry phase, navigation software functions similarly to the deorbit phase (i.e., three-state vectors computed using the Super-G algorithm corresponding to each inertial measurement unit) with the exception that additional external sensor data are sequentially incorporated. This information is used to provide the accuracy necessary to bring the orbiter to a pinpoint landing and to some extent to maintain vehicle control. The TACAN system provides slant range and magnetic bearing to various fixed stations around the landing site and becomes available at about 156,000 feet altitude until 1500 feet above ground level. The ADTA system provides pressure data to compute angle of attack, Mach number, equivalent airspeed, true airspeed, dynamic pressure, barometric altitude, and altitude rate. Only barometric altitude is used for the navigation software. The microwave landing system precisely determines slant range, azimuth, and elevation to the ground stations located along the side of the landing runway. When landing at runways with microwave landing system ground stations, data become available at 14,000 feet for processing by navigation.

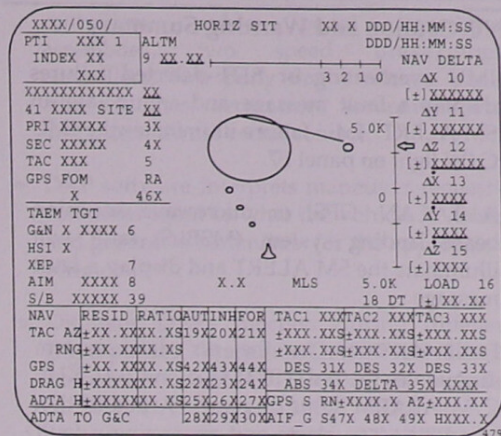
Another tool used by the navigation software is a "software sensor" called drag altitude, which uses a model of the atmosphere to correlate the drag acceleration measured by the inertial measurement units to altitude. The drag altitude data are important in keeping downrange and altitude errors bounded until TACAN data is available.



TAEM Guidance Subphases

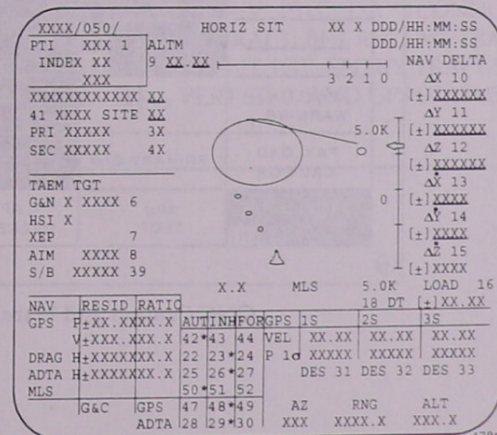
The navigation software also maintains a statistical estimate of the expected error in the state vector. When an external sensor, such as TACAN, becomes available to the navigation software, a check is made to see if the data lie within the current expected range of error. Crew controls are provided on the HORIZ SIT display to force the software to accept or inhibit the external sensor data regardless of whether they lie within this expected range. There is also a control on the display that may be selected to allow the software to use the external sensor data to update its state vector as long as the data lie within the expected range. This scheme is part of what is called Kalman filtering and is used to prevent navigation from being polluted by bad sensor data. The navigation parameters computed as a result of this filter can be seen by the crew on the dedicated displays when NAV is selected as the data source. In addition to providing insight and control over navigation parameters, the HORIZ SIT display supplies the crew with spacecraft position and heading information.

GPS-equipped vehicles will not have TACAN data to incorporate into the three-state vectors corresponding to each IMU. Similar to the other navigation sensors, GPS data are constantly checked to make sure they lie within an expected error range. Crew controls (via the HORIZ SIT display) allow the navigation software to automatically incorporate a GPS vector if the vector falls within the expected range or to force the software to accept or inhibit the data regardless of whether the infor-



HORIZ SIT Display (SPEC 50) (Three-String TACAN Vehicles)

mation lies within the expected range. As described in the Deorbit subsection, navigation software will select and incorporate a GPS vector every 42 seconds up to 17,000 feet and then every 9 seconds thereafter to allow for smoother updates to navigation software in the event that MLS is not available. If MLS is available, MLS will update navigation software as described above and GPS updates will automatically be inhibited by the navigation software.



HORIZ SIT Display (SPEC 50) (Three-String GPS Vehicles)

GNC Caution and Warning Summary

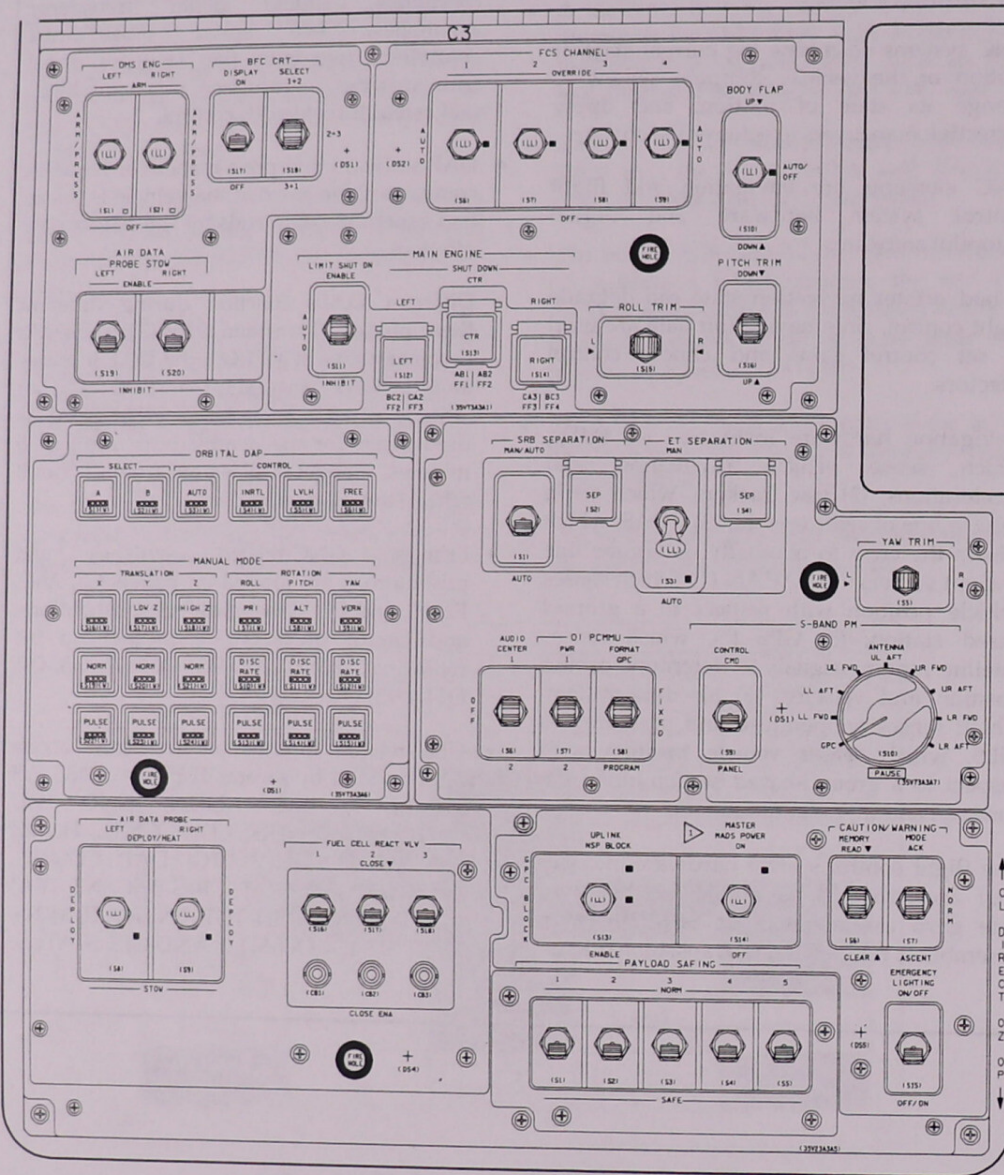
- IMU overheating or BITE-detected failures display a fault message and annunciate an SM ALERT. IMU failure illuminates the IMU C/W light on panel F7.
- A TACAN, GPS, or microwave scanning beam landing system (MSBLS) fault will illuminate the SM ALERT and display a fault message.
- Fault detection in the air data system illuminates the red AIR DATA and BACKUP C/W ALARM lights on panel F7, in addition to sounding an alarm and generating a fault message.
- The RGA/ACCEL light on panel F7 is not supported. RGA or AA failure will sound an alarm and generate a CRT fault message.
- A malfunction in the commander's RHC will illuminate the LEFT RHC light on panel F7; a malfunction in the pilot's RHC or the aft RHC will illuminate the RIGHT /AFT RHC light.
- If the hydraulic system pressure drops below 2,800 psi, the HYD PRESS and BACKUP C/W ALARM lights will illuminate.
- The yellow FCS CHANNEL light illuminates to indicate a failed channel; the red FCS SATURATION light is illuminated if one of the four elevons is set at more than +12° (down) or less than -15° (up).
- The OMS TVC light illuminates if the left or right OMS gimbal fails, or if software detects a TVC failure.
- The LEFT or RIGHT OMS light illuminates if the left or right OMS engine fails.

O ₂ PRESS	H ₂ PRESS	FUEL CELL REAC (R)	FUEL CELL STACK TEMP	FUEL CELL PUMP
CABIN ATM. (R)	O ₂ HEATER TEMP	MAIN BUS UNDERVOLT	AC VOLTAGE	AC OVERLOAD
FREON LOOP	AV BAY/ CABIN AIR	IMU	FWD RCS (R)	RCS JET
H ₂ O LOOP	RGA/ACCEL	AIR DATA (R)	LEFT RCS	RIGHT RCS (R)
—————	LEFT RHC (R)	RIGHT/AFT RHC	LEFT OMS (R)	RIGHT OMS (R)
PAYLOAD WARNING (R)	GPC	FCS SATURATION (R)	OMS KIT	OMS TVC (R)
PAYLOAD CAUTION	PRIMARY C/W	FCS CHANNEL	MPS (R)	—————
BACKUP C/W ALARM (R)	APU TEMP	APU OVERSPEED	APU UNDERSPEED	HYD PRESS

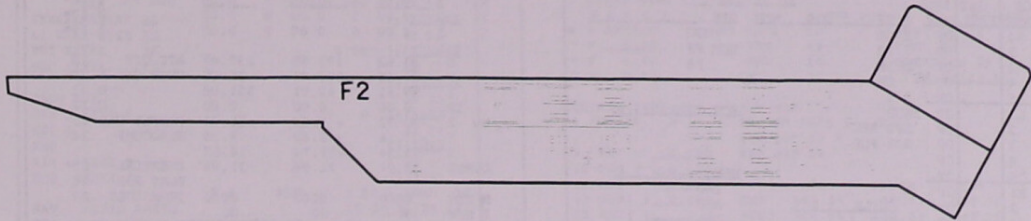
GNC Caution and Warning Lights on Panel F7

GNC Summary Data

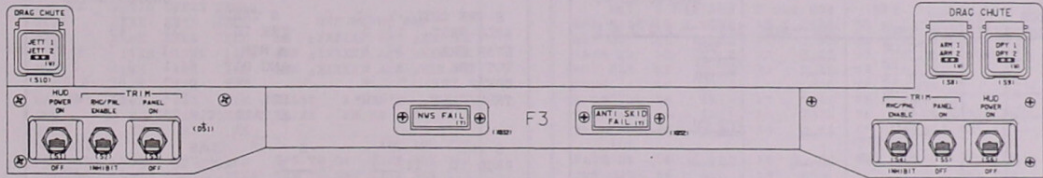
- GNC systems determine the current state of motion of the vehicle, compute actions to change its state of motion, and apply corrective maneuvers to achieve the change.
- GNC elements are navigation and flight control system hardware and digital autopilot software.
- A bad orbiter navigation state can degrade flight control, since navigation data are used to set control gains and choose control effectors.
- Navigation hardware includes: (1) IMUs, which sense vehicle orientation and accelerations; (2) star trackers, which sense vehicle line of sight vectors; (3) COAS, which allows the crew to manually determine line of sight vectors; (4) TACAN (*), which senses vehicle position with respect to a ground based station; (5) GPS (*), which senses satellite ranging signals to determine orbiter position and velocity; (6) air data system, which senses temperature and pressure; (7) MLS, which senses vehicle position with respect to a ground-based station along the runway; and (8) radar altimeters.
- The flight control system hardware includes four accelerometer assemblies, four orbiter rate gyro assemblies, four SRB rate gyro assemblies, rotational and translational hand controllers, rudder pedal transducer assemblies, two speed brake/thrust controllers, two body flap switches, panel trim switches, aerosurface servoamplifiers, and ascent thrust vector control.
- DAP software interprets maneuver requests, compares them to what the vehicle is doing, and generates commands for the appropriate effectors.
- Different DAPs function during different flight phases. Transition DAP (TRANSDAP) becomes active at MECO; orbit DAP includes an RCS DAP, an OMS TVC DAP, and an attitude processor module. TRANSDAP is used again for the deorbit burn until ET-5 minutes. Aerojet DAP is used from EI-5 until wheel stop on landing.
- Primary GNC-related switches and pushbuttons are located on panels C3, A6U, F2, F3, and F4. Other switches, pushbuttons, and circuit breakers are located on the following: F6, F7, F8, O5, O6, O7, O8, O9, O14, O15, O16, O17, and L1.
- GNC-related information and crew access are provided by several displays: GNC SYS SUMM 1, IMU ALIGN, GND IMU CNTL/MON, S TRK/COAS CNTL, HORIZ SIT, MNVR, UNIV PTG, DAP CONFIG, PASS ASCENT TRAJ 1, BFS ASCENT TRAJ 2, REL NAV, ORBIT TGT, ENTRY TRAJ 1-5, VERT SIT 1, VERT SIT 2, AND GPS STATUS



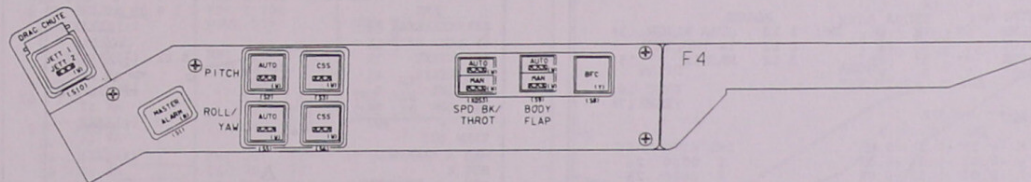
Panel C3



Panel F2



Panel F3



Panel F4

2011/ /018		GNC SYS SUMM 1		1 000/02:46:03		000/00:00:00	
RCS	JET	ISOL				DPS	1 2 3 4 5
MANF	FATL	VLV	SURF	POS	MOM		
F1	OP	L OB				GPC	
2	OP	IB				MDM FF	
3	OP	R IB				FA	
4	OP	OB					
5	OP	AIL					
L1	OP	RUD				FCS CH 1 2 3 4	
2	OP	SPD BRK					
3	OP	BDY FLP					
4	OP						
5	OP						
R1	OP					NAV 1 2 3 4	
2	OP					IMU	
3	OP	CNTLR 1 2 3				ACC	
4	OP	RHC L				RGA	
5	OP	R				TAC	
	OP	A				MLS	
	OP	THC L				ADTA	
	OP	A					
	OP	SBTC L					
	OP	R					

GNC SYS SUMM 1 Display

9011/104/		GND IMU CNTL/MON		2 150/12:20:13		000/00:44:47	
IMU	1	2	3				
X	1 0.00	4 0.00	7 0.00			SEL IMU 1 16*	
Y	2 0.00	5 0.00	8 0.00				2 17*
Z	3 0.00	6 0.00	9 0.00				3 18*
O	83.62	192.88	297.47			ATT DET	19
M	23.65	301.81	26.65			HNGR CAL A	20
I	99.91	42.01	351.09				B 21
IR	0.00	0.00	0.00				C 22
DV X	-10.72	+ 9.50	+25.73			PREFLT CAL	23
Y	+27.14	+ 6.88	- 9.28			GYROCOMP	24
Z	-13.24	+29.74	-16.57				
DVRSS	32.04	31.96	31.98			INERTIAL	25*
E HDW	8000	8000	8000			PLAT POS	26
I S/W	00	00	00			TERM/IDLE	27
TSTAT	3F	3F	3F			28 MM WRITE	1
PWR ON	*	*	*			READ	29
I/O						MM STATUS	
STBY	10	11	12			30 SITE SEL	7
OPER	13*	14*	15*			ACTUAL	39B

GND IMU CNTL/MON Display (SPEC 104)
(available on OPS 9 only)

3011/ /018		GNC SYS SUMM 1		1 000/02:46:03		000/00:00:00	
RCS	JET	ISOL				DPS	1 2 3 4 5
MANF	FATL	VLV	SURF	POS	MOM		
F1	OP	L OB				GPC	
2	OP	IB				MDM FF	
3	OP	R IB				FA	
4	OP	OB					
5	OP	AIL					
L1	OP	RUD				FCS CH 1 2 3 4	
2	OP	SPD BRK					
3	OP	BDY FLP					
4	OP						
5	OP						
R1	OP					NAV 1 2 3 4	
2	OP					IMU	
3	OP	CNTLR 1 2 3				ACC	
4	OP	RHC L				RGA	
5	OP	R				TAC	
	OP	A				MLS	
	OP	THC L				ADTA	
	OP	A					
	OP	SBTC L					
	OP	R					

GNC SYS SUMM 1 Display
(Three-String GPS Vehicles)

3011/022/		S TRK/COAS CNTL		1 006/09:35:06		000/00:00:00	
S TRK CNTL	-Y	-Z		S TABLE	1	2	3
SELF-TEST	1 2			TRK ID	15	43	0
STAR TRK	3 4			Δ MIN	1	1	0
TGT TRK	5 6			ANG DIF	84.1	0.0	0.0
BREAK TRK	7 8			ERR	0.02	0.00	0.00
TERM/IDLE	9* 10*			SEL	17*	18*	19
				S TABLE CLR	20		
S TRK	-Y	-Z		COAS			
REQD ID	11 0	12 0		REQD ID	21 0		
TRK ID	0	0		ADEG X			-0.2
S PRES				Y			+0.3
AANG	+0.00	+0.00		SIGHT MODE	22		
THOLD	13 0	14 0		ACCEPT	23		
SHUTTER	CL	CL		CAL MODE	24		
MAN OP	15	16		DES	25		
STATUS				POS	+X 26	-Z 27*	
				ABIAS	0.00	0.00	
				UPDATE	28	29	

S TRK/COAS CNTL Display

3011/021/		IMU ALIGN		1 006/09:34:09		000/00:00:00	
STAT	OK	OK	OK	IMU	1 10	STAR ALIGN	13*
TEMP	21	22	23		2 11	14 IMU/IMU	
STBY	4*	5*	6*		3 12	MATRIX	15
OPER	7	8	9				
DES							
ACC						EXEC	16
						TERM	17
X	-0.03	+0.01	-0.03			IMU BITE MASK	
Y	-0.02	-0.01	+0.03			1 0000	24
Z	-0.01	-0.02	-0.03			2 0000	25
						3 0000	26
ANG						NAV ΔV THRESH	
X	299.07	299.16	299.12			18	3840
Y	339.17	339.09	339.14				
Z	160.65	160.72	160.64				
ΔX	+0.00	+0.00	+0.00			MM READ	19
ΔY	+0.00	+0.00	+0.00				
ΔZ	+0.00	+0.00	+0.00				

IMU ALIGN Display (SPEC 21)

XXXX/050/		HORIZ SIT		XX X DDD/HH:MM:SS		DDD/HH:MM:SS	
PTI	XXX 1	ALTM					NAV DELTA
INDEX	XX 9	XX XX					
XXX				3 2 1 0			ΔX 10
XXXXXXXXXXXX	XX						[+]XXXXXX
41 XXXX	SITE XX						ΔY 11
PRI XXXXX	3X						[+]XXXXXX
SEC XXXXX	4X						ΔZ 12
TAC XXX	5						[+]XXXXXX
GPS FOM	RA						ΔX 13
X	46X						[+]XXXX
TAEM TGT							ΔY 14
G&N X	XXXX 6						[+]XXXX
HSI X							ΔZ 15
XEP	7						[+]XXXX
AIM	XXXX 8	X.X	MLS	5.0K			LOAD 16
S/B	XXXXX 39						18 DT [a]XX XX
NAV	RESID	RATIO	AUTIN	HFOR	TAC1	XXXTAC2	XXXTAC3
TAC	AZ+XX.XXXX	XS19X20X21X	+XXX	XXS+XXX	XXS+XXX	XXS+XXX	XXS
	RNG+XX.XXXX	XS	+XXX	XXS+XXX	XXS+XXX	XXS+XXX	XXS
GPS	+XX.XXXX	XS42X43X44X	DES	31X	DES	32X	DES 33X
DRAG	H+XXXXXXXX	XS22X23X24X	ABS	14X	DELTA	35X	XXXX
ADTA	H+XXXXXXXX	XS25X26X27X	GPS	S RN+XXXX	X A2+XXX	XX	
ADTA	TO G&C	28X29X30X	RAIF_G	S47X	48X	49X	XXXX X

HORIZ SIT Display (SPEC 50)
(Three-String TACAN Vehicles)

```

XXXX/050/          HORIZ SIT      XX X DDD/HH:MM:SS
PTI   XXX 1  ALTM          DDD/HH:MM:SS
INDEX XX 9  XX  XX          NAV DELTA
      XXX                3 2 1 0      AX 10
XXXXXXXXXXXXXX XX          (+)XXXXXX
41 XXXX SITE XX          AY 11
PRI XXXXX 3X          (+)XXXXXX
SEC XXXXX 4X          (+)XXXXXX
TAEM TGT                AX 13
G&N X XXXX 6          0 (+)XXXX
HSI X                    AY 14
XEP 7                    (+)XXXX
ATM XXXX 8              AY 15
S/B XXXXX 39           (+)XXXX
      X.X  MLG  5.0K  LOAD 16
NAV RESID RATIO          18 DT (+)XX.XX
GPS P:XX.XXXX.X  AUTINHFORGPS 1S 2S 3S
V:XXX.XXX.X 42*43 44 VEL XX.XX XX.XX XX.XX
DRAG H:XXXXXXXX.X 22 23*24 P 1c XXXXX XXXXX XXXXX
ADTA H:XXXXXXXX.X 25 26*27  DES 31 DES 32 DES 33
MLG 50*51 52
      G&C  GPS 47 48*49  AZ  RNG  ALT
      ADTA 28 29*30  XXX XXXX.X XXX.X
    
```

HORIZ SIT Display (SPEC 50)
(Three-string GPS Vehicles)

```

2011/ /          UNIV PTG          2 000/02:44:58
CUR MNVR COMPL 02:55:29          000/00:00:00
1 START TIME 0/000:00:00
MNVF OPTION  START MNVR 18  CUR FUT  CUR FUT
5 R 0.00      TRK 19 *    RBST 25 X X
6 P 0.00      ROT 20      CNCL 26
7 Y 0.00      CNCL 21      DURATION 27
                          XX:XX:XX XX
TRK/ROT OPTIONS  ATT MON
8 TGT ID 2       22 MON AXIS 1 +X
ERR TOT 23 *
9 RA 0.000      ERR DAP 24
10 DEC [ ] 0.000
11 LAT [ ] 0.000      ROLL  PITCH  YAW
12 LON [ ] 0.000      CUR 163.59 40.77 338.38
13 ALT [ ] 0.0      REQD 304.04 139.80 342.99
                          ERR + 74.86 - 62.92 + 86.93
14 BODY VECTOR 3  RATE - 0.266 - 0.367 + 0.443
15 P 00.00
16 Y 0.00
17 OM 270.00
    
```

UNIV PTG Display

```

XXXX/055/          GPS STATUS      XX X DDD/HH:MM:SS
I/O 10  GPS1S GPS2S GPS3S          DDD/HH:MM:SS
STAT XXXX XXXX XXXX          GPS MINUS NAV
MODE XXXX XXXX XXXX          AH ±XXXXXX AH ±XXX.XX
S/TEST 11XS 12XS 13XS          ADR ±XXXXXX ADR ±XXX.XX
INIT 14X 15X 16X          ACR ±XXXXXX ACR ±XXX.XX
NAV 17X 18X 19X
RESTART 20X 21X 22X X LAT X LON ALT
IMU 23 XX 24 XX 25 XX XX.XX XX.XX XXX.XXXX
GDOP XX XX XX
DG FAIL S S S          AUT INH FOR
DES RCVR 26X 27X 28X GPS TO G&C S32X 33X 34X
QA OVRD 29XS 30XS 31XS GPS TO NAV S35X 36X 37X
SF CAND X X X          METERING OVERRIDE 38X
QA1 P 1cXXXXXXXXXXXXXXXXXXXXX
QA2 POS X.XXS X.XXS X.XXS          SATELLITES
VEL X.XXS X.XXS X.XXS          TRKD C1 C2 C3 C4 C5 C6
QA3 POS X.XXS X.XXS X.XXS          GPS1 XX XX XX XX XX XX
VEL X.XXS X.XXS X.XXS          GPS2 XX XX XX XX XX XX
1-2 2-3 3-1          GPS3 XX XX XX XX XX XX
QA4 POS X.XXS X.XXS X.XXS
VEL X.XXS X.XXS X.XXS          DES 43 XX XX XX XX
XXX.X LAST SEL FIL UPDATE          XX XX XX XX
    
```

GPS STATUS Display (SPEC 55)

```

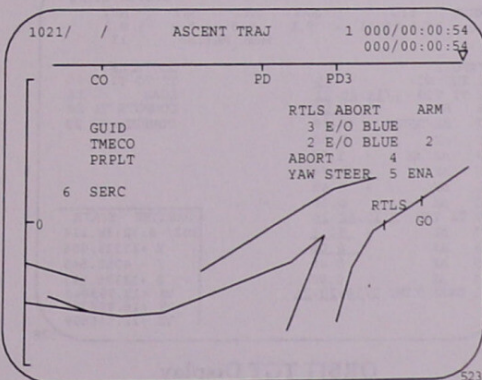
2011/020/          DAP CONFIG      1 000/19:07:32
PRI 1 DAP A08 2 DAP B08          PRI DAP EDIT
ROT RATE 10 0.2000 30 0.2000 50 0.2000 3 DAP A08
ATT DB 11 1.00 31 1.00 51 1.00 4 DAP B
RATE DB 12 0.10 32 0.10 52 0.10 5 LOAD
ROT PLS 13 0.10 33 0.10 53 0.10
COMP 14 0.00 34 0.00 54 0.00
P OPTION 15 TAIL 35 TAIL 55 TAIL
Y OPTION 16 TAIL 36 TAIL 56 TAIL
TRAN PLS 17 0.05 37 0.05 57 0.05          NOTCH FLTR
ALD ALT          ENA 6X
RATE DB 18 0.200 38 0.200 58 0.200          XJETS ROT
JET OPT 19 ALL 39 ALL 59 ALL          ENA 7X
# JETS 20 2 40 2 60 2
ON TIME 21 0.08 41 0.08 61 0.08          REBOOST
DELAY 22 0.00 42 0.00 62 0.00          8 CFG X
VERN          VERN          9 INTVL
ROT RATE 23 0.2000 43 0.2000 63 0.2000          XXX XX
ATT DB 24 1.000 44 1.000 64 1.000
RATE DB 25 0.020 45 0.020 65 0.020
ROT PLS 26 0.010 46 0.010 66 0.010
COMP 27 0.000 47 0.000 67 0.000
CNTL ACC 28 0 48 0 68 0
    
```

DAP CONFIG Display

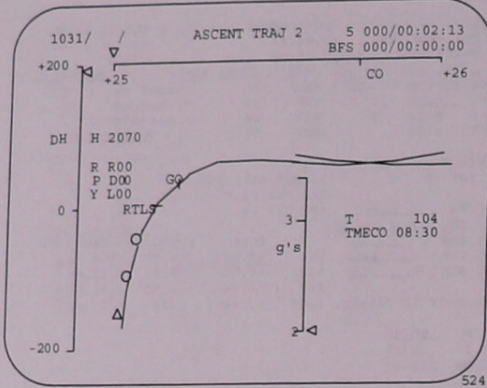
```

1041/          OMS 1 MNVR EXEC      1 000/00:40:23
OMS BOTH 1*          000/00:15:37
L 2          BURN ATT
R 3          24 R 083
RCS SEL 4          25 P 195
S TV ROLL 180          26 Y 300
TRIM LOAD          MNVR 27*
6 P [-] 1          VGO X +
7 LY [-] 5.7          Y +
8 RY [-] 5.7          Z +
9 WT 217047          HA HP
10 TIG          TGT 130 +129
          P +0.4 +0.4          CUR 130 + 9
          Y +5.8 +5.8
14 C1          PRI 28* 29* 35 ABORT TGT
15 C2 [-]          SEC 30 31          FWD RCS
16 HT          OFF 32 33          ARM 36
17 0T          GMBL CK 34          DUMP 37
18 PRPLT [-]          SURE DRIVE
TGT PEG 7          ON 39
19 AVX [-]          OFF 40*
20 AVY [+]
```

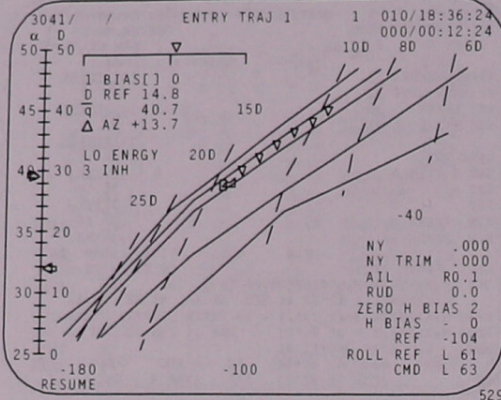
MNVR Display



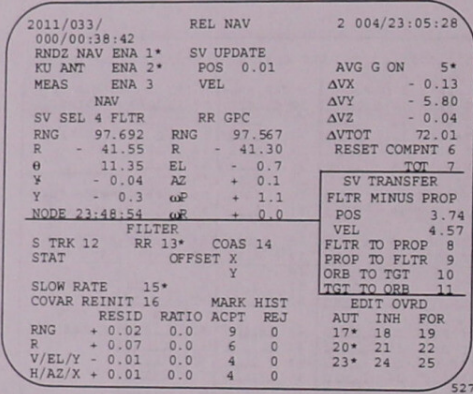
PASS ASCENT TRAJ Display



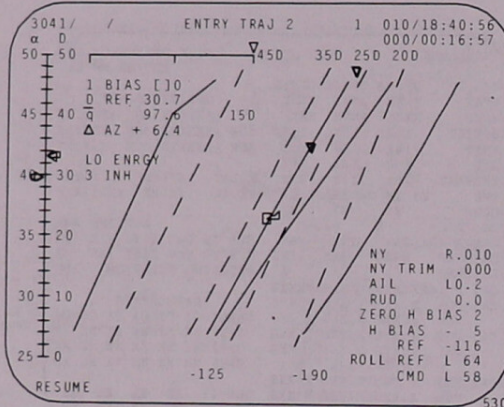
BFS ASCENT TRAJ 2 Display



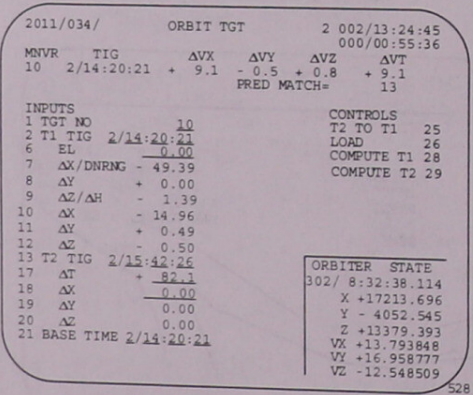
ENTRY TRAJ 1 Display



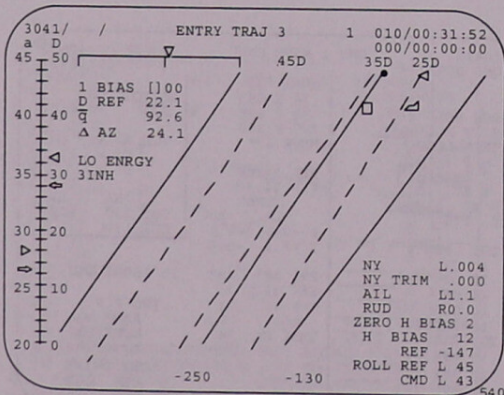
REL NAV Display



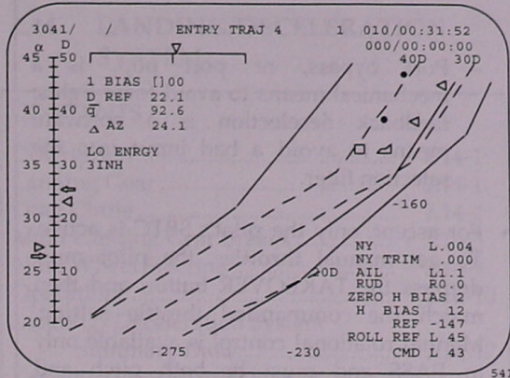
ENTRY TRAJ 2 Display



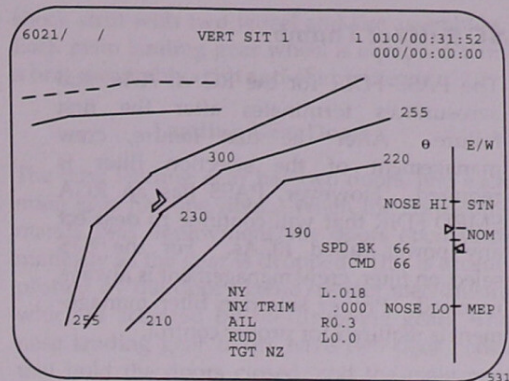
ORBIT TGT Display



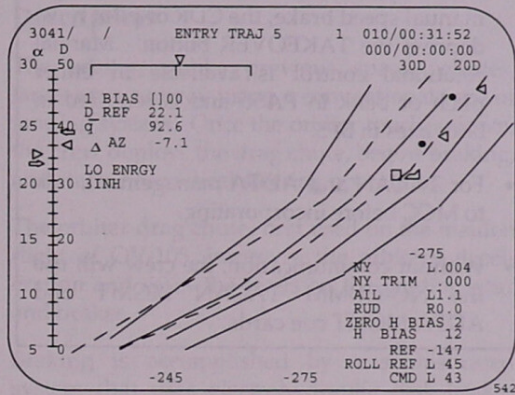
ENTRY TRAJ 3 Display



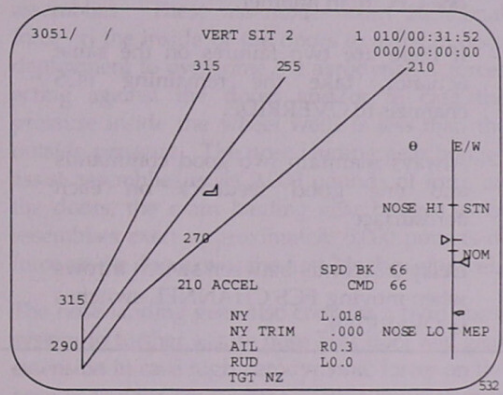
ENTRY TRAJ 4 Display



VERT SIT 1 Display



ENTRY TRAJ 5 Display



VERT SIT 2 Display

GNC Rules of Thumb

- The PASS FDIR for the RGAs, AAs, and aerosurfaces terminates after the first failure. After the first failure, crew management of the selection filter is required. However, PASS has an RGA SMRD FDIR that will continue to deselect any power failed RGAs. For the BFS selection filter, crew management is always required. Proper selection filter management is required for proper control.
- For FCS channel management:
 - Never have more active channels on one GPC than another.
 - If there are two failures on the same actuator, take the remaining FCS channels to OVERRIDE.
 - Always maintain two good commands and one good feedback on each aerosurface.
 - Delay 2 seconds between switch throws when moving FCS CHANNEL switches to OVERRIDE.
- Port bypass, or port pop, is a mechanical means to avoid force fights; feedback deselection is a software means to avoid a bad input into the selection filter.
- For ascent, only the pilot's SBTC is active. To get manual throttles, the pilot must depress the TAKEOVER button and then match the commanded throttle setting. Manual rotational control is available only in PASS and must be both pitch and roll/yaw.
- For entry, both SBTCs are active. To get manual speed brake, the CDR or pilot must depress the TAKEOVER button. Manual rotational control is available in either pitch or bank in PASS and is required in both axes in BFS.
- For TACAN and ADTA management, talk to MCC before incorporating.
- Without communication, the crew will use the NO-COMM TACAN MGMT and ADTA MGMT cue cards.

2.14 LANDING/DECELERATION SYSTEM

CONTENTS

Description	2.14-1
Landing Gear	2.14-1
Drag Chute	2.14-4
Main Landing Gear Brakes	2.14-5
Nose Wheel Steering	2.14-9
Operations	2.14-10
Landing/Deceleration System Summary Data	2.14-17
Landing/Deceleration System Rules of Thumb	2.14-17

Description

The orbiter, unlike previous space vehicles, lands on a runway using a conventional type of landing system. Once the orbiter touches down, the crew deploys the drag chute, begins braking, and starts nose wheel steering operations.

The orbiter drag chute, first used on the maiden flight of OV-105, improves the orbiter's deceleration and eases the loads on the landing gear and brakes.

Braking is accomplished by a sophisticated system that uses electrohydraulic disk brakes with an anti-skid system. Only the two main gear sets have braking capability, and each can be operated separately.

Three primary steering options are available. The crew can use the rudder to assist steering while at higher ground speeds. By selecting nose wheel steering, the crew can use the rudder pedal assembly to operate a hydraulic steering actuator incorporated in the nose landing gear. By applying variable pressure to the brakes, the crew can steer the vehicle by a method called differential braking.

Landing Gear

The orbiter landing gear system is a tricycle configuration consisting of a nose landing gear and a left and right main landing gear. The nose landing gear is located in the lower forward fuselage, and the main landing gear is in the lower left and right wing area adjacent to the midfuselage. Each landing gear includes a

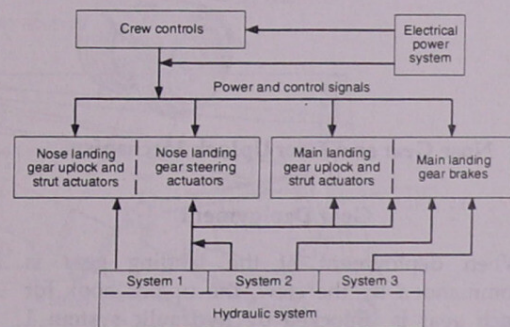
shock strut with two wheel and tire assemblies. Each main landing gear wheel is equipped with a brake assembly with anti-skid protection.

Landing Gear Doors

The nose landing gear has two doors, and each main gear has one door. When the crew commands gear deployment, the doors open automatically as the gear is dropped. This is accomplished by the door extend/retract mechanism, which is actuated by the dropping gear. The nose landing gear doors have two door hooks that hold the doors closed, and the main gear doors have four door hooks.

In addition, the doors have door-assist bungee assemblies. These assemblies exert additional force on the inside of the doors to assist in door deployment to overcome the aerodynamic forces acting against the doors and/or in case the pressure inside the wheel wells is less than the outside pressure. The nose landing gear bungee assist assemblies exert 2,000 pounds of force on the doors; the main landing gear bungee assist assemblies exert approximately 5,000 pounds of force on the doors over the first 2 inches of travel.

The nose landing gear also contains a pyro boost system to further assure nose gear door and gear extension in case high aerodynamic forces on the nose gear door are present. This pyro system is fired each time the landing gear is deployed.



Landing/Deceleration Interfaces

Each of the landing gear doors has high-temperature reusable surface insulation tiles on the outer surface and a thermal barrier or door seal to protect the landing gear from the high temperatures encountered during reentry.

Shock Struts

The shock strut of each landing gear is the primary source of impact attenuation at landing. The struts have air/oil shock absorbers to control the rate of compression/extension and prevent damage to the vehicle by controlling load application rates and peak values.

Each landing gear shock strut assembly is constructed of high-strength, stress- and corrosion-resistant steel alloys, aluminum alloys, stainless steel, and aluminum bronze. The shock strut is a pneumatic-hydraulic shock absorber containing gaseous nitrogen and hydraulic fluid. Because the shock strut is subjected to zero-g conditions during space flight, a floating piston separates the gaseous nitrogen from the hydraulic fluid to maintain absorption integrity.

The nose landing gear shock strut has a 22-inch stroke. The maximum allowable derotation rate is approximately 9.9° per second or 11.5 feet per second, vertical sink rate.

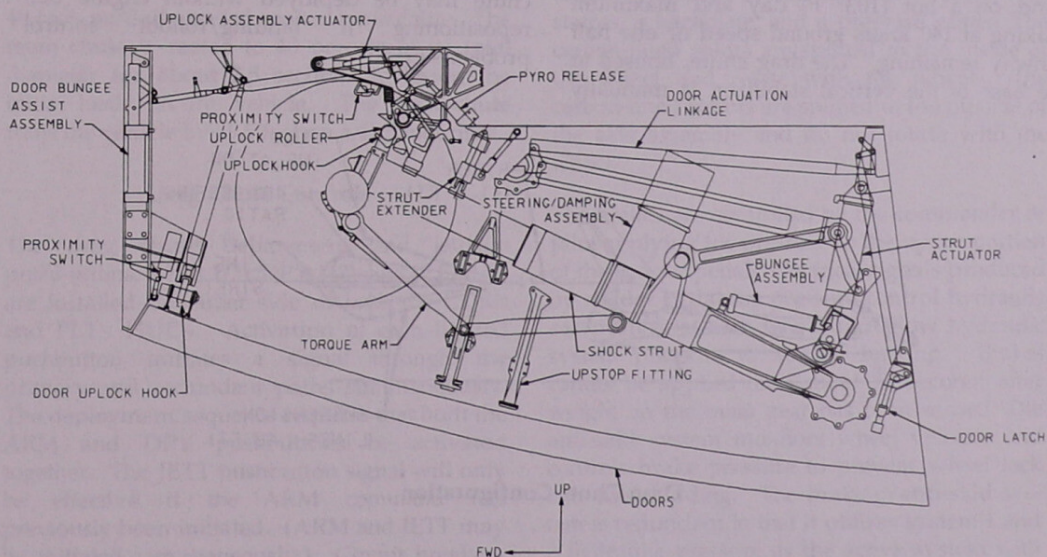
The main landing gear shock strut stroke is 16 inches. The allowable main gear sink rate for a 211,000-pound orbiter is 9.6 feet per second; for a 240,000-pound orbiter, it is 6 feet per second.

With a 20-knot crosswind, the maximum allowable gear sink rate for a 211,000-pound orbiter is 6 feet per second; for a 240,000-pound orbiter, it is approximately 5 feet per second. (Current maximum operational crosswind is limited to 15 knots.)

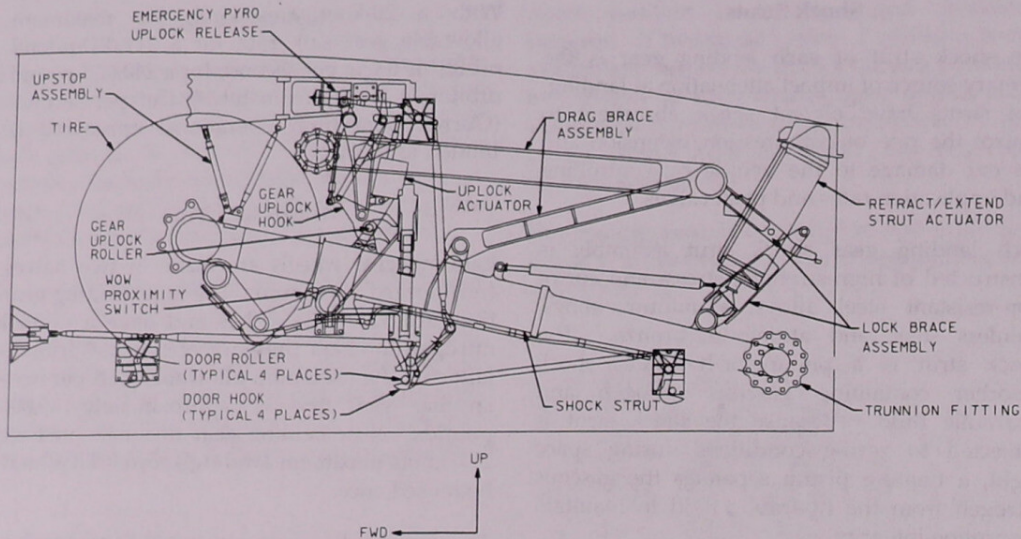
Wheels and Tires

Landing gear wheels are made in two halves from forged aluminum. The nose landing gear tires are 32 by 8.8 inches and have a normal nitrogen inflation pressure of 350 psi prior to launch. The maximum allowable load per nose landing gear tire is approximately 45,000 pounds. Nose landing gear tires are rated for 217 knots maximum landing speed. They may be reused once.

The main landing gear tires are 44.5 by 21 inches and have 16 cord layers in a bias-ply design. They are normally inflated with nitrogen to a pressure of 370 psi. The maximum allowable load per main landing gear tire is 132,000 pounds. With a 60/40 percent tire load distribution, the maximum tire load on a strut is 220,000 pounds. The main gear tires are rated at 225 knots maximum ground speed and have a life of one landing.



Nose Landing Gear Stowed

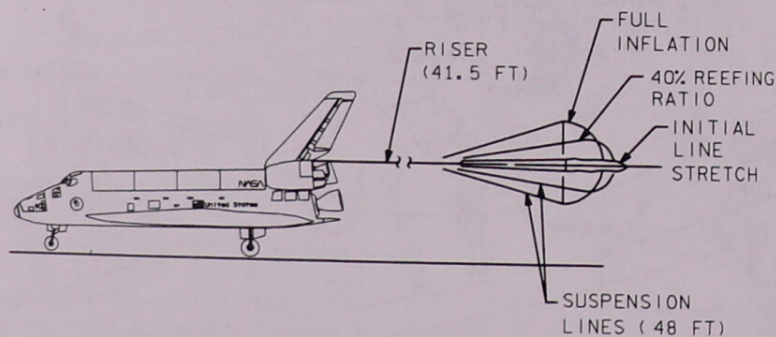


Main Landing Gear Stowed

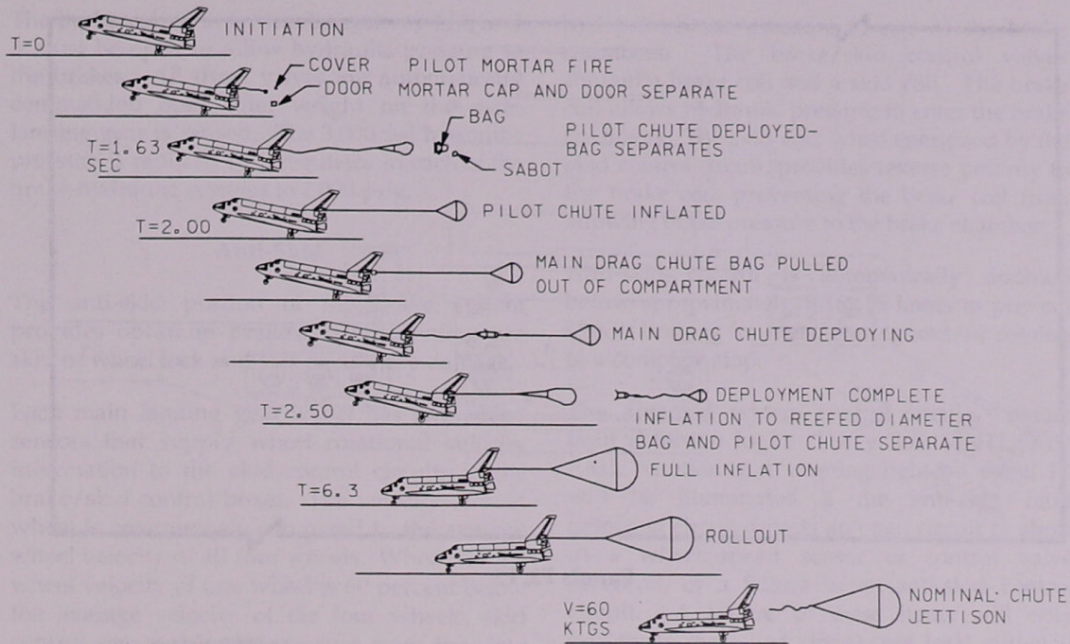
Drag Chute

The orbiter drag chute was designed to assist the deceleration system in safely stopping the vehicle on the runway at end of mission (EOM) and abort weights. Design requirements included the ability to stop a 248,000 lb TAL abort orbiter in 8,000 feet with a 10 knot tailwind on a hot (103° F) day and maximum braking at 140 knots ground speed or one half runway remaining. The drag chute, housed at the base of the vertical stabilizer, is manually

deployed by redundant commands from the CDR or PLT prior to derotation. The drag chute is jettisoned at 60 (± 20) knots ground speed to prevent damage to the main engine bells. The drag chute will be used on lake bed and concrete runways except with crosswinds greater than 15 knots or in the presence of main engine bell repositioning problems. The drag chute may be deployed without engine bell repositioning if landing/rollout control problems exist.



Drag Chute Configuration



Nominal Sequence of Drag Chute Deployment, Inflation, and Jettison

Pilot and Main Chutes

When drag chute deployment is initiated, the door is blown off of the chute compartment by pyros and a mortar fires deploying a nine foot pilot chute. The pilot chute in turn extracts the 40 foot, partially reefed conical main chute. The main chute is reefed to 40 percent of its total diameter for about 3.5 seconds to lessen the initial loads on the vehicle. The main chute trails the vehicle by 89.5 feet on a 41.5 foot riser.

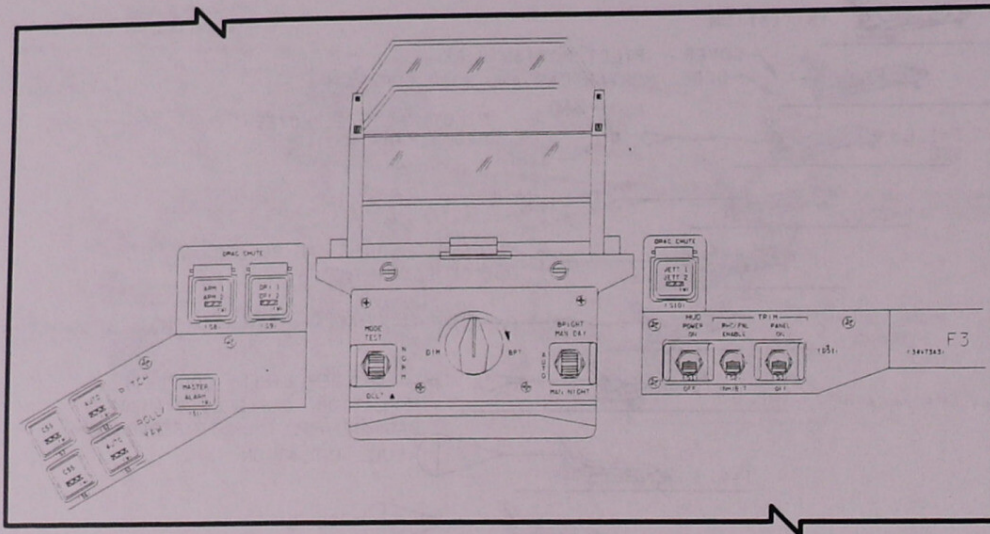
Drag Chute Controls

The drag chute deployment and jettison pushbuttons, ARM 1(2), DPY 1(2), and JETT 1(2) are installed on either side of both the CDR's and PLT's HUDs. Activation of each lighted pushbutton initiates a signal through the primary and redundant paths simultaneously. The deployment sequence requires that both the ARM and DPY pushbuttons be activated together. The JETT pushbutton signal will only be effective if the ARM command has previously been initiated. (ARM and JETT may be initiated simultaneously.) Circuit breakers for the drag chute controls are located on panels O15 and O16.

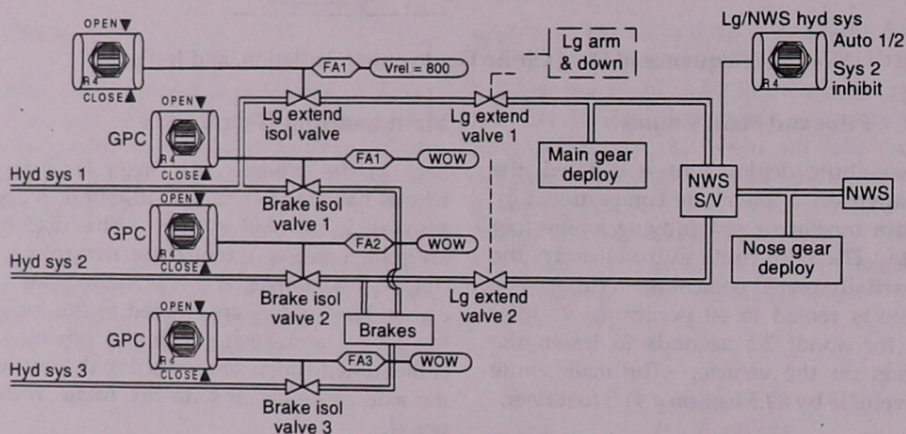
Main Landing Gear Brakes

Each of the orbiter's four main landing gear wheels has electrohydraulic disc brakes and an associated anti-skid system. The disc brake assembly consists of nine discs, five rotors, four stators, a backplate, and a pressure plate. The carbon-lined rotors are splined to the inside of the wheel and rotate with the wheel. The carbon-lined stators are splined to the outside of the axle assembly and do not rotate with the wheel.

The brakes are controlled by the commander or pilot applying toe pressure to the upper portion of the rudder pedals; electrical signals produced by rudder pedal toe pressure control hydraulic servovalves at each wheel and allow hydraulic system pressure to actuate braking. Brakes cannot be applied until about 1.9 seconds after weight on the main gear has been sensed. The anti-skid system monitors wheel velocity and controls brake pressure to prevent wheel lock and tire skidding. The braking/anti-skid system is redundant in that it utilizes system 1 and 2 hydraulic pressure as the active system with system 3 as standby, and it also utilizes all three main dc electrical systems.



Panels F2, F3



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Landing Gear Hydraulics

Brake System Hydraulic Power

Each of the four main landing gear wheel brake assemblies is supplied with pressure from two different hydraulic systems. Each brake hydraulic piston housing has two separate brake supply chambers. One chamber receives hydraulic source pressure from hydraulic system 1 and the other from hydraulic system 2. There are eight hydraulic pistons in each brake assembly. Four are manifolded together from hydraulic system 1 in a brake chamber. The remaining four pistons are manifolded together from hydraulic system 2. When the brakes are

applied, the eight hydraulic pistons press the discs together, providing brake torque.

When hydraulic system 1 or 2 source pressure drops below approximately 1,000 psi, switching valves provide automatic switching to hydraulic system 3. Loss of hydraulic system 1, 2, or both would have no effect on braking capability, because standby system 3 would automatically replace either system. Loss of hydraulic system 3 and either 1 or 2 would cause the loss of half of the braking power on each wheel, and additional braking distance would be required.

The brake valves in hydraulic systems 1, 2, and 3 must be open to allow hydraulic pressure to the brakes. All three valves are automatically commanded open after weight on the main landing gear is sensed. The 3,000 psi hydraulic pressure is reduced by a regulator in each of the brake hydraulic systems to 2,000 psig.

Anti-Skid

The anti-skid portion of the brake system provides optimum braking by preventing tire skid or wheel lock and subsequent tire damage.

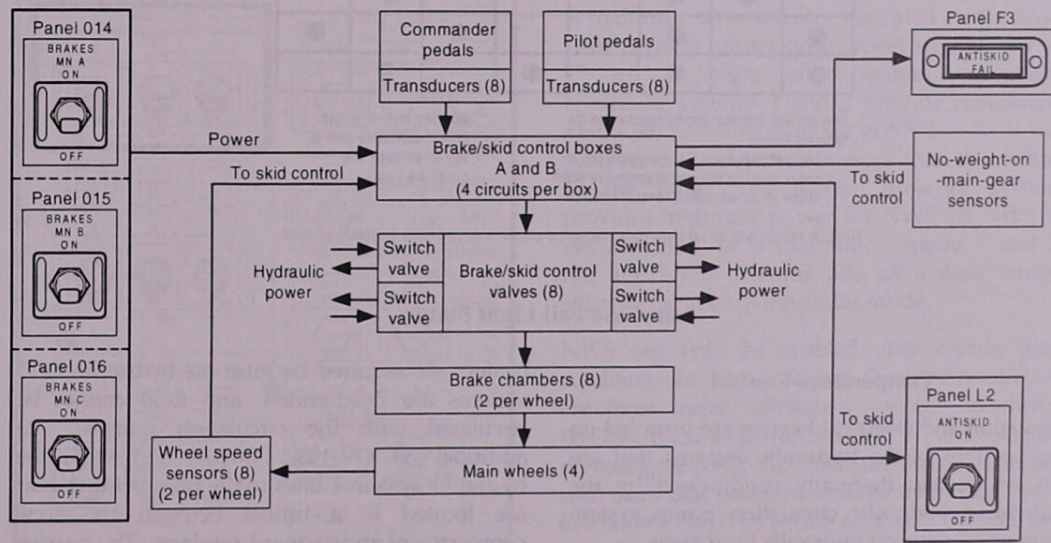
Each main landing gear wheel has two speed sensors that supply wheel rotational velocity information to the skid control circuits in the brake/skid control boxes. The velocity of each wheel is continuously compared to the average wheel velocity of all four wheels. Whenever the wheel velocity of one wheel is 60 percent below the average velocity of the four wheels, skid control removes brake pressure from the slow wheel until the velocity of that wheel increases to an acceptable range.

The brake system contains eight brake/skid control valves. Each valve controls the

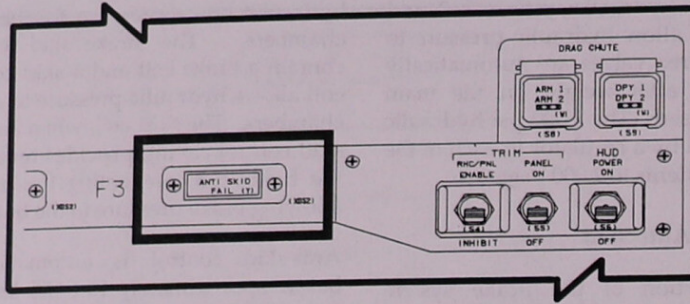
hydraulic brake pressure to one of the brake chambers. The brake/skid control valves contain a brake coil and a skid coil. The brake coil allows hydraulic pressure to enter the brake chambers. The skid coil, when energized by the skid control circuit, provides reverse polarity to the brake coil, preventing the brake coil from allowing brake pressure to the brake chamber.

Anti-skid control is automatically disabled below approximately 10 to 15 knots to prevent loss of braking for maneuvering and/or coming to a complete stop.

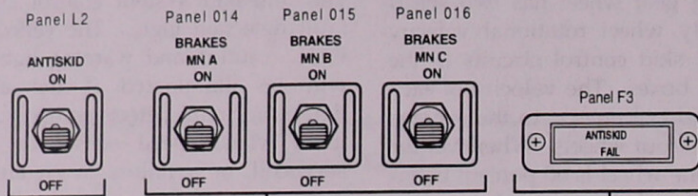
The anti-skid system control circuits contain fault detection logic. The yellow ANTI SKID FAIL caution and warning light on panel F3 will be illuminated if the anti-skid fault detection circuit detects an open circuit or short in a wheel speed sensor or control valve servocoil, or a failure in an anti-skid control circuit. A failure of these items will only deactivate the failed circuit, not total anti-skid control. If the BRAKES switches on panels O14, O15, and O16 are ON, and the ANTISKID switch on panel L2 is OFF, the ANTISKID FAIL caution and warning light will also be illuminated.



Brake/Skid Control System Overview



ANTI SKID FAIL Caution and Warning Light on Panel F3



Anti-skid Switch		Brake Power Switch		Anti-skid Failure*		Anti-skid** Fail Light	
ON	OFF	ON	OFF	YES	NO	ON	OFF
			●				●
	●	●				●	
●		●			●		●
●		●		●		●	

* Anti-skid fault detection circuits detect any of the following failures:
 - Open or short in a wheel speed sensor circuit
 - Open or short in a skid control servovalve circuit
 - Failure in an anti-skid control circuit

** Applies only if brake power switches MN B, MN C or both are activated.

Note: A failure will deactivate only the failed circuit and not total anti-skid control.

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Anti-Skid Fail Light Status

Temperature Control

Insulation and electrical heaters are installed on the portions of the hydraulic systems that are not adequately thermally conditioned by the individual hydraulic circulation pump system because of stagnant hydraulic fluid areas.

Redundant electrical heaters are installed on the main landing hydraulic flexible lines located on the back side of each main landing gear strut between the brake module and brakes. These

heaters are required because the hydraulic fluid systems are dead-ended, and fluid cannot be circulated with the circulation pumps. In addition, on OV-103, OV-104, and -105, the hydraulic system 1 lines to the nose landing gear are located in a tunnel between the crew compartment and forward fuselage. The passive thermal control systems on OV-103, OV-104, and OV-105 are attached to the crew compartment, which leaves the hydraulic system 1 lines to the nose landing gear exposed to environmental temperatures, thus requiring electrical heaters on

the lines in the tunnel. Since the passive thermal control system on OV-102 is attached to the inner portion of the forward fuselage rather than the crew compartment, no heaters are required on the hydraulic system 1 lines to the nose landing gear on OV-102.

The *HYDRAULICS BRAKE HEATER* A, B, and C switches on panel R4 enable the heater circuits. On OV-103, OV-104 and -105, *HYDRAULICS BRAKE HEATER* switches A, B, and C provide electrical power from the corresponding main buses A, B, and C to the redundant heaters on the main landing gear flexible lines and the hydraulic system 1 lines in the tunnel between the crew compartment and forward fuselage leading to the nose landing gear.

The *HYDRAULICS BRAKE HEATER* A, B, and C switches on panel R4 enable the heater circuits on only the main landing gear hydraulic flexible lines on OV-102.

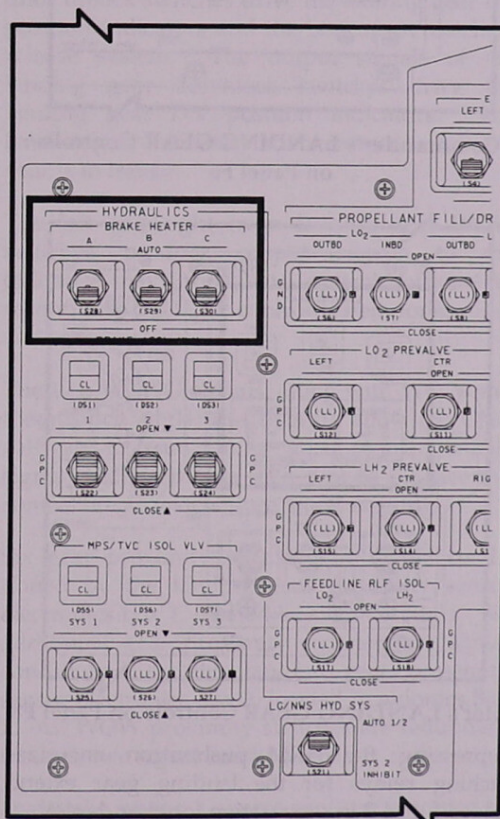
Nose Wheel Steering

The nose landing gear contains a hydraulic steering actuator that responds to electronic commands from the commander's or pilot's rudder pedals. Two types of operation are available, GPC and caster. The GPC mode is supported by hydraulic systems 1 and 2 through the selection of nose wheel steering (NWS) system 1 or 2 (*NWS 1(2)*). This provides redundant avionics modes regardless of hydraulic system support. NWS 1 or 2 will work with either hydraulic system 1 or 2.

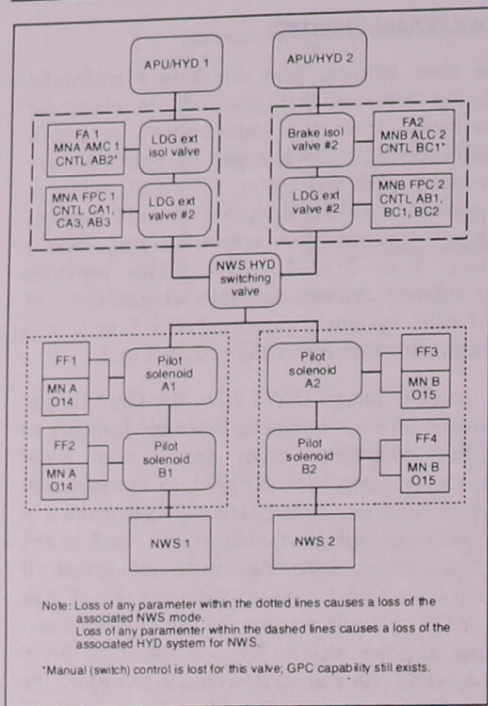
In the GPC modes (*NWS 1(2)*), the flight control software uses accelerometer assembly feedback to modify commands from the rudder pedal transducer assemblies (RPTAs) to automatically counter hardovers or large lateral accelerations due to gear or tire malfunctions. If GPC 1 or 2, or FF1 or 2 is inoperative, steering downmodes to caster if NWS 1 is selected. Similarly, the loss of GPC 3 or 4, or FF3 or 4 will prevent the use of NWS 2 and cause a downmode. The loss of either NWS system will only cause a downmode to castor. The other NWS system must be selected if required. In caster, no positive control over the nose wheel position is available, and differential braking and rudder are used for directional control.

A hydraulic servoactuator mounted on the nose strut permits orbiter nose wheel steering up to 9° left or right after system activation. Hydraulic systems 1 and 2 provide redundant hydraulic pressure to either NWS 1 or 2. If the pressure in one system is more than twice that in the other, the higher pressure system provides hydraulic power for NWS. If NWS is not activated, or if hydraulic systems 1 and 2 fail, the NWS actuator acts as a nose wheel shimmy damper in the caster mode.

NWS can only be enabled after certain preconditions are met. Among these preconditions are three major milestones: weight-on-wheels (WOW), pitch angle (θ) less than 0°, and weight-on-nose-gear (WONG). There are three sensors on each main gear designed to sense when main gear touchdown (MGTD) occurs so that WOW can be set. One sensor is a proximity sensor and the other two are wheel speed sensors (one per tire). Once WOW is set, the speed brake is commanded full open, flat turn discrete is set, half gain RHC is enabled, and the HUD format downmodes. After WOW is set on one strut, brakes are also enabled.



HYDRAULICS BRAKE HEATER Switches on Panel R4



OI-21 NWS Functional Drawing

WONG can be set by either of two proximity sensors located on the nose gear. Once WONG is set (presupposing WOW is already set and the vehicle attitude (theta) is less than zero), the ground speed enable "flag" is set. This enables NWS and the I-loaded downward deflection of the elevons for tire load relief. As a backup to the WOW and WONG discretes, the crew nominally selects SRB SEP MAN/AUTO and presses the associated pushbutton. This will manually bypass the WOW/WONG discretes and set the ground speed enable "flag." Per the entry procedure, this should be accomplished just after nose gear touchdown. Taking the F7 SEP Switch to MAN and pressing the associated pushbutton is an alternate method of manually backing up WOW/WONG.

Operations

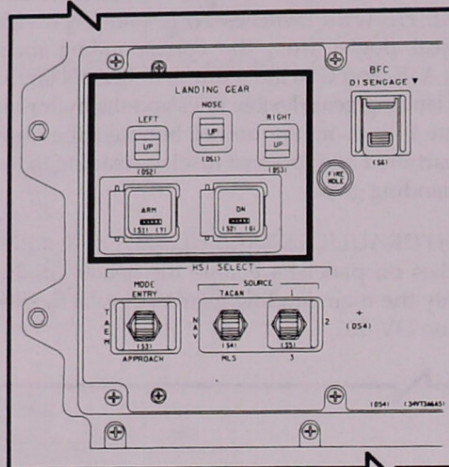
Landing Gear

Landing gear deployment is initiated when the commander (on panel F6) or pilot (on panel F8) depresses the guarded *LANDING GEAR ARM*

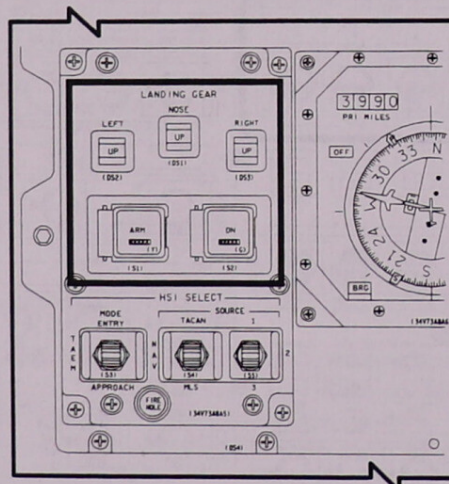
pushbutton and then the guarded DN pushbutton.

NOTE

Deploying the landing gear at equivalent airspeeds greater than 312 knots may result in high aerodynamic loads on the doors and interference with the normal opening sequence.



Commander's LANDING GEAR Controls on Panel F6



Pilot's LANDING GEAR Controls on Panel F8

Depressing the ARM pushbutton energizes latching relays for the landing gear extend valves 1 and 2 in preparation for gear deploy. It also arms the nose and main landing gear pyrotechnic initiator controllers and illuminates

the yellow light in the ARM pushbutton. This is normally performed by the pilot at approximately 2,000 feet AGL.

The DN pushbutton is then depressed. This energizes latching relays that open the hydraulic system 1 extend valve 1 and hydraulic system 2 landing gear extend valve 2. Fluid in hydraulic system 1 flows to the landing gear uplock and strut actuators and the nose wheel steering switching valve. The green light in the DN pushbutton indicator is illuminated. Normally, the DN pushbutton is pressed at least 15 seconds before touchdown at an altitude of 300 feet \pm 100 feet and at an airspeed no greater than 312 KEAS.

The proximity switches on the nose and main landing gear doors and struts provide electrical signals to control the *LANDING GEAR NOSE*, *LEFT*, and *RIGHT* indicators on panels F6 and F8. The output signals of the landing gear and door uplock switches drive the landing gear *UP* position indicators and the backup pyrotechnic release system. The output signals of the landing gear downlock switches drive the landing gear *DN* position indicators. The landing gear indicators are barberpole when the gear is in transit.

The left and right main landing gear WOW switches produce output signals to the guidance, navigation, and control software to reconfigure the flight control system for landing and rollout gains.

The two WONG signals, along with WOW and theta (pitch angle) less than 0°, allow the GNC software to issue a nose wheel steering enable signal. This signal is then sent to the steering control box to enable nose wheel steering.

Six gear proximity switches are signal conditioned by the landing gear proximity sensor electronics box 1, located in avionics bay 1. Six additional gear proximity switches are signal conditioned by the landing gear proximity sensor electronics box 2, located in avionics bay 2. All WOW proximity switches are redundant through two signal conditioners.

Hydraulic system 1 source pressure is routed to the nose and main landing gear uplock actuators, which releases the nose and main

landing gear and door uplock hooks. As the uplock hooks are released, the gear begins its deployment. During gear extension, a camming action opens the landing gear doors. The landing gear free falls into the extended position, assisted by the strut actuators and airstream in the deployment. The hydraulic strut actuator incorporates a hydraulic fluid flow-through orifice (snubber) to control the rate of landing gear extension and thereby prevent damage to the gear's downlock linkages.

The *BRAKE ISOL VLV 1, 2, and 3* switches on panel R4 control the corresponding landing gear isolation valve in hydraulic systems 1, 2, and 3. When the switch is positioned to *CLOSE*, hydraulic system 1 is isolated from the main landing gear brakes. The talkback indicator above the switch would indicate *CL*. The landing gear isolation valves cannot be opened or closed with hydraulic pressures less than approximately 100 psi. When the valve is open, hydraulic system 1 pressure is available to the main landing gear brake control valves. The normally closed landing gear extend valve 1, located downstream of the landing gear isolation valve, is not energized until a *LANDING GEAR DN* command is initiated by the commander or pilot on panel F6 or panel F8.

The *BRAKE ISOL VLV 2 and 3* switches on panel R4 positioned to *CLOSE* isolate the corresponding hydraulic system from the main landing gear brake control valves. The adjacent talkback indicator would indicate *CL*. When switches 2 and 3 are positioned to *OPEN*, the corresponding hydraulic system source pressure is available to the main landing gear brake control valves. The corresponding talkback indicator would indicate *OP*. Landing gear extend valve 2 is located downstream of brake isolation valve 2. This valve further isolates hydraulic system 2 supply pressure from the nose wheel steering and nose landing gear deploy actuators and is opened by a *LANDING GEAR DN* command.

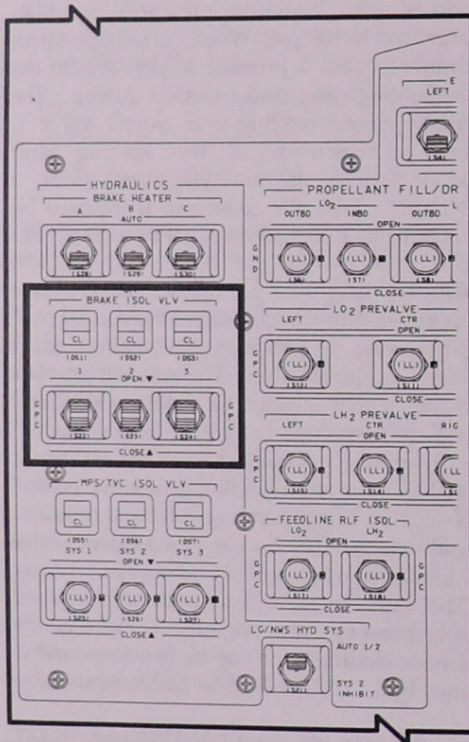
When the nose and main *LANDING GEAR DN* command is initiated, hydraulic system 1 pressure is directed to the nose and main landing gear uplock hook actuators and strut actuators (provided that the *LG/NWS HYD SYS* switch is in the *AUTO 1/2* position) to actuate the mechanical uplock hook for each landing gear and allow the gear to be deployed and also

provide hydraulic system 1 pressure to the nose wheel steering actuator. The landing gear/nose wheel steering hydraulic system switching valve will automatically select hydraulic system 2 supply pressure if system 1 should fail, thereby providing redundant hydraulics for NWS actuation and nose gear deploy.

NOTE

Hydraulic system 1 is the only hydraulic system for deploy of the main landing gear.

The GPC position of the BRAKE ISOL VLV 1, 2, and 3 switches on panel R4 permits the onboard computer to automatically control the valves in conjunction with computer control of the corresponding hydraulic system circulation pump.



BRAKE ISOL VLV Switches and Talkbacks on Panel R4

Two series valves, landing gear retract control valve 1 and 2, prevent hydraulic pressure from being directed to the retract side of the nose and main landing gear uplock hook actuators and

strut actuators if the retract/circulation valve fails to open during nose and main landing gear deployment.

Prior to entry, the *BRAKE ISOL VLV 1, 2, and 3* switches are positioned to *GPC*. This allows automatic opening of the valves after weight on main gear is sensed with *GPC* command via *MDM FA1, FA2, and FA3*, respectively. At 800 feet per second, the landing gear extend isolation valve automatic opening sequence begins under *GNC* software control. If the landing gear extend isolation valve is not opened automatically, the flight crew will be requested to manually open the valve by positioning the switch to *OPEN*.

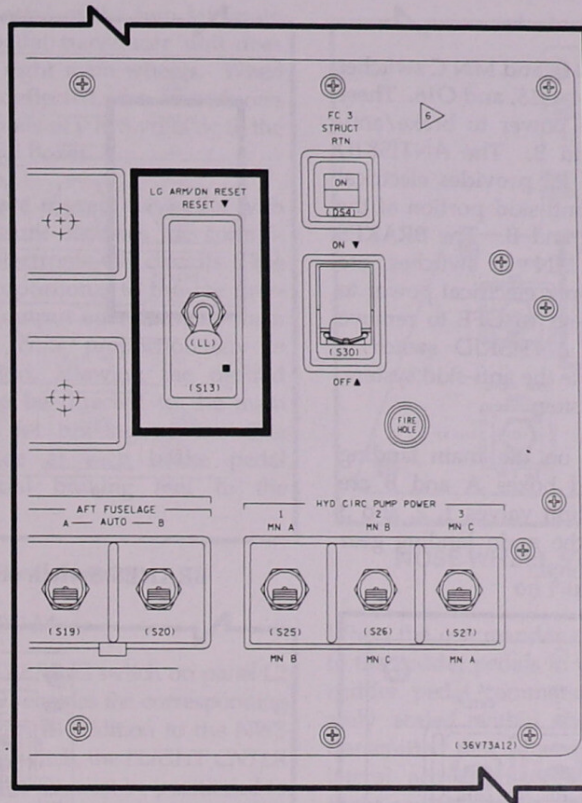
If the hydraulic system fails to release the landing gear within 1 second after the *DN* pushbutton is depressed, the nose and left and right main landing gear uplock sensors (proximity switches) will provide inputs to the pyro initiator controllers (PICs) for initiation of the redundant NASA standard initiators (pyro system 1 and 2). They release the same uplock hooks as the hydraulic system. As mentioned earlier, the nose landing gear, in addition, has a PIC and redundant NASA standard initiators that initiate a pyrotechnic power thruster 2 seconds after the *DN* pushbutton is depressed to assist gear deployment. This "nose gear pyro assist" pyro fires every time the gear are deployed.

The landing gear drag brace overcenter lock and spring-loaded bungee lock the nose and main landing gear in the down position.

Ground Reset

Landing gear reset is primarily a post landing function, which will be performed by the crew.

The *LG ARM/DN RESET* switch on panel A12 positioned to *RESET* unlatches the relays that were latched during landing gear deployment by the *LANDING GEAR ARM* and *DN* pushbutton indicators. The primary function of this procedure is to remove power to the PIC circuits that are still charged as a backup landing gear deploy method. The *RESET* position also will extinguish the yellow light in the *ARM* pushbutton indicator and the green light in the *DN* pushbutton.



LG ARM/DN RESET Switch on Panel A12

Drag Chute

During entry, at a velocity between 8000 to 3500 fps, the main engine bells are repositioned 10° below the nominal to preclude damage during drag chute deployment. The crew cannot monitor the bell repositioning but can determine that the system is enabled at item 19 on the SPEC 51 OVERRIDE display. The crew can inhibit the repositioning while in MM 301-304 by toggling item 19 in SPEC 51. Nominal EOM drag chute deployment will be initiated only if main engine bell repositioning is enabled.

Although the drag chute may be deployed at speeds up to 230 KEAS, current EOM procedures call for its deployment at 195 KEAS with a crosswind component no greater than 15 knots. If the drag chute is deployed above 230 KEAS, the drag chute pivot pin is designed to fail, resulting in the chute being jettisoned. Approximately one second after the CDR or PLT presses the ARM 1(2) and DPY 1(2) pushbuttons simul-

taneously, the pilot chute deploys. Within 1 second, the pilot chute extracts the main chute, which deploys to its 40 percent reefed diameter. After about 3.5 seconds of reefed deployment, two cutters sever the reefing ribbon allowing the main chute to inflate to its full 40-foot diameter.

WARNING

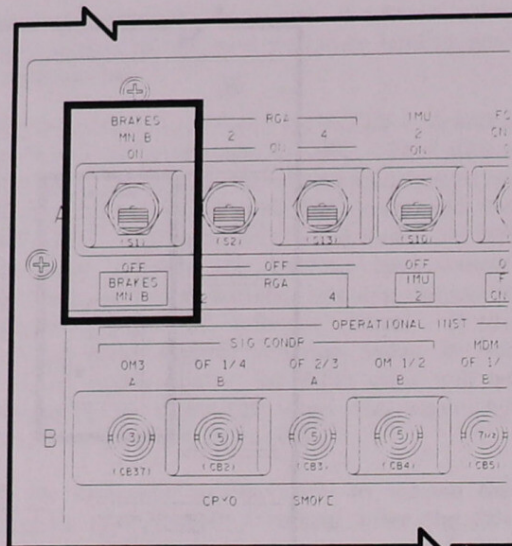
Deployment of the drag chute between 135 and 40 ft AGL can cause loss of control of the vehicle. Drag chute jettison must be initiated immediately to prevent loss of the vehicle and crew.

At 60 (±20) KGS, the drag chute will be jettisoned. Below 40 KGS, if drag chute jettison has not been initiated, the chute will be retained until the orbiter has stopped to minimize damage to the main engine bells.

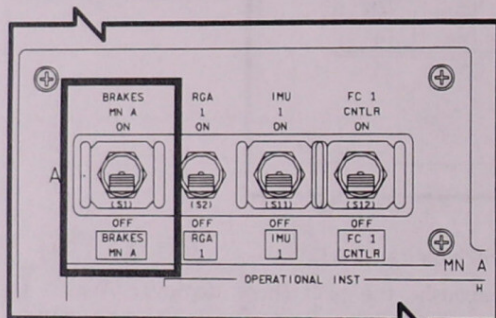
Brake Controls

The BRAKES MN A, MN B, and MN C switches are located on panels O14, O15, and O16. These switches allow electrical power to brake/anti-skid control boxes A and B. The ANTISKID switch located on panel L2 provides electrical power for enabling the anti-skid portion of the braking system boxes A and B. The BRAKES MN A, MN B, and MN C switches are positioned to ON to supply electrical power to brake boxes A and B, and to OFF to remove electrical power. The ANTISKID switch is positioned to ON to enable the anti-skid system, and OFF to disable the system.

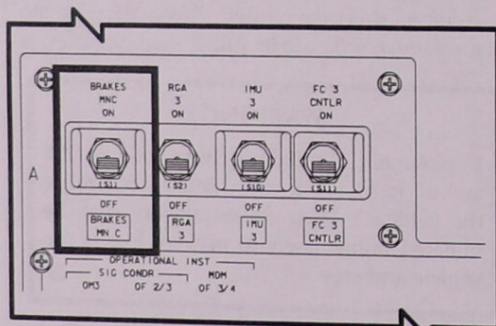
When weight is sensed on the main landing gear, the brake/anti-skid boxes A and B are enabled and brake isolation valves 1, 2, and 3 are opened, permitting the main landing gear brakes to become operational.



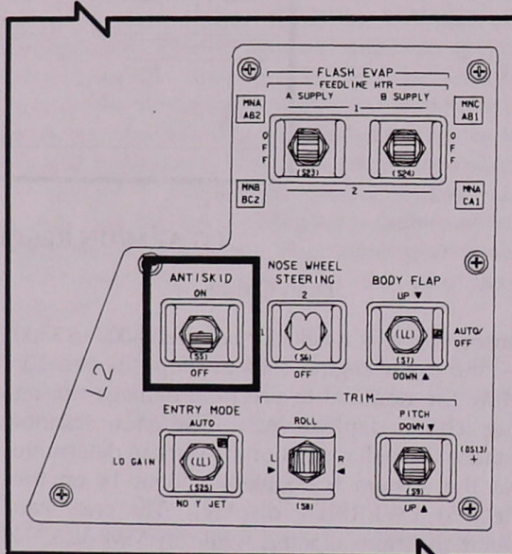
BRAKES Switch on Panel O15



BRAKES Switch on Panel O14



BRAKES Switch on Panel O16



ANTISKID Switch on Panel L2

The main landing gear brakes controlled by the commander's or pilot's brake pedals are located on the rudder pedal assemblies at the commander's and pilot's stations. Pressure on the toe of the adjustable brake/rudder pedals results in a command to the wheel braking system.

Each brake pedal has four transducers. The left pedal transducer unit outputs four separate braking signals through the brake/skid control

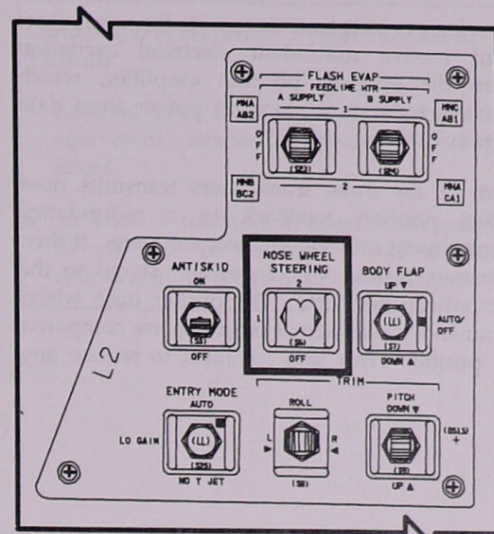
boxes for braking control of the two left main wheels. The right pedal transducer unit does likewise for the two right main wheels. When the brake pedal is deflected, the transducers transmit electrical signals of 0 to 5 volts dc to the brake/anti-skid control boxes.

If both right pedals are moved, the pedal with the greatest toe pressure becomes the controlling pedal through electronic OR circuits. The electrical signal is proportional to the toe pressure. The electrical output energizes the main landing gear brake coils proportionately to brake pedal deflection, allowing the desired hydraulic pressure to be directed to the main landing gear brakes for braking action. The brake system bungee at each brake pedal provides the artificial braking feel to the crewmember.

Nose Wheel Steering

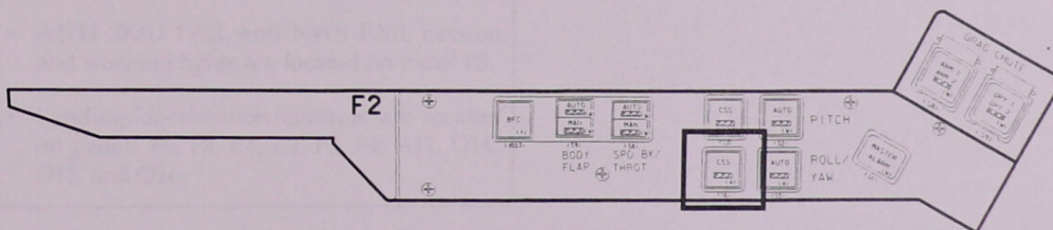
GPC Mode

The *NOSE WHEEL STEERING* switch on panel L2 positioned to *NWS 1(2)* enables the corresponding NWS (avionics) system. In addition to the NWS mode selections of the switch, the *FLIGHT CNTLR POWER* switch on panel F8 must be positioned to *ON*, and the flight control system *ROLL/YAW CSS* pushbutton on panel F2 or F4 must be depressed to enable the GPC for nose wheel steering. When either pushbutton is depressed, a white light illuminates the pushbutton.

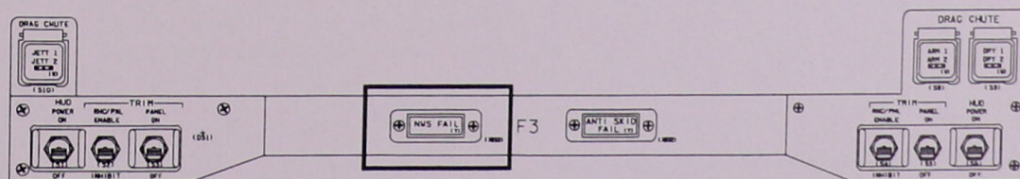


NOSE WHEEL STEERING Switch
on Panel L2

When the commander or pilot makes an input to the rudder pedals in the NWS 1(2) mode, the rudder pedal command position is appropriately scaled within the GPC's software and transmitted to a summing network, along with lateral accelerometer inputs from within the flight control system. The accelerometer inputs are utilized to prevent any sudden orbiter lateral deviation. From this summing network, a nose wheel steering command is sent to a comparison network, as well as to the steering servo system.



ROLL/YAW CSS Pushbutton on Panel F2



NWS FAIL Light on Panel F3

Steering position transducers on the nose wheel strut receive redundant electrical excitation from the steering position amplifier, which receives redundant electrical power from data display unit 2.

Each of the three transducers transmits nose wheel position feedback to a redundancy management mid-value-select software. It then transmits a nose wheel position signal to the comparison network. The orbiter nose wheel commanded and actual positions are compared for position error and for rates to reduce any

error. Absence of an error condition will allow nose wheel steering to be enabled after WOW, WONG, and theta less than 0° are sensed in the software. The enable signal permits hydraulic system 1(2) pressure to be applied to the nose wheel steering actuator via the NWS switching valve. If hydraulic system 1 is lost, hydraulic system 2 provides the pressure for nose wheel steering. If both systems' pressures drop below approximately 1,325 psi, the actuator remains in the caster mode and a failure is annunciated to the NWS FAIL C/W yellow light on panel F3.

Landing/Deceleration System Summary Data

- The orbiter has the capability of landing on a runway using a tricycle type of landing gear system. Once the orbiter touches down, the crew begins braking and steering operations.
- The landing gear consists of a nose landing gear and a left and right main landing gear. Each landing gear includes a shock strut with two wheel and tire assemblies.
- The nose wheels are co-rotating through a common axle, whereas the main gear wheels rotate independently.
- Each of the four main landing gear wheels has electrohydraulic brakes and an anti-skid system. Each gear wheel brake assembly is supplied with pressure from two different hydraulic systems. Systems 1 and 2 are the primary hydraulic systems for brake pressure; system 3 can back up either or both systems.
- Redundant electrical heaters are installed on the main landing hydraulic flexible lines located on the back side of each main landing gear strut between the brake module and brakes.
- The orbiter nose wheel is steerable after nose wheel touchdown at landing.
- ANTI SKID FAIL and NWS FAIL caution and warning lights are located on panel F3.
- Landing/deceleration controls are located on panels F6, F8, R4, L2, F2, F4, A12, O14, O15, and O16.

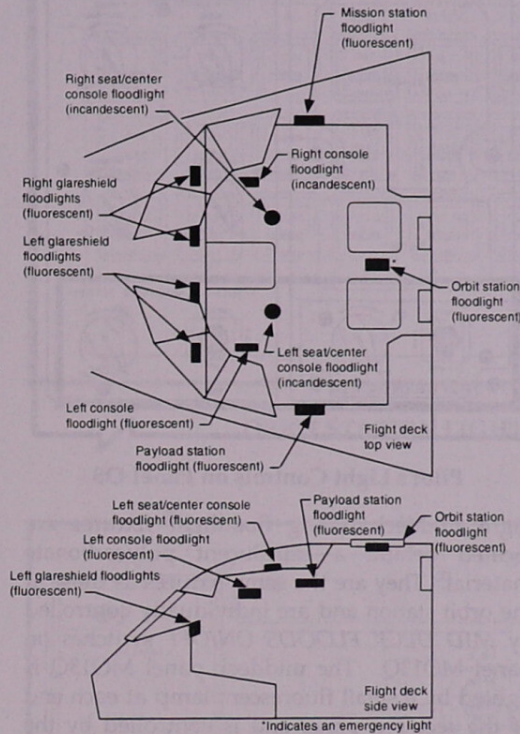
Landing/Deceleration System Rules of Thumb

- Landing gear should not be deployed at equivalent airspeeds greater than 312 knots.
- ± 1 knot of touchdown speed corresponds to ± 90 feet of distance. This is often rounded up to 100 feet for convenience.

2.15 LIGHTING SYSTEM

CONTENTS

Description	2.15-1
Interior Lighting	2.15-1
Exterior Lighting	2.15-12
Lighting System Summary Data	2.15-14
Lighting System Rules of Thumb	2.15-14



**Floodlight Locations -
Flight Deck Forward and Aft**

Description

The orbiter lighting system provides both interior and exterior lighting. The interior lighting provides illumination for display and control visibility and for general crew station and crew equipment operations. Exterior lighting provides illumination for payload bay door operations, extravehicular activity, remote manipulator system operations, and station-keeping and docking. Interior lighting consists of floodlights, panel lights, instrument lights, numeric lights, and annunciator lights. Exterior lighting consists of floodlights and spotlights.

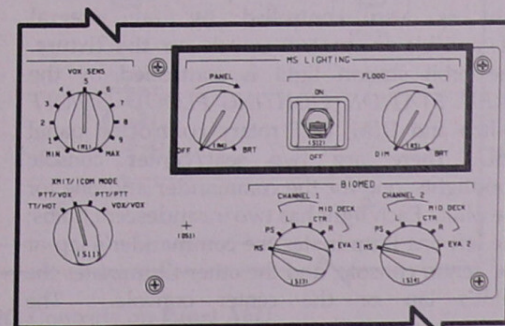
Interior Lighting

Interior floodlights provide general illumination throughout the crew cabin and allow the flight crew to function within the flight deck, middeck, airlock, tunnel adapter, and Spacehab (if installed). Circuit breakers, switches, and variable controls are used to operate the lights. Both fluorescent and incandescent lamps are used.

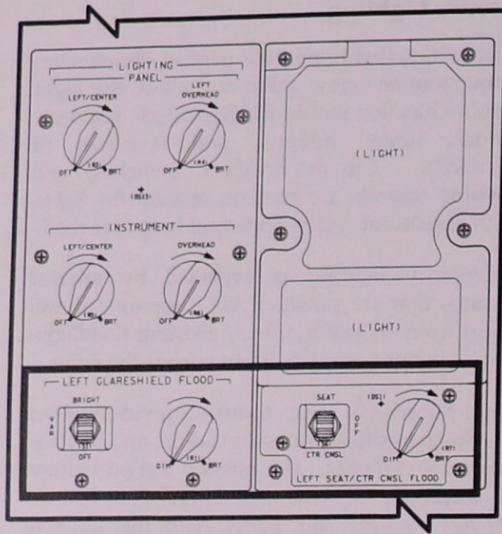
Emergency lighting is provided by selected fixtures that are powered via a separate power input from an essential bus. Existing floodlights are used, but a separate input powers the lights.

Dual fluorescent lamp fixtures provide lighting for the glareshield, mission station, and payload station floodlights. The mission station lighting is controlled by the *MS LIGHTING FLOOD ON/OFF* switch on panel R10; the adjacent rotary control *DIM/BRT* switch controls brightness. The payload station lighting is controlled by the *PS FLOOD ON/OFF* switch on panel L9, which also has an adjacent *DIM/BRT* rotary switch to control brightness.

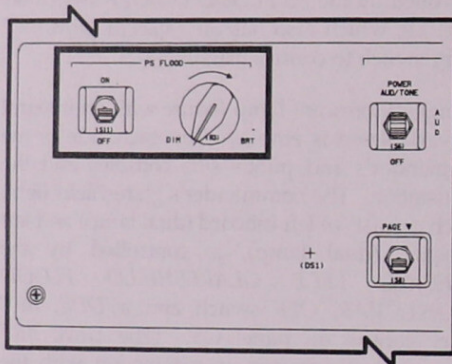
A single fluorescent lamp fixture with an integral off/variable-on is employed on each side of the commander's and pilot's side consoles and the orbit station. The commander's glareshield light, which consists of left inboard (dual lamp) and left outboard (dual lamp), is controlled by the *LIGHTING LEFT GLARESHIELD FLOOD BRIGHT, VAR, OFF* switch and a *DIM, BRT* rotary control on panel O6. (The *DIM, BRT* rotary control operates in conjunction with the *VAR* position.) The pilot's glareshield light functions the same as the commander's, except the controls (*LIGHTING RIGHT GLARESHIELD FLOOD* and *DIM, BRT*) are on panel O8.



MS LIGHTING Controls on Panel R10



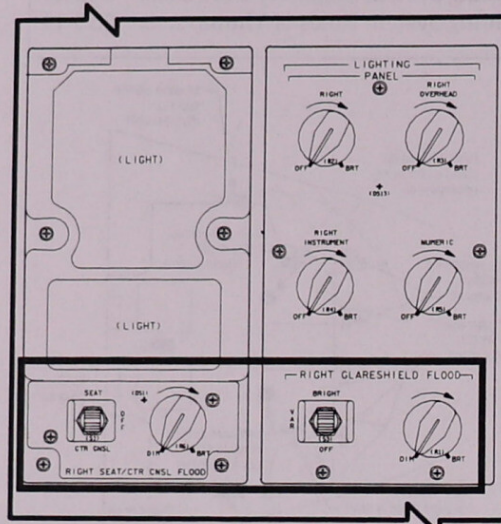
MS LIGHTING Controls on Panel R10



PS FLOOD Lighting Controls on Panel L9

The commander's side console light is controlled by an integral off/variable-on control switch on the fixture. The pilot's side console light is also controlled by an integral off/variable-on control switch on the fixture. The orbit station light is controlled by the *ORBIT STATION LIGHTING FLOOD ON/OFF* switch and *DIM, BRT* rotary control on panel A6U. There are two seat/center console floodlights: one for the commander and one for the pilot. Each light has two incandescent bulbs: the left one illuminates the commander's lap or the center console, and the other illuminates the pilot's lap or the center console. The commander or pilot can select either the lap or center console, but not both at once. The commander's seat or console light is controlled

by the *LEFT SEAT/CTR CNSL FLOOD, SEAT/OFF/CTR CNSL* switch and the *DIM, BRT* rotary control on panel O6. The pilot's seat or console light is controlled by the *RIGHT SEAT/CTR CNSL FLOOD, SEAT/OFF/CTR CNSL* switch and the *DIM, BRT* rotary control on panel O8.



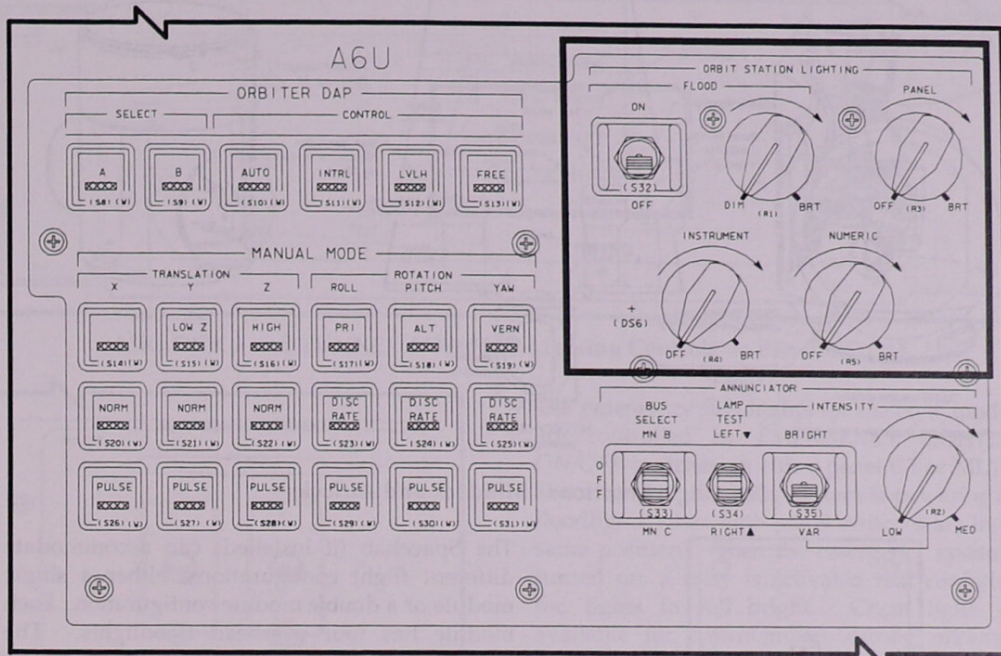
Pilot's Light Controls on Panel O8

Eight middeck ceiling floodlight fixtures are located behind a translucent polycarbonate material. They are the same fixtures as those at the orbit station and are individually controlled by *MID DECK FLOODS ON/OFF* switches on panel MO13Q. The middeck panel MO13Q is lit by a small fluorescent lamp at each end of the recessed panel and is controlled by the *MO13Q LTG ON/OFF* switch on the panel.

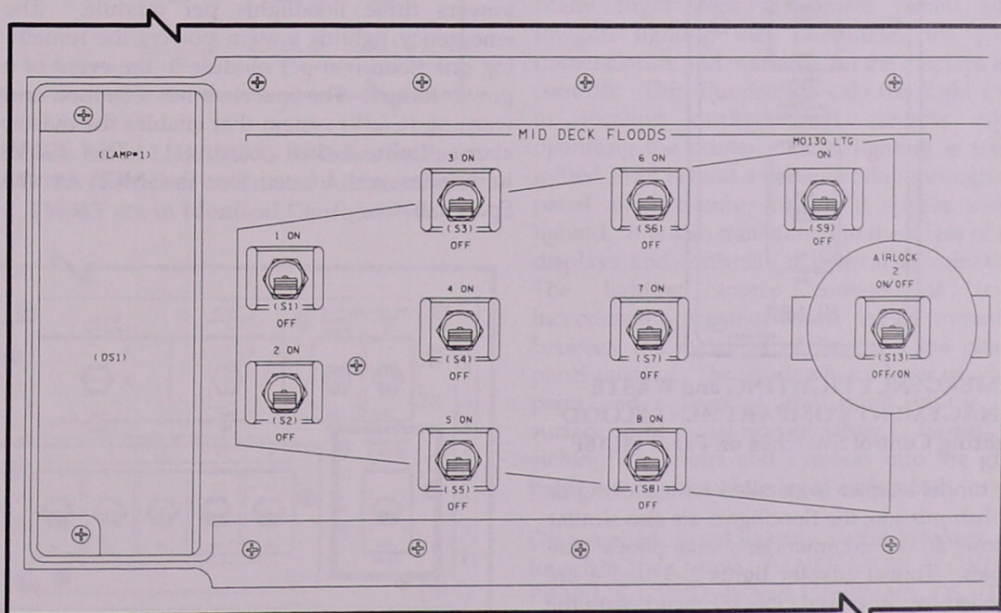
The waste management compartment floodlight is also the same as the orbit station fixture and is controlled by the *WASTE MANAGEMENT COMPARTMENT FLOOD ON/OFF* switch on panel ML18F.

The middeck sleep station bunks (if installed) use the same floodlights as the commander's and pilot's flight deck consoles and are also controlled individually.

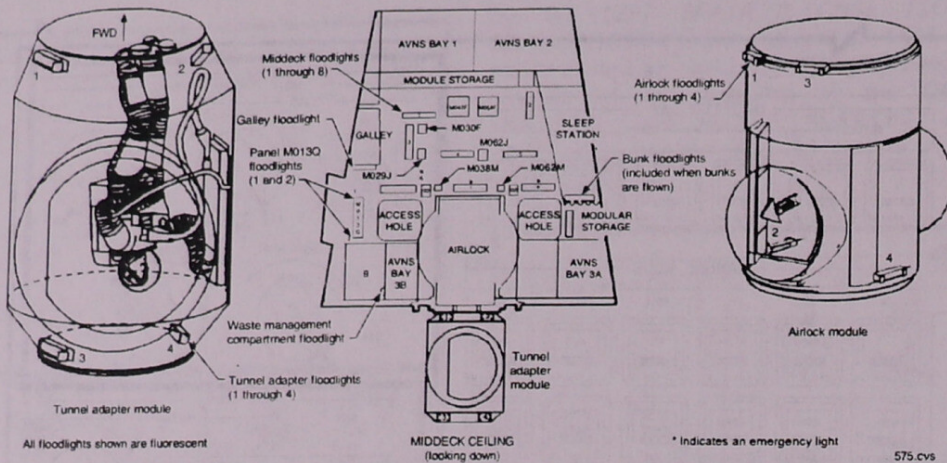
The airlock floodlights are similar to those at the commander's and pilot's flight deck side consoles, except they are controlled by *LIGHTING FLOOD* switches on panel AW18A and an *AIRLOCK 2* switch on panel MO13Q.



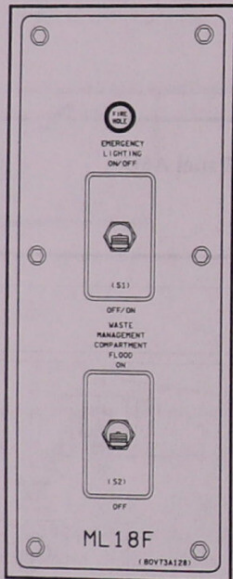
ORBIT STATION LIGHTING Controls on Panel A6U



ORBIT STATION LIGHTING Controls on Panel A6U



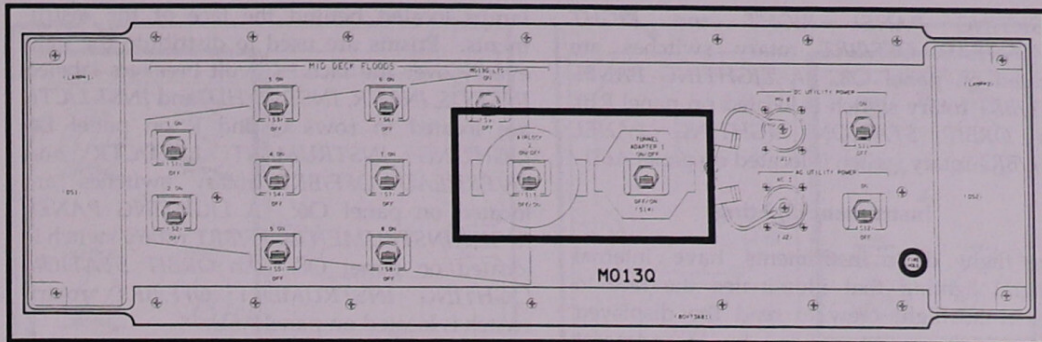
Floodlight Locations - Middeck and Airlock



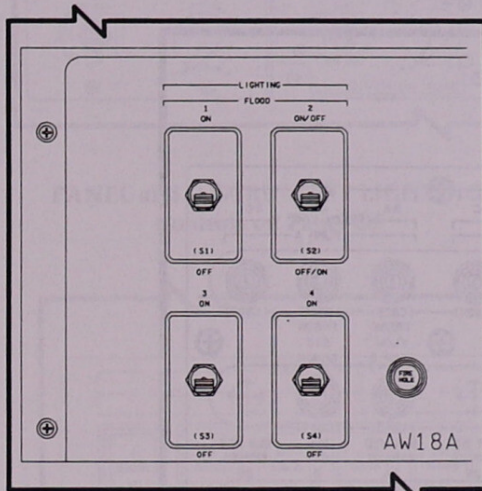
EMERGENCY LIGHTING and WASTE MANAGEMENT COMPARTMENT FLOOD Lighting Control Switches on Panel ML18F

If the tunnel adapter is installed for a docking or Spacehab mission, the floodlights are also similar to those at the commander's and pilot's side consoles. Tunnel adapter lights 2, 3, and 4 are controlled by individual ON/OFF switches on the tunnel adapter panel TW58T. Tunnel adapter light 1 is controlled by the TUNNEL ADAPTER 1 ON/OFF switch on panel MO13Q and the ON/OFF 1 switch on the tunnel adapter panel.

The Spacehab (if installed) can accommodate different flight configurations, either a single module or a double module configuration. Each module has four overhead floodlights. The fixtures are single-lamp floodlights with an integral dimmer control on three. There is a main switch located on the monitor and control panel (MCP) at the entrance of the module that powers three floodlights per module. The emergency lighting system powers the remaining one floodlight per module in the event of a power failure. The Spacehab has a caution and warning (C&W) system that enables the master alarm light switch closure. The C&W luminaries are located on the MCP in the Spacehab.



AIRLOCK 2 and TUNNEL ADAPTER Lighting Controls on Panel M013Q

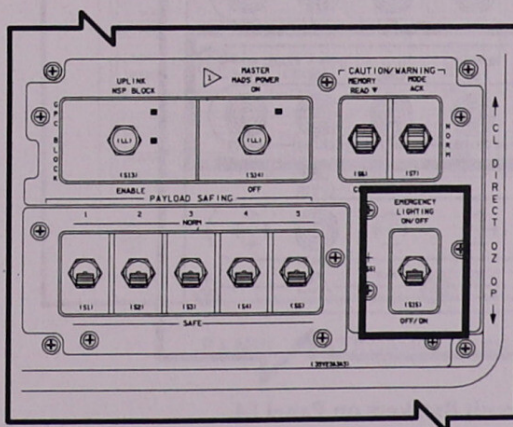


Airlock Flood LIGHTING Switches on Panel AW18A (Switches on Tunnel Adapter Panel TW58T are in Identical Configuration)

The emergency floodlights for the crew module are controlled by *EMERGENCY LIGHTING ON/OFF* switches on either panel C3 or ML18F. The emergency lighting system is powering the floodlights when both panel switches are in the same position. When the emergency system is turned on, a relay is activated that configures the lights to full bright. Chem lights are available for crewmembers during minimum floodlight operations.

Panel Lighting

Many flight deck instrument panels have integral lighting that illuminates the panel nomenclature and markings on the displays and controls. This illumination aids the flight crew in locating displays and controls while operating the orbiter. Panel lighting is transmitted from behind a panel overlay through the panel nomenclature, making it appear white-lighted. It is also transmitted to the edges of the displays and controls for general illumination. The lighting source consists of small incandescent, grain-of-wheat lamps mounted between the metal panel face and the plastic panel overlay. The overlay has a layer of white paint and a layer of gray paint on the top surface. The panel nomenclature is formed by etching the letters and symbols into the gray paint, leaving the white layer underneath.



EMERGENCY LIGHTING Switch on Panel C3

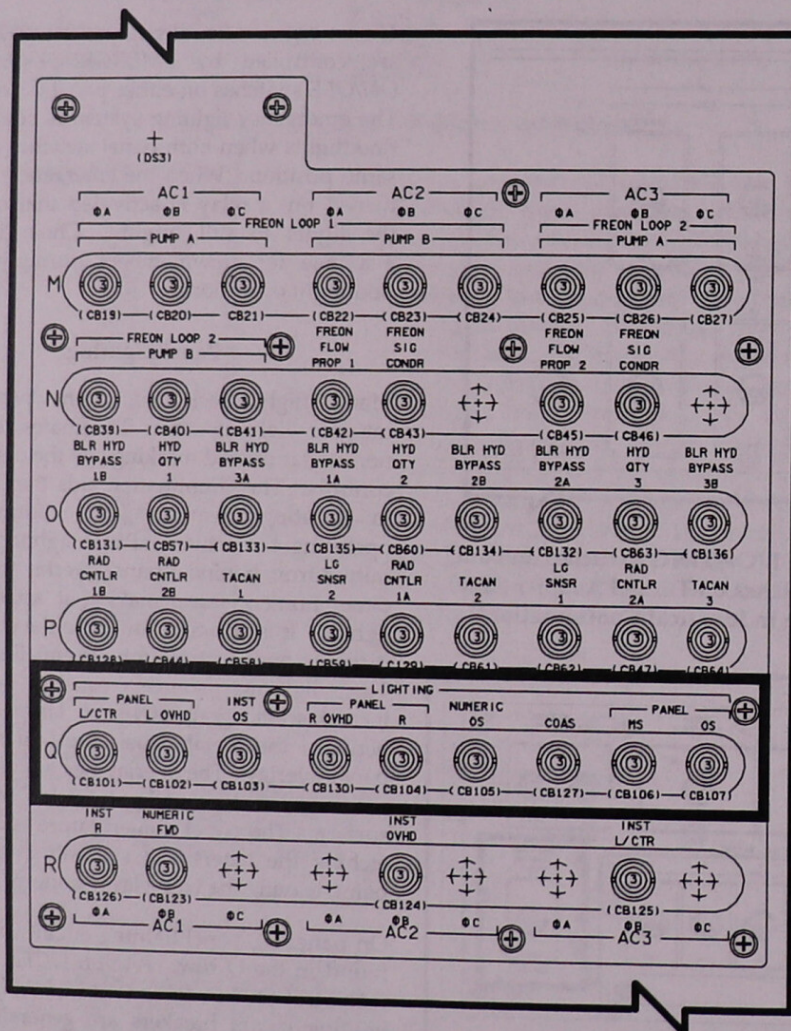
On panel L4, panel lighting circuit breakers are found in the Q row: *PANEL L/CTR*, *L OVHD*; *PANEL R OVHD*, *R*; and *PANEL MS*, *OS*. The lighting circuit breakers are generally out for day launches. *LIGHTING PANEL LEFT/CENTER* and *LEFT OVERHEAD OFF/BRT* rotary switches are found on panel O6.

LIGHTING PANEL RIGHT and RIGHT OVERHEAD OFF/BRT rotary switches are located on panel O8. A LIGHTING PANEL OFF/BRT rotary switch is located on panel R10. An ORBIT STATION LIGHTING PANEL OFF/BRT rotary switch is located on panel A6U.

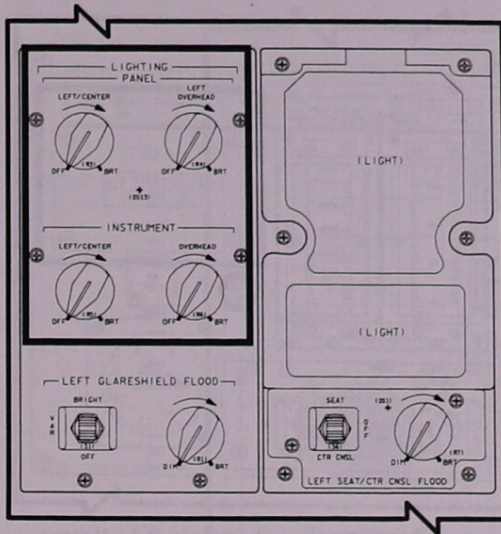
Instrument Lighting

The flight deck instruments have internal integral lighting that illuminates the face to enable the flight crew to read the displayed data. Lighting is provided by incandescent

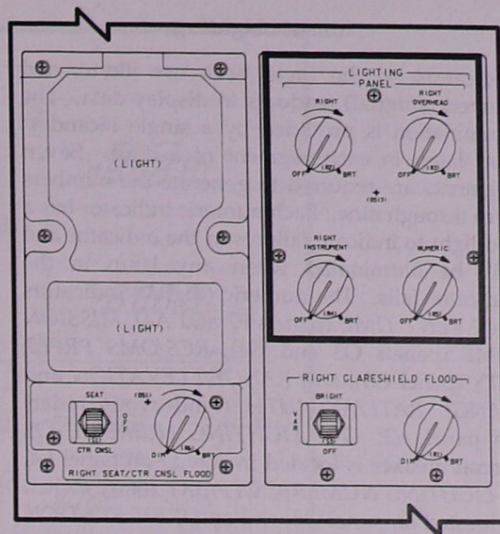
lamps located behind the face of the instruments. Prisms are used to distribute the light evenly over the face. Circuit breakers labeled INST OS, INST R, INST OVHD, and INST L/CTR are located in rows Q and R on panel L4. LIGHTING INSTRUMENT LEFT/CTR and OVERHEAD OFF/BRT rotary switches are located on panel O6. A LIGHTING PANEL RIGHT INSTRUMENT OFF/BRT rotary switch is located on panel O8. An ORBIT STATION LIGHTING INSTRUMENT OFF/BRT rotary switch is located on panel A6U.



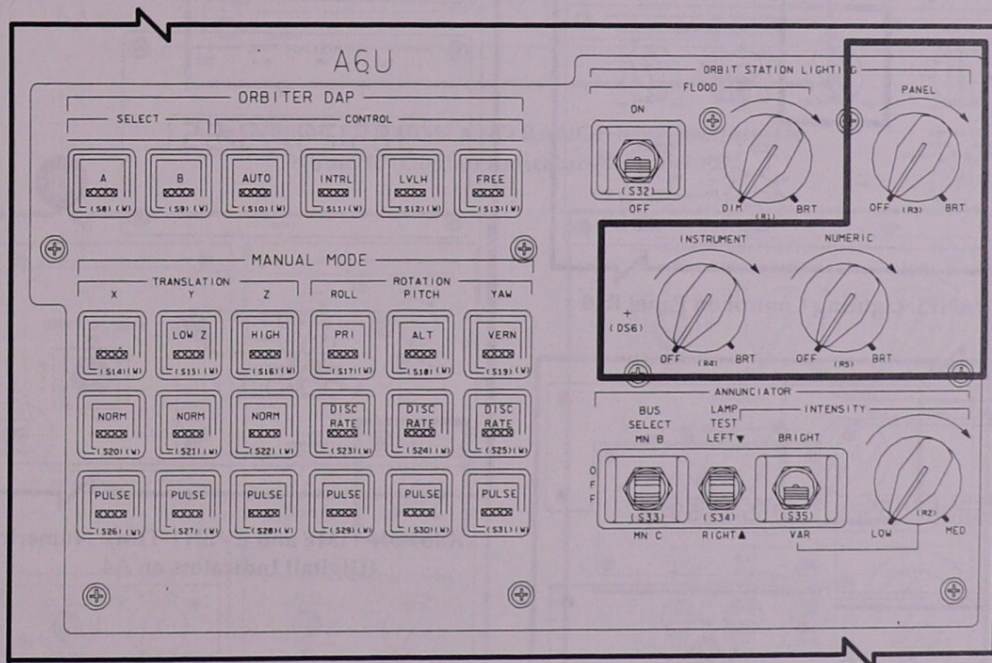
PANEL INST and NUMERIC Circuit Breakers on Panel L4



PANEL and INSTRUMENT Lighting Controls on Panel O6



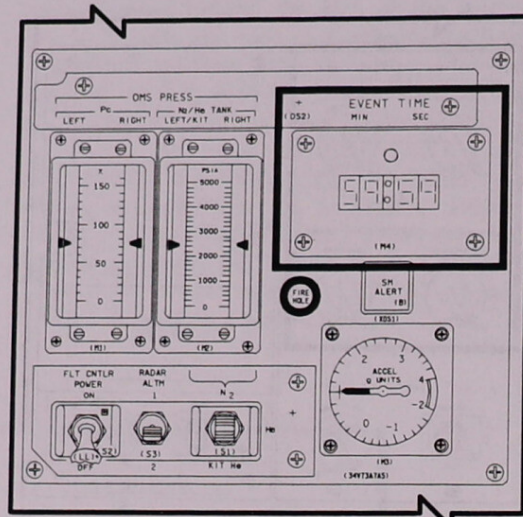
PANEL, INSTRUMENT, and NUMERIC Lighting Controls on Panel O8



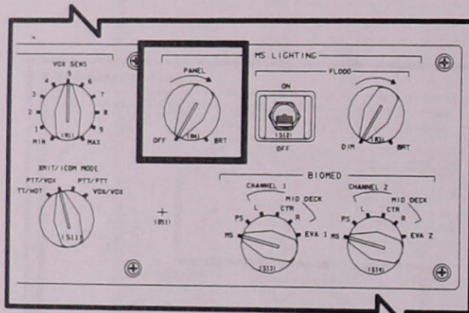
PANEL, INSTRUMENT, and NUMERIC Lighting on Panel A6U

Numeric Lighting

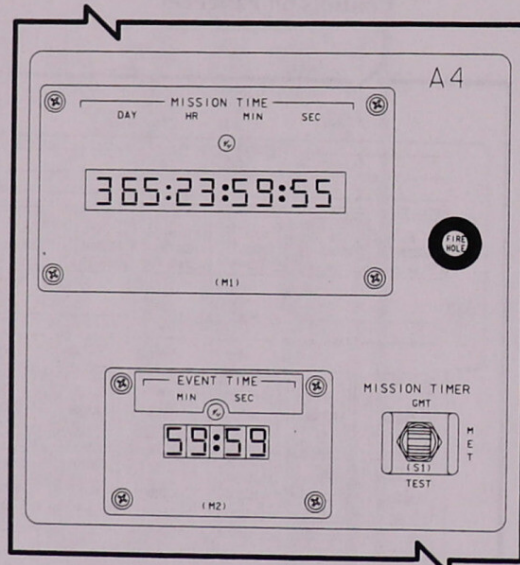
Indicators on the flight deck use illuminated numeric (digital) readouts to display data. The illumination is provided by a single incandescent lamp in each segment of a digit. Seven segments are required to generate the numbers zero through nine. Each numeric indicator has a red light to indicate failures in the indicator and will be illuminated when any lamp in the indicator fails. The numeric (digital) indicators are *EVENT TIME* (panels F7 and A4), *MISSION TIME* (panels O3 and A4), *RCS/OMS PRPLT QTY* (panel O3), and *RANGE/ELEVATION* and *RANGE RATE/AZIMUTH* (rendezvous radar) on panel A2. The *LIGHTING NUMERIC OS* circuit breaker is located in row Q on panel L4. A *LIGHTING NUMERIC OFF/BRT* rotary switch is located on panel O8, and an *ORBIT STATION LIGHTING NUMERIC OFF/BRT* rotary switch is located on panel A6U. The RMS (if installed) has numeric readouts on panel A8U.



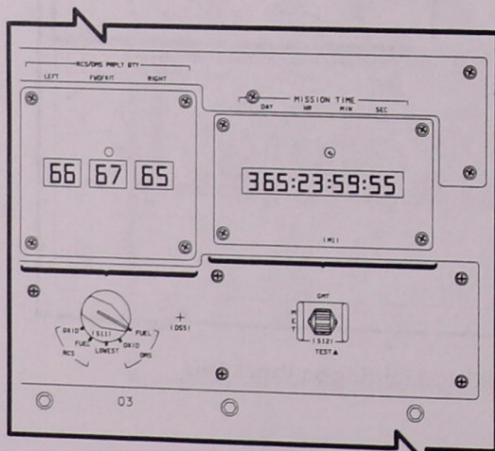
EVENT TIME Numeric (Digital) Indicator on Panel F7



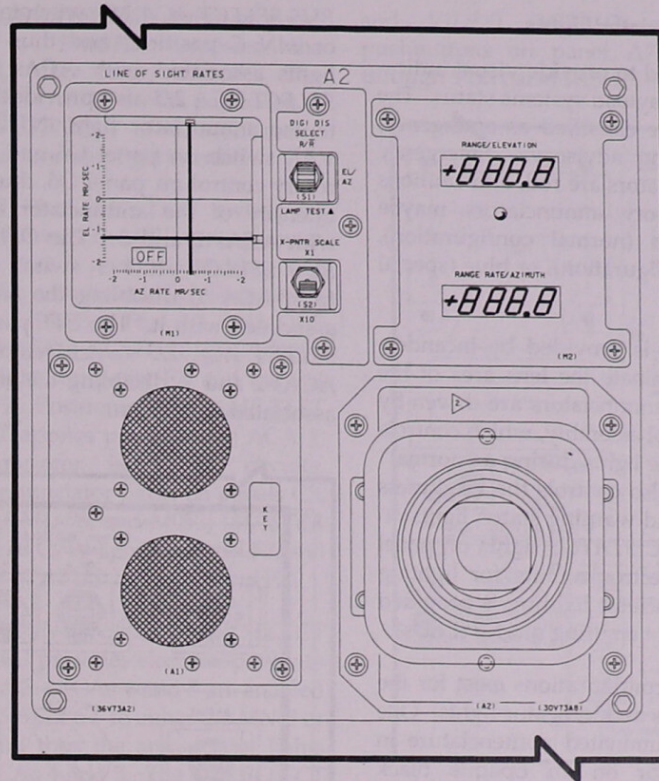
PANEL Lighting Control on Panel R10



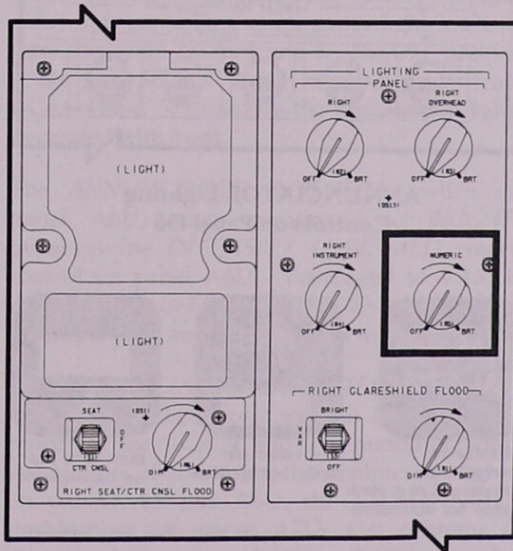
MISSION TIME and EVENT TIME Numeric (Digital) Indicators on A4



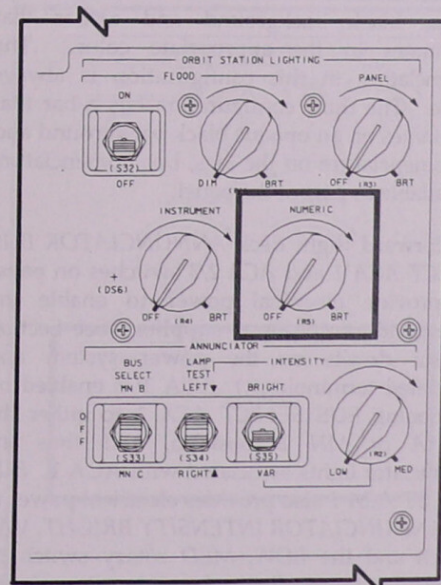
RCS/OMS PRPLT QTY and MISSION TIME Numeric (Digital) Indicators on panel O3



**RANGE/ELEVATION AND RANGE RATE/AZIMUTH
Numeric (Digital) Indicators on Panel A2**



**LIGHTING NUMERIC Rotary Switch on
Panel O8**



**ORBIT STATION LIGHTING NUMERIC
Rotary Switch on Panel A6U**

Annunciator Lights

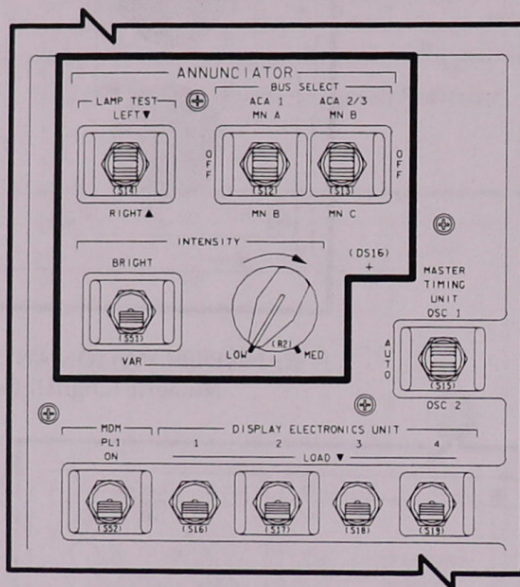
Annunciators are used to provide visual indications of vehicle and payload systems status. The annunciator lights are classified as emergency, warning, caution, and advisory. Emergency and warning annunciators are red, and cautions are yellow. Advisory annunciators may be white (status), green (normal configuration), yellow (alternate configuration), or blue (special applications).

Annunciator lighting is provided by incandescent lamps that illuminate the lens area of the annunciators. Most annunciators are driven by an annunciator control assembly, which controls the illumination of the lights during a "normal" or "test" input and also controls the brightness level. The caution and warning status lights on panel F7 and the *GPC STATUS* lights on panel O1 have separate electronic units for lighting control. Some annunciator lighting is provided by directly driven light emitting diodes (LEDs).

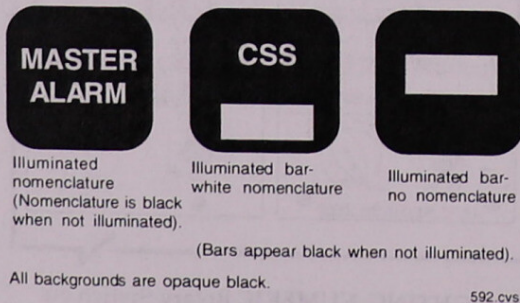
Three different lens configurations exist for the pushbutton indicators and indicator lights. One configuration has illuminated nomenclature in the appropriate color on an opaque black background. The nomenclature cannot be seen until it is illuminated. Another configuration has non-illuminated white nomenclature on an opaque black background and a bar that illuminates in the appropriate color. The nomenclature in this configuration is always visible. The third configuration has a bar that illuminates on an opaque black background and no nomenclature on the lens, but nomenclature is available as part of the panel.

The forward flight deck *ANNUNCIATOR BUS SELECT ACA 1* and *ACA 2/3* switches on panel O6 provide electrical power to enable the corresponding ac power supplies. (See Section 2.8 for details on the power system and associated terminology.) *ACA 1* is enabled by positioning *BUS SELECT ACA 1* to either the *MN A* or *MN B* position, and thus the annunciator lights associated with *ACA 1*. *BUS SELECT ACA 1* also provides electrical power to the *ANNUNCIATOR INTENSITY BRIGHT, VAR* switch and the *LOW, MED* rotary switch on panel O6, controlling the intensity of the annunciator lights associated with *ACA 1*. *ACAs 2 and 3* are enabled by positioning the

BUS SELECT ACA 2/3 switch to either the *MN B* or *MN C* position, and thus the annunciator lights associated with *ACAs 2 and 3*. *BUS SELECT ACA 2/3* also provides electrical power to the annunciator light *INTENSITY BRIGHT, VAR* switch on panel O6 and the *LOW, MED* rotary control on panel O6, thus controlling the intensity of the annunciator lights associated with *ACAs 2 and 3*. The *OFF* position of the *BUS SELECT ACA 1* switch removes power from *ACA 1*, disabling the annunciator lights associated with it. The *OFF* position of the *BUS SELECT ACA 2/3* switch removes power from *ACAs 2 and 3*, disabling the annunciator lights associated with them.



ANNUNCIATOR Lighting Controls on Panel O6



Typical Annunciator Configurations

592.cvs

The *ANNUNCIATOR INTENSITY* switch on panel O6 positioned to *BRIGHT* bypasses the *INTENSITY LOW, MED* rotary control. The *ANNUNCIATOR INTENSITY* switch positioned to *VAR* permits the *INTENSITY LOW, MED* rotary control to control annunciator light intensity.

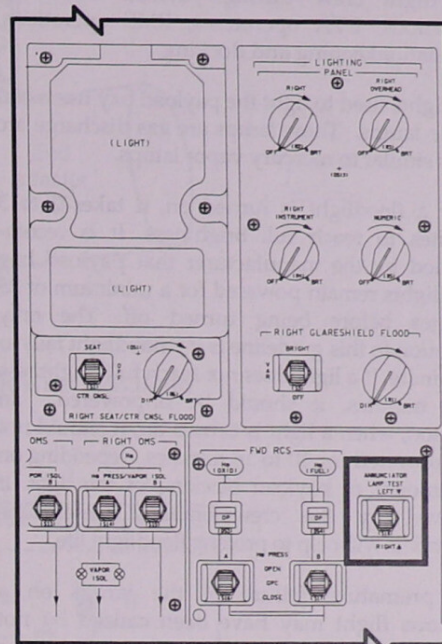
The *ANNUNCIATOR LAMP TEST* switch on panel O6 or O8 positioned to *LEFT* applies power to the ACA 1, 2, and 3 annunciator lamp test circuits, illuminating annunciator lights on panels F2 (*MASTER ALARM*), F6, L1 (*SMOKE DETECTION*), O1 (*GPC STATUS*), and M029], the left 20 C/W lights on panel F7, and the *SM ALERT* on panel F7. Positioning the *LAMP TEST* switches to *RIGHT* applies power to the ACA 1, 2, and 3 annunciator lamp test circuits, illuminating the annunciator lights on panels C3, F4 (*MASTER ALARM*), F8, and M052] (*MASTER ALARM*), the right 20 C/W lights on panel F7, and the *MAIN ENGINE STATUS* lights on panel F7.

The aft flight deck *ANNUNCIATOR BUS SELECT* switch on panel A6U provides electrical power to enable ACAs 4 and 5. ACAs 4 and 5 are enabled by positioning *BUS SELECT* to either the *MN B* or *MN C* position, and thus the annunciator lights associated with ACAs 4 and 5. The *BUS SELECT* switch also provides electrical power to the annunciator light *INTENSITY BRIGHT, VAR* switch and the *LOW, MED* rotary control on panel A6U, thus controlling annunciator light intensity associated with ACAs 4 and 5. The *OFF* position of the *BUS SELECT* switch removes power from ACAs 4 and 5, disabling the annunciator lights associated with them.

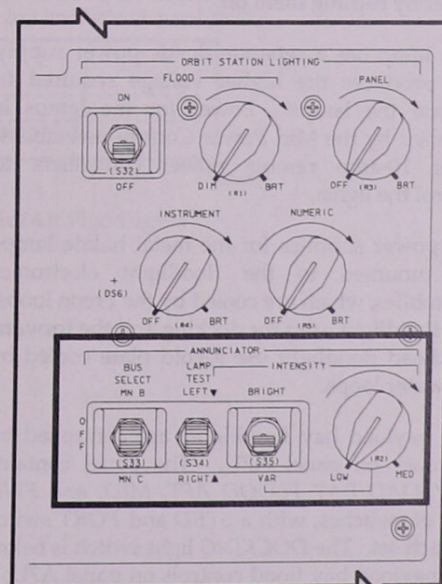
The *ANNUNCIATOR INTENSITY* switch on panel A6U, when positioned to *BRIGHT*, bypasses the *INTENSITY LOW, MED* rotary control on panel A6U. Positioned to *VAR*, it permits the *INTENSITY LOW, MED* rotary control to vary annunciator light intensity.

The *ANNUNCIATOR LAMP TEST* switch on panel A6U, when positioned to *LEFT*, applies power to the ACA 4 and 5 annunciator lamp test circuits, illuminating the annunciator lights on panels A2 and A6U, the *VIDEO INPUT* pushbuttons on panel A7U, and columns 0 through 4 on panel R13U. Positioning the switch to *RIGHT* applies power to the ACA 4 and 5 annunciator lamp test circuits, illuminating the annunciator lights (*MASTER ALARM*)

and *VIDEO OUTPUT* and *ALC/GAMMA* pushbuttons on panel A7U and columns 5 through 9 on panel R13U.



ANNUNCIATOR LAMP TEST Switch
on Panel O8



ANNUNCIATOR Lighting Controls
on Panel A6U

Exterior Lighting

The exterior floodlights improve visibility for the flight crew during payload bay door operations, EVA operations, RMS operations, and stationkeeping and docking.

The lights used to light the payload bay use metal halide lamps. These lamps are gas discharge arc tubes similar to mercury vapor lamps.

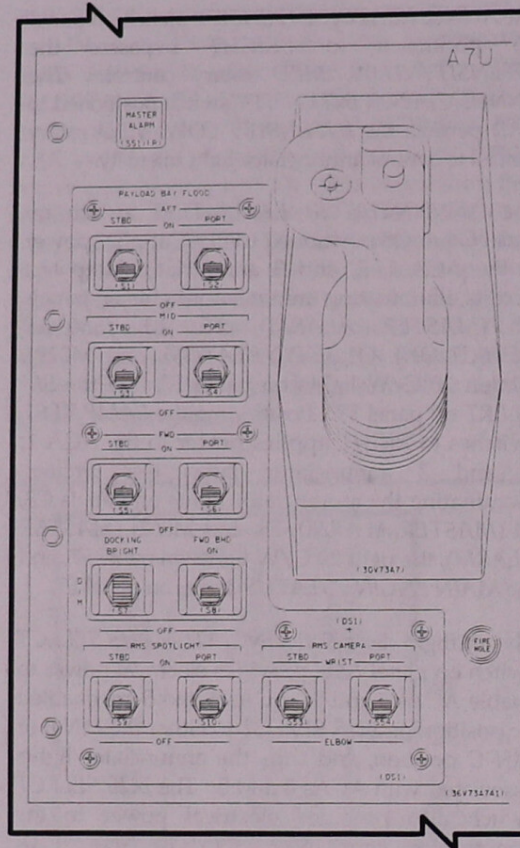
After a floodlight is turned on, it takes 2 to 3 minutes to reach full brightness. It is recommended by the manufacturer that payload bay floodlights remain powered for a minimum of 25 minutes before being turned off. The only exception to this guideline is if a floodlight fails to illuminate. If a light does not reach full brightness in 5 minutes, it should be unpowered. In addition, when a light is turned off, it should not be repowered for 10 to 16 minutes, depending on the amount of payload blocking of the light. If followed by the crewmembers, these time constraints will help to prolong floodlight life.

The premature failure of the lamps on a previous flight may have been caused by not waiting the required time before repowering the lamps. It is better to leave the lamps powered until the task is finished than to try to save power by turning them off.

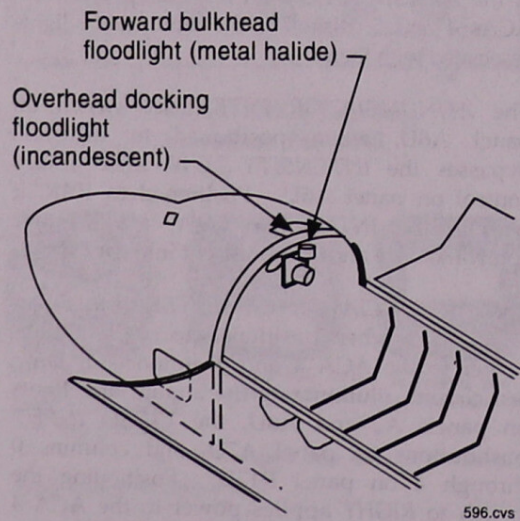
Each lamp has a separate dc/dc power supply that produces the higher voltage required to operate the lamps. Power for the lamps is supplied by the Mid Power Control assemblies, using 10-amp remote power controllers to control the lights.

The power supplies for the metal halide lamps are mounted to the floodlight electronics assemblies, which are cooled by the Freon loops. The floodlight used for docking and the forward bulkhead floodlight use a cold plate cooled by the water loops.

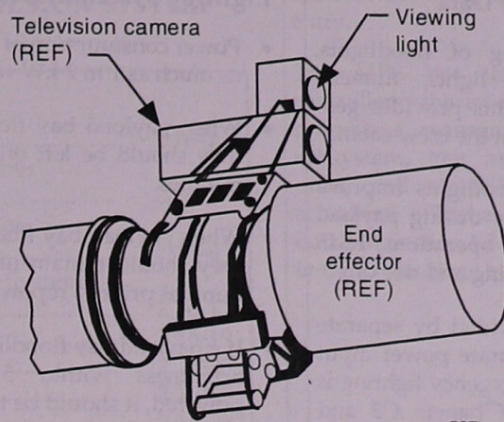
The payload bay floodlights are controlled by switches on panel A7U. The panel contains *PAYLOAD BAY FLOOD AFT*, *MID*, and *FWD* sets of switches, with a *STBD* and *PORT* switch in each set. The *DOCKING* light switch is below the payload bay flood controls on panel A7U; it has *BRIGHT*, *DIM*, and *OFF* settings. The RMS floodlight is controlled by *RMS SPOTLIGHT STBD* and *PORT* switches on panel A7U.



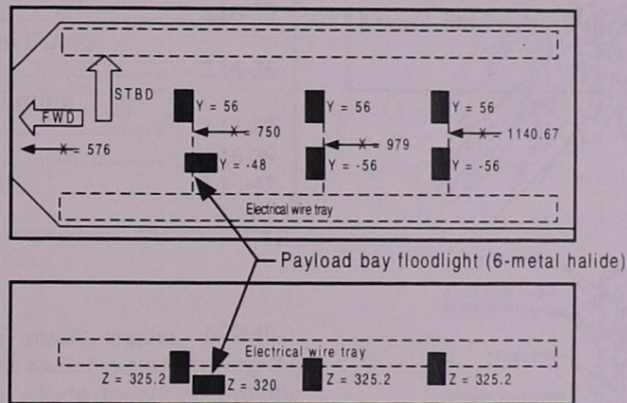
PAYLOAD BAY FLOOD, DOCKING, and RMS Lighting Controls on Panel A7U



Bulkhead Floodlights



Remote Manipulator System Wrist Floodlight



Payload Bay Forward/Mid/Aft Floodlights

Lighting System Summary Data

- Interior lighting consisting of floodlights, panel lights, instrument lights, numeric lights, and annunciator lights provides general illumination throughout the crew cabin.
- Exterior floodlights and spotlights improve visibility for the flight crew during payload bay door operations, EVA operations, RMS operations, and stationkeeping and docking.
- Emergency lighting is provided by separate fixtures powered by a separate power input from an essential bus. Emergency lighting is controlled by switches on panels C3 and ML18F.
- Switches controlling the lighting system are distributed over panels R10, L9, O8, A6U, A7U, MO13Q, ML18F, AW18A, and O6.
- Lighting system circuit breakers are located on panel L4.

Lighting System Rules of Thumb

- Power consumption of cockpit lighting can be as much as 1 to 2 kW with all lights on.
- When payload bay floodlights are powered, they should be left on for a minimum of 25 minutes.
- When payload bay floodlights are turned off, they should remain unpowered for 10 to 16 minutes prior to repowering.
- If a payload bay floodlight does not reach full brightness within 5 minutes of being powered, it should be turned off.

2.16 MAIN PROPULSION SYSTEM (MPS)

CONTENTS

Description	2.16-1
Space Shuttle Main Engines (SSMEs)	2.16-3
Space Shuttle Main Engine Controllers	2.16-8
Propellant Management System (PMS)	2.16-13
Helium System	2.16-19
MPS Hydraulic Systems	2.16-23
Malfunction Detection	2.16-25
Operations	2.16-28
Post Insertion	2.16-34
Orbit	2.16-35
Deorbit Prep	2.16-35
Entry	2.16-35
RTLS Abort Propellant Dump Sequence	2.16-35
TAL Abort Propellant Dump Sequence	2.16-36
MPS Caution and Warning Summary	2.16-37
MPS Summary Data	2.16-39
MPS Rules of Thumb	2.16-42

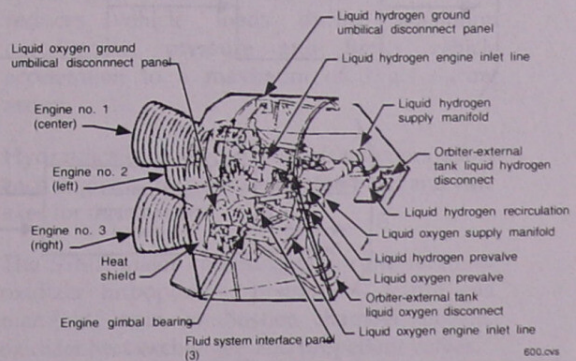
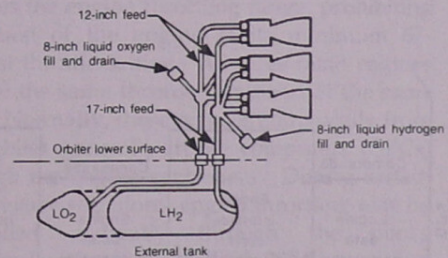
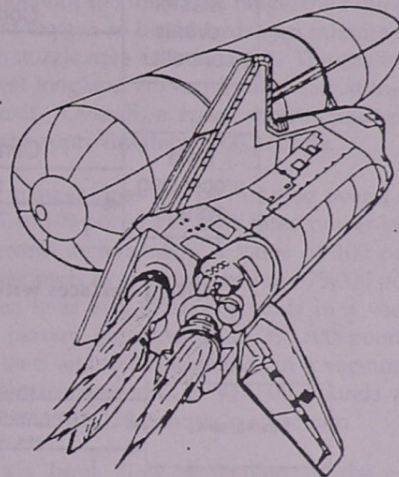
Description

The space shuttle main engines (SSMEs), assisted by two solid rocket motors during the initial phases of the ascent trajectory, provide vehicle acceleration from lift-off to main engine cutoff (MECO) at a predetermined velocity.

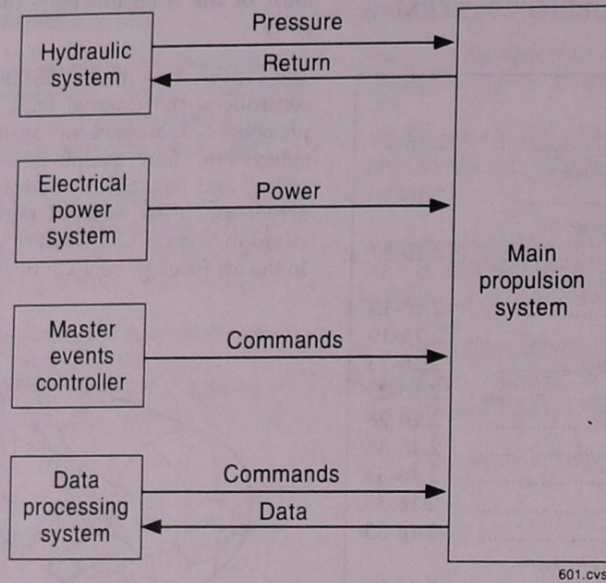
The MPS has critical interfaces with the orbiter hydraulic system, electrical power system, master events controller, and data processing system. The hydraulic system supplies hydraulic pressure to operate the main engine valves and gimbal actuators. The electrical power system furnishes ac power to operate the main engine controllers and dc power to operate the valves and transducers in the propellant management and helium systems. The master events controller initiates firings of pyrotechnic devices for separating the SRBs from the external tank and the external tank from the orbiter. The data processing system controls

most of the MPS functions during ascent and entry.

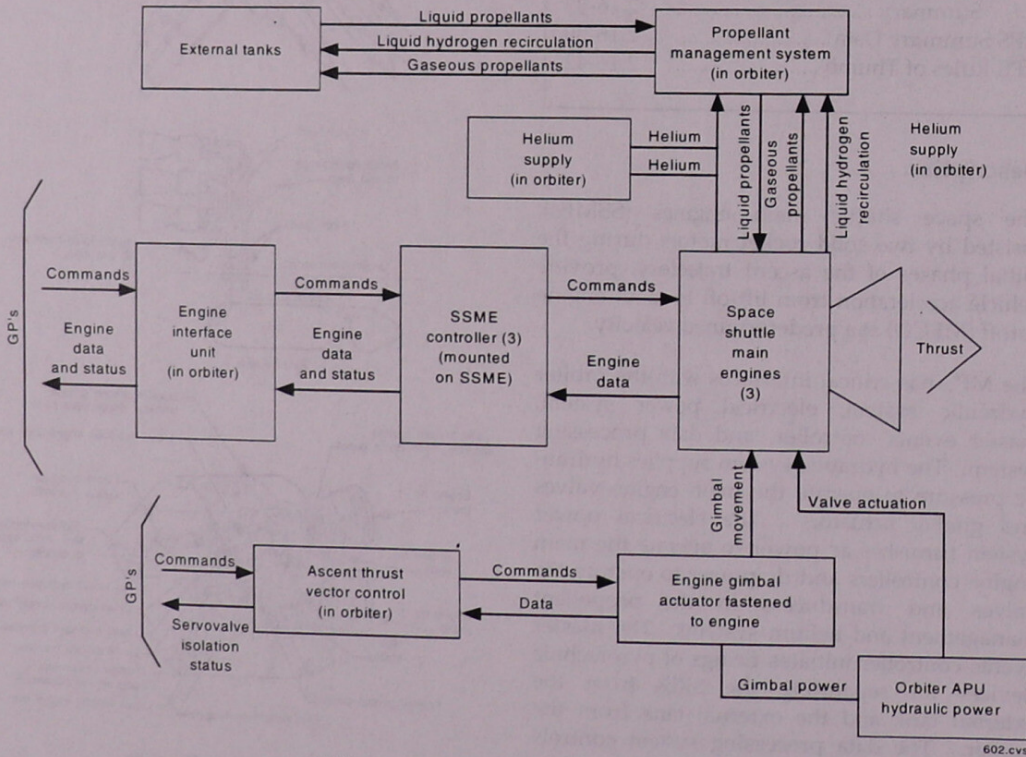
The MPS has three SSMEs, three SSME controllers, the external tank, the orbiter MPS propellant management system and helium subsystem, four ascent thrust vector control units, and six SSME hydraulic TVC servo-actuators. (The external tank is described in detail in Section 1.3.) Most of the MPS is located in the aft fuselage beneath the vertical stabilizer.



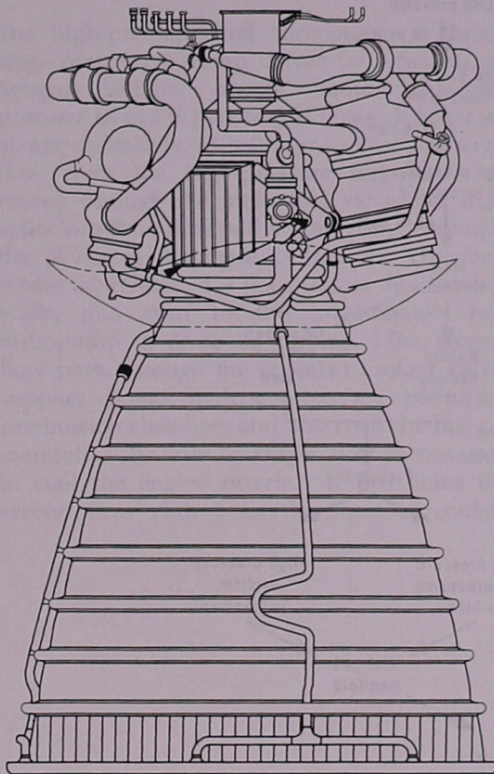
Main Propulsion System



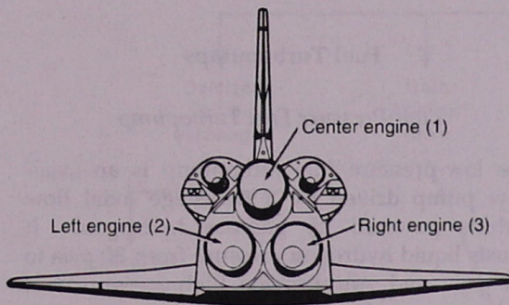
Critical Interfaces with the Main Propulsion System



Main Propulsion System Subsystem



Space Shuttle Main Engine



Main Engine Numbering System

Space Shuttle Main Engines (SSMEs)

The three SSMEs are reusable, high-performance, liquid propellant rocket engines with variable thrust. The engines use liquid hydrogen for fuel and cooling and liquid oxygen as an oxidizer. The propellant is carried in separate tanks within the external tank and is supplied to

the main engines under pressure. Using a staged combustion cycle, the propellants are partially burned at high pressure and relatively low temperature in two preburners, then completely burned at high pressure and high temperature in the main combustion chamber.

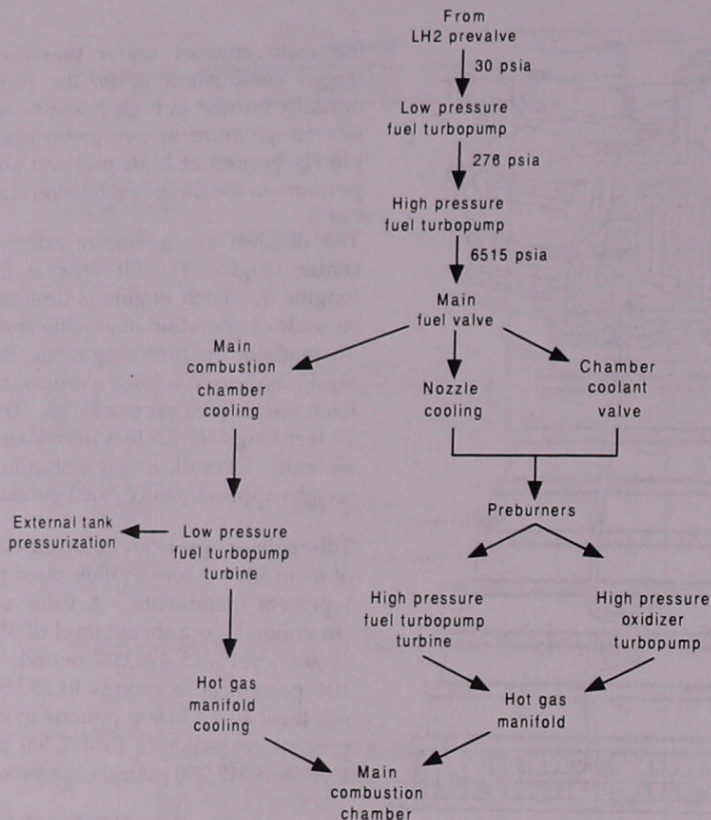
The engines are generally referred to as the center (engine 1), left (engine 2), and right (engine 3). Each engine is designed for 15,000 seconds of operation over a life span of 30 starts. Throughout the throttling range, the ratio of the liquid oxygen to liquid hydrogen mixture is 6:1. Each nozzle area ratio is 77.5:1. The engines are 14 feet long and 7.5 feet in diameter at the nozzle exit. Overall, a space shuttle main engine weighs approximately 7,000 pounds.

The main engines can be throttled over a range of 67 to 109 percent of their rated power level in 1-percent increments. A value of 100 percent corresponds to a thrust level of 375,000 pounds at sea level and 470,000 pounds in a vacuum; 104 percent corresponds to 393,800 pounds at sea level and 488,800 pounds in a vacuum; 109 percent corresponds to 417,300 pounds at sea level and 513,250 pounds in a vacuum.

At sea level, flow separation in the nozzle reduces the engine throttling range, prohibiting operation of the engine at its minimum 67-percent throttle setting. All three main engines receive the same throttle command at the same time. Normally, these come automatically from the orbiter general-purpose computers (GPCs) through the engine controllers. During certain contingency situations, engine throttling may be controlled manually through the pilot's speedbrake/thrust controller. SSME throttling reduces vehicle loads during maximum aerodynamic pressure and limits vehicle acceleration to a maximum of 3 g's during ascent.

Hydraulically powered gimbal actuators allow each engine to be gimballed in the pitch and yaw axes for thrust vector control.

The SSME major components are the fuel and oxidizer turbopumps, preburners, a hot gas manifold, main combustion chamber, nozzle, oxidizer heat exchanger, and propellant valves.



605.cvs

Main Engine Fuel Flow

Block IIA and Block II SSMEs

The Block IIA is currently flying. It first flew on STS-89 in 1997.

The modifications to the Block IIA SSMEs are designed to improve the safety and reliability of the engine. The modifications to the Block IIA SSME include a new high-pressure oxidizer turbopump (HPOT), a two-duct powerhead, and a single coil heat exchanger.

Design and testing are also underway on the Block II SSME. The Block II engine will incorporate all of the improvements of the Block IIA engine, plus a new high-pressure fuel turbopump (HPFT). The first flight of the Block II SSME is scheduled for 2001.

Fuel Turbopumps

Low-Pressure Fuel Turbopump

The low-pressure fuel turbopump is an axial-flow pump driven by a two-stage axial flow turbine powered by gaseous hydrogen. It boosts liquid hydrogen pressure from 30 psia to 276 psia and supplies the high-pressure fuel turbopump. During engine operation, this pressure increase allows the high-pressure fuel turbopump to operate at high speeds without cavitating. The low-pressure fuel turbopump operates at approximately 16,185 rpm, measures approximately 18 by 24 inches, and is flange-mounted to the SSME at the inlet to the low-pressure fuel duct.

High-Pressure Fuel Turbopump

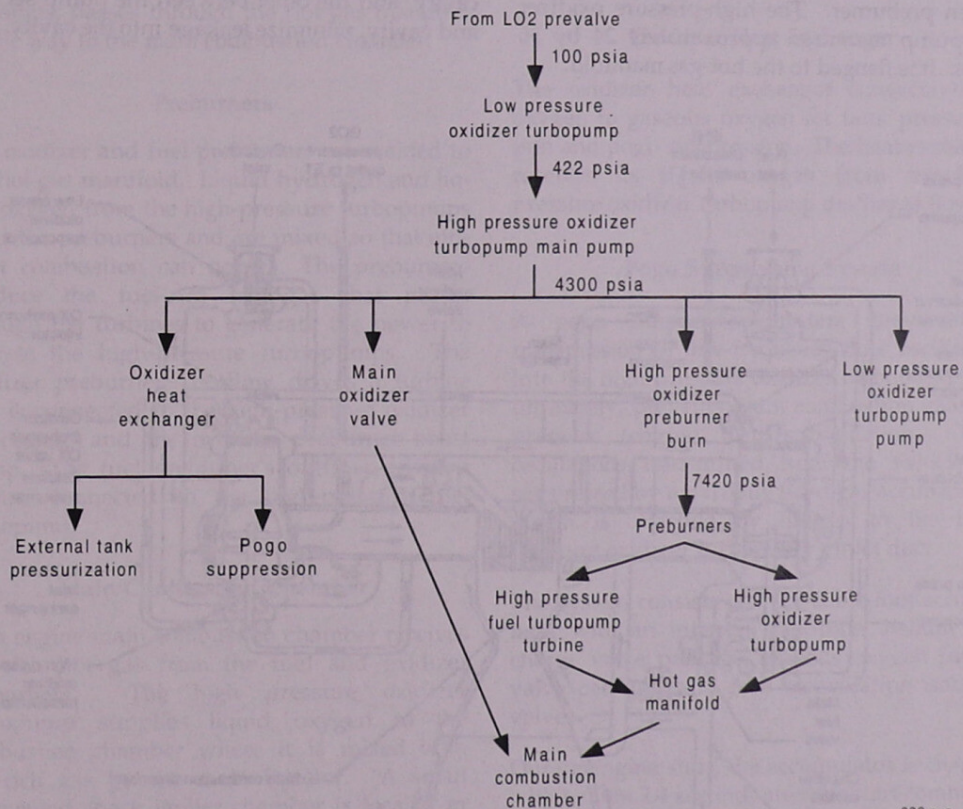
The high-pressure fuel turbopump, a three-stage centrifugal pump driven by a two-stage, hot-gas turbine, boosts liquid hydrogen pressure from 276 psia to 6,515 psia. It operates at approximately 35,360 rpm. The discharge flow from the high-pressure turbopump is routed through the main fuel valve and then splits into three flow paths. One path is through the jacket of the main combustion chamber, where the hydrogen is used to cool the chamber walls, and then to the low-pressure fuel turbopump to drive its turbine. The second flow path, through the chamber coolant valve, supplies liquid hydrogen to the preburner combustion chambers and also cools the hot gas manifold. The third hydrogen flow path is used to cool the engine nozzle. It then joins the second flow path from the chamber coolant

valve. The high-pressure fuel turbopump is approximately 22 by 44 inches and is flanged to the hot-gas manifold.

Oxidizer Turbopumps

Low-Pressure Oxidizer Turbopump

The low-pressure oxidizer turbopump is an axial-flow pump driven by a six-stage turbine powered by liquid oxygen. It boosts the liquid oxygen pressure from 100 psia to 422 psia. The flow is supplied to the high-pressure oxidizer turbopump to permit it to operate at high speeds without cavitating. The low-pressure oxidizer turbopump operates at approximately 5,150 rpm, measures approximately 18 by 18 inches, and is flange-mounted to the orbiter propellant ducting.



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Main Engine Oxidizer Flow

High-Pressure Oxidizer Turbopump

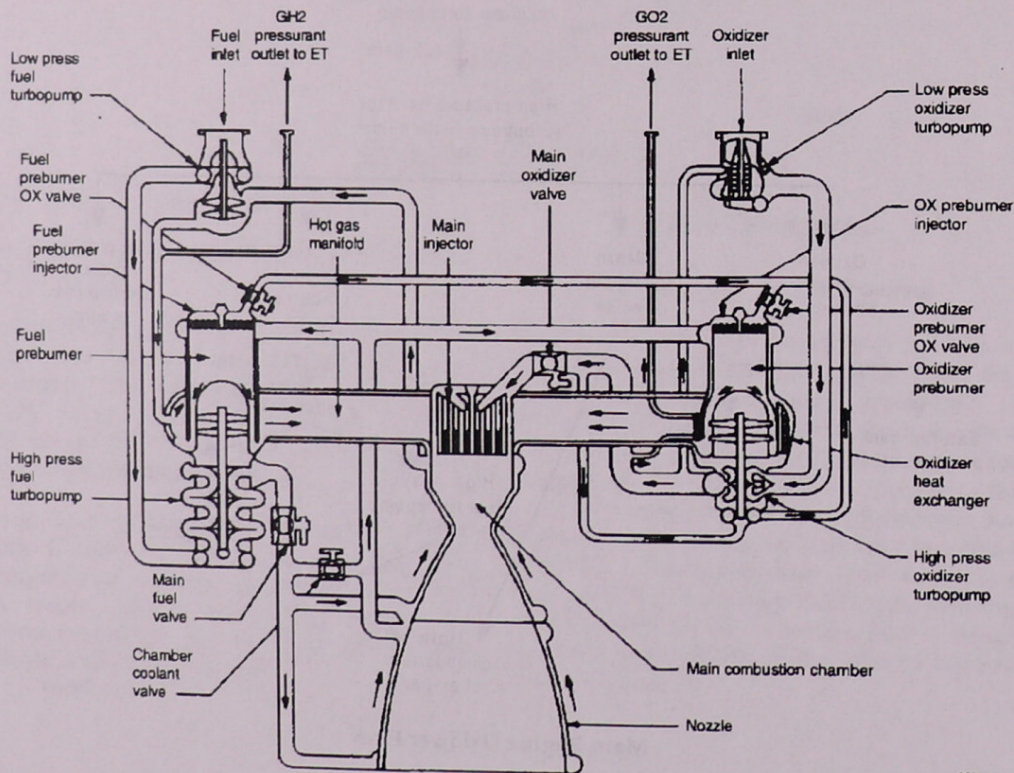
The high-pressure oxidizer turbopump consists of two single-stage centrifugal pumps (a main pump and a preburner pump) mounted on a common shaft and driven by a two-stage, hot-gas turbine. The main pump boosts liquid oxygen pressure from 422 psia to 4,300 psia while operating at approximately 28,120 rpm. The high-pressure oxidizer turbopump discharge flow splits into several paths, one of which is routed to drive the low-pressure oxidizer turbopump turbine. Another path is routed through the main oxidizer valve and enters the main combustion chamber. Another small flow path is tapped off and sent to the oxidizer heat exchanger, where it is vaporized and then used to pressurize the external tank. The final path enters the preburner boost pump to raise the liquid oxygen's pressure from 4,300 psia to 7,420 psia at the inlet to the liquid oxygen preburner. The high-pressure oxidizer turbopump measures approximately 24 by 36 inches. It is flanged to the hot-gas manifold.

Bellows

The low-pressure oxygen and low-pressure fuel turbopumps are mounted 180° apart on the engine. The lines from the low-pressure turbopumps to the high-pressure turbopumps contain flexible bellows that enable them to flex when loads are applied. This prevents them from cracking during engine operations.

Helium Purge

Because the high-pressure oxidizer turbopump turbine and pumps are mounted on a common shaft, mixing the fuel-rich hot gas in the turbine section and the liquid oxygen in the main pump could create a hazard. To prevent this, the two sections are separated by a cavity that is continuously purged by the MPS engine helium supply during engine operation. Two seals, one located between the turbine section and the cavity, and the other between the pump section and cavity, minimize leakage into the cavity.



Main Engine Schematic

607.cvs

WARNING

Depletion of the MPS helium supply or closure of both MPS isolation valves will cause loss of helium pressure in the cavity separating the fuel-rich hot gas and the liquid oxygen in the main pump. This condition results in an automatic engine shutdown if limits are enabled. If limits are inhibited, leakage through one or both of the seals and mixing of the propellants could result in uncontained engine damage when helium pressure is lost.

Hot Gas Manifold

The hot-gas manifold is the structural backbone of the engine. It supports the two preburners, the high-pressure turbopumps, and the main combustion chamber. Hot gas generated by the preburners, after driving the high-pressure turbopumps, passes through the hot-gas manifold on the way to the main combustion chamber.

Preburners

The oxidizer and fuel preburners are welded to the hot-gas manifold. Liquid hydrogen and liquid oxygen from the high-pressure turbopumps enter the preburners and are mixed so that efficient combustion can occur. The preburners produce the fuel-rich hot gas that passes through the turbines to generate the power to operate the high-pressure turbopumps. The oxidizer preburner's outflow drives a turbine that is connected to the high-pressure oxidizer turbopump and the oxidizer preburner boost pump. The fuel preburner's outflow drives a turbine connected to the high-pressure fuel turbopump.

Main Combustion Chamber

Each engine main combustion chamber receives fuel-rich hot gas from the fuel and oxidizer preburners. The high pressure oxidizer turbopump supplies liquid oxygen to the combustion chamber where it is mixed with fuel-rich gas by the main injector. A small augmented spark igniter chamber is located in the center of the injector. The dual-redundant igniter is used during the engine start sequence to initiate combustion. The igniters are turned off after approximately 3 seconds because the

combustion process is self-sustaining. The main injector and dome assembly are welded to the hot-gas manifold. The main combustion chamber is bolted to the hot-gas manifold. The combustion chamber, as well as the nozzle, is cooled by gaseous hydrogen flowing through coolant passages.

The nozzle assembly is bolted to the main combustion chamber. The nozzle is 113 inches long, with an exit plane of 94 inches. The physical dimension of the nozzle creates a 77.5:1 expansion ratio. A support ring welded to the forward end of the nozzle is the engine attach point to the engine heat shield. Thermal protection is provided for the nozzles to protect them from the high heating rates experienced during the launch, ascent, on-orbit, and entry phases. The insulation consists of four layers of metallic batting covered with a metallic foil and screening.

Oxidizer Heat Exchanger

The oxidizer heat exchanger converts liquid oxygen to gaseous oxygen for tank pressurization and pogo suppression. The heat exchanger receives its liquid oxygen from the high-pressure oxidizer turbopump discharge flow.

Pogo Suppression System

A pogo suppression system prevents the transmission of low-frequency flow oscillations into the high-pressure oxidizer turbopump and, ultimately, prevents main combustion chamber pressure (engine thrust) oscillation. Flow oscillations transmitted from the vehicle are suppressed by a partially filled gas accumulator, which is attached by flanges to the high-pressure oxidizer turbopump's inlet duct.

The system consists of a 0.6-cubic-foot accumulator with an internal standpipe, helium pre-charge valve package, gaseous oxygen supply valve package, and four recirculation isolation valves.

During engine start, the accumulator is charged with helium 2.4 seconds after the start command to provide pogo protection until the engine heat exchanger is operational, and gaseous oxygen is available. The accumulator is partially chilled by liquid oxygen during the engine chill-down

operation. It fills to the overflow standpipe line inlet level, which is sufficient to preclude gas ingestion at engine start. During engine operation, the accumulator is charged with a continuous gaseous oxygen flow.

The liquid level in the accumulator is controlled by an internal overflow standpipe, which is orificed to regulate the gaseous oxygen overflow at varying engine power levels. The system is sized to provide sufficient supply of gaseous oxygen at the minimum flow rate and to permit sufficient gaseous oxygen overflow at the maximum pressure transient in the low-pressure oxidizer turbopump discharge duct. Under all other conditions, excess gaseous and liquid oxygen are recirculated to the low-pressure oxidizer turbopump inlet through the engine oxidizer bleed duct. The pogo accumulator is also pressurized at engine shutdown to provide a positive pressure at the high-pressure oxidizer turbopump inlet. The post-charge prevents turbine overspeed in the zero-gravity environment.

CAUTION

Insufficient helium supply for engine shutdown could result in engine damage during shutdown. A pre-MECO manual shutdown may be required if a leak develops in the helium system.

Valves

Each engine has five propellant valves (oxidizer preburner oxidizer, fuel preburner oxidizer, main oxidizer, main fuel, and chamber coolant) that are hydraulically actuated and controlled by electrical signals from the engine controller. They can be fully closed by using the MPS engine helium supply system as a backup actuation system.

High-pressure oxidizer turbopump and high-pressure fuel turbopump turbine speed depends on the position of the oxidizer and fuel preburner oxidizer valves. The engine controller uses the preburner oxidizer valves to control engine thrust by regulating the flow of liquid oxygen to the preburners. The oxidizer and fuel preburner oxidizer valves increase or decrease the liquid oxygen flow into the preburner, thereby increasing or decreasing

preburner chamber pressure and high-pressure oxidizer turbopump and high-pressure fuel turbopump turbine speed. This directly affects liquid oxygen and gaseous hydrogen flow into the main combustion chamber, which in turn can increase or decrease engine thrust. The fuel preburner oxidizer valve is used to maintain a constant 6:1 propellant mixture ratio.

The main oxidizer valve controls liquid oxygen flow into the engine combustion chamber. The main fuel valve controls the total liquid hydrogen flow into the engine cooling circuit, the preburner supply lines, and the low-pressure fuel turbopump turbine. When the engine is operating, the main valves are fully open.

A chamber coolant valve on each engine combustion chamber coolant bypass duct regulates the amount of gaseous hydrogen allowed to bypass the nozzle coolant loop to control engine temperature. The chamber coolant valve is 100 percent open before engine start, and at power levels between 100 and 109 percent. For power levels between 67 and 100 percent, the valve's position will range from 68.3 to 100 percent open.

Propellant Dump

The main oxidizer valve is opened to allow residual liquid oxygen to be dumped overboard through the engine nozzle after engine shutdown. Both liquid hydrogen fill/drain valves, as well as the fuel bleed valve, are opened after engine shutdown to allow residual liquid hydrogen to drain overboard.

Space Shuttle Main Engine Controllers

The controller is a pressurized, thermally conditioned electronics package attached to the thrust chamber and nozzle coolant outlet manifolds on the low-pressure fuel turbopump side of the engine. Each controller contains two redundant digital computer units, referred to as units A and B. Normally, A is in control, and unit B electronics are active, but not in control. Instructions to the engine control elements are updated 50 times per second (every 20 milliseconds). Engine reliability is enhanced by a dual-redundant system that allows normal digital computer unit operation after the first

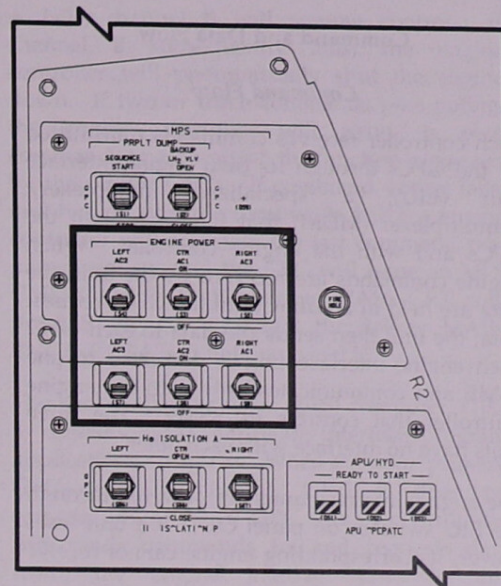
failure and a fail-safe shutdown after a second failure. High-reliability electronic parts are used throughout the controller. The digital computer is programmable, allowing engine control equations and constants to be modified by changing the software.

The controller is packaged in a sealed, pressurized chassis and is cooled by convection heat transfer through pin fins as part of the main chassis. The electronics are distributed on functional modules with special thermal and vibration protection.

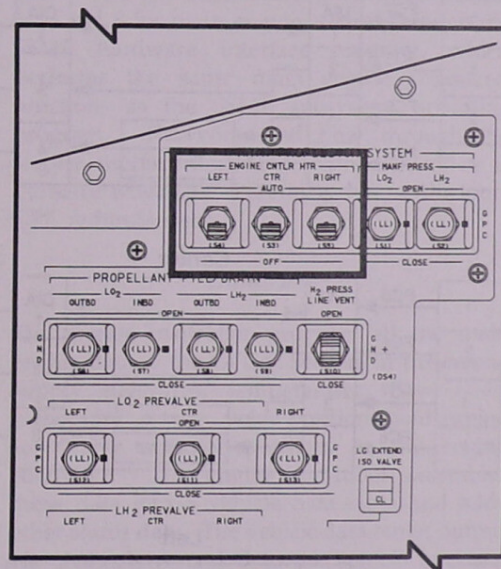
Operating in conjunction with engine sensors, valves, actuators, and spark igniters, the controllers form a self-contained system for engine control, checkout, and monitoring. The controller provides engine flight readiness verification, engine start and shutdown sequencing, closed-loop thrust and propellant mixture ratio control, sensor excitation, valve actuator and spark igniter control signals, engine performance limit monitoring, and performance and maintenance data. The controller also provides onboard engine checkout, response to vehicle commands, and transmission of engine status.

Controller power is supplied by the three ac buses in a manner that protects their redundancy. Each computer unit within a controller receives its power from a different bus. The buses are distributed among the three controllers such that the loss of any two buses will result in the loss of only one engine. The digital computer units require all three phases of an ac bus to operate. There are two MPS ENGINE POWER switches on panel R2 for each engine controller (LEFT, CTR, RIGHT); the top switch is for digital computer unit A, and the bottom switch is for digital computer unit B. Cycling an MPS ENGINE POWER switch to OFF and back to ON will cause the affected digital computer unit to stop processing.

The MAIN PROPULSION SYSTEM ENGINE CNTLR HTR LEFT, CTR, RIGHT switches on panel R4 are non-functional. The heaters were not installed in Block II controllers due to analysis that showed the Block I heaters were not required.



MPS ENGINE POWER Switches on Panel R2



MAIN PROPULSION SYSTEM ENGINE CNTLR HTR Switches on Panel R4

Command and Data Flow

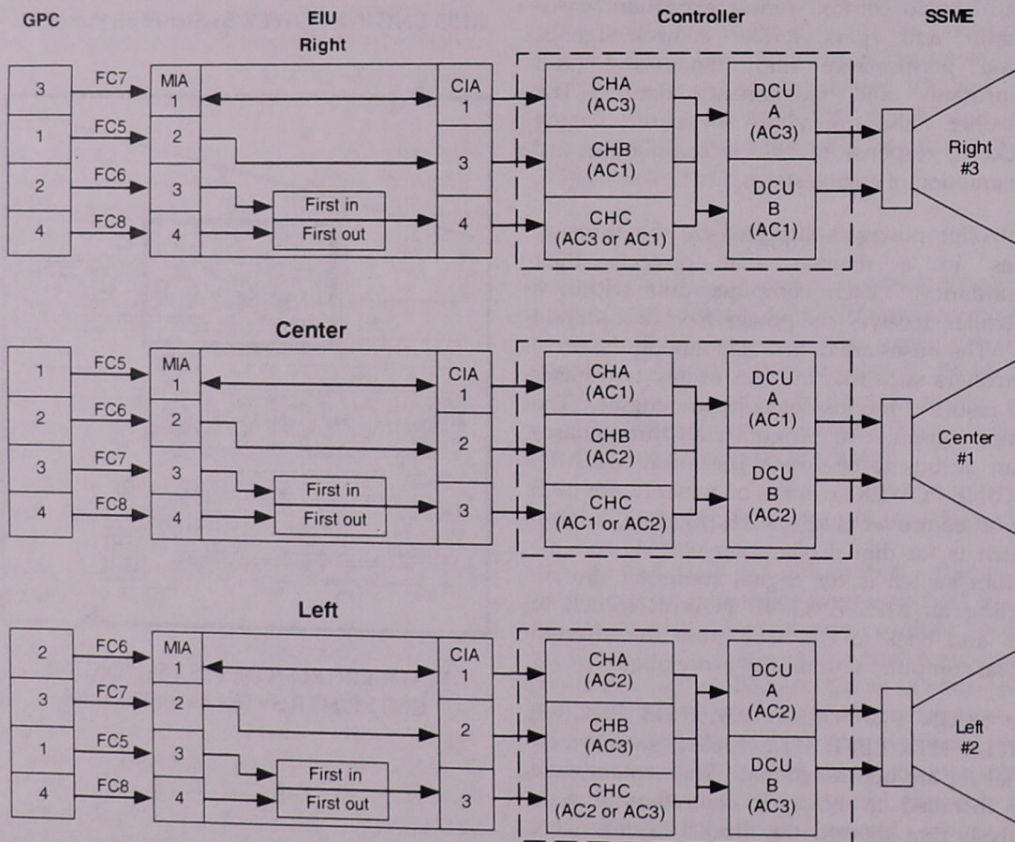
Command Flow

Each controller receives commands transmitted by the GPCs through its own engine interface unit (EIU), a specialized multiplexer/demultiplexer (MDM) that interfaces with the GPCs and with the engine controller. When engine commands are received by the unit, the data are held in a buffer until the GPCs request data; the unit then sends the data to each GPC. Each engine interface unit is dedicated to one SSME and communicates only with the engine controller that controls its SSME. The three units have no interface with each other.

The engine interface units are powered through the EIU switches on panel O17. If a unit loses power, its corresponding engine cannot receive

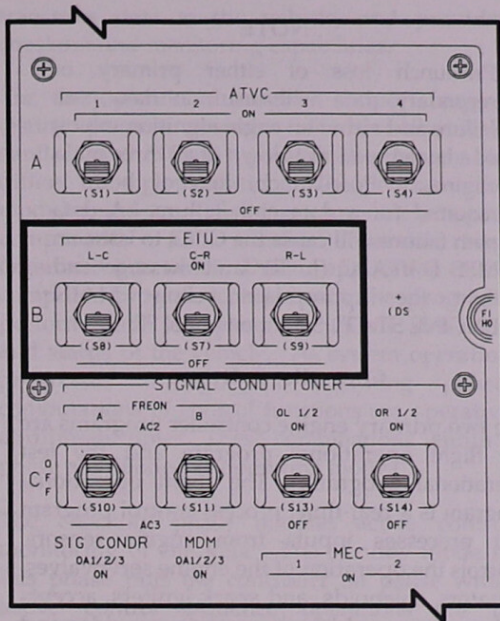
any throttle, shut down, or dump commands, and will not be able to communicate with the GPCs. As a result, the controller will maintain the last valid command until it is shut down manually via the MPS ENGINE POWER switches on panel R2.

Each orbiter GPC, operating in a redundant set, issues engine commands from resident SSME subsystem operating programs to the EIUs for transmission to their corresponding engine controllers. Engine commands are output over the GPC's assigned flight-critical data bus (a total of four GPCs outputting over four flight-critical data buses). Therefore, each EIU will receive four commands. The nominal ascent configuration has GPCs 1, 2, 3, and 4 outputting on flight-critical data buses 5, 6, 7, and 8, respectively. Each data bus is connected to one multiplexer interface adapter in each EIU.



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Main Engine Command Flow



EIU Switches on Panel O17

The EIU checks the received engine commands for transmission errors. If there are none, the EIU passes the validated engine commands on to the controller interface assemblies, which output the validated engine commands to the engine controller. An engine command that does not pass validation is not sent to the controller interface assembly. Instead, it is dead-ended in the multiplexer interface adapter. Commands that come through multiplex interface adapters 1 and 2 are sent to controller interface assemblies 1 and 2 respectively. Commands that come to multiplex interface adapters 3 and 4 pass through controller interface assembly 3 data-select logic. This logic outputs the command that arrives at the interface first. The other command is dead-ended. The selected command is output through controller interface assembly 3. In this manner, the EIU reduces the four input commands to three output commands.

The engine controller vehicle interface electronics receive the three engine commands, check for transmission errors (hardware validation), and send controller hardware-validated engine commands to the controller channel A and B electronics. Normally, channel A electronics are in control, with channel B electronics active, but not in control. If channel

A fails, channel B will assume control. If channel B subsequently fails, the engine controller will pneumatically shut the engine down. If two or three commands pass voting, the engine controller will issue its own commands to accomplish the function requested by the orbiter GPCs. If command voting fails, and two or all three commands fail, the engine controller will maintain the last command that passed voting, and the GPC will issue an MPS CMD C (L, R) fault message (PASS CRT only pre-BFS engage) and light the yellow MAIN ENGINE STATUS light on panel F7.

The backup flight system (BFS) computer, GPC 5, contains SSME hardware interface program applications software. When the four primary GPCs are in control, GPC 5 does no commanding. When GPC 5 is in control, the BFS sends commands to, and requests data from, the engine interface unit; in this configuration, the four primary GPCs neither command nor listen. The BFS, when engaged, allows GPC 5 to command flight-critical buses 5, 6, 7, and 8 for main engine control through the SSME hardware interface program, which performs the same main engine command functions as the SSME subsystem operating program. The command flow through the engine interface units and engine controllers is the same when GPC 5 is engaged as for the four-GPC redundant set.

Data Flow

The engine controller provides all the main engine data to the GPCs. Sensors in the engine supply pressures, temperatures, flow rates, turbopump speeds, valve positions, and engine servovalve actuator positions to the engine controller. The engine controller assembles these data into a vehicle data table and adds other status data. The vehicle data tables output via channels A and B to the vehicle interface electronics for transmission to the engine interface units. The vehicle interface electronics output data over both the primary and secondary data paths.

The vehicle data table is sent by the controller to the engine interface unit. There are only two data paths versus three command paths between the engine controller and the engine interface unit. The data path that interfaces

with controller interface assembly 1 is called primary data. Primary data consist of the first 32 words of the SSME vehicle data table. Secondary data is the path that interfaces with controller interface assembly 2. Secondary data consist of the first six words of the vehicle data table. Primary and secondary data are held in buffers until the GPCs send a primary and secondary data request command to the engine interface units. Primary data are output only through multiplex interface adapter 1 on each engine interface unit. Secondary data are output only through multiplex interface adapter 4 on each engine interface unit.

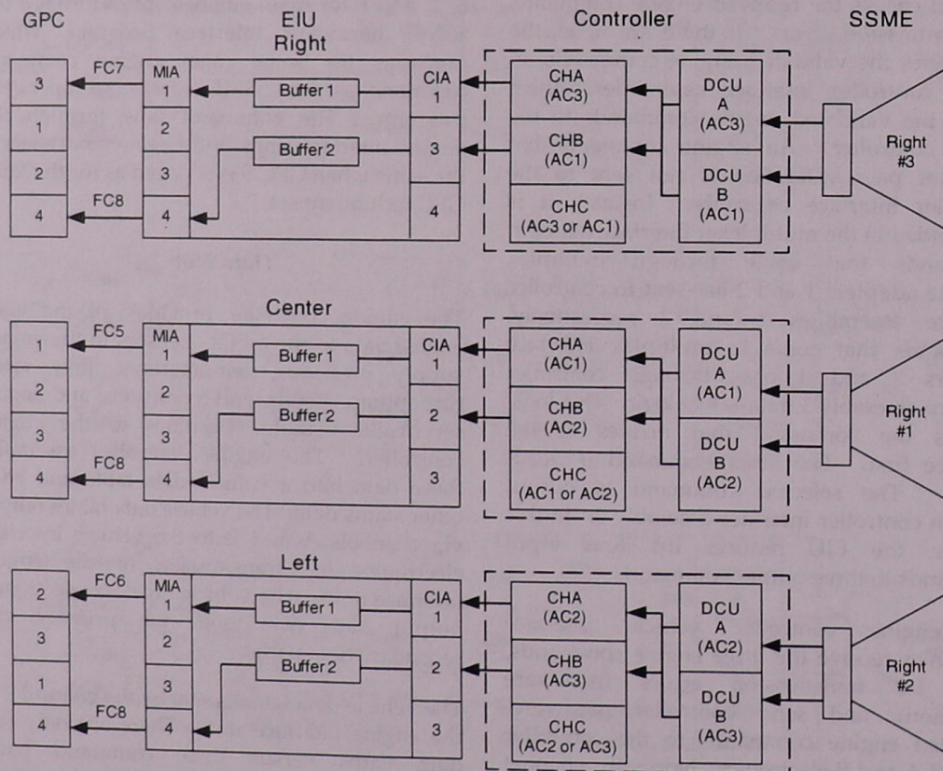
At T minus zero, the orbiter GPCs request both primary and secondary data from each engine interface unit. For no failures, only primary data are looked at. If there is a loss of primary data (which can occur between the engine controller channel A electronics and the SSME subsystem operating procedure), only the secondary data are transmitted to the GPCs.

NOTE

Prelaunch loss of either primary or secondary data will result in data path failure and either an engine ignition inhibit or a launch pad shutdown of all three main engines. Post-launch, loss of both is required for a data path failure. A data path failure will cause the GPCs to issue an MPS DATA C (L, R) fault message and light the appropriate yellow MAIN ENGINE STATUS light on panel F7.

Controller Software

The two primary engine controller programs are the flight operational program and the test operational program. The flight operational program is a real-time, process-control program that processes inputs from engine sensors, controls the operation of the engine servovalves, actuators, solenoids, and spark igniters, accepts and processes vehicle commands, provides and



612.cvs

Main Engine Data Flow

transmits data to the vehicle, and provides checkout and monitoring capabilities.

The test operational program supports engine testing prior to launch. Functionally, it is similar to the flight operational program but differs in implementation. The programs are modular and are defined as computer program components. Each consists of a data base organized into tables. During application of the computer program components, the programs perform data processing for failure detection and status of the vehicle. As system operation progresses through an operating phase, combinations of control functions are operative at different times. These combinations within a phase are defined as operating modes.

The checkout phase initiates active control monitoring or checkout. The standby mode in this phase puts the controller on pause while active control sequence operations are in process. Monitoring functions that do not affect engine hardware status are continually active during this mode. Such functions include processing vehicle commands, updating engine status, and self-testing the controller. During checkout, data and instructions can be loaded into the engine controller's computer memory, permitting updates to the software and data as necessary to proceed with engine-firing or checkout operations. Component checkout is also performed during this mode.

The start preparation phase consists of system purges and propellant conditioning in preparation for engine start. Purge sequence 1 mode is the first. It includes oxidizer system and intermediate seal purge operation. Purge sequence 2 mode is the second purge sequence, including fuel system purge operation and the continuation of purges initiated during purge sequence 1. Purge sequence 3 mode includes propellant recirculation (bleed valve operation). Purge sequence 4 mode includes fuel system purges and indicates that the engine is ready to enter the start phase. The engine-ready mode occurs when proper engine thermal conditions for start have been attained, and other criteria for start have been satisfied, including a continuation of the purge sequence 4 mode.

The start phase covers engine ignition operations and scheduled open-loop operation of the

propellant valves. The start initiation mode includes all functions before ignition confirm and the closing of the thrust control loop. During thrust buildup, the main combustion chamber pressure is monitored to verify closed-loop sequencing is in progress.

Main stage is automatically entered upon successful completion of the start phase. Mixture ratio control and thrust control are active.

The shutdown phase covers operations to reduce main combustion chamber pressure and drive all valves closed to effect full engine shutdown.

The post-shutdown phase is entered upon completion of SSME shutdown. During the terminate sequence, all propellant valves are closed, and all solenoid and torque motor valves are de-energized.

Propellant Management System (PMS)

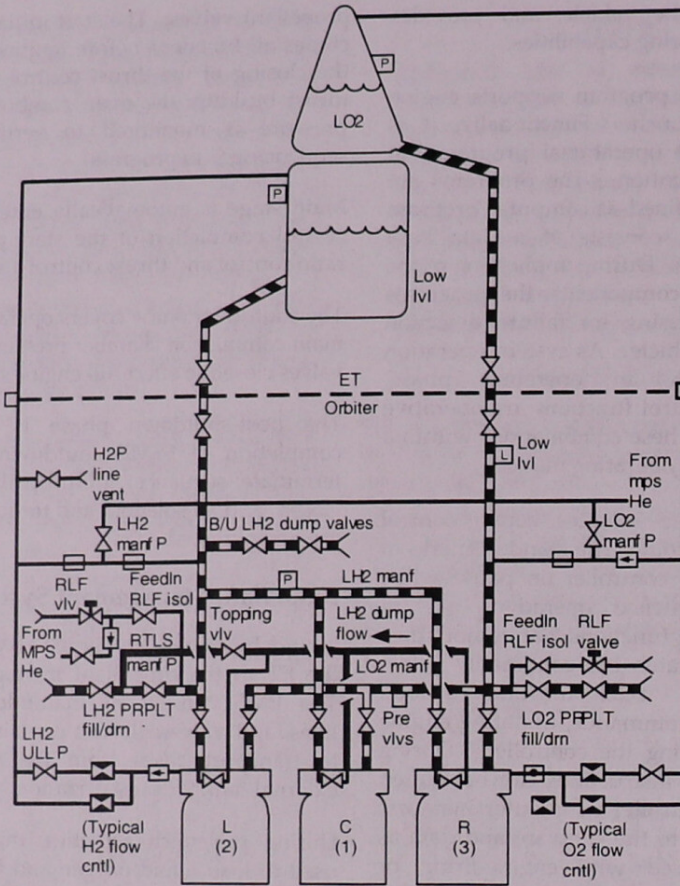
Liquid hydrogen and liquid oxygen pass from the ET to the propellant management system. The PMS consists of manifolds, distribution lines, and valves. It also contains lines needed to transport gases from the engines to the external tank for pressurization.

During prelaunch activities, this subsystem is used to load liquid oxygen and liquid hydrogen into the external tank. After MECO, the PMS is used to complete a liquid oxygen and liquid hydrogen dump and vacuum inerting. It is also used for manifold repressurization during entry.

Propellant Manifolds

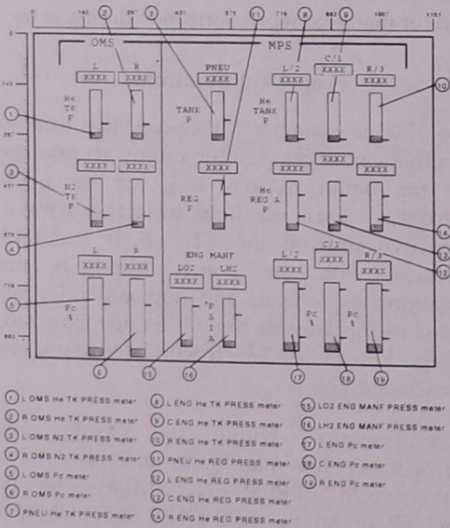
Two 17-inch-diameter MPS propellant feedline manifolds are located in the orbiter aft fuselage, one for liquid oxygen and one for liquid hydrogen. Each manifold interfaces with its respective line on the ET. Both manifolds interface with an 8-inch fill/drain line containing an inboard and outboard fill/drain valve in series. Inside the orbiter, the manifolds diverge into three 12-inch SSME feedlines, one for each engine.

Fluid pressures within the oxygen and hydrogen feedline manifolds can be monitored on the two MPS PRESS ENG MANF meters on panel F7 or on the BFS GNC SYS SUMM 1 display (MANF P LH2, LO2).



613.cvs

MPS Propellant Management System Schematic from the Ascent Pocket Checklist



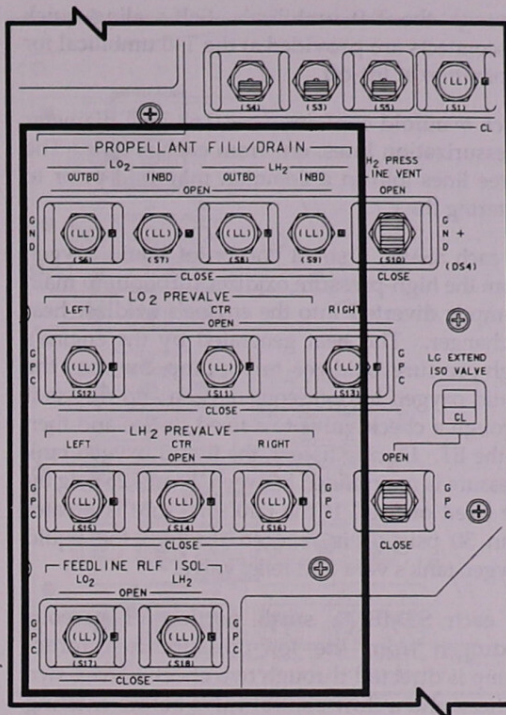
OMS/MPS Display

Feedline Disconnect Valves

Two disconnect valves are found in each feedline where the orbiter meets the external tank. One is on the orbiter side of the manifold, and the other is on the external tank side. All four are closed automatically prior to external tank separation.

Fill/Drain Valves

Two (outboard and inboard) 8-inch-diameter liquid oxygen and liquid hydrogen fill/drain valves are connected in series. They are used to load the external tank before launch and to vacuum inert the feedline manifolds after the post-MECO MPS propellant dump. The valves can be manually controlled by the PROPELLANT FILL/DRAIN LO₂, LH₂, OUTBD, INBD switches on panel R4. Each switch has OPEN, GND, and CLOSE positions.



PROPELLANT FILL/DRAIN, REVALVE and FEEDLINE RLF ISOL Switches on Panel R4

1011/ /018		GNC SYS SUMM 1		5 000/02:46:03	
				BFS 000/00:00:00	
SURF	POS	MDM	DPS	1	2 3 4
L OB			MDM	FF	
IB			FA		
R IB			PL		
OB					
AIL			FCS	CH	1 2 3 4
RUD					
SPD BRK					
BDY FLP					
MPS	I	C	R	NAV	1 2 3 4
HE TK P	4280	4230	4240	IMU	
REG P A	784	768	768	TAC	
B	776	766	770	ADTA	
dp/dT					
ULL P LH2	42.5	42.7	42.9	MPS PNEU HE P	
LO2	21.1	21.0	20.8	TK	4350
				REG	798
				ACUM	760
GH2 OUT P	701	501	401	MANF P LH2	46
GO2 OUT T	791	971	701	LO2	110

GNC SYSTEM SUMMARY 1

Relief Valves

Each 8-inch liquid hydrogen and liquid oxygen manifold has a 1-inch-diameter line that is routed to a feedline relief isolation valve and then to a feedline relief valve. When the feedline relief isolation valve is opened automatically after MECO, the corresponding manifold can relieve

excessive pressure overboard through its relief valve. The relief isolation valves can also be manually controlled by the MAIN PROPULSION SYSTEM FEEDLINE RLF ISOL LO₂ and LH₂ switches on panel R4. The switches have OPEN, GPC, and CLOSE positions.

Backup Liquid Hydrogen Dump Valves

The backup liquid hydrogen dump line connects the feedline manifold to an overboard port above the left wing of the orbiter. The line, designed primarily for a post-MECO liquid hydrogen dump during a return-to-launch site abort, is also used to vent the liquid hydrogen manifold after a nominal MECO. Since liquid hydrogen evaporates quickly, this vent is used to prevent pressure buildup in the hydrogen manifold from repeatedly cycling the relief valve before the propellant dump begins.

Flow through the lines is controlled by two valves in series, which are normally commanded by the GPCs. However, during OPS 1, they can be manually controlled by the MPS PRPLT DUMP BACKUP LH₂ VLV switch on panel R2, which has OPEN, GPC, and CLOSE positions. In an RTLS abort dump, liquid hydrogen is dumped overboard through a port at the outer aft fuselage's left side between the OMS/RCS system pod and the upper surface of the wing. These valves are also known as the LH₂ RTLS Dump valves.

Topping Valve

This valve controls the flow of liquid hydrogen through the tank topping manifold, which is used for prelaunch liquid hydrogen tank topping and thermal conditioning. During thermal conditioning, propellants flow through the engine components to cool them for engine start.

Liquid hydrogen is loaded through the outboard fill/drain valve, circulates through the topping valve to the engines for thermal conditioning, and is pumped into the external tank for tank topping. (The part of the topping recirculation line that goes to the external tank is not shown on the pocket checklist schematic.) The topping valve can be controlled indirectly by the crew via the LH₂ inboard FILL DRAIN switch on panel R4. When this switch is taken

to OPEN, both the LH2 inboard fill drain and topping valves open.

There is no topping valve for liquid oxygen. Since liquid oxygen is harmless in the atmosphere, it is not circulated back to the external tank during thermal conditioning. Rather, it is dumped overboard through the engine liquid oxygen bleed valves and out the overboard bleed valve.

Liquid Hydrogen and Liquid Oxygen Bleed Valves

Three liquid hydrogen bleed valves, one in each engine, connect the engine internal liquid hydrogen line to the topping valve manifold. The valves are used to route liquid hydrogen through the engines during prelaunch thermal conditioning and to dump the liquid hydrogen trapped in the engines post-MECO.

There are also three liquid oxygen bleed valves that are not shown on the pocket checklist schematic. They connect the engine internal liquid oxygen lines to an overboard port and are used only during prelaunch thermal conditioning.

Prevalves

The prevalve in each of the three 12-inch feedlines to each engine isolates liquid oxygen and liquid hydrogen from each engine or permits liquid oxygen and liquid hydrogen to flow to each engine. Most of the prevalve functions are automatic, but they can also be controlled by the LO₂ and LH₂ PREVALVE, LEFT, CTR, RIGHT switches on panel R4. Each switch has OPEN, GPC, and CLOSE positions.

Ullage Pressure System

Ullage refers to the space in each tank not occupied by propellants. The ullage pressure system consists of the sensors, lines, and valves needed to route gaseous propellants from the three main engines and supply them to the external tank to maintain propellant tank pressure during engine operation.

There are two external tank pressurization manifolds, one for gaseous oxygen and one for gaseous hydrogen. During prelaunch, the manifolds are used to supply ground support pressurization of the ET using helium routed

through the T-0 umbilical. Self-sealing quick disconnects are provided at the T-0 umbilical for separation at lift-off.

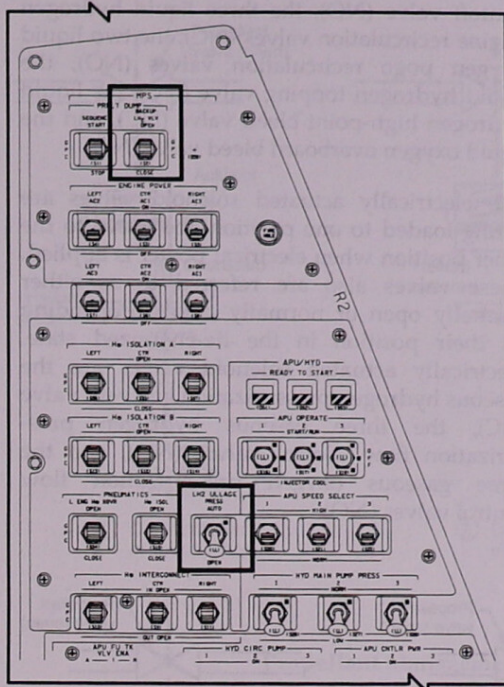
Each manifold contains three 0.63-inch-diameter pressurization lines, one from each engine. The three lines join in a common manifold prior to entering the ET.

In each SSME, a small portion of liquid oxygen from the high-pressure oxidizer turbopump main pump is diverted into the engine's oxidizer heat exchanger. The heat generated by the engine's high-pressure oxidizer turbopump converts the liquid oxygen into gaseous oxygen and directs it through a check valve to a fixed orifice and then to the ET. During ascent, the liquid oxygen tank pressure is maintained between 20 and 25 psig by the fixed orifice. If the tank pressure is greater than 30 psig, it is relieved through the liquid oxygen tank's vent and relief valve.

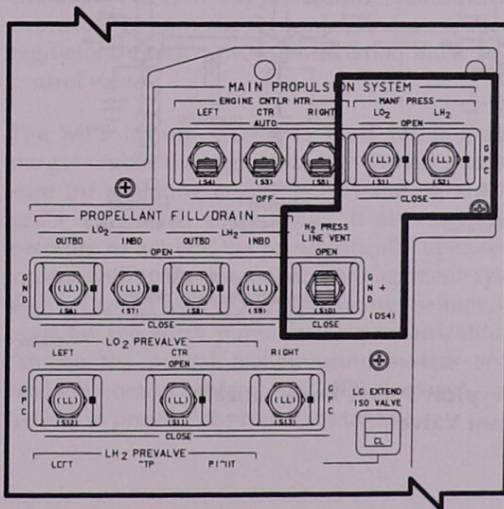
In each SSME, a small portion of gaseous hydrogen from the low-pressure fuel turbopump is directed through two check valves, two orifices, and a flow control valve before entering the ET. During ascent, the liquid hydrogen tank's pressure is maintained between 32 and 34 psia using both a variable and a fixed orifice in each SSME supply system. The active flow control valve is controlled by one of three liquid hydrogen pressure transducers. When the tank pressure decreases below 32 psia, the valve opens; when the tank pressure increases to 33 psia, the valve closes. If the tank pressure exceeds 35 psia, the pressure is relieved through the liquid hydrogen tank's vent and relief valve. If the pressure falls below 32 psia, the LH2 ULLAGE PRESS switch on panel R2 is positioned from AUTO to OPEN, causing all three flow control valves to go to full open.

The three liquid hydrogen and three liquid oxygen ullage pressures are displayed on the BFS GNC SYS SUMM 1 display (ULL P).

The SSME/ET liquid hydrogen pressurization system also contains a line that is used to vent the liquid hydrogen pressurization manifold during inerting. It is controlled by the H₂ PRESS LINE VENT switch on panel R4. This valve is normally closed, but is positioned open during vacuum inerting for a 1-minute period. The GND position allows the launch processing system to control the valve during ground operations.



MPS PRPLT DUMP BACKUP LH₂ VLV Switch and LH₂ ULLAGE PRESS Switch on Panel R2



MAIN PROPULSION SYSTEM MANF PRESS and H₂ PRESS LINE VENT Switches on Panel R4

Manifold Repress Valves

The liquid hydrogen and liquid oxygen manifold repress valves route helium from the MPS helium system into the feedline manifolds. The helium pressure is used to expel propellants during the MPS propellant dump and to repressurize the propellant lines during entry. The valves can be controlled manually using the MAIN PROPULSION SYSTEM MANF PRESS switches on panel R4.

MPS Valve Types

All the valves in the MPS are either electrically or pneumatically operated. Pneumatic valves are used where large loads are encountered, such as in the control of liquid propellant flows. Electrical valves are used for lighter loads, such as the control of gaseous propellant flows.

The pneumatically actuated valves are divided into two types: type 1, which requires pneumatic pressure to open and close the valve, and type 2, which is spring-loaded to one position and requires pneumatic pressure to move to the other position.

Each type 1 valve actuator is equipped with two electrically actuated solenoid valves, which control helium pressure to an "open" or "close" port on the actuator. Energizing the solenoid valve on the open port allows helium pressure to open the pneumatic valve. Energizing the solenoid on the close port allows helium pressure to close the pneumatic valve. Removing power from a solenoid valve removes helium pressure from the corresponding port of the pneumatic actuator and allows the helium pressure trapped in that side of the actuator to vent into the aft compartment. Removing power from both solenoids allows the pneumatic valve to remain in the last commanded position. This is known as a bi-stable valve.

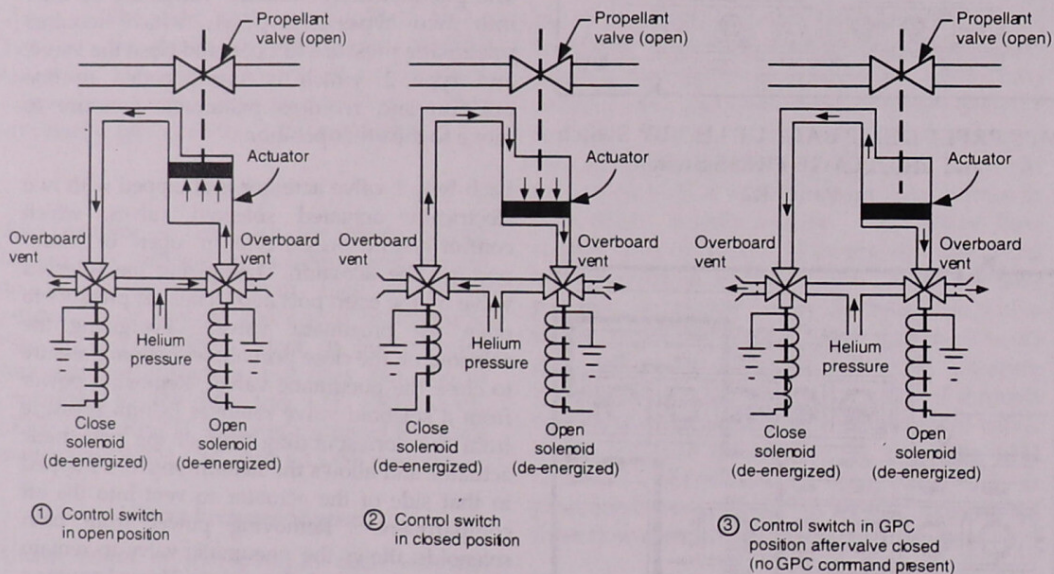
Type 1 valves are used for the liquid oxygen and liquid hydrogen feedline 17-inch umbilical disconnect valves, the liquid oxygen and liquid hydrogen prevalues, the liquid hydrogen and liquid oxygen inboard and outboard fill and drain valves, and the liquid hydrogen 4-inch recirculation disconnect valves.

Each type 2 valve is a single electrically actuated solenoid valve that controls helium pressure to either an open or a close port on the actuator. Removing power from the solenoid valve removes helium pressure from the corresponding port of the pneumatic actuator and allows helium pressure trapped in that side of the actuator to vent overboard. Spring force takes over and drives the valve to the opposite position. If the spring force drives the valve to the open position, the valve is referred to as a normally open (NO) valve. If the spring force drives the valve to a closed position, the valve is referred to as a normally closed (NC) valve.

Type 2 pneumatic valves are used for the liquid hydrogen RTLS inboard dump valve (NC), the liquid hydrogen RTLS outboard dump valve (NC), the liquid hydrogen feedline relief shutoff valve (NO), the liquid oxygen feedline relief

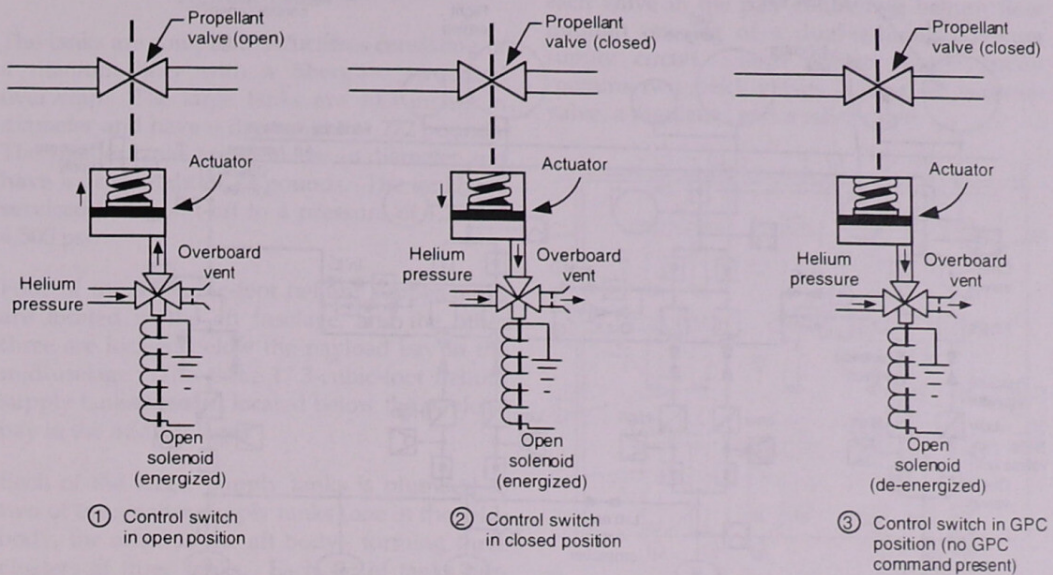
shutoff valve (NO), the three liquid hydrogen engine recirculation valves (NC), the two liquid oxygen pogo recirculation valves (NO), the liquid hydrogen topping valve (NC), the liquid hydrogen high-point bleed valve (NC), and the liquid oxygen overboard bleed valve (NO).

The electrically actuated solenoid valves are spring-loaded to one position and move to the other position when electrical power is applied. These valves also are referred to as either normally open or normally closed, depending on their position in the de-energized state. Electrically actuated solenoid valves are the gaseous hydrogen pressurization line vent valve (NC), the three gaseous hydrogen pressurization flow control valves (NO), and the three gaseous oxygen pressurization flow control valves (NO).



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Propellant Management Subsystem Typical Type 1 Pneumatically Actuated Propellant Valve



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Propellant Management Subsystem Typical Type 2 Pneumatically Actuated Propellant Valve Helium System

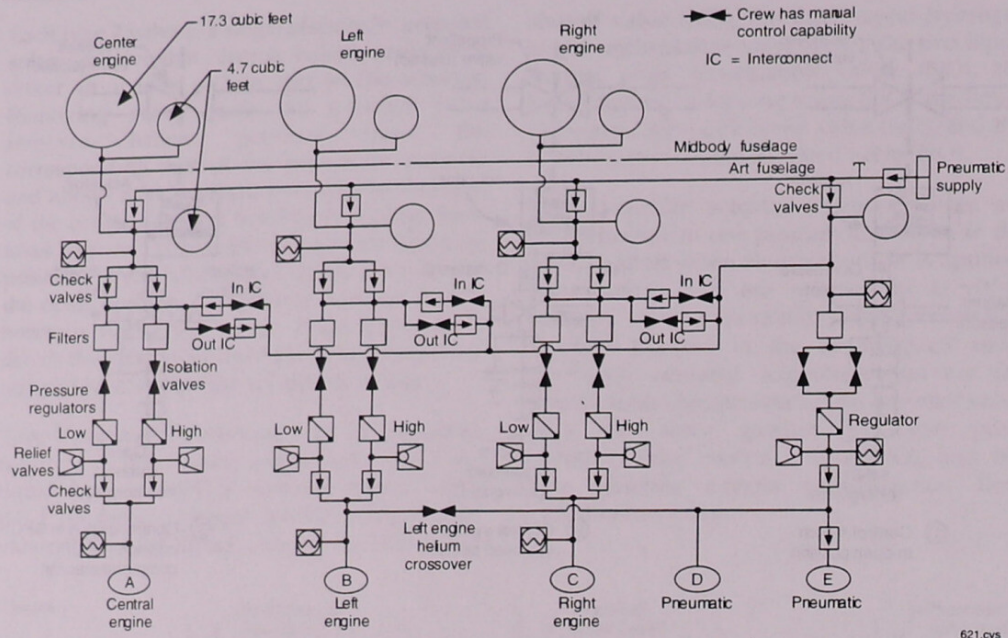
Helium System

The MPS helium system consists of seven 4.7-cubic-foot helium supply tanks, three 17.3-cubic-foot helium supply tanks, and associated regulators, check valves, distribution lines, and control valves.

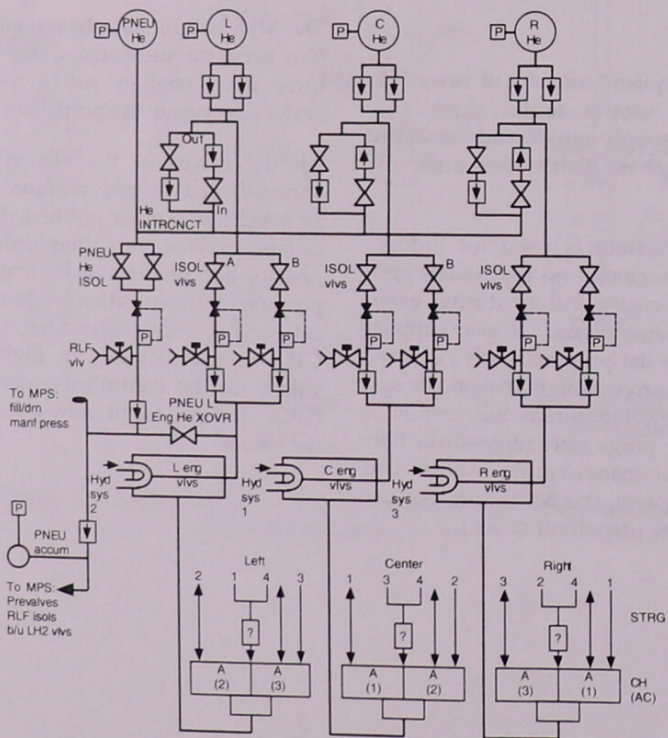
The MPS helium system is used for in-flight purges within the engines, and it provides pressure for actuating engine valves during emergency pneumatic shutdowns. It also supplies pressure to actuate the pneumatically operated valves within the propellant management system. During entry, the remaining helium is used for the entry purge and repressurization. (Unlike the orbital maneuvering system and reaction control system, the MPS does not use helium to pressurize propellant tanks.)

The MPS helium supply system is divided into four separate subsystems, one for each of the three main engines and a fourth pneumatic system to operate the propellant valves.

All the valves in the helium subsystem are spring-loaded to one position and electrically actuated to the other position. The supply tank isolation valves are spring-loaded to the closed position and pneumatically actuated to the open position. Valve position is controlled via electrical signals either generated by the onboard GPCs or manually by the flight crew. All the valves can be controlled automatically by the GPCs, and the flight crew can control some of the valves.



Helium System Storage and Supply



Main Propulsion System Helium Schematic from the Ascent Pocket Checklist

Helium Tanks

The tanks are composite structures consisting of a titanium liner with a fiberglass structural overwrap. The large tanks are 40.3 inches in diameter and have a dry weight of 272 pounds. The smaller tanks are 26 inches in diameter and have a dry weight of 73 pounds. The tanks are serviced before lift-off to a pressure of 4,100 to 4,500 psi.

Four of the 4.7-cubic-foot helium supply tanks are located in the aft fuselage, and the other three are located below the payload bay in the midfuselage. The three 17.3-cubic-foot helium supply tanks are also located below the payload bay in the midfuselage.

Each of the larger supply tanks is plumbed to two of the smaller supply tanks (one in the mid-body, the other in the aft body), forming three clusters of three tanks. Each set of tanks normally provides helium to only one engine and is commonly referred to as left, center, or right engine helium, depending on the engine serviced. Each set normally provides helium to its designated engine for in-flight purges and provides pressure for actuating engine valves during emergency pneumatic shutdown.

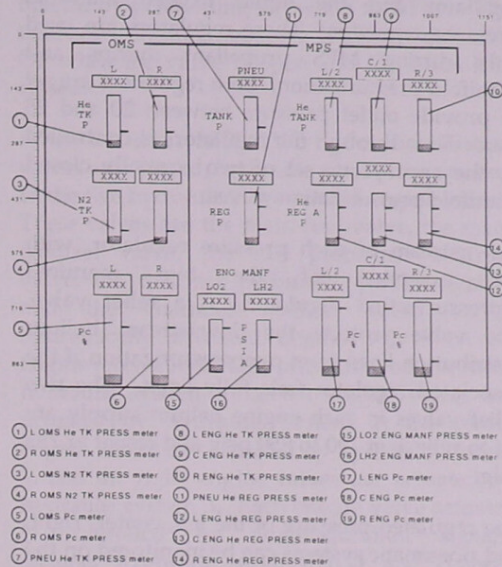
The remaining 4.7-cubic-foot helium tank is referred to as the pneumatic helium supply tank. It provides pressure to actuate all the pneumatically operated valves in the propellant management subsystem.

The helium pressure of the pneumatic, left, center, and right supply systems can be monitored on the MPS PRESS HELIUM, PNEU, L, C, R meters on panel F7 by positioning the switch below the meters to TANK. Left, center, right, and pneumatic tank pressures can be monitored on the BFS GNC SYS SUMM 1 display (MPS L, C, R HE TK P and MPS PNEU HE P TK).

Helium Isolation Valves

Eight helium supply tank isolation valves grouped in pairs control the flow of helium from the tanks. One pair of valves is connected to each of the three tank clusters, and one pair is connected to the pneumatic supply tank. In the engine helium supply tank system, each pair of isolation valves is connected in parallel, with

each valve in the pair controlling helium flow through one leg of a dual-redundant helium supply circuit. Each helium supply circuit contains two check valves, a filter, an isolation valve, a regulator, and a relief valve.



OMS/MPS Display

The two isolation valves connected to the pneumatic supply tanks are also connected in parallel. The rest of the pneumatic supply system consists of a filter, the two isolation valves, a regulator, a relief valve, and a single check valve.

Each engine helium supply isolation valve can be individually controlled by the He ISOLATION A LEFT, CTR, RIGHT, and He ISOLATION B LEFT, CTR, RIGHT switches on panel R2. The switches have OPEN, GPC, and CLOSE positions. The two pneumatic helium supply isolation valves are controlled by a single PNEUMATICS He ISOL switch on panel R2, which also has OPEN, GPC, and CLOSE positions.

Helium Pressure Regulators

Each engine helium supply tank has two pressure regulators operating in parallel. Each regulator controls pressure to within 730 to 785 psia in one leg of a dual-redundant helium supply circuit and is capable of providing all the helium needed by the main engines.

The pressure regulator for the pneumatic helium supply system is not redundant and regulates outlet pressure between 715 to 770 psig. Downstream of the pneumatic regulator are the liquid hydrogen manifold pressure regulator and the liquid oxygen manifold pressure regulator. These regulators are used only during MPS propellant dumps and manifold pressurization. Both regulators are set to provide outlet pressure between 20 and 25 psig. Flow through the regulators is controlled by the appropriate set of two normally closed manifold pressurization valves.

Downstream of each pressure regulator, with the exception of the two manifold repressurization regulators, is a relief valve. The valve protects the downstream helium distribution lines from overpressurization if the associated regulator fails fully open. The two relief valves in each engine helium supply are set to relieve at 790 to 850 psig and reseal at 785 psig.

The regulated pressure of the left, center, right, and pneumatic systems can be monitored on the BFS GNC SYS SUMM 1 display (MPS L, C, R REG P and MPS PNEU REG). They can also be displayed on the MPS PRESS HELIUM PNEU, L, C, and R meters on panel F7 by placing the switch below the meters to REG. The meters however, only display the A reg pressure. B reg pressure can only be seen on BFS GNC SYS SUMM 1.

Pneumatic Left Engine Helium Crossover Valve

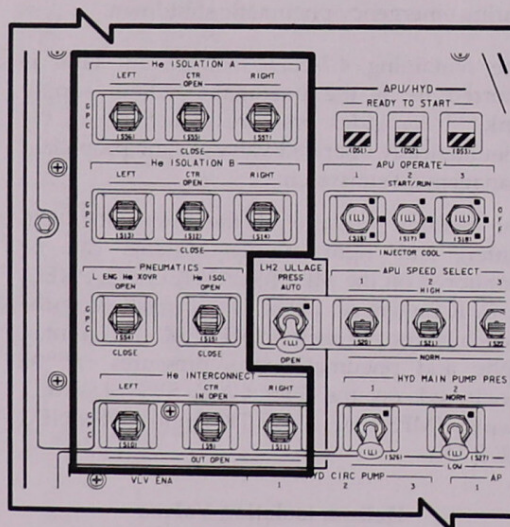
The crossover valve between the pneumatic and left engine helium systems serves as a backup for the nonredundant pneumatic pressure regulator system. In the event of a pneumatic helium regulator failure or a leak in the pneumatic helium system, the left engine helium system can provide regulated helium through the crossover valve to the pneumatic helium distribution system. The PNEUMATICS L ENG He XOVR switch is on panel R2.

Helium Interconnect Valves

Normally, each of the four helium supply systems operates independently until after MECO. Each engine helium supply has two

interconnect (crossover) valves associated with it, and each valve in the pair of interconnect valves is connected in series with a check valve. The check valves allow helium to flow through the interconnect valves in one direction only. One check valve associated with one interconnect valve controls helium flow in one direction, and the other interconnect valve and its associated check valve permit helium flow in the opposite direction. The in/open interconnect valve controls helium flow into the associated engine helium distribution system from the pneumatic distribution system. The out/open interconnect valve controls helium flow out of the associated engine helium supply system to the pneumatic distribution system.

Each pair of interconnect valves is controlled by a single switch on panel R2. Each He INTERCONNECT LEFT, CTR, RIGHT switch has three positions: IN OPEN, GPC, and OUT OPEN. With the switch in the IN OPEN position, the in/open interconnect valve is open, and the out/open interconnect valve is closed. The OUT OPEN position does the reverse. With the switch in GPC, the valves are controlled by the orbiter software.



He ISOLATION, PNEUMATICS L ENG He XOVR and He ISOL, and He INTERCONNECT Switches on Panel R2

Manifold Pressurization

Manifold pressurization valves, located downstream of the pneumatic helium pressure regulator, are used to control the flow of helium to the LO2 propellant manifold for a nominal LO2 propellant dump and for LH2 and LO2 manifold repressurization on entry. There are four of these valves grouped in pairs. One pair controls helium pressure to the liquid oxygen propellant manifold, and the other pair controls helium pressure to the liquid hydrogen propellant manifold.

There are additional regulators just past the manifold repress valves that regulate the pneumatic helium from the normally regulated pressure of 750 psi to a lower, usable pressure. The LH2 manifolds are pressurized to 17 to 30 psig and the LO2 manifolds are pressurized to 20 to 25 psig during the MPS dump and entry manifold repressurization.

Additionally, on the LH2 propellant manifold, there are RTLS manifold pressurization valves that open on the RTLS and TAL propellant dumps to assist in removing LH2 from the manifold.

Pneumatic Control Assemblies

There is one pneumatic control assembly on each SSME. The assembly is essentially a manifold pressurized by one of the engine helium supply systems and contains solenoid valves to control and direct pressure to perform various essential functions. The valves are energized by discrete ON/OFF commands from the output electronics of the SSME controller. Functions controlled by the pneumatic control assembly include the high-pressure oxidizer turbopump intermediate seal cavity and preburner oxidizer dome purge, pogo system postcharge, and pneumatic shutdown.

MPS Hydraulic Systems

Hydraulic System Operation

The three orbiter hydraulic systems (see Section 2.1 for details on the hydraulic system) supply hydraulic pressure to the SSME to provide thrust vector control and actuate engine valves on each SSME. The three hydraulic supply

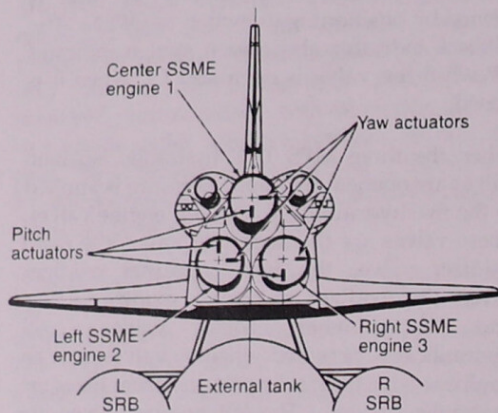
systems are distributed to the thrust vector control (TVC) valves. These valves are controlled by HYDRAULICS MPS/TVC ISOL VLV switches (one for each of the three hydraulic systems) on panel R4. A valve is opened by positioning its switch to OPEN. The talkback indicator above each switch indicates OP when the valve is open and CL when it is closed.

When the three MPS TVC hydraulic isolation valves are opened, hydraulic pressure is applied to the five hydraulically actuated engine valves. These valves are the main fuel valve, the main oxidizer valve, the fuel preburner oxidizer valve, the oxidizer preburner oxidizer valve, and the chamber coolant valve. All hydraulically actuated engine valves on an engine receive hydraulic pressure from the same hydraulic system. The left engine valves are actuated by hydraulic system 2, the center engine valves are actuated by hydraulic system 1, and the right engine valves are actuated by hydraulic system 3. Each engine valve actuator is controlled by dual-redundant signals: channel A/engine servovalve 1 and channel B/engine servovalve 2 from that engine's controller electronics. As a backup, all the hydraulically actuated engine valves on an engine are supplied with helium pressure from the helium subsystem left, center, and right engine helium tank supply system.

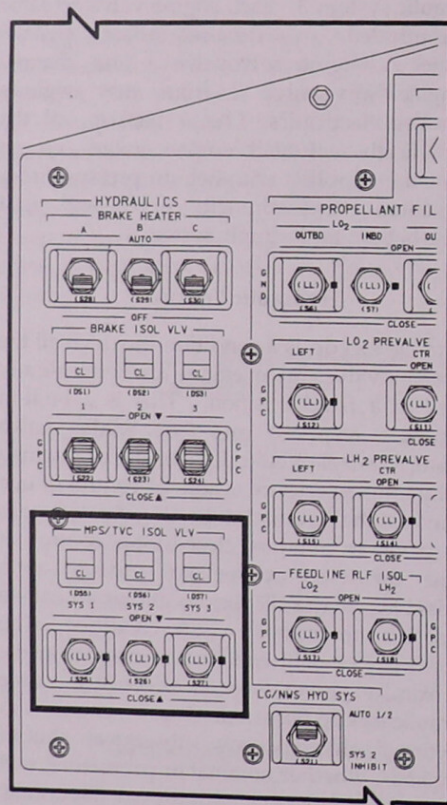
Hydraulic Lockup

Hydraulic lockup is a condition in which all the propellant valves on an engine are hydraulically locked in a fixed position. This is a built-in protective response of the SSME valve actuator/control circuit. It takes effect any time low hydraulic pressure or loss of control of one or more of the five hydraulically actuated main engine valves renders closed-loop control of engine thrust or propellant mixture ratio impossible. Hydraulic lockup allows an engine to continue to burn in a safe condition. The affected engine will continue to operate at the approximate power level in effect at the time hydraulic lockup occurred. Once an engine is in a hydraulic lockup, any subsequent shutoff commands, whether nominal or premature, will cause a pneumatic engine shutdown. Hydraulic lockup does not affect the capability of the engine controller to monitor critical operating

parameters or issue an automatic shutdown if an operating limit is out of tolerance, but the engine shutdown would be accomplished pneumatically.



Main Engine Gimbal Actuators



MPS/TVC ISOL VLV Switches and Talkbacks on Panel R4

Thrust Vector Control

The three MPS thrust vector control valves must also be opened to supply hydraulic pressure to the six main engine TVC actuators. There are two servoactuators per SSME: one for yaw and one for pitch. Each actuator is fastened to the orbiter thrust structure and to the powerheads of the three SSMEs.

Two actuators per engine provide attitude control and trajectory shaping by gimbaling the SSMEs in conjunction with the solid rocket boosters during first-stage and without the solid rocket boosters during second-stage ascent. Each SSME servoactuator receives hydraulic pressure from two of the three orbiter hydraulic systems; one system is the primary system, and the other is a standby system. Each servoactuator has its own hydraulic switching valve. The switching valve receives hydraulic pressure from two of the three orbiter hydraulic systems and provides a single source to the actuator.

Normally, the primary hydraulic supply is directed to the actuator; however, if the primary system were to fail and lose hydraulic pressure, the switching valve would automatically switch over to the standby system, and the actuator would continue to function. The left engine's pitch actuator uses hydraulic system 2 as the primary and hydraulic system 1 as the standby. The engine's yaw actuator uses hydraulic system 1 as the primary and hydraulic system 2 as the standby. The center engine's pitch actuator uses hydraulic system 1 as the primary and hydraulic system 3 as the standby, and the yaw actuator uses hydraulic system 3 as the primary and hydraulic system 1 as the standby. The right engine's pitch actuator uses hydraulic system 3 as the primary and hydraulic system 2 as the standby. Its yaw actuator uses hydraulic system 2 as the primary and hydraulic system 3 as the standby.

The SSME servoactuators change each main engine's thrust vector direction as needed during the flight sequence. The three pitch actuators gimbal the engine up or down a maximum of 10.5° from the installed null position. The three yaw actuators gimbal the engine left or right a maximum of 8.5° from the installed position. The installed null position for

the left and right main engines is 10° up from the X axis in a negative Z direction and 3.5° outboard from the engine centerline parallel to the X axis. The center engine's installed null position is 16° above the X axis for pitch and on the X axis for yaw. When any engine is installed in the null position, the other engines do not come in contact with it.

There are three actuator sizes for the main engines. The piston area of the center engine upper pitch actuator is 24.8 square inches, its stroke is 10.8 inches, it has a peak flow of 50 gallons per minute, and it weighs 265 pounds. The piston area of the two lower pitch actuators is 20 square inches, their stroke is 10.8 inches, their peak flow is 45 gallons per minute, and they weigh 245 pounds. All three yaw actuators have a piston area of 20 square inches, a stroke of 8.8 inches, a peak flow of 45 gallons per minute, and weigh 240 pounds. The minimum gimbale rate is 10° per second; the maximum rate is 20° per second.

Detailed information about ascent thrust vector control is provided in Section 2.13.

Hydraulic System Isolation On Orbit

The HYDRAULICS MPS/TVC ISOL VLV SYS 1, SYS 2, and SYS 3 switches on panel R4 are positioned to CLOSE during on-orbit operations to protect against hydraulic leaks downstream of the isolation valves. In addition, there is no requirement to gimbal the main engines from the stow position. During on-orbit operations when the MPS TVC valves are closed, the hydraulic pressure supply and return lines within each MPS TVC component are interconnected to enable hydraulic fluid to circulate for thermal conditioning.

Malfunction Detection

There are three separate means of detecting malfunctions within the MPS: the engine controllers, the hardware caution and warning system, and the software C/W system.

The SSME controller, through its network of sensors, has access to numerous engine operating parameters. A group of these parameters has been designated critical operating parameters, and special limits defined

for these parameters are monitored by the main engine controller. Several MPS parameters are monitored by hardware and software. If a violation of any hardware limit is detected, the caution and warning system will illuminate the red MPS caution and warning light on panel F7. The light will be illuminated if any of the following conditions are sensed by the hardware C/W system:

- "MPS LH2/02 MANF" -MPS liquid oxygen manifold pressure is above 249 psia or the liquid hydrogen manifold pressure is above 65 psia
- "MPS HE P C(L,R)" - MPS regulated (A leg only) left, center, or right helium pressure is less than 680 or greater than 810 psia
- "MPS HE P C(L,R)" - MPS center, left, or right tank pressure is less than 1,150 psia

In addition to the MPS light, the Backup C&W light on panel F7 will also illuminate. The limits for the backup C&W system are identical to the hardware C&W. The backup C&W is what generates the applicable C&W message.

The flight crew can monitor the MPS PRESS HELIUM PNEU, L, C, R meter on panel F7 when the switch below the meter is placed in the TANK or REG position. However, the meters only display the "A" regulator pressure when in the REG position. Pressure is also shown on the BFS GNC SYS SUMM 1 display. The MPS PRESS ENG MANF LO₂, LH₂ meter can also be monitored on panel F7. A number of conditions will require crew action. For example, an ET ullage pressure low message will require the flight crew to pressurize the external liquid hydrogen tank by setting the LH₂ ULLAGE PRESS switch on panel R2 to OPEN. A low helium tank pressure may require the flight crew to interconnect the pneumatic helium tank to an engine supply using the MPS He INTERCONNECT LEFT, CTR, and RIGHT switches on panel R2.

MAIN ENGINE STATUS LEFT, CTR, RIGHT lights on panel F7 are divided into two parts: the top half lights red and the bottom half lights yellow. The top half is illuminated for SSME shutdown and redline exceedances.

The yellow bottom half of the MAIN ENGINE STATUS light will be illuminated by the following failures:

- Electrical lockup
- Hydraulic lockup
- Command path failure (loss of two or more command channels or command reject between the GPCs and the SSME controller)
- Data path failure (loss of both primary and secondary data from the SSME controller)

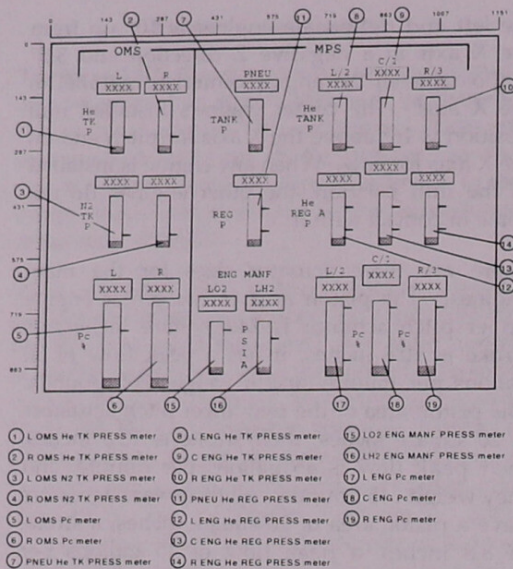
In an electrical lockup for the affected SSME, loss of data from fuel flowrate sensors or the chamber pressure sensors will result in the propellant valve actuators being maintained electronically in the positions existing at the time the last sensor failed. For both sensors to be considered failed, it is only necessary for one sensor to actually fail. In hydraulic lockup, electrical lockup, or command path failure all engine-throttling capability for the affected engine is lost; subsequent throttling commands to that engine will not change the thrust level.

Biased sensors will affect main engine performance. During engine mainstage operation, measurements of the combustion chamber pressure and fuel flowrate are used by the controller to closely control power level and mixture ratio.

There are two chamber pressure transducers on each SSME (an "A" and a "B"). Each consists of two bridges (Wheatstone-type strain gauges) for a total of four controller measurements (an A1, A2 pair and a B1, B2 pair). Each of these measurements is monitored for reasonableness before being used by the controller.

The fuel flow meter is located in the duct between the low and high pressure liquid hydrogen pumps. Four measurements (A1, A2 and B1, B2) come from the flow meter for use by the controller after each passes reasonableness checks.

Biases of either the flow meter or chamber pressure transducers can cause off-nominal engine operation. Essentially, the crew has no



OMS/MPS Display

insight into this type of failure and must rely on Mission Control for assistance. The controller will adjust the engine valves to maintain the commanded power level as seen by the chamber pressure transducers, and this is what is displayed to the crew.

The red upper half of the MAIN ENGINE STATUS LEFT, CTR, RIGHT lights on panel F7 will be illuminated for an engine in shutdown or post-shutdown phase or for the following redline exceedances with limits inhibited:

- The high-pressure fuel turbopump's discharge temperature is above 1960° R
- The high-pressure oxidizer turbopump's discharge temperature is above 1760° R or below 720° R
- The high-pressure oxidizer turbopump's intermediate seal purge pressure is below 159 psia
- The high-pressure oxidizer turbopump's secondary seal purge pressure is above 100 psia (Phase II SSME only)
- The main combustion chamber's pressure is 400 psig below the reference chamber pressure

Because of the rapidity with which it is possible to exceed these limits, the engine controller has been programmed to sense the limits and automatically shut down the engine if the limits are exceeded. Although a shutdown as a result of violating operating limits is normally automatic, the flight crew can, if necessary, inhibit an automatic shutdown by using the MAIN ENGINE LIMIT SHUT DN switch on panel C3. The switch has three positions: ENABLE, AUTO, and INHIBIT. The ENABLE position allows any engine that violates operating limits to be shut down automatically. The AUTO position allows only the first engine that violates operating limits to be shut down automatically. If either of the two remaining engines subsequently violates operating limits, it would be inhibited from automatically shutting down. Should a remaining engine violate operating limits, it will not be shut down automatically unless the switch is manually taken to ENABLE and then to AUTO. The INHIBIT position inhibits all automatic shutdowns. The MAIN ENGINE SHUT DOWN LEFT, CTR, RIGHT pushbuttons on panel C3 have spring-loaded covers (guards). When the guard is raised, and the pushbutton is depressed, the corresponding engine shuts down immediately, provided the engine command is operational.

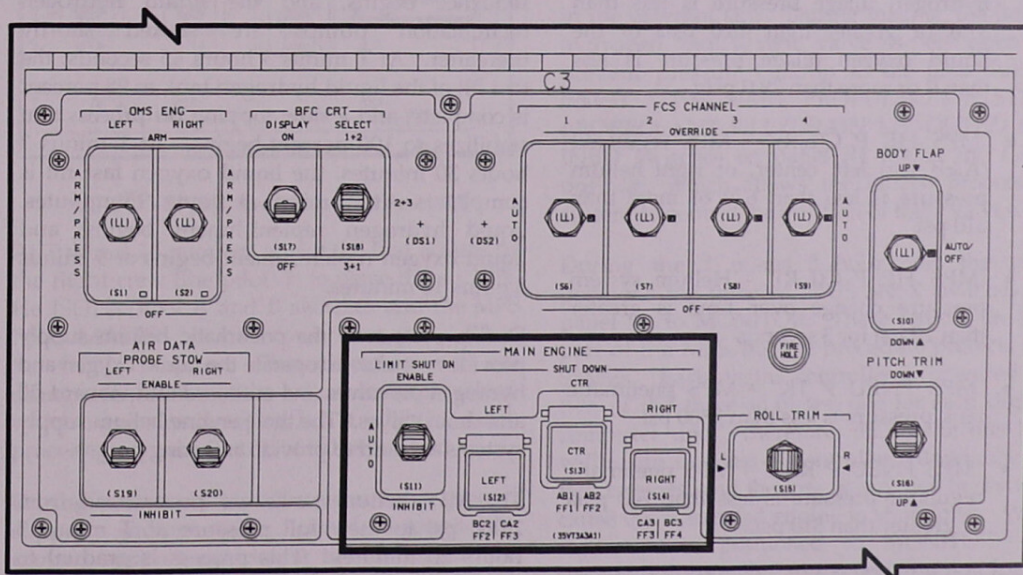
WARNING

Failure of an engine with limit shutdown inhibited will probably result in engine and controller damage, which will prevent detection of the engine failure by the GPCs.

The software caution and warning processing of the orbiter GPC's can detect certain specified out-of-limit or fault conditions of the MPS. The SM alert light on panel F7 is illuminated, a fault message appears on the PASS and/or BFS CRT displays, and an audio tone sounds if:

PASS and BFS generated fault messages

- "MPS DATA C(L,R)" - Data path failures occur due to loss of both primary and secondary data from the main engine controller
- "MPS CMD C(L,R)" - Command path failures occur due to loss or rejection of GPC commands to the main engine controller (PASS only pre-engage)
- "MPS HYD C(L,R)" - Hydraulic lockups occur due to the failure of any one of the five hydraulically actuated valves from achieving its commanded position



MAIN ENGINE LIMIT SHUT DN Switch and MAIN ENGINE SHUT DOWN Pushbuttons on Panel C3

- "MPS ELEC C(L,R)" Electric lockups occur due to the loss of all Pc data or all fuel flow rate data from the engine
- "ET SEP-INH" - ET separation inhibits occur due to feedline disconnect failures or excessive vehicle rates(>0.7 deg/sec in any axis)
- "SSME FAIL C(L,R)" - Premature main engine shutdown (backup C&W light and master alarm only, no MPS light)
- "MPS H2 OUT P C(L,R)" - SSME GH₂ outlet pressure less than 1050 psia (engine failure)
- "MPS O2 OUT T C(L,R)" - SSME GO₂ outlet temperature less than 125° F (engine failure)

PASS only generated fault messages

- "ET SEP-MAN" or "ET SEP SEP-AUT" - ET separation switch failures (PASS annunciated only) occur when the GPCs can't determine the position of the ET SEPARATION switch on panel C3
- "ME SHDN SW C(L,R)" - Main engine pushbutton failures (PASS annunciated only occur when there is a failure of one of the two contacts on an SSME shutdown pushbutton resulting in a switch dilemma)

BFS only generated fault messages

- "MPS LH2/O2 ULL" - ET liquid hydrogen ullage pressure is less than 31.6 or greater than 46.0 psia or the liquid oxygen ullage pressure is less than 0 or more than 29.0 psig
- "MPS HE P C(L,R)" - MPS regulated (A&B leg) left, center, or right helium pressure is less than 679 or more than 810 psi
- "MPS HE P C(L,R)" - Helium system pressure change over time is greater than 20 psi for 3 seconds
- "MPS PNEU P TK" - MPS pneumatic tank pressure is less than 3800 psi
- "MPS PNEU P REG" - MPS pneumatic regulator pressure is less than 700 psia or greater than 810 psia
- "MPS PNEU P ACUM" - MPS pneumatic accumulator pressure is less than 700 psia

These failures have messages that are annunciated in OPS 1 and 6. Also, the BFS does all processing of the MPS helium and ullage pressure systems. In OPS 3, the MPS parameters on the BFS SYS SUMM 1 will be blanked, except for helium REG A and B pressure. In OPS 2 there is no software caution and warning for the MPS. Therefore, if either manifold pressure (LO2 or LH2) violates limits while on orbit, the only indication the crew will see is hardware caution and warning (MPS light and master alarm.) There will be no message on the CRT.

Operations

Prelaunch

At T minus 5 hours 50 minutes, the launch processing system initiates the SSME liquid hydrogen chill-down sequence in preparation for liquid hydrogen loading. At T minus 5 hours 15 minutes, the fast-fill portion of the liquid oxygen and liquid hydrogen loading sequence begins, and the liquid hydrogen recirculation pumps are started shortly thereafter. At T minus 3 hours 45 seconds, the fast fill of the liquid hydrogen tank to 98 percent is complete, and a slow topping off process that stabilizes to 100 percent begins. At T minus 3 hours 30 minutes, the liquid oxygen fast fill is complete. At T minus 3 hours 15 minutes, liquid hydrogen replenishment begins, and liquid oxygen replenishment begins at T minus 3 hours 10 minutes.

During prelaunch, the pneumatic helium supply provides pressure to operate the liquid oxygen and hydrogen prevalues and outboard and inboard fill and drain valves. The three engine helium supply systems are used to provide anti-icing purges.

The MPS helium tanks are pressurized from 2,000 psi to their full pressure at T minus 3 hours 20 minutes. This process is gradual to prevent excessive heat buildup in the supply tank. Regulated helium pressure is between 715 and 775 psi.

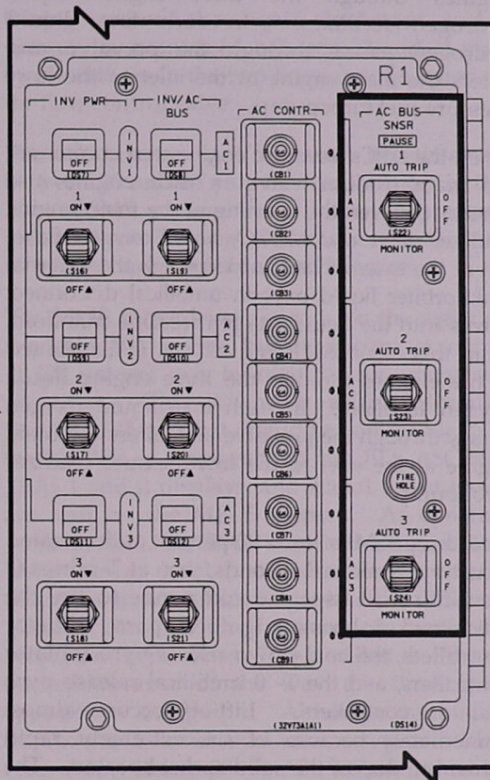
At this time, the MPS He ISOLATION A and B switches, the MPS PNEUMATICS L ENG He XOVR and He ISOL switches, and the MPS He INTERCONNECT LEFT, CTR, RIGHT switches on panel R2 are in the GPC position. With the switches in this position, the eight helium isolation valves are open, and the left engine crossover and the six helium interconnect valves are closed.

liquid oxygen feedline manifold. The liquid oxygen exits the orbiter at the liquid oxygen feedline umbilical disconnect and enters the liquid oxygen tank in the external tank.

During loading, the liquid oxygen tank's vent and relief valves are open to prevent pressure buildup in the tank due to liquid oxygen loading. The MAIN PROPULSION SYSTEM PROPELLANT FILL/DRAIN LO₂ OUTBD and INBD switches on panel R4 are in the GND (ground) position, which allows the launch processing system to control the positions of these valves. Just prior to lift-off, the launch processing system will first command the liquid oxygen inboard fill and drain valve to close. The liquid oxygen in the line between the inboard and outboard fill and drain valves is then allowed to drain back into the ground support equipment, and the launch processing system commands the outboard fill and drain valve to close.

Also during prelaunch, liquid hydrogen supplied through the ground support equipment liquid hydrogen T-0 umbilical passes through the liquid hydrogen outboard fill and drain valve, the liquid hydrogen inboard fill and drain valve, and the liquid hydrogen feedline manifold. The liquid hydrogen then exits the orbiter at the liquid hydrogen feedline umbilical disconnect and enters the liquid hydrogen tank in the external tank. During loading, the liquid hydrogen tank's vent valve is left open to prevent pressure buildup in the tank due to boiloff. The MAIN PROPULSION SYSTEM PROPELLANT FILL/DRAIN LH₂ OUTBD and INBD switches on panel R4 are in the GND position, which allows the launch processing system to control the position of these valves.

During the T minus 3 hour hold the pilot positions the three AC BUS SNSR switches on panel R1 to MONITOR. These sensors are not part of the MPS, but the procedure protects the SSMEs. Each engine controller is powered by two of the three ac buses, one for each digital computer unit. Therefore, the loss of one bus will result in a loss of controller redundancy on two engines, and the loss of any two buses will cause the associated engine to shut down. With the switches positioned to MONITOR, the sensors will provide caution and warning for an over/undervoltage or overload condition, but they will not trip a bus off line.



AC BUS SNSR Switches on Panel R1

At T minus 16 minutes, one of the first actions by the flight crew (the pilot) is to place the six MPS He ISOLATION A and B switches and the MPS PNEUMATICS He ISOL switch on panel R2 in the OPEN position. This procedure will not change the position of the helium isolation valves, which were already open, but it inhibits launch processing system control of valve position.

During prelaunch, liquid oxygen from ground support equipment is loaded through the ground support equipment liquid oxygen T-0 umbilical and passes through the liquid oxygen outboard fill and drain valve, the liquid oxygen inboard fill and drain valve, and the orbiter

Engine Start

At T minus 4 minutes, the fuel system purge begins. It is followed at T minus 3 minutes 25 seconds by the beginning of the engine gimbal tests, during which each gimbal actuator is operated through a canned profile of extensions and retractions. If all actuators function satisfactorily, the engines are gimbaled to a predefined position at T minus 2 minutes 15 seconds. The engines remain in this position until engine ignition.

At T minus 2 minutes 55 seconds, the launch processing system closes the liquid oxygen tank vent valve, and the tank is pressurized to 21 psig with ground support equipment-supplied helium. The liquid oxygen tank's pressure can be monitored on the BFS GNC SYS SUMM 1 CRT (MANF P LO2). The 21-psig pressure corresponds to a liquid oxygen engine manifold pressure of 105 psia.

At T minus 1 minute 57 seconds, the launch processing system closes the liquid hydrogen tank's vent valve, and the tank is pressurized to 42 psig with ground support equipment-supplied helium. The pressure is monitored on the BFS GNC SYS SUMM 1 CRT display (MANF P LH2).

At T minus 31 seconds, the onboard redundant set launch sequence is enabled by the launch processing system. From this point on, all sequencing is performed by the orbiter GPCs in the redundant set, based on the onboard clock time. The GPCs still respond, however, to hold, resume count, and recycle commands from the launch processing system.

At T minus 16 seconds, the GPCs begin to issue arming commands for the solid rocket booster ignition pyro initiator controllers, the hold-down release pyro initiator controllers, and the T-0 umbilical release pyro initiator controllers.

At T minus 9.5 seconds, the engine chill-down sequence is complete, and the GPCs command the liquid hydrogen prevalues to open (the liquid oxygen prevalues are open during loading to permit engine chill-down). The MAIN PROPULSION SYSTEM LO₂ and LH₂ PREVALVE LEFT, CTR, RIGHT switches on panel R4 are in the GPC position.

At T minus 6.6 seconds, the GPCs issue the engine start command, and the main fuel valve in each engine opens. Between the opening of the main fuel valve and MECO, liquid hydrogen flows out of the external tank/orbiter liquid hydrogen disconnect valves into the liquid hydrogen feedline manifold. From this manifold, liquid hydrogen is distributed to the engines through the three engine liquid hydrogen feedlines. In each line, liquid hydrogen passes through the prevalue and enters the main engine at the inlet to the low-pressure fuel turbopump.

When the GPCs issue the engine start command, the main oxidizer valve in each engine also opens. Between the opening of the main engine oxidizer valve and MECO, liquid oxygen flows out of the external tank and through the external tank/orbiter liquid oxygen umbilical disconnect valves into the liquid oxygen feedline manifold. From this manifold, liquid oxygen is distributed to the engines through the three engine liquid oxygen feedlines. In each line, liquid oxygen passes through the prevalue and enters the main engine at the inlet to the low-pressure oxidizer turbopump.

If all three SSMEs reach 90 percent of their rated thrust by T minus 3 seconds, then at T minus 0, the GPCs will issue the commands to fire the solid rocket booster ignition pyro initiator controllers, the hold-down release pyro initiator controllers, and the T-0 umbilical release pyro initiator controllers. Lift-off occurs almost immediately because of the extremely rapid thrust buildup of the solid rocket boosters. The 3 seconds to T minus zero allow the vehicle base bending loads to return to minimum by T minus 0.

If one or more of the three main engines do not reach 90 percent of their rated thrust at T minus 3 seconds, all SSMEs are shut down, the solid rocket boosters are not ignited, and a pad abort condition exists.

Ascent

Beginning at T minus 0, the SSME gimbal actuators, which were locked in their special preignition position, are first commanded to their null positions for solid rocket booster start and then are allowed to operate as needed for thrust vector control.

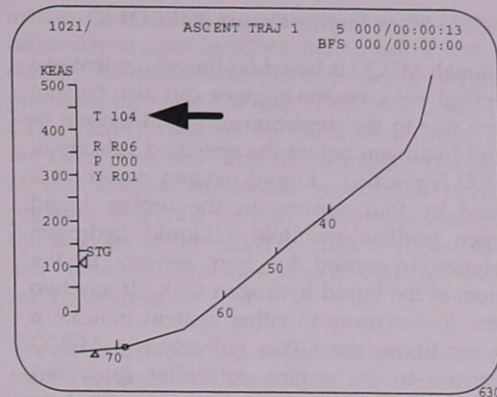
Between lift-off and MECO, as long as the SSMEs perform nominally, all MPS sequencing and control functions are executed automatically by the GPCs. During this period, the flight crew monitors MPS performance, backs up automatic functions, if required, and provides manual inputs in the event of MPS malfunctions.

During ascent, the liquid hydrogen tank's pressure is maintained between 32 and 34 psig by the orifices in the two lines and the action of the flow control valve.

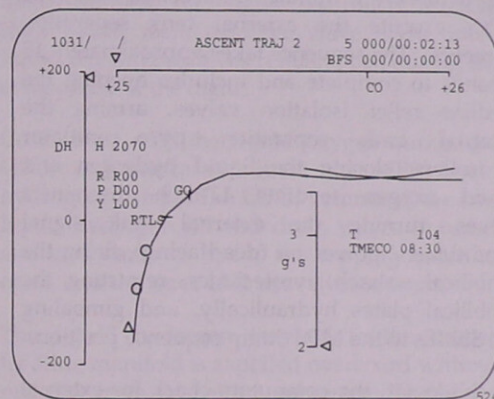
The liquid oxygen tank's pressure is maintained between 20 and 25 psig by fixed orifices in the ET to SSME pressurization lines. A pressure greater than 30 psig will cause the tank to relieve through its vent and relief valve.

The SSME thrust level depends on the flight: it is usually 104 percent, but the maximum setting of 109 percent may be required for emergency situations. This is known as max throttle. Percent of thrust that would be commanded (T) by the BFS is displayed on the BFS ASCENT TRAJ 1 and 2 displays, and actual thrust levels are read on the MEDS display. As dynamic pressure rises, the GPCs throttle the engines to a lower power level (minimum 67 percent) to minimize structural loading while the orbiter is passing through the region of maximum aerodynamic pressure. This is called the "thrust bucket" because of the way the thrust plot appears on the graph. Although the bucket duration and thrust level vary, a typical bucket runs from about 30 to 65 seconds, mission elapsed time (MET). The solid rocket booster propellant is also shaped to reduce thrust. At approximately 65 seconds MET, the engines are once again throttled up to the appropriate power level (104 percent) and remain at that setting for a normal mission until 3-g throttling is initiated.

SRB separation is the next major event on ascent. The SRBs burn out after about 2 minutes of flight. Appearance of an overbright "Pc < 50" (chamber pressure in the SRBs in psi) on the trajectory display indicates to the crew that the SRB separation sequence has begun. Actual separation occurs about 5 seconds later to allow for SRB thrust tailoff.



BFS ASCENT TRAJ 1 DISPLAY
(percent of thrust commanded by the BFS)



BFS ASCENT TRAJ 2 DISPLAY

Liquid oxygen manifold pressure is greatly affected by acceleration from the SRBs, but because of its low density, liquid hydrogen is not. At SRB separation, the liquid oxygen manifold pressure will drop from well over 100 psia to approximately 50 psia. Pressure rises again as the vehicle approaches 3 g's. The crew can monitor the manifold pressures on the BFS GNC SYS SUMM 1 display (MANF P) and on the MPS PRESS ENG MANF meters on panel F7.

Beginning at approximately 7 minutes 40 seconds MET, the engines are throttled back to maintain vehicle acceleration at 3 g's or less. Three g's is an operational limit devised to prevent excessive physical stress on the flight crew and vehicle. Approximately 6 seconds before main engine cutoff, the engines are throttled back to 67 percent in preparation for shutdown.

Main Engine Cutoff (MECO)

Although MECO is based on the attainment of a specified velocity, the engines can also be shut down due to the depletion of liquid oxygen or liquid hydrogen before the specified velocity of MECO is reached. Liquid oxygen depletion is sensed by four sensors in the orbiter liquid oxygen feedline manifold. Liquid hydrogen depletion is sensed by four sensors in the bottom of the liquid hydrogen tank. If any two of the four sensors in either system indicate a dry condition, the GPCs will issue a MECO command to the engine controller (provided they go dry after the arming mass is reached).

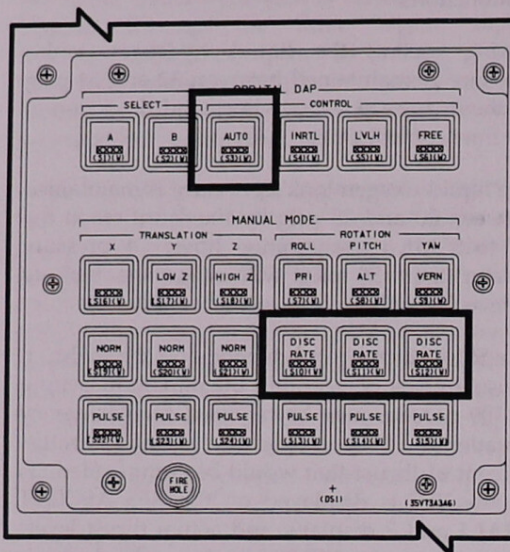
Once MECO has been confirmed at approximately 8 minutes 30 seconds MET, the GPCs execute the external tank separation sequence. The sequence takes approximately 18 seconds to complete and includes opening the feedline relief isolation valves, arming the external tank separation pyro initiator controllers, closing the liquid hydrogen and liquid oxygen feedline 17-inch disconnect valves, turning the external tank signal conditioners' power off (deadfacing), firing the umbilical unlatch pyrotechnics, retracting the umbilical plates hydraulically, and gimbaling the SSMEs to the MPS dump sequence position.

At this point, the computers check for external tank separation inhibits. If the vehicle's pitch, roll, and yaw rates are greater than 0.7 degree per second, or the feedline disconnect valves fail to close, automatic external tank separation is inhibited. If these inhibit conditions are met, the GPCs issue the commands to the external tank separation pyrotechnics. As with the SRBs, the crew has the capability to override the external tank separation with the ET SEPARATION switch located on panel C3. In crew-initiated external tank separation or RTLS aborts, the inhibits are overridden.

At orbiter/external tank separation, the gaseous oxygen and gaseous hydrogen feedlines are sealed at the umbilicals by self-sealing quick disconnects.

In the cockpit, the crew observes MECO through the illumination of the three red MAIN ENGINE STATUS lights on panel F7. In addition, the Pc meters on panel F7 drop to 0 percent. Four of the ORBITAL DAP pushbutton

lights on panel C3 illuminate when the MECO CONFIRMED software flag has been set. This flag must be set to enter the ET separation sequence. Remember, the DAP lights will not illuminate on an RTLS abort since the trans DAP is not entered at MECO as it is uphill or on a TAL abort.



ORBITAL DAP CONTROL AUTO Light on Panel C3

Post-MECO

Ten seconds after main engine cutoff, the backup liquid hydrogen dump valves are opened for 2 minutes to ensure that the liquid hydrogen manifold pressure does not result in operation of the liquid hydrogen feedline relief valve.

After MECO confirmed plus 20 seconds, the GPCs interconnect the pneumatic helium and engine helium supply system by opening the center and right out/open interconnect valves and the left in/open interconnect valve if the MPS He INTERCONNECT LEFT, CTR, RIGHT switches on panel R2 are in the GPC position. This connects all 10 helium supply tanks to a common manifold, and it ensures that sufficient helium is available to perform the liquid oxygen and liquid hydrogen propellant dumps.

After external tank separation, approximately 1,700 pounds of propellant are still trapped in the SSMEs, and an additional 3,700 pounds of

propellant remain trapped in the orbiter's MPS feedlines. This 5,400 pounds of propellant represents an overall center-of-gravity shift for the orbiter of approximately 7 inches. Non-nominal center-of-gravity locations can create major guidance problems during entry. The residual liquid oxygen, by far the heavier of the two propellants, poses the greatest impact on center-of-gravity travel.

A hazard from the trapped liquid hydrogen occurs during entry, when any liquid or gaseous hydrogen remaining in the propellant lines may combine with atmospheric oxygen to form a potentially explosive mixture. In addition, if the trapped propellants are not dumped overboard, they will sporadically outgas through the orbiter liquid oxygen and liquid hydrogen feedline relief valves, causing slight vehicle accelerations.

The MPS propellant dumps (LO2 and LH2) occur simultaneously. Both dumps are completely automatic. The helium subsystem is used during the MPS dump to help expel the liquid oxygen from the LO2 manifold. To support this, the GPCs command the center and right helium interconnects to out/open and the left interconnect to in/open at MECO plus 20 seconds. This occurs provided the helium interconnects are in the GPC position.

The MPS dump starts automatically at MECO plus 2 minutes. The MPS dump may be started manually by taking the MPS PRPLT DUMP SEQUENCE switch to START. The earliest that the manual MPS dump can be performed is MECO plus 20 seconds. The only reason that the crew may need to start the dump prior to MECO plus 2 minutes is if the LO2 or LH2 manifold pressure rises unexpectedly. The MPS dump will start automatically prior to MECO plus 2 minutes if the LH2 manifold pressure is greater than 60 psi. The dump takes 2 minutes to complete. The STOP position of the MPS PRPLT DUMP SEQUENCE switch is used to prevent the automatic dump from starting during the ET separation sequence if it is delayed by an RCS leak or feedline disconnect valve failure.

For the LO2 dump, the GPCs command the two liquid oxygen manifold repressurization valves to open (the MAIN PROPULSION SYSTEM MANF PRESS LO2 switch on panel R4 must be

in the GPC position), command each engine controller to open its SSME main oxidizer valve (MOV), and command the three liquid oxygen prevalues to open (the LO2 PREVALVE LEFT, CTR, RIGHT switches on panel R4 must be in the GPC position). The liquid oxygen trapped in the feedline manifolds is expelled under pressure from the helium subsystem through the nozzles of the SSMEs. This is propulsive and typically provides about 9-11 feet-per-second of delta V.

The pressurized liquid oxygen dump continues for 90 seconds. At the end of this period, the GPCs automatically terminate the dump by closing the two liquid oxygen manifold repressurization valves, wait 30 seconds, and then command the engine controllers to close their SSME main oxidizer valve. The three liquid oxygen prevalues remain open during the orbit phase of the flight.

Concurrent with the liquid oxygen dump, the GPCs automatically initiate the MPS liquid hydrogen dump. The GPCs command the two liquid hydrogen fill and drain valves (inboard and outboard) to open, the topping valve to open, and the three LH2 prevalues to open.

The liquid hydrogen trapped in the orbiter feedline manifold is expelled overboard without pressure from the helium subsystem. The liquid hydrogen flows overboard through the inboard and outboard fill and drain valves, and the topping valve for 2 minutes. The GPCs automatically stop the dump by closing the liquid hydrogen outboard fill and drain valve and the topping valve.

At the end of the liquid oxygen and liquid hydrogen dumps, the GPCs close the helium out/open and in/open interconnect valves, provided the He INTERCONNECT LEFT, CTR, RIGHT switches on panel R2 are in the GPC position. After the MPS dump is complete, the SSMEs are gimballed to their entry stow position with the engine nozzles moved inward (toward one another) to reduce aerodynamic heating. Although the gimbals move to an MPS dump position during the external tank separation, the I-loads are currently the same as the entry stow position. At this time, the BODY FLAP lights on panel F2 and F4 turn off. This is the crew's indication that the MPS dump is complete.

In the post OMS-1 procedures, the pilot positions all six MPS ENGINE POWER switches on panel R2 to OFF, which removes all power to the main engine controllers. Once power is removed from the controllers, the main oxidizer valves, which are necessary for the liquid oxygen portion of the dump, can no longer be operated.

The pilot also positions the six He ISOLATION switches and the PNEUMATIC He ISOLATION switch to GPC at this time. When this is done, the helium isolation valves automatically close, but the pneumatic helium isolation valve stays open to operate the pneumatic valves during the vacuum inert. The external tank gaseous hydrogen pressurization manifold is manually vacuum inerted by opening the hydrogen pressurization line vent valve by placing the MAIN PROPULSION SYSTEM H2 PRESS LINE VENT switch on panel R4 to OPEN.

After a 1 minute inert period, the switch is taken back to the GND position, which closes the valve. The hydrogen pressurization vent line valve is electrically activated; however, it is normally closed (spring-loaded to the closed position). Removing power from the valve solenoid closes the valve.

NOTE

After the helium isolation valves are closed, multiple MASTER ALARMS are annunciated as the helium pressure in the regulators bleeds down.

Vacuum Inerting

Fifteen minutes after the MPS dump stops, the GPCs initiate the sequence for vacuum inerting the orbiter's liquid oxygen and liquid hydrogen manifolds. Vacuum inerting allows traces of liquid oxygen and liquid hydrogen trapped in the propellant manifolds to be vented into space.

The LO2 vacuum inerting is accomplished by the GPCs opening the LO2 inboard and outboard fill and drain valves. The LH2 vacuum inerting is accomplished by the GPCs opening the LH2 outboard fill and drain valve and the topping valve (the inboard fill and drain valve was left open at the end of the MPS dump).

The liquid oxygen and hydrogen lines are inerted simultaneously for 1 minute. At the end of the sequence, the GPCs close the LO2 and LH2 outboard fill drain valves. The LO2 and LH2 inboard valves are left open to prevent a pressure buildup between the inboard and outboard valves.

Any GPC or FA MDM failure that will not allow the automatic vacuum inert to function properly will require the crew to perform a manual vacuum inerting procedure.

Following the OMS 2 burn, the LH2 system requires a second vacuum inerting to evacuate all of the residual liquid hydrogen. Residual hydrogen ice sublimates quickly after the OMS 2 burn (and the LH2 manifold pressure rises) due to the vibrations induced by the firing of the OMS engines.

This second vacuum inerting of the LH2 manifold is a crew procedure and is accomplished by opening the LH2 inboard and outboard fill and drain valves for 1 minute. Upon termination of the procedure, the outboard fill and drain valve is closed. The inboard fill and drain valve is left in the open position to prevent a pressure buildup between the inboard and outboard valves.

Post Insertion

In the post insertion portion of the flight, the following switches are powered off since the systems are no longer used: Ascent thrust vector control 1, 2, 3, and 4, EIUs L-C, C-R, R-L, and MECs 1 and 2, all of which are on panel O17. The hardware caution and warning system is reconfigured to inhibit caution and warning on the left, center, and right helium tank pressures and the "A" regulators since the helium system is secured and no longer used. Remember, only the "A" regulators have caution and warning. The LH2 and LO2 manifold pressure caution and warning left enabled to alert the crew to a possible high manifold pressure while on orbit. The engine controller heaters, which are not used, are located on R4 and should remain in the OFF position for the entire mission.

Orbit

All main propulsion systems have been secured by the time post insertion is complete. The MPS orbit procedures deal with off-nominal manifold pressures and are not normally performed. The concern on orbit is possible high manifold pressures due to an incomplete vacuum inert or MPS dump. If high manifold pressures were detected during orbit, the MCC would advise the crew to perform a manual vacuum inert. If the MCC were not available, the manifold pressure caution and warning parameter (left enabled during post insertion) would alert the crew of the high manifold pressure and the malfunction procedure would be performed, relieving the pressure or deducing a manifold pressure transducer failure.

Deorbit Prep

During the deorbit prep timeframe, the MPS hardware caution and warning is reconfigured in preparation for entry. Specifically, the MPS helium "A" regulators are re-enabled since helium will be provided for the entry purge and manifold repressurization. A regulator failed high would alert the crew to the problem and possible over-pressurization of the aft compartment. The manifold pressure caution and warning is inhibited at this time since the manifolds are at a vacuum state and do not need to be monitored during entry. Lastly, the ATVC switches are powered back on to allow the main engine nozzles to return to their entry stow positions, since they typically drift while on orbit.

Entry

The GPCs reconfigure the MPS helium system in preparation for the entry repressurization and purge at the MM 303 transition.

NOTE

Expect the F7 MPS light to be on until MM 303.

Once MM 303 is entered, the GPCs command the PNEUMATIC ISOLATION A and B, and the L ENG He XOVR to OPEN provided the switch is in the GPC position. At the same time, the MPS He INTERCONNECTS CTR and RIGHT

are commanded out/open, while the MPS He INTERCONNECT LEFT is commanded in/open. This feeds all the MPS helium through the left engine, through the PNEUMATICS L ENG He XOVR, and through the pneumatic isolation valves. Also at this time, the LH2 RTLS dump valves go open to insure the LH2 manifold is completely vented prior to entry.

At a ground relative velocity of 5,300 feet-per-second (between 130,000 and 110,000 feet altitude, depending on the entry trajectory), the helium blowdown valves open which allows helium to continuously purge the aft compartment, OMS pods, and the LH2 umbilical cavity area. There is no manual control of the blowdown valves. The blowdown purge continues for 650 seconds and typically ends a few minutes after touchdown. At ground relative velocity of 5,300 fps, the MAIN PROPULSION SYSTEM MANF PRESS LH2 & LO2 valves are commanded OPEN, provided the switches on panel R4 are in the GPC position. This allows the LH2 and LO2 manifolds to be pressurized, preventing contaminants from entering the manifolds during entry. Removing contamination from the manifolds or feedlines can be a long and costly process since it involves disassembly of the affected parts. The manifold repress continues until the ground crews install the throat plugs in the main engine nozzles. The LH2 backup dump valves and the LO2 prevalues go closed at the 5,300 feet-per-second velocity.

RTLS Abort Propellant Dump Sequence

For RTLS abort, immediately post-MECO, the valve sequencing is the same as for a nominal MECO. After ~25 seconds, the vehicle enters MM 602 and the RTLS dump begins. The RTLS entry dump differs only slightly from the nominal entry dump.

During the RTLS dump, liquid oxygen is initially dumped through the LO2 prevalues and through the main oxidizer valves (MOV's) in the SSMEs. When the dynamic pressure is above 20 (plus an I-load) psf, there is a subsequent venting through the liquid oxygen fill and drain valves. This dump is done without helium pressurization and relies on the self-boiling properties of the liquid oxygen. In the RTLS liquid oxygen dump, the GPCs

terminate the dump whenever the ground relative velocity drops below 3,800 feet-per-second. The liquid oxygen system is repressurized when the 3,800 feet-per-second velocity is attained, and repressurization continues as in a nominal entry.

LH2 manifold is expelled in the same manner as the nominal post-MECO dump (with one exception) until a ground relative velocity of 3,800 feet per second, at which time the valves are closed. The only exception is that the RTLS LH2 dump is assisted by helium pressurization through the RTLS manifold pressurization valves for 2 minutes, beginning at RTLS dump start.

The entry repressurization and the aft compartment surge also occur during the RTLS.

The helium blowdown valves are opened at Vrel 5,300 feet-per-second, followed by the manifold repress valves opening at 3,800 feet-per-second. As with the nominal entry, the blowdown valves remain open until a few minutes after landing.

TAL Abort Propellant Dump Sequence

For a TAL abort, the entire dump sequence is the same as that for RTLS. On the TAL, the dump begins at the transition to MM 304.

The LO2 is also dumped at the MM 304 transition through the LO2 prevalues and then out the MOVs, just as in the nominal dump. To assist in removing the LO2 propellants, the LO2 inboard and outboard fill drains are opened at a Vrel of 20,000 feet per second if the LO2 manifold pressure is less than 30 psi.

MPS Caution and Warning Summary

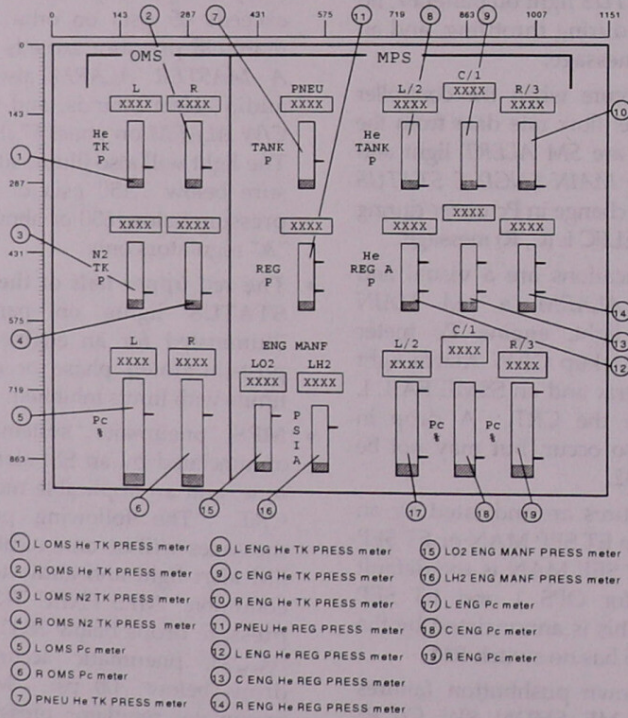
- **Data path failure** is the loss of both the primary and secondary data paths from an engine. Data path failure indications include an *SM ALERT* light and audio tone, a yellow *MAIN ENGINE STATUS* light on panel F7, the engine Pc meter on panel F7 driven to zero, and an *MPS DATA L (C, R)* message.
- **Command path failure** is the loss or rejection of GPC commands to the main engine controller. The engine will no longer throttle or accept commands. Indications include an *SM ALERT* light and audio tone, yellow *MAIN ENGINE STATUS* light on panel F7, no change in the Pc meter during throttling, and an *MPS CMD L (C, R)* message. This message will only annunciate on the *PASS* pre-BFS engage.
- **Hydraulic lockup** occurs when any of the five hydraulically actuated engine valves fails to achieve its commanded position; the engine does not throttle. Indications are an *SM ALERT* light and audio tone, a yellow *MAIN ENGINE STATUS* light on panel F7, no change in Pc meter during throttling, and an *MPS HYD L (C, R)* message.
- **Electrical lockup** occurs when the controller loses all Pc or all fuel flow rate data from the engine. Indications are *SM ALERT* light and audio tone, a yellow *MAIN ENGINE STATUS* light on panel F7, no change in Pc meter during throttling, and *MPS ELEC L (C, R)* message.
- **Engine failure** indications are a visual and audible *MASTER ALARM*, a red *MAIN ENGINE STATUS* light, engine Pc meter reading of zero, a Backup C&W Alarm light on the F7 C/W matrix and an *SSME FAIL L (C, R)* message on the CRT. A drop in acceleration will also occur, but may not be detectable in MM 102.
- **ET SEP** switch failures are indicated by an SM alert light and an *ET SEP MAN* or *ET SEP AUTO* message. *ET SEP MAN* is the default software position for OPS 1 and *ET SEP AUTO* for OPS 6. This is annunciated by the *PASS* only since BFS has no switch RM.
- Main engine shutdown pushbutton failures may result in an *ME SHDN SW C(L,R)* message and an SM alert light and tone. This is annunciated by the *PASS* only since BFS has no switch RM.
- **Liquid hydrogen ullage pressure below 28.0 psia** is indicated by an *SM ALERT* light and audio tone, one or more down arrows by the LH2 pressure readings on the BFS GNC SYS SUMM 1 display, and an *MPS LH2/O2 ULL* message on the BFS CRT.
- **High liquid hydrogen or liquid oxygen manifold pressure** indications are: a visual and audible *MASTER ALARM*, an up arrow by the applicable *MANF P* reading on the BFS GNC SYS SUMM 1 display, and an *MPS LH2/LO2 MANF* message on the CRT. The limits are 249 psia for liquid oxygen, and 65 psia for liquid hydrogen.
- **Helium tank leaks** or regulator failure are indicated by an *SM ALERT* light and audio tone, an up arrow by the applicable *dP/dT* or regulator on the BFS GNC SYS SUMM 1 display, and an *MPS He P C (L, R)* message.
- **ET separation inhibit** is indicated by an *SM ALERT* light and audio tone and an *ET SEP INH* message.
- **The MPS** light on panel F7 will illuminate (red) if liquid hydrogen manifold pressure exceeds 65 psia on orbit or liquid oxygen manifold pressure exceeds 249 psia on orbit. A *MASTER ALARM* also illuminates, an audio alarm sounds, and the red *BACKUP C/W ALARM* on panel F7 illuminates as well. The light will also illuminate for helium pressure below 1,150 psia or regulated helium pressure below 680 or above 810 psia on the "A" regulators only.
- **The red upper half of the MAIN ENGINE STATUS** lights on panel F7 will be illuminated for an engine in shutdown or post-shutdown phase or exceeding redline limits with limits inhibited.
- **MPS** pneumatic system anomalies are annunciated by an SM alert light and audio tone, and an applicable message on the BFS CRT. The following pneumatic system messages will be annunciated along with an SM alert light and audio tone for the given condition. *MPS PNEU TK*, pneumatic tank pressure drops below 3800 psi. *MPS PNEU ACUM*, pneumatic accumulator pressure drops below 700 psi. *MPS PNEU REG*, pneumatic regulator pressure drops below 700 psi or goes above 810 psi.

MPS Caution and Warning Summary (continued)

O ₂ PRESS	H ₂ PRESS	FUEL CELL REAC (R)	FUEL CELL STACK TEMP	FUEL CELL PUMP
CABIN ATM (R)	O ₂ HEATER TEMP	MAIN BUS UNDERVOLT	AC VOLTAGE	AC OVERLOAD
FREON LOOP	AV BAY/ CABIN AIR	IMU	FWD RCS (R)	RCS JET
H ₂ O LOOP	RGA/ACCEL	AIR DATA (R)	LEFT RCS	RIGHT RCS (R)
_____	LEFT RHC (R)	RIGHT/AFT RHC	LEFT OMS (R)	RIGHT OMS
PAYLOAD WARNING (R)	GPC	FCS (R) SATURATION	OMS KIT	OMS TVC (R)
PAYLOAD CAUTION	PRIMARY C/W	FCS CHANNEL	MPS (R)	_____
BACKUP C/W ALARM (R)	APU TEMP	APU OVERSPEED	APU UNDERSPEED	HYD PRESS

633.cvs

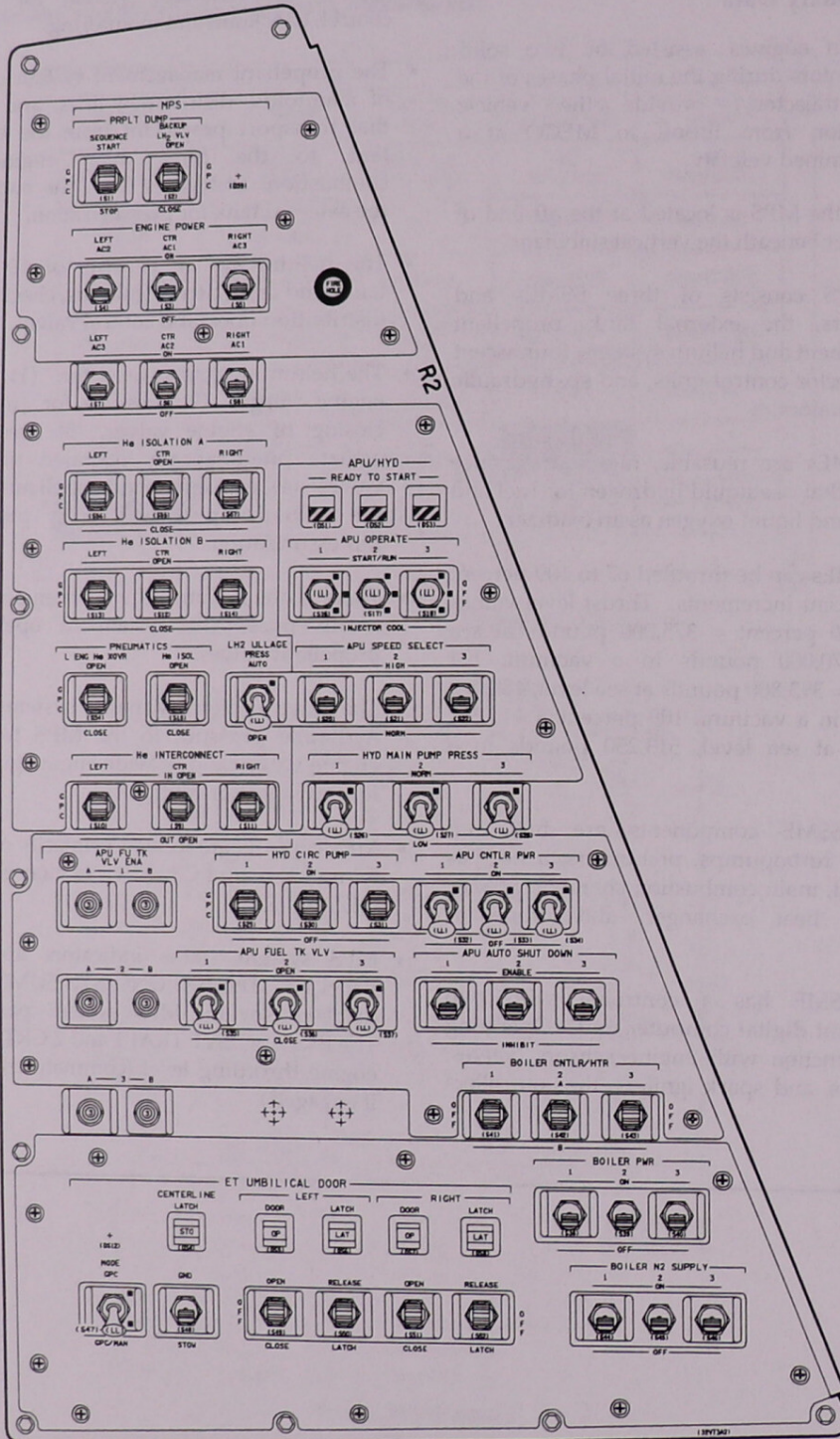
MPS Caution and Warning Lights on Panel F7



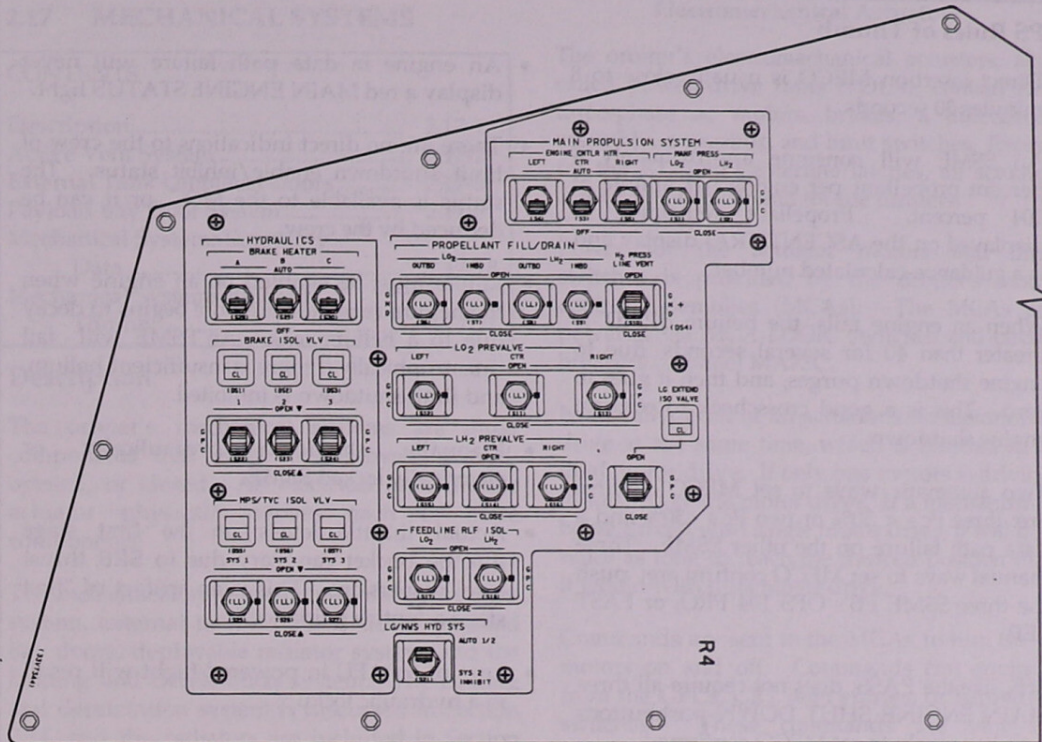
OMS/MPS Display

MPS Summary Data

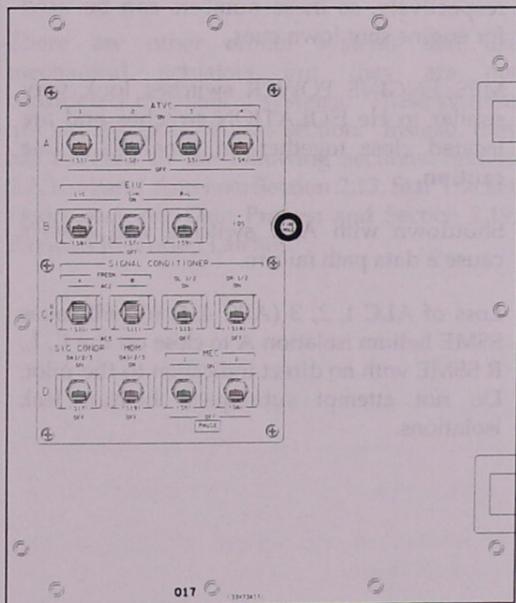
- The main engines, assisted by two solid rocket motors during the initial phases of the ascent trajectory, provide the vehicle acceleration from lift-off to MECO at a predetermined velocity.
- Most of the MPS is located at the aft end of the orbiter beneath the vertical stabilizer.
- The MPS consists of three SSMEs and controllers, the external tank, propellant management and helium systems, four ascent thrust vector control units, and six hydraulic servoactuators.
- The SSMEs are reusable, high-performance engines that use liquid hydrogen for fuel and cooling and liquid oxygen as an oxidizer.
- The SSMEs can be throttled 67 to 109 percent in 1 percent increments. Thrust level values are: 100 percent = 375,000 pounds at sea level, 470,000 pounds in a vacuum; 104 percent = 393,800 pounds at sea level, 488,000 pounds in a vacuum; 109 percent = 417,300 pounds at sea level, 513,250 pounds in a vacuum.
- Major SSME components are fuel and oxidizer turbopumps, preburners, a hot gas manifold, main combustion chamber, nozzle, oxidizer heat exchanger, and propellant valves.
- Each SSME has a controller with two redundant digital computer units. Operating in conjunction with engine sensors, valves, actuators, and spark igniters, the controllers form a self-contained system for engine control, checkout, and monitoring.
- The propellant management system consists of manifolds, distribution lines, and valves that transport propellant from the external tank to the three main engines for combustion, and gases from the engines to the external tank for pressurization.
- The helium system consists of 10 supply tanks and associated regulators, check valves, distribution lines, and control valves.
- The helium system is used for: (1) in-flight engine purges, (2) pressure for emergency closing of engine valves, (3) pressure to actuate pneumatically operated propellant valves, (4) expelling the propellants during the MPS dump and (5) entry purge and repressurization.
- There is one helium system per engine, plus a fourth pneumatic system to operate the propellant valves.
- The three orbiter hydraulic systems supply hydraulic pressure to the MPS to actuate engine valves and provide engine gimbaling for thrust vector control.
- MPS controls are located primarily on panels R2 and R4, and C3 with a few on panels F7, O17, and R1.
- MPS system status indicators appear on panel F7. The BFS GNC SYS SUMM 1 CRT displays several MPS system parameters. The BFS ASCENT TRAJ 1 and 2 CRT displays engine throttling level (commanded by BFS, if engaged).



Panel R2



Panel R4



Panel O17

1011/ /018 GNC SYS SUMM 1 5 000/02:46:03
BFS 000/00:00:00

SURF	POS	MDM	DPS	1	2	3	4			
L	OB		MDM	FF						
R	IB			FA						
	OB			PL						
AIL										
RUD										
SPD	BRK									
BDY	FLP									
				FCS	CH	1	2	3	4	
MPS										
HE	TK	P	L	C	R	NAV	1	2	3	4
			4280	4230	4240	IMU				
REG	P	A	784	768	768	TAC				
		B	776	766	770	ADTA				
dp/dt										
ULL	P	LH2	42.5	42.7	42.9	MPS	PNEU	HE	P	
		LO2	21.1	21.0	20.8		TK		4350	
							REG		798	
							ACUM		760	
GH2	OUT	P	701	501	401	MANF	P	LH2	46	
GO2	OUT	T	791	971	701			LO2	110	

BFS GNC SYS SSUMM 1

MPS Rules of Thumb

- Direct insertion MECO is usually close to 8 minutes 30 seconds.
- An SSME will consume approximately 4 percent propellant per engine per minute at 104 percent. Propellant remaining is displayed on the ASCENT TRAJ display and is a guidance-calculated number.
- When an engine fails, the helium dP/dT is greater than 40 for several seconds, due to engine shutdown purges, and then it goes to zero. This is a good crosscheck to confirm engine shutdown.
- Two automatic ways to set MECO confirm are: three Pc's < 30% or two Pc's < 30% and a data path failure on the other SSME. Three manual ways to set MECO confirm are: push the three SSME PB's OPS 104 PRO, or FAST SEP.
- BFS, like the PASS, does not require all three MAIN ENGINE SHUT DOWN pushbuttons simultaneously to set MECO confirmed.
- To shut an engine down, both contacts on the MAIN ENGINE SHUT DOWN pushbutton must be good. If one contact is commfaulted, the button can be used to set the safing flag on an engine that failed under a data path failure. If a contact is power-failed, the button is inoperative to shutdown an engine but can be used to safe an engine that shuts down behind a data path if the corresponding FF is commfaulted.
- If a MAIN ENGINE SHUT DOWN pushbutton is commfaulted in BFS, or failed otherwise, it is inoperative.
- An SSME command path failure must always be shut down manually with the A/C switches and PBs.
- An SSME FAIL C (L, R) message indicates that the GNC software has recognized an engine shut down. Two of these messages will enable single engine roll control mode.
- An engine in data path failure will never display a red MAIN ENGINE STATUS light.
- There are no direct indications to the crew of limit shutdown enable/inhibit status. The status is available to the MCC, or it can be deduced by the crew.
- Limits must be enabled on an engine when the helium regulator pressure begins to decay due to a helium leak. An SSME will fail catastrophically if there is insufficient helium, and limit shutdown is inhibited.
- Manually shutdown hydraulically or electrically locked SSME.
- Actual throttle levels on the first stage throttle bucket can vary due to SRB thrust level dispersions. This is an artifact of "first stage adaptive guidance."
- Loss of an APU in powered flight will result in a hydraulic lockup.
- 23 k, 22.5 k, and 24.5 k V_1 are about 30 seconds before MECO on the three-engine uphill, TAL, and two-engine uphill cases, respectively, so these numbers can be used for engine shutdown cues.
- MPS ENGINE POWER switches look very similar to He ISOLATION switches and are located close together on panel R2. **Use caution.**
- Shutdown with A/C switches will always cause a data path failure.
- Loss of ALC 1, 2, 3 (APC 4, 5, 6) will cause SSME helium isolation A to close on the C, L, R SSME with no direct indication to the pilot. Do not attempt subsequent helium leak isolations.

2.17 MECHANICAL SYSTEMS

CONTENTS

Description	2.17-1
Active Vent System	2.17-2
External Tank Umbilical Doors	2.17-5
Payload Bay Door System	2.17-9
Mechanical Systems Summary	
Data	2.17-18
Mechanical Systems Rules of	
Thumb	2.17-21

Description

The orbiter's mechanical systems are those components that must be deployed, stowed, opened, or closed. An electrical or hydraulic actuator physically moves each of these components.

The mechanical systems include the active vent system, external tank umbilical doors, payload bay doors, deployable radiator system, and the landing and deceleration system. The landing and deceleration system is discussed in Section 2.14, and the radiators are included in Section 2.9. Descriptions of the remaining systems, as well as their operations are discussed in this section.

There are other orbiter systems that use mechanical actuators but they are not considered mechanical systems. These systems are not discussed in this section. Instead, they are covered in the following sections: Section 2.4, Ku-band Antenna; Section 2.13, Star Tracker Doors and Air Data Probes; and Section 2.19, Payload Retention Latches.

Electromechanical Actuators

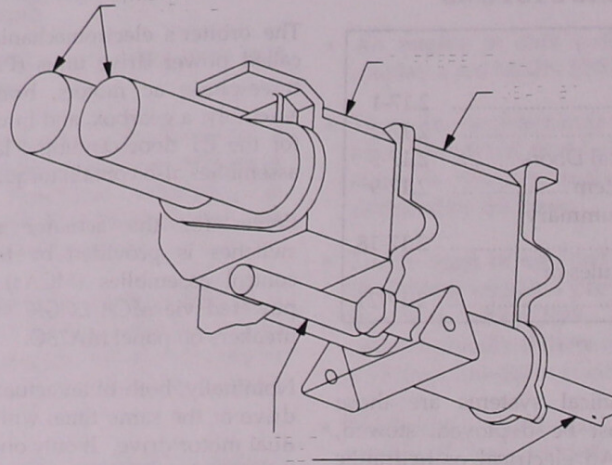
The orbiter's electromechanical actuators, also called power drive units (PDUs), contain two three-phase ac motors, brakes, a differential assembly, a gearbox, and limit switches. Except for the ET door centerline latches, all actuator assemblies also contain torque limiters.

Power for the actuator motors and limit switches is provided by the orbiter's motor control assemblies (MCAs). The MCAs are powered via MCA LOGIC switches and circuit breakers on panel MA73C.

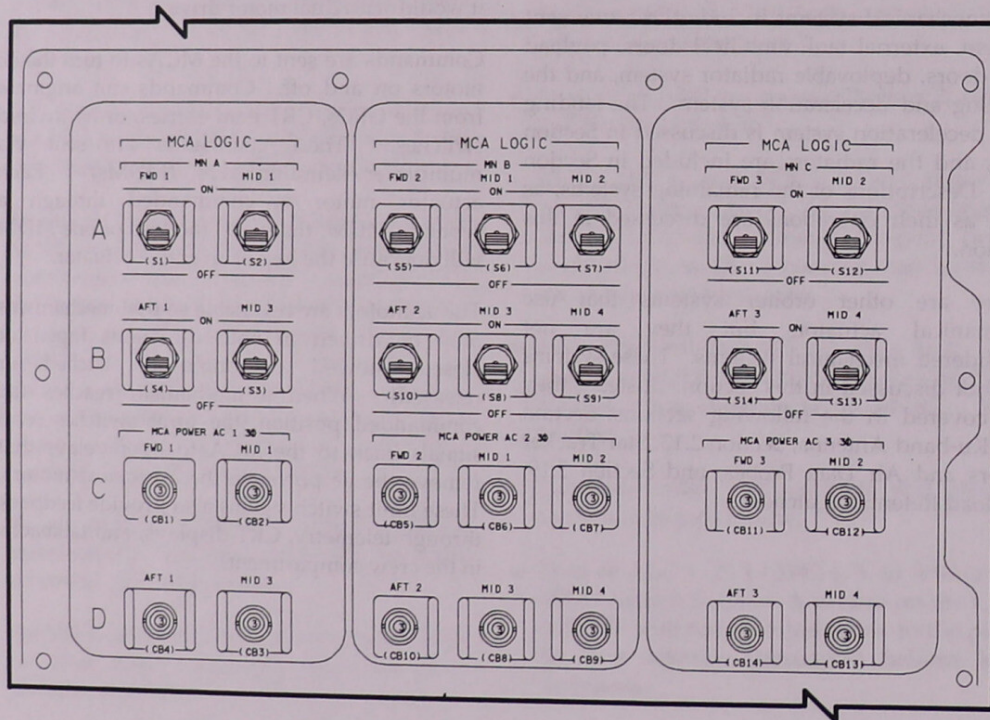
Nominally, both of an actuator's ac motors will drive at the same time, which is referred to as dual motor drive. If only one motor is driving, it is called single motor drive. If a mechanism is being driven with single motor drive, it will take twice as long to reach the desired position than it would with dual motor drive.

Commands are sent to the MCAs to turn the ac motors on and off. Commands can originate from the GPCs, CRT item entries, or hardwired switches. These commands are sent via multiplexer/demultiplexers (MDMs). Each actuator motor is commanded through a separate MDM; therefore, the loss of one MDM will not cause the loss of an entire actuator.

The ac motors are reversible so that mechanisms may be driven in both directions (open or closed, stowed or deployed, latched or released). When a mechanism reaches the commanded position, the limit switches send signals back to the MCA to open relays that remove the ac power to the associated motors. These limit switch signals also provide feedback through telemetry, CRT displays, and talkbacks in the crew compartment.



Electromechanical Actuator



MCA Controls on Panel MA73A

Active Vent System

The active vent system (AVS) equalizes the orbiter's unpressurized compartments to the ambient environment as the orbiter travels from

the pressurized atmosphere of Earth to the vacuum of space.

The AVS consists of 18 vent ports (9 on each side) in the orbiter fuselage. For identification, each door is numbered forward to aft.

Fourteen of the vent ports/doors are functional. An engineering analysis showed that vent ports 3, 5, and 6 provide sufficient venting of the payload bay and mid-fuselage compartments. Because of this, vent ports 4 and 7 were permanently capped shut on both sides of Atlantis, Columbia, and Discovery. The associated actuators and linkages also were removed. Endeavour did not have the equipment installed.

Each vent door has a pressure seal and a thermal seal, and is driven inward by its associated electromechanical actuator. The vent openings are sized according to the volume to be vented.

The doors for the vent ports are opened and closed during the mission to perform the functions of the AVS. Normal opening or closing time is 5 seconds for each vent door, with dual motor drive.

Some of the vent doors (1, 2, 8, and 9) also have intermediate positions to provide the capability to purge the unpressurized compartments with dry air or nitrogen. Purge operations are performed on the ground to provide thermal conditioning, moisture control, and to exclude hazardous gases or contaminants.

Vent Operations

The vent doors are controlled by a GNC software sequence that can be started by a master timing unit, major mode transition, velocity, or CRT item entry.

During countdown, the vent doors are in their purge positions until T-28 seconds, when the OPEN sequence is automatically called by the redundant set launch sequencer (RSLs). The vent doors are commanded open in a staggered sequence at approximately 2.5-second intervals.

The vent doors remain open during ascent, orbital insertion, and all on-orbit phases. During entry preparation, the crew performs a CRT item entry on GNC SPEC 51 OVERRIDE to close the vent doors. At this time, all the vent doors are commanded closed and then port vents 1, 2, 8, and 9 are automatically reopened. These vents are left open to vent any hazardous gases during the deorbit burn and to prevent vehicle overpressurization should a rapid OMS/RCS leak occur. These vents are automatically closed at the MM304 transition.

PASS/BFS		
Major Mode (RTLS)	Command	
	OPEN ITEM 43	CLOSE ITEM 44
301	All doors open	All doors close; then port 1, 2, 8, 9 Auto reopen
302	All doors open	All doors close
303	All doors open	All doors close
304	Port 1, 2, 8, 9 open	All doors close
305	All doors open	Command not available until rollout flag set
(602)	All doors open	All doors close
(603)	All doors open	Command not available until rollout flag set

Manual Vent Door Command Capability during Entry

External Tank Umbilical Doors

Electrical and fuel umbilicals between the external tank (ET) and the orbiter enter the shuttle through two aft umbilical openings located on the underside of the orbiter. These umbilical cavities contain the orbiter/ET attachment points and the fuel and electrical disconnects. The left cavity contains the liquid hydrogen umbilical, and the right cavity contains the liquid oxygen umbilical.

Each umbilical cavity has an associated ET door. During ascent, this door is open to allow the umbilical connections between the orbiter and the ET. After the ET separates from the orbiter, the two aft umbilical openings are exposed. The ET doors are closed to cover these exposed areas and to shielding them from entry heating.

A closeout curtain is installed at each of the orbiter/external tank umbilicals. After ET separation, the residual liquid oxygen in the main propulsion system is dumped through the three SSMEs and the residual liquid hydrogen is dumped overboard. The umbilical curtain prevents hazardous gases (gaseous oxygen and hydrogen) from entering the orbiter aft fuselage through the umbilical openings before the umbilical doors are closed.

Each umbilical door, which is approximately 50 in², is covered with reusable thermal protection system

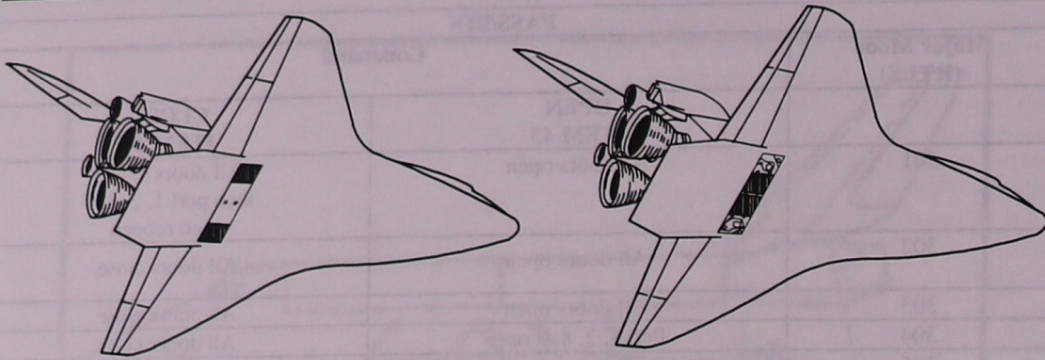
tiles. Additionally, each door has an aerothermal barrier that requires approximately 6 psi to seal it with adjacent thermal protection tiles..

There are two types of latches associated with the ET doors, centerline latches and uplock latches. The centerline latches hold the ET doors open during ascent, and the uplock latches secure the doors when they are closed.

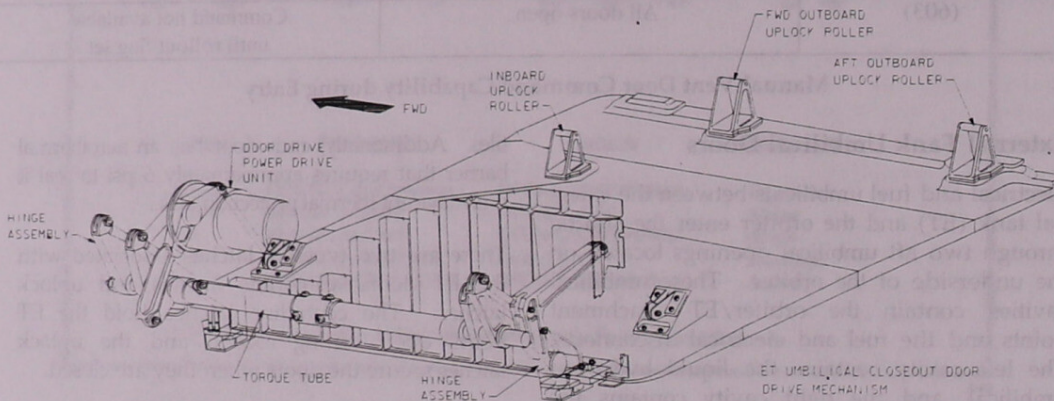
The centerline latches must be disengaged from the doors before both ET doors can be closed. In the latched position, each centerline latch fits into a notch on the outer edge of the left and right ET doors. When stowed, the two centerline latches rotate and retract into the body of the orbiter so that they are flush with the orbiter thermal protection system mold line.

After the ET doors are closed, uplock latches pull the doors fully closed, compressing them against aerothermal seals and positioning them flush with the orbiter body. These latches secure each door closed and prevent them from vibrating or opening during reentry.

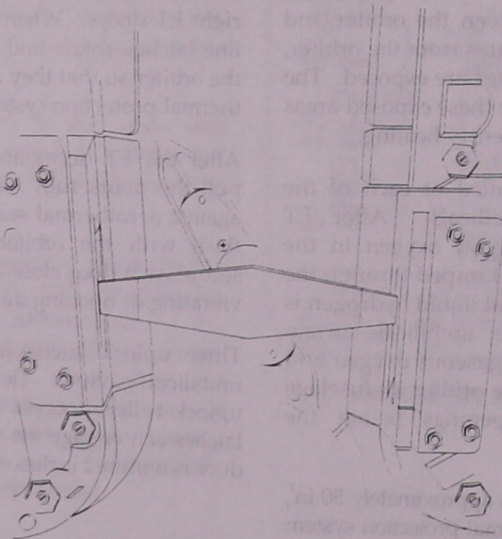
Three uplock latches are located inside each umbilical cavity. The latches engage three uplock rollers located on each ET door. The latches can engage the rollers as long as the ET door is within 2 inches of being closed.



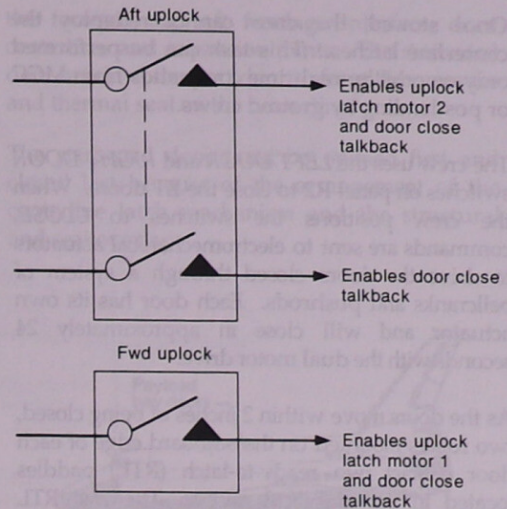
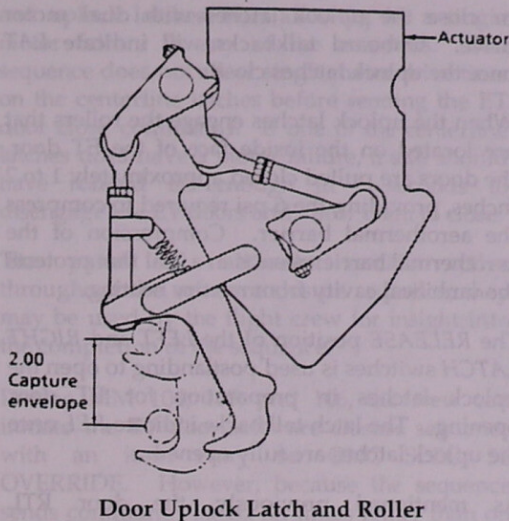
ET Door Positions



Right Side ET Umbilical Door



Centerline Latch Movement



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Uplock Latch Limit Switches

CAUTION

Thermal damage will occur if the ET doors are not fully latched flush with the orbiter body.

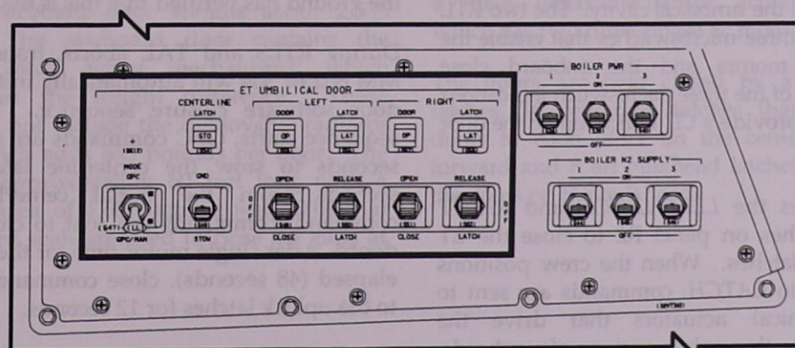
ET Door Operations

The ET doors are closed post OMS-1 burn after MPS vacuum inerting. The doors and latches must be sequenced in an orderly manner to prevent damage. First, the centerline latches are stowed, then the doors are closed, and finally the doors are latched.

The doors are nominally closed by the crew with the *ET UMBILICAL DOOR* switches located on panel R2. The *MODE* switch must be in the *GPC/MAN* position to enable manual crew control with the panel R2 switches.

The crew stows the centerline latches by taking the *CENTERLINE LATCH* switch to the *STOW* position. Each centerline latch is driven by one electromechanical actuator. Nominally, 6 seconds are required to stow the centerline latches with dual motor drive. The *GND* position of this switch removes commands from the centerline latch motors.

The talkback above the *CENTERLINE LATCH* switch has two positions. The microswitches that drive the talkback are located within the centerline latch drive mechanisms and are activated based on the position of the latches. The talkback will be barberpole when the latches are deployed or in transit, and will be *STO* when the latches are stowed.



ET UMBILICAL DOOR Controls on Panel R2

Once stowed, the crew cannot redeploy the centerline latches. This task can be performed only on orbit by real-time commands from MCC or postlanding by ground crews.

The crew uses the *LEFT DOOR* and *RIGHT DOOR* switches on panel R2 to close the ET doors. When the crew positions the switches to *CLOSE*, commands are sent to electromechanical actuators to drive the doors closed through a system of bellcranks and pushrods. Each door has its own actuator and will close in approximately 24 seconds with the dual motor drive.

As the doors move within 2 inches of being closed, two rollers mounted on the outboard edge of each door contact two ready-to-latch (RTL) paddles located in the umbilical cavity. The two RTL paddles drive three RTL microswitches that enable the uplock latch motors and drive the *CL* position of the *DOOR* talkback. Two of the three microswitch indications are needed to provide a *CL* indication on the door drive talkback. Each door also has two open microswitches that drive the *OP* position of the door talkback.

The *ET UMBILICAL DOOR LEFT DOOR* and *RIGHT DOOR* switches on panel R2 are used by the crew to close the ET doors. Positioning the switches to *CLOSE* provides electrical power to redundant ac reversible motors, which drive the doors through a system of bellcranks and pushrods. With both motors in operation, the doors will close in approximately 24 seconds. As the doors move within 2 inches of being closed, two operations take place. First, microswitches within the door power drive unit inhibit power from the door drive motors. Second, two rollers mounted on the outboard edge of each door contact two RTL paddles in the umbilical cavity. The two RTL paddles drive three microswitches that enable the uplock latch motors and the onboard close talkback. Two of the three microswitch indications are needed to provide a *CL* indication on the door drive talkback.

The crew uses the *LEFT LATCH* and *RIGHT LATCH* switches on panel R2 to close the ET door uplock latches. When the crew positions the switches to *LATCH*, commands are sent to electromechanical actuators that drive the uplock latches through a system of pushrods. Each set of three uplock latches is driven by one actuator. Nominally, it takes 6 seconds to open

or close the uplock latches with dual motor drive. Onboard talkbacks will indicate *LAT* once the uplock latches close.

When the uplock latches engage the rollers that are located on the inside face of the ET door, the doors are pulled closed approximately 1 to 2 inches, providing the 6 psi required to compress the aerothermal barrier. Compression of the aerothermal barrier results in a seal that protects the umbilical cavity from reentry heating.

The *RELEASE* position of the *LEFT* and *RIGHT LATCH* switches is used postlanding to open the uplock latches in preparation for ET door opening. The latch talkbacks indicate *REL* once the uplock latches are fully opened.

As mentioned previously, the door RTL microswitches drive the door *CL* talkback and enable the uplock latch motors. If an ET door closes but microswitch failures prevent the uplock latches from being enabled, an override is available.

The system is designed so that the *LEFT LATCH* switch can override the right RTL microswitches, and the *RIGHT LATCH* switch can override the left RTL microswitches. The override is performed by placing both the *LEFT LATCH* and *RIGHT LATCH* switches in the *LATCH* position. By doing this, one switch overrides the missing microswitch indications, enabling the uplock latch motors, while the other switch sends its latch command.

Mission Control has additional telemetry to determine if missing RTL indications have prevented the uplock latches from being enabled. The crew should not attempt this override until the ground has verified that this is the case.

During RTLS and TAL aborts, transition into MM 602 or 304 will automatically initiate an ET door software closure sequence. When the sequence starts, GPC commands are sent for 12 seconds to stow the centerline latches. Six seconds from the initial centerline latch command, commands are sent to close the ET doors. After single motor time for the doors has elapsed (48 seconds), close commands are sent to the uplock latches for 12 seconds.

Note that the automatic closure sequence doubles the normal drive times on the doors

and unlock latches, thus allowing for a single motor failure in any of the actuators. The sequence does not allow single motor drive time on the centerline latches before sending the ET door close commands. If one of the centerline latches does have a motor failure, it still should have rotated far enough in 6 seconds to disengage the ET doors and allow them to close.

The panel R2 talkbacks remain active throughout the software closure sequence; they may be used by the flight crew for insight into the completion of the sequence.

During MM 104, 105, and 106, the crew can initiate the ET door software closure sequence with an item entry on GNC SPEC 51 OVERRIDE. However, because the sequence sends commands based on times rather than on microswitch indications, crew initiation of the automatic sequence should only be considered as a backup method during an AOA.

Postlanding, the crew opens the ET umbilical doors using the panel R2 switches, which gives the ground crews access to the umbilical cavities.

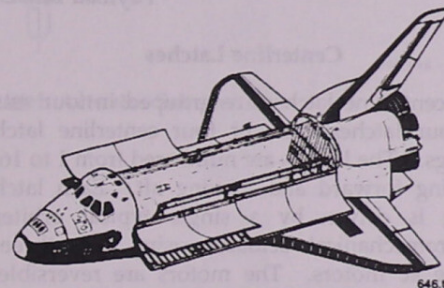
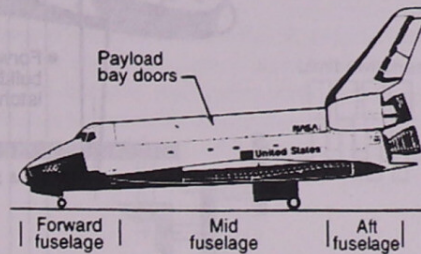
Payload Bay Door System

The payload bay doors provide an opening for payload deployment from and retrieval into the payload bay. The doors provide structural support for the orbiter midbody, and they house the ECLSS radiators that transfer heat from the vehicle to space.

There are two doors, port and starboard. Each door consists of five segments interconnected by expansion joints. The port door with attached systems weighs approximately 2,375 pounds, and the starboard door weighs about 2,535 pounds. The starboard door contains the centerline latch active mechanisms, which accounts for the weight difference. These weights do not include the deployable radiator system, which adds 833 pounds per door. The doors are approximately 60 feet long with a combined area of 1,600 square feet. Thermal and pressure seals are used to close the gaps at

the forward and aft fuselage interface, door centerline, and expansion joints. The starboard door overlaps the port door to form the pressure and thermal seal on the centerline.

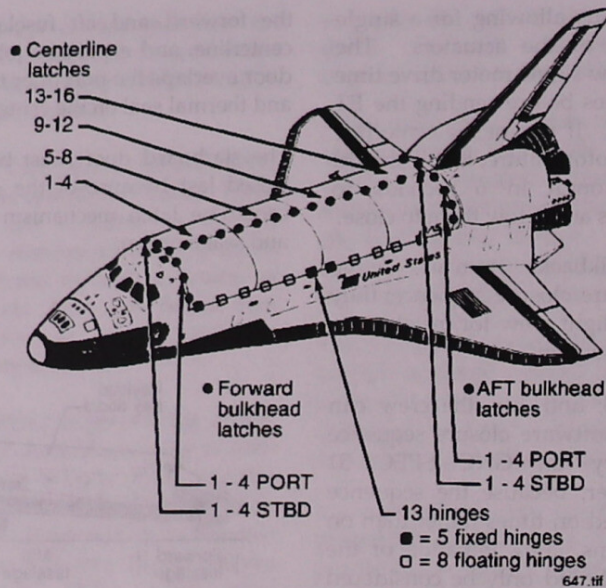
The starboard door must be opened first and closed last because of the arrangement of the centerline latch mechanism and the structural and seal overlap.



Payload Bay Doors Location

Each door is connected to the midfuselage by 13 hinges; i.e., 5 shear hinges (nonmoving hinges) and 8 floating hinges (moving hinges that allow for thermal expansion and contraction of the doors). Each door is driven open and closed by a single electromechanical actuator, each of which has two three-phase ac motors.

The doors are held closed by a total of 32 latches, 16 centerline latches that secure the doors to each other on the centerline and 8 forward and 8 aft bulkhead latches that secure the doors on the bulkheads.



647.tif
Payload Bay Door Latch Locations

Centerline Latches

The centerline latches are grouped in four sets of four latches each, or four centerline latch "gangs." The latches are numbered from 1 to 16, starting forward and moving aft. Each latch gang is driven by a single typical orbiter electromechanical actuator using two three-phase ac motors. The motors are reversible, which allows the crew to latch or unlatch the doors from each other at the centerline.

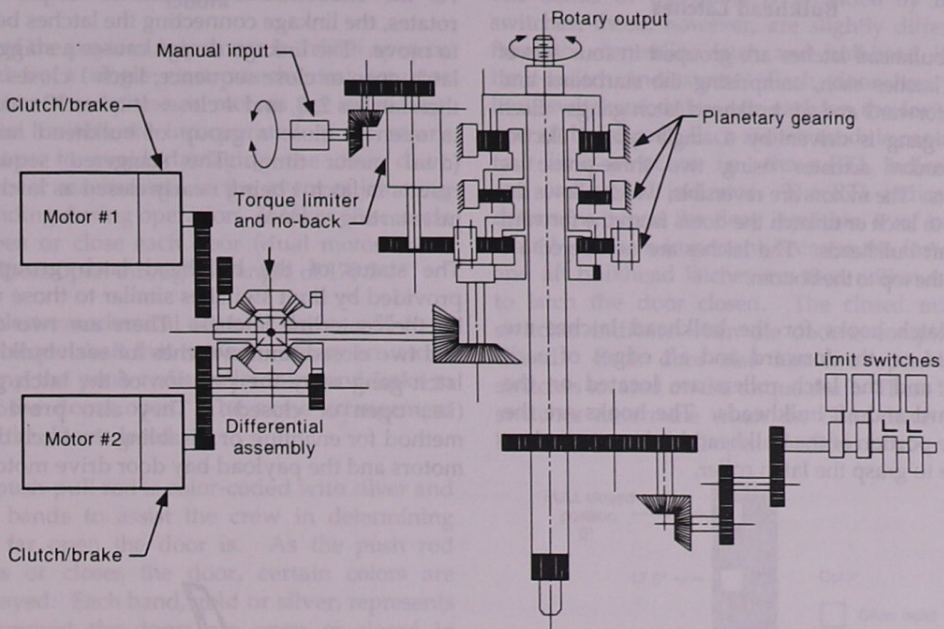
The starboard door contains the centerline latch hooks and the port door contains the centerline latch rollers. The hooks are the active portion of the centerline latch system; they rotate to grasp the latch rollers.

The starboard door contains the centerline latch hooks, and the port door contains the centerline

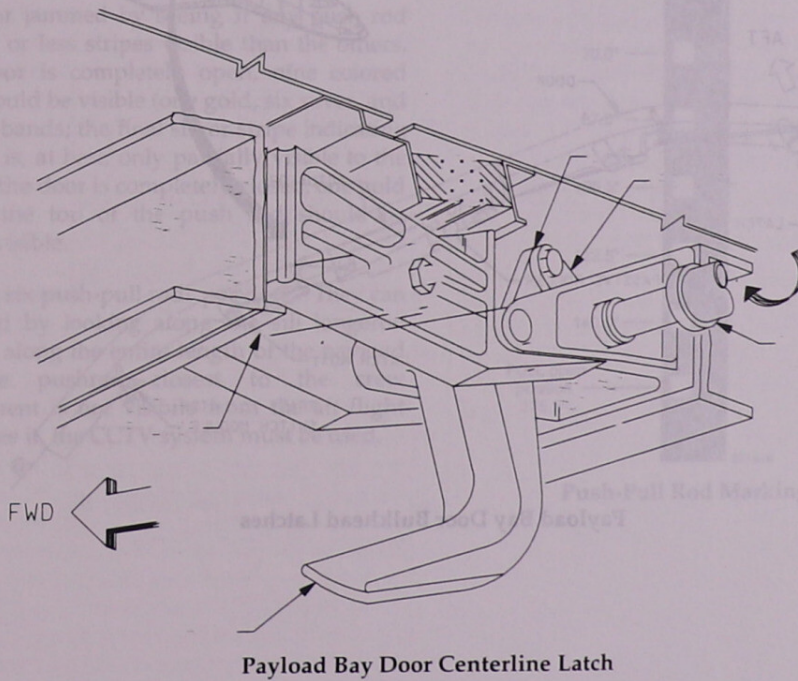
latch rollers. The hooks are the active portion of the centerline latch system; they rotate to grasp the latch rollers.

As the electromechanical actuator torque shaft rotates, the bellcrank and link cause the hook to rotate closed or open, engaging the latch roller on the port door. It takes 20 seconds to open or close a gang of centerline latches (dual motor time).

The status of the centerline latch gang is provided by limit switches. Two open and two closed limit switches are associated with each centerline latch gang. These limit switch indicators relay the position of the latch gang (i.e., latch gang is open or closed). They also provide a method for enabling and disabling latch drive motors.



Payload Bay Door Centerline Latch Actuator Schematic



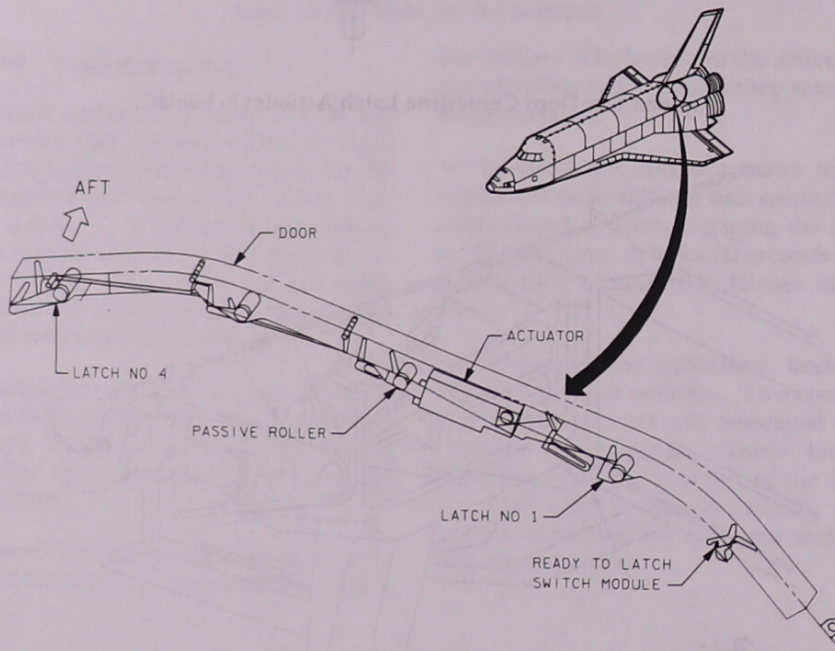
Bulkhead Latches

The bulkhead latches are grouped in four sets of four latches each, comprising the starboard and port forward and aft bulkhead latch gangs. Each latch gang is driven by a single typical electromechanical actuator using two three-phase ac motors. The motors are reversible, which allows the crew to latch or unlatch the doors from the forward and aft bulkheads. The latches are numbered 1-4 from the top to the bottom.

The latch hooks for the bulkhead latches are located on the forward and aft edges of each door, and the latch rollers are located on the forward and aft bulkheads. The hooks are the active portion of the bulkhead latch system; they rotate to grasp the latch roller.

As the electromechanical actuator torque shaft rotates, the linkage connecting the latches begins to move. The linkage design causes a staggered latch open or close sequence; latch 1 closes first, then latches 2, 3, and 4 close. It takes 30 seconds to open or close a group of bulkhead latches (dual motor time). The staggered sequence results in latch 1 being nearly closed as latch 4 is just starting to close.

The status of the bulkhead latch groups is provided by limit switches similar to those used by the centerline latches. There are two open and two closed limit switches for each bulkhead latch gang relay the position of the latch gang (i.e., open or closed). They also provide a method for enabling or disabling the latch drive motors and the payload bay door drive motors.



Payload Bay Door Bulkhead Latches

Doors

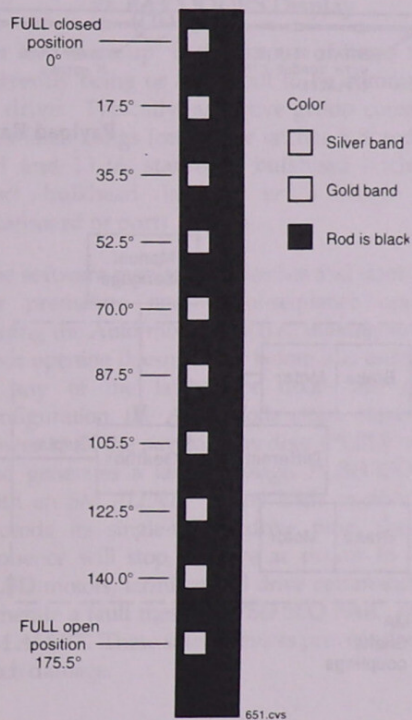
Each of the payload bay doors is driven open or closed by a single electromechanical actuator with two three-phase ac motors per drive unit. Torque limiters are incorporated in the rotary actuators to avoid damaging the door drive motors or mechanisms in the event of jamming or binding during operation. It takes 63 seconds to open or close each door (dual motor time). The doors open through an angle of 175.5°.

The electromechanical actuator drives a 55-foot-long torque shaft that turns the rotary actuators, causing the push rods, bellcranks, and links to push the doors open. The same arrangement pulls the doors closed.

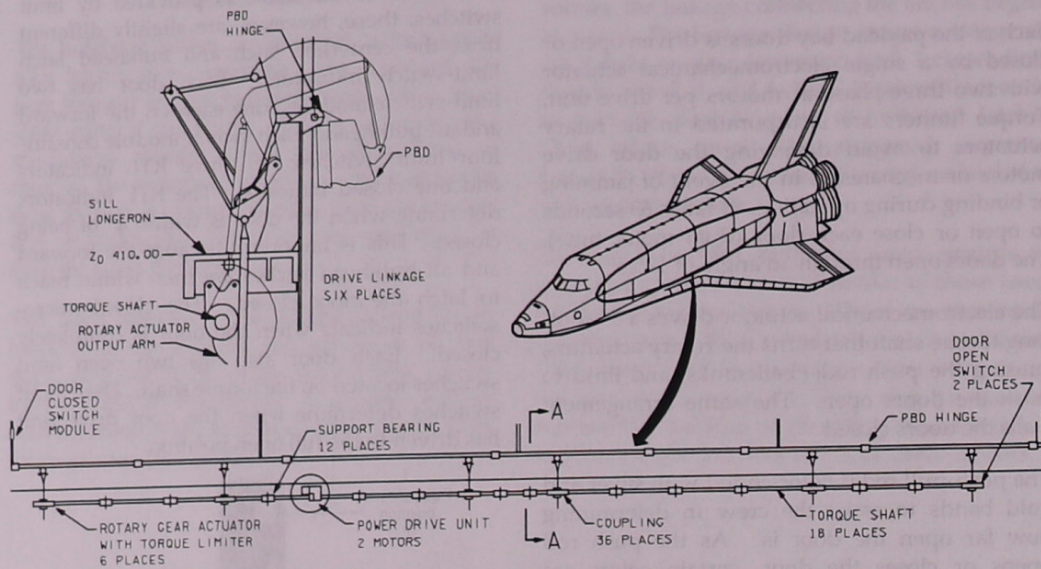
The push-pull rod is color-coded with silver and gold bands to assist the crew in determining how far open the door is. As the push rod opens or closes the door, certain colors are displayed. Each band, gold or silver, represents the amount the doors are open or closed in degrees of rotation; the distance between stripes indicates about 17.5° of motion. The crew can use this information to determine if the door is warped or jammed by seeing if any push rod has more or less stripes visible than the others. If the door is completely open, nine colored bands should be visible (one gold, six silver, and two gold bands; the final silver stripe indicating full open is, at best, only partially visible to the crew). If the door is completely closed, one gold band at the top of the push rod should be partially visible.

There are six push-pull rods per door. They can be located by looking along the sill longeron that runs along the entire length of the payload bay. The pushrod closest to the crew compartment is not visible from the aft flight deck; to see it, the CCTV system must be used.

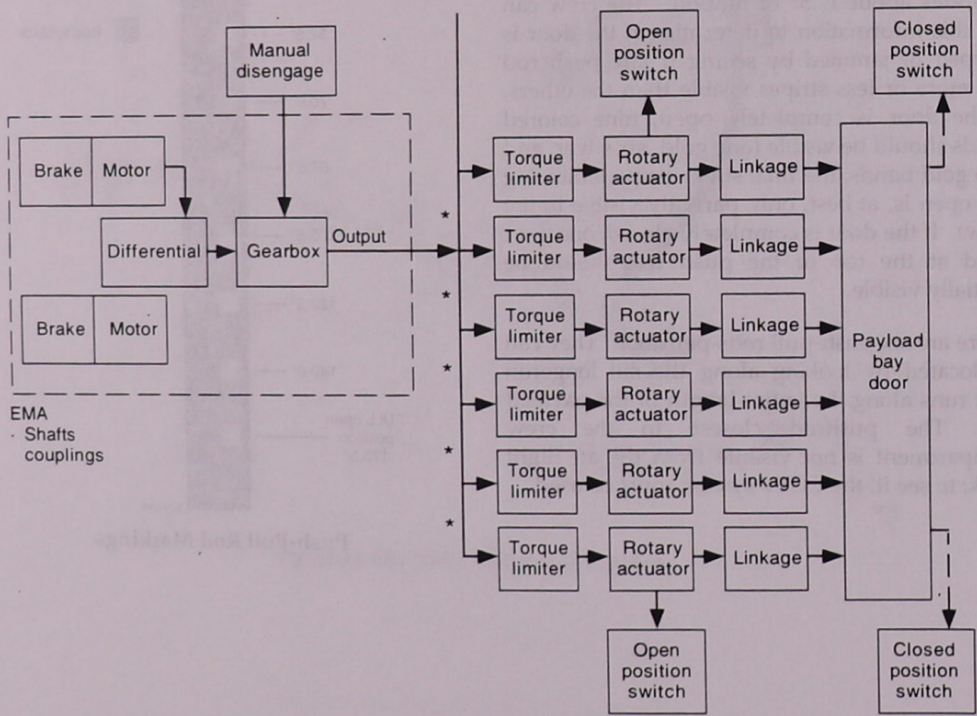
The status of the doors is provided by limit switches; these, however, are slightly different from the centerline latch and bulkhead latch limit-switch indicators. Each door has two limit-switch modules, one each on the forward and aft bulkhead. Each switch module contains four limit switches; i.e., three RTL indicators and one closed indicator. The RTL indicators determine when the door is within 4° of being closed. This is important because the forward and aft bulkhead latches are then within reach to latch the door closed. The closed micro-switches indicate when the door is completely closed. Each door also has two open limit switches located on the torque shaft. These limit switches determine when the door drive unit has driven to the full open position.



Push-Pull Rod Markings



Payload Bay Door Drive System



Payload Bay Door Drive System Mechanical Block Diagram

Payload Bay Door Operations: Opening

The crew can use either the Auto or Manual mode to open the payload bay doors. Both sequences are controlled by software. In either mode, the crew makes item entries to the PL BAY DOORS display, which provides the interface between the crew and the doors. The display can be called up as PASS SM OPS 202 (or 402) or as BFS SM SPEC 63. Each operates exactly the same. Nominally, the doors are opened and closed using PASS in OPS 202, but when the primary software is not in OPS 2, and payload bay door operations are needed, the BFS is used. This occurs when the doors must be opened early (loss of cooling, for example) or when the doors are closed late in preparation for entry. In addition, the crew uses control switches and talkbacks on panel R13L.

The PL BAY DOORS display has 17 manual item entries and several columns of status data. When selected, Item 1, AC POWER ON, applies ac power to the latch and door drives. Item 2, AC POWER OFF, removes the ac power. Items 1 and 2 are mutually exclusive. Item 3, AUTO MODE SEL, allows the user to select the Auto mode to open and close the doors and latches. Items 4 through 13 select a latch or door to move manually (listed in the order in which they will be performed from the top of the page to the bottom for opening the doors, from the bottom up for closing the doors). Item 14, PBD SW BYPASS, manually bypasses the PL BAY DOOR switch on panel R13L in case it has failed or if the crew cannot get to the switch for some reason; the status of this hardware switch is indicated at the top right of the display as the PBD-SW status (which will read OP, CL, STOP, or FAIL). If the switch is manually bypassed with an Item 14, Items 15 through 17 are used to "move" the switch to its various locations. The OP/CL status column reflects the state of the mechanism, based on how the software interprets the microswitch status. The AUTO SEQ column shows any Auto Sequence failures. Finally, the right side of the display represents the microswitches as seen by the software; a 1 means that the indication "C" (closed) or "O" (open) is present, a 0 means it is not present. For the latches, two positive indications are required for a confirmed state of the latch, which is then reflected in the OP/CL column. For the doors, a combination of open, closed, and RTL

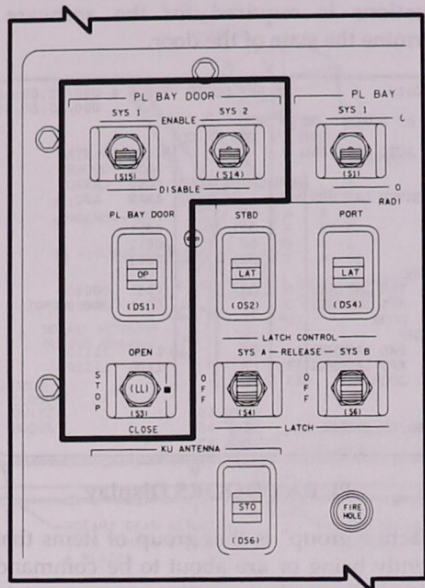
indications is required for the software to determine the state of the door.

2021/ /		PL BAY DOORS		4 000/02:00:00 000/00:00:00	
AC POWER	ON 1*				
	OFF 2				
AUTO MODE	SEL 3	PBD SW-CL			
				MICRO-SW STAT	
CENTER LATCHES	MAN SEL	OP/CL	AUTO SEQ	LATS	DOORS
5-8	4	OP		CC00	CRRRO
9-12	5	OP		ABAB	ABC
1-4	6	OP		0011	
13-16	7	OP		0011	
STBD					
FWD LATCHES	8	OP		0011	00000
AFT LATCHES	9	OP		0011	00000
DOOR	10*				
PORT					
FWD LATCHES	11	CL		1100	11110
AFT LATCHES	12	CL		1100	11110
DOOR	13	CL			
PBD SW BYPASS	14				
		OPEN	15		
		STOP	16		
		CLOSE	17		

PL BAY DOORS Display

An "active group" is that group of items that is currently being or are about to be commanded to drive. Typically, an active group consists of two latch gangs (centerline latches 5-8 and 9-12, 1-4 and 13-16, starboard bulkhead latches, or port bulkhead latches) or a single door (starboard or port).

The software monitors the latches and door drives for premature and out-of-sequence operation during the Auto mode only (i.e., making sure that door opening doesn't occur before it is unlatched). If any of the latches or doors are out of configuration, the Auto mode stops, removes ac power to all the payload bay door (PLBD) motors, and generates a fault message, PLBD CONFIG, with an SM ALERT. If any latch or door drive exceeds its single-motor drive time, the Auto sequence will stop, remove ac power to all the PLBD motors, terminate all drive commands, and generate a fault message, PBD SEQ FAIL, with an SM ALERT. These safety devices prevent door and latch damage.



PL BAY DOORS Controls on Panel R13L

The *PL BAY DOOR SYS 1* and *SYS 2* switches on panel R13L close dc powered relays that allow ac power to reach the motors in the electromechanical actuators. The third switch on panel R13L used for PLBD operations is the *PL BAY DOOR* switch, which has three positions (open, stop, close) to initiate the opening and closing sequences.

The status of the sequence as it proceeds should be monitored both on the display and visually out the window. Crewmembers should time the various mechanism motions to verify dual motor time.

Payload Bay Door Operations: Opening

The payload bay doors are opened approximately 1 hour 25 minutes into a nominal flight. Certain conditions must be met before the doors can be opened. The following table lists the failures that will force the crew to leave the doors closed and deorbit after three orbits.

If none of these conditions exists, Mission Control will give the crew the go-ahead to open the doors. The doors and latches must be opened in an orderly manner to prevent possible damage. The doors and latches are normally opened in Auto mode, though they may be opened in Manual mode based on crew

preference, various failures, or as specified by the procedures.

RAD/PLBD OPS NO GO FOR FOLLOWING FAILURES			
OMS/RCS	GNC	ECLS/EPS	MECH
2 OMS Engs	2 IMUs	1 H2O or Freon Loop	2 LG DPY METHODS
1 OMS Eng and 1 +X RCS Jet	3 RGAs 3 AAs	Both RFCAs Both Cab Fans	PRES or REDNT WINDOW PANE FAILURE
1 OMS Inlet line	3 ADTAs	3 OF 6 Av Bay Fans	
OMS Prop TK Leak			<u>DPS</u>
Aft RCS He or Prop Leak	3 Elevon or 2 BF Pos Fdbks (same surface)	2 FCs Any Mn or 3 phase AC Bus	3 GPCs 2 PL MDMs
<u>COMM</u>			2 FF or FA MDMs
No Voice and No CMD	2 FCS CH (same surface)	Any CNTL or MPC Bus	<u>APU/HYD</u>
		3 IMU Fans	2 APU/HYD/WSB

Opening Doors in Auto Mode

In Auto mode, the software controls the sequence of opening the latches and doors, commanding the next group only after the previous group has completely moved to its end of travel open.

The crew will first configure the ac and dc power sources and select the Auto mode on the CRT display. They have no active role in the sequence of opening other than to monitor times and microswitches and to take manual action if a failure occurs.

First, centerline latch groups 5-8 and 9-12 open. These groups secure the mid-centerline region of the doors. When the orbiter is exposed to the cold environment of space, warping of the doors is likely. Opening these two groups first relieves the tension in the doors caused by thermal expansion and contraction.

Next to open are centerline latch groups 1-4 and 13-16, which secure the centerline near the forward and aft bulkhead. Opening these groups next helps relieve the tension in the door caused by thermal warping. Centerline latches must be opened before the bulkhead latches to decrease tension in the doors.