

Shuttle Flight Operations Manual

Volume 2 Electrical Power Systems

Mission Operations Directorate
Training Division

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Shuttle Flight Operations Manual Volume 2 : Electrical Power Systems

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Electrical Power System

The electrical power system (EPS) consists of the equipment and reactants which produce electrical power for distribution throughout the Orbiter, fulfilling all the Orbiter, external tank, solid rocket booster (SRB), and payload power requirements when not connected to ground support equipment (GSE).

The EPS may be functionally divided into three systems, as shown in figure 1-1:

- Power reactants storage and distribution system (PRSD) - The major function of PRSD is to store and supply the reactants, hydrogen (H_2) and oxygen (O_2), to the fuel cell system, and to supply oxygen to the environmental control and life support system (ECLSS).

- Fuel cell system - The fuel cell system, consisting of three fuel cells, transforms the reactants into electricity through a chemical reaction.
- Electrical power distribution and control system (EPDC) - The EPDC distributes the electricity throughout the Orbiter.

Each system will be described individually on the following pages.

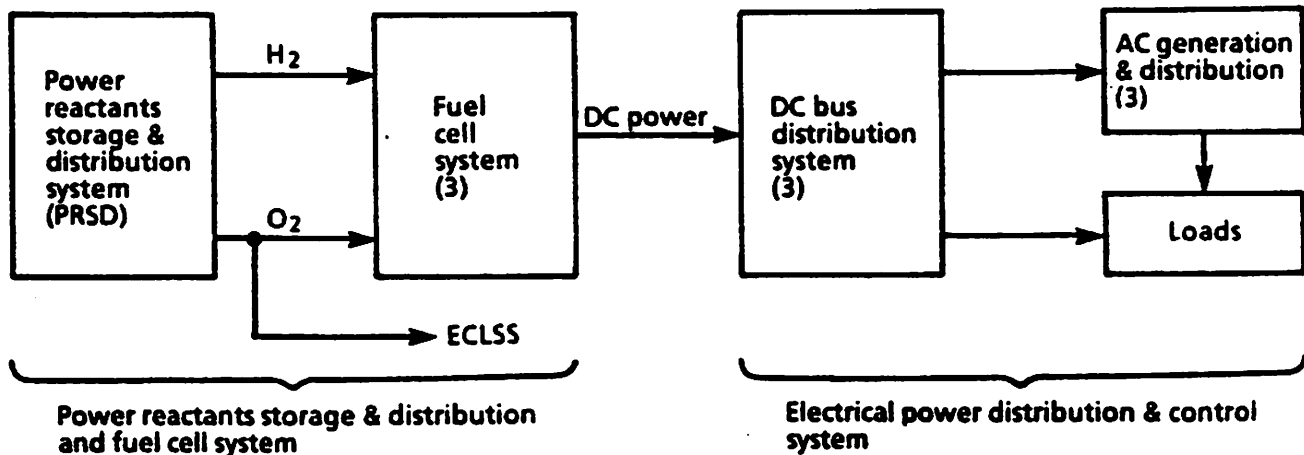


Figure 1-1. - PRSD, fuel cell systems, and EPDC.

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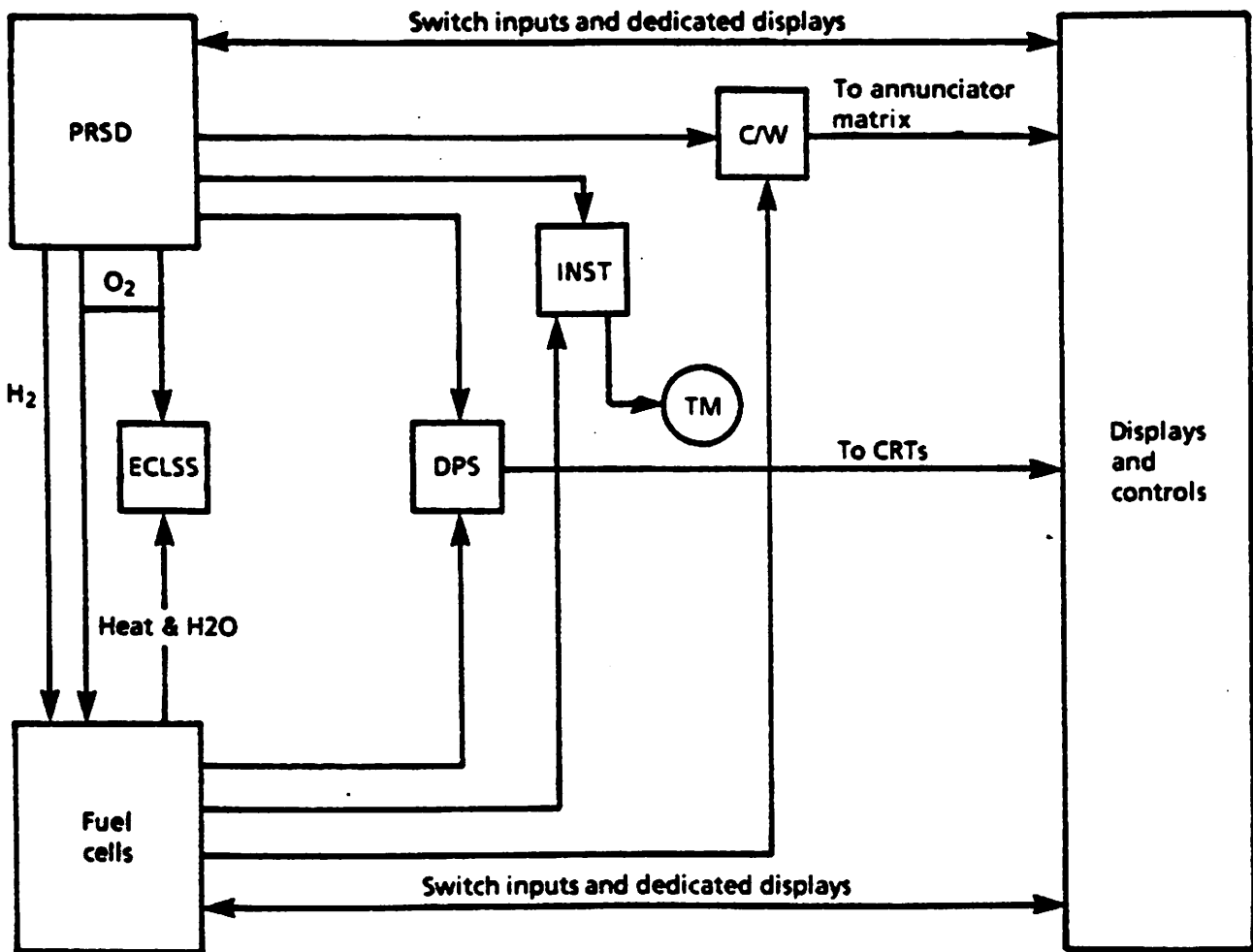


Figure 1-2.- PRSD interfaces.

Section 1: Power Reactants Storage and Distribution System

1.1 Introduction

The power reactants storage and distribution system (PRSD) has the function of storing the cryogenic reactants, H₂ and O₂, and then supplying these reactants to the fuel cells for electrical power generation during all mission phases. Additionally, O₂ is supplied to the environmental control and life support system (ECLSS) for breathable oxygen. The cryogenic reactants are stored in double-walled, thermally insulated tanks. Heaters in the tanks add heat energy to the reactants from the tanks through a common manifold to the fuel cells at pressures of approximately 812 to 855 psia for O₂ and between 200 to 226 for H₂. Several crew-controlable valves in the manifolds allow isolation of malfunctioning components within this system. All PRSD components are located in the mid-body area (X₀693 to X₀1191) under the payload bay envelope.

1.2 Interfaces

The PRSD system has interfaces as described below and shown in figure 1-2.

- A. Fuel cells – The PRSD supplies H₂ and O₂ for electrical power.
- B. ECLSS – O₂ is provided for crew breathing.
- C. Caution and warning (C/W) – Sensor outputs are continuously checked for out-of-limits conditions.
- D. Data processing system (DPS) – Sensor outputs are provided for systems management (SM) conditioning, monitoring, and display of PRSD parameters on CRT displays.
- E. Onboard displays and controls (D&C) – The PRSD has dedicated meters that provide status information to the crew. Switches, circuit breakers, and talkbacks allow the crewmembers control of the system and verification capability.
- F. Instrumentation (INST) – Sensor outputs are conditioned and telemetered.

1.3 Functional Description

The PRSD functional description is divided into component descriptions. Refer to specified figures to aid in the description.

1.3.1 H₂ and O₂ Tanks

The cryogenic reactants are stored in a supercritical condition in thermally insulated, double-walled spherical tanks with a vacuum annulus between the spheres. Refer to figures 1-3 and 1-4 for O₂ tank 1 and H₂ tank 1, respectively. All O₂ tanks are identical, as are all H₂ tanks. Heat leakage into the supercold inner tanks (initial storage temperatures are 420°F and -285°F for H₂ and O₂, respectively) is kept at a minimum by a vacuum annulus, to prevent convection heat transfer. A radiation shield between the tank walls is used to minimize radiant heat transfer, and non-conductive material is used at the physical attach points between the inner and outer tanks to minimize conductive heat transfer. A vacuum pump, which is powered by ground support equipment (GSE), is used during ground servicing operations to evacuate the annulus.

Each O₂ inner storage tank has a diameter of 33.435 inches, a volume of 11.24 ft³, and stores 781 pounds of O₂. Each H₂ inner storage tank has a diameter of 41.516 inches, a volume of 21.39 ft³, and stores 92 lb of H₂. Each tank has

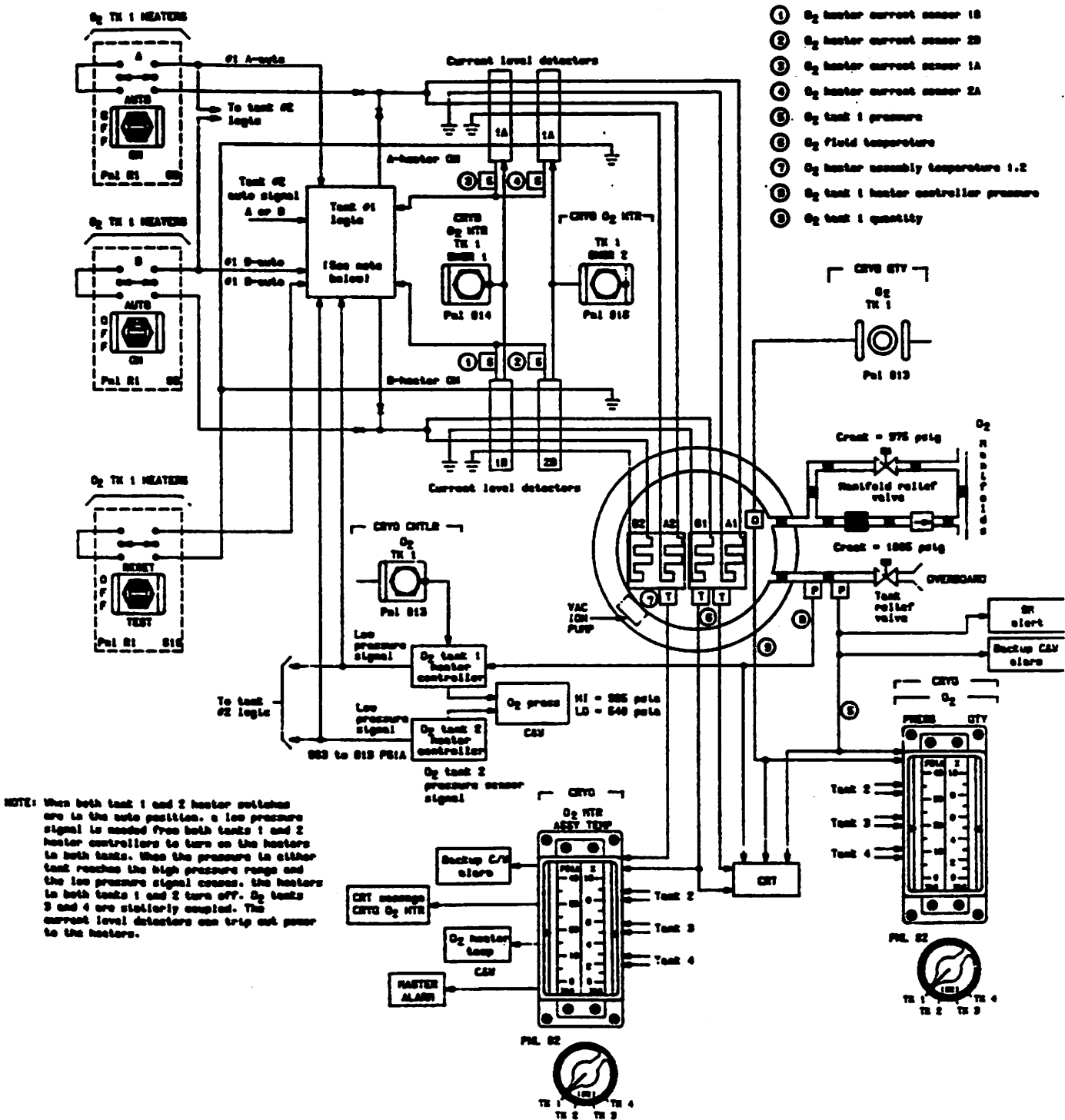


Figure 1-3.-PRSD O₂ tank 1.

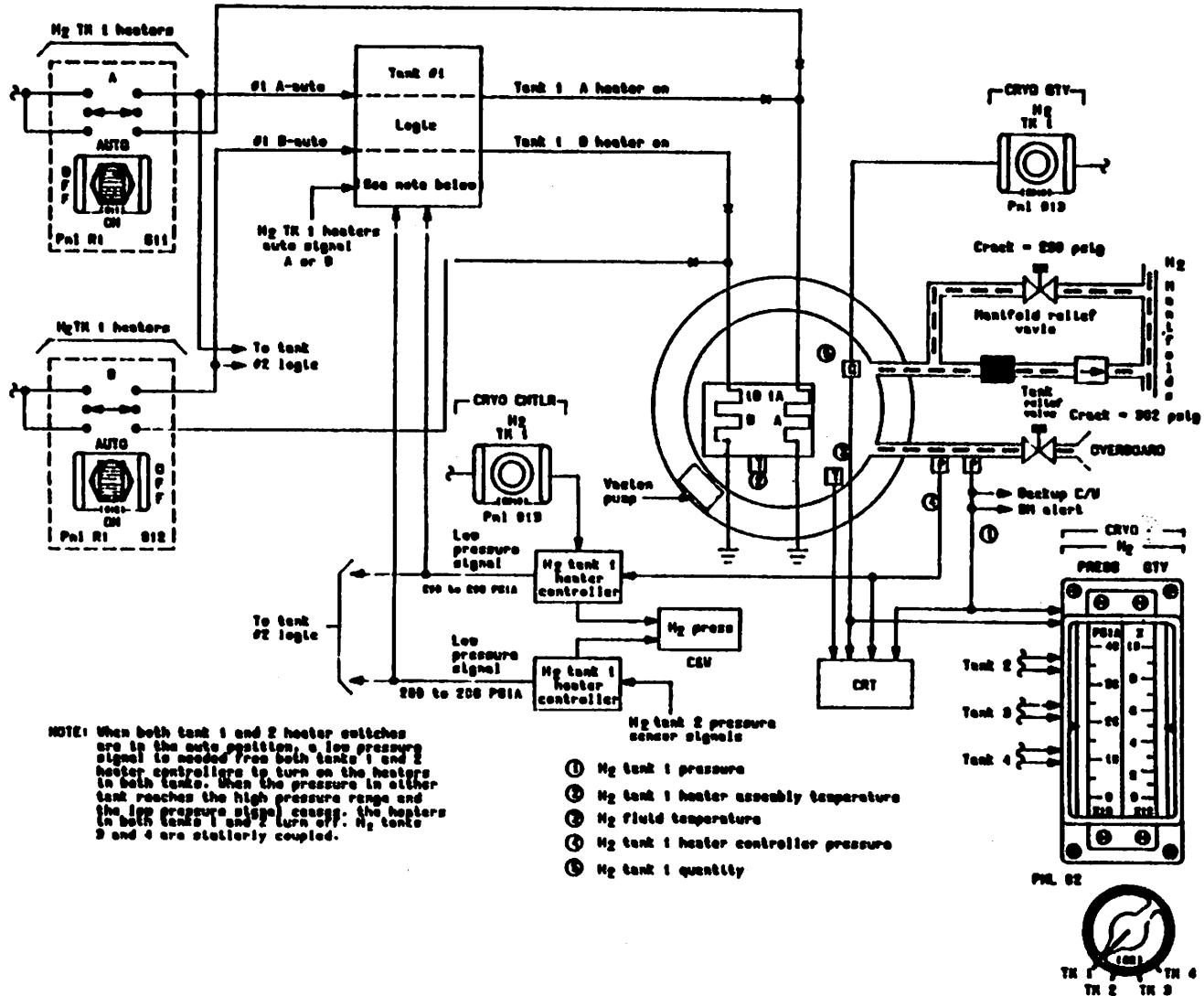


Figure 1-4. - PRSD H₂ tank 1.

temperature, pressure, and quantity sensors whose data is used for CRT displays, dedicated displays, caution and warning (C/W), BACKUP C/W, SM ALERTS, and Telemetry (TM). In the O₂ tank, there is a quantity sensor powered by circuit breakers on panel O13 for O₂ tanks 1 and 2, and panel ML86B for tanks 3 and 4. The quantity sensor's data is sent to a gage on panel O2, to the CRT display, and to TM. The O₂ tank also contains temperature sensors located on each heater assembly; this heater assembly temperature data is sent to the O₂ HTR ASSY TEMP gage on panel O2, to the O₂ HEATER TEMP C/W light on panel F7, to the CRT display, and to TM. The temperature sensor measuring O₂ fluid temperatures has its data sent to the CRT display and to TM. There are two tank pressure sensors for each O₂ tank. One sensor sends its data to the heater controllers, the O₂ PRESS C/W light, the CRT display, and to TM. The second pressure sensor sends data to the pressure gage on panel O2, the SM ALERT program, BACKUP C/W, and to TM. The H₂ tank has identical sensors to the O₂ tanks, and their data, like the O₂ sensor data, is sent to similar areas.

1.3.2 Tank Heaters

Both O₂ and H₂ tanks have two separate internal heaters. As the reactant in the tanks is depleted, the heaters add energy to the stored cryo to maintain the operational pressure of the tanks. For increased heating capability, the O₂ tanks have two elements in each heater; whereas the H₂ tanks have only one element per heater. There are two modes of operation for the heaters, manual and automatic. In the manual mode of operation, the crewmember controls the heaters by using the ON/OFF positions of the heater switches located on panel R1. The crewmember can observe a high or low pressure in the tanks on the CRT display or tank pressure gage on panel O2. In the automatic mode, which is selected by the AUTO position of the heater switches, the heaters are controlled by individual O₂ and H₂ tank heater controllers. The heater controllers control the status of the tank heaters, based on tank pressure. Each heater

controller receives a signal from a tank pressure sensor; if the tank pressure is at a low limit, the controller will send a low pressure signal to the heater logic to turn the heater on.

When the tank pressure reaches its high limit, the heater controller removes this low pressure signal from the tank heater logic and the heaters turn off. The tank pressure high/low limits for each tank are as follows:

Pressure limits (psia)	Low	High
H ₂ tank 1, 2 Heater Controllers	200-206	220-226
H ₂ tank 3, 4 Heater Controllers	217-223	237-243
O ₂ tank 1, 2 Heater Controllers	803-819	838-854
O ₂ tank 3, 4 Heater Controllers	832-848	866-882

A dual mode heater operation capability is available for both O₂ and H₂ tanks. If the heaters of both tanks 1 and 2 or tanks 3 and 4 are selected to the auto mode, then their tank heater logic will be interconnected. This implies that the heater controllers of both of the interconnected tanks must send a low pressure signal to the heater logic before the heaters in both tanks will turn on. Once the heaters are on, if either heater controller senses a high pressure in its tank, the low pressure signal is removed and the heaters in both interconnected tanks will turn off.

For most flights, four tank sets (H₂ tanks 1, 2, 3, and 4 and O₂ tanks 1, 2, 3, and 4) will be used to supply cryogenics to the fuel cells. However, there is a capability to install five sets of tanks under the payload bay envelope for longer missions and increased power needs.

All tank heaters will not be enabled during most flight phases. For lift-off, only the 'B' heaters in the O₂ and H₂ tanks 1 and 2 are in the AUTO position. All of the other tank heaters are disabled. After OMS-1, the 'A' heaters in tanks 1 and 2 are placed in AUTO. Once in

orbit, tanks 3 and 4 heater switches are also placed in the AUTO position. Because tanks 3 and 4 heater controller pressure limits are set at a higher pressure than tanks 1 and 2, they will supply the reactants to the fuel cells while on-orbit. Normally, tank pressures will be maintained by use of tank heaters in AUTO. In the case of a malfunction, manual pressure control will be used as required to maintain tank pressures. For descent, tanks 3 and 4 are placed in the OFF position, and tanks 1 and 2 will again supply the reactants to the fuel cells. The "B" heater in O₂ tanks 1 and 2 is disabled for entry.

The O₂ tank heaters have current level detectors built into the system to prevent continuous electrical shorts in the heaters. There are two current detectors for each heater in the tanks, the second detector being for redundancy. Each detector is divided into an A and B detector, with the A detector measuring heater A currents and the B detector measuring heater B currents. The detectors are powered by circuit breakers on panels O14, O15, O16, and ML86B. These circuit breakers are labeled CRYO O₂ HTR TK 1 (2,3,4) SNSR 1 (2). Each detector measures the current into and out of a heater, and if the current difference is 0.9 A or greater for 1.5 msec, a trip signal will be 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 of that heater will be removed. A TEST-RESET switch on panel R1 can be used to reset a tripped detector, which will reapply power to the heaters. If it appears that the O₂ heater is disabled by a short or if the heater is not required, the heater will not be reset and will be deactivated. The TEST position of this switch will cause 1.4 A delta current to flow through all four detectors, causing them to "trip out." During on-orbit operations, the crew-member will be alerted to a current level detector "trip out" by receiving an SM ALERT, a fault message on the CRT display, and a down arrow (↓) on the CRYO CRT display next to the detector that tripped out.

1.3.3 Reactant Distribution

The cryogenic reactants are distributed from the tanks to the fuel cells through two modules and a common manifold. Figure 1-5 shows how the reactants are distributed from the tanks to the fuel cells. The oxygen is supplied to the manifold from the tank at a pressure of 803-854 psia, and the hydrogen is supplied at a pressure of 200-226 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 pressure decrease occurs in the manifolds.

After leaving the tank, the reactants first flow through a relief valve/filter package module that contains the tank relief valve and a 5 μ filter. Additionally, O₂ and H₂ tanks 1 and 2 have manifold relief valves within this module. The tank relief valves serve to relieve overboard excess pressure that has built up in the tanks. The O₂ tank relief valve cracks at 1005 psia, and the H₂ tank relief valve cracks at 302 psia. The 5 μ filter extracts impurities from the H₂ and O₂ which could cause fuel cell degradation. The manifold relief valves are located within a plumbing line which leads from the manifold back to the line coming out of H₂ tanks 1 and 2 and O₂ tanks 1 and 2. The purpose of the manifold relief valves will be discussed later.

The second module that the reactants flow through are the valve modules. There are four of these: H₂ valve module 1, H₂ valve module 2, O₂ valve module 1, and O₂ valve module 2. Each valve module contains a check valve for each tank line coming in, a manifold valve, and fuel cell reactant valves. The O₂ valve modules 1 and 2 also contain the atmosphere pressure control O₂ system 1 and 2 supply valves, respectively. All manifold valves and fuel cell reactant valves will normally be open during all mission phases. These valves are controlled by the crew through switches and talkbacks located on panel R1. When a fuel cell reactant valve closes, the crew is alerted by the FUEL CELL REAC C/W light on panel F7, accompanied by a class 2 C/W tone. The computer also senses a closed reactant valve and responds by lighting the BACKUP C/W light on panel F7 with its associated class 2

When pressure drops on O₂ cell are sent to the alarm program

- ① O₂ manifold 1 pressure
- ② O₂ manifold 2 pressure
- ③ O₂ manifold 1 limitation valve
- ④ O₂ manifold 2 limitation valve
- ⑤ O₂ manifold 1 pressure
- ⑥ O₂ manifold 2 pressure
- ⑦ O₂ manifold 1 limitation valve
- ⑧ O₂ manifold 2 limitation valve

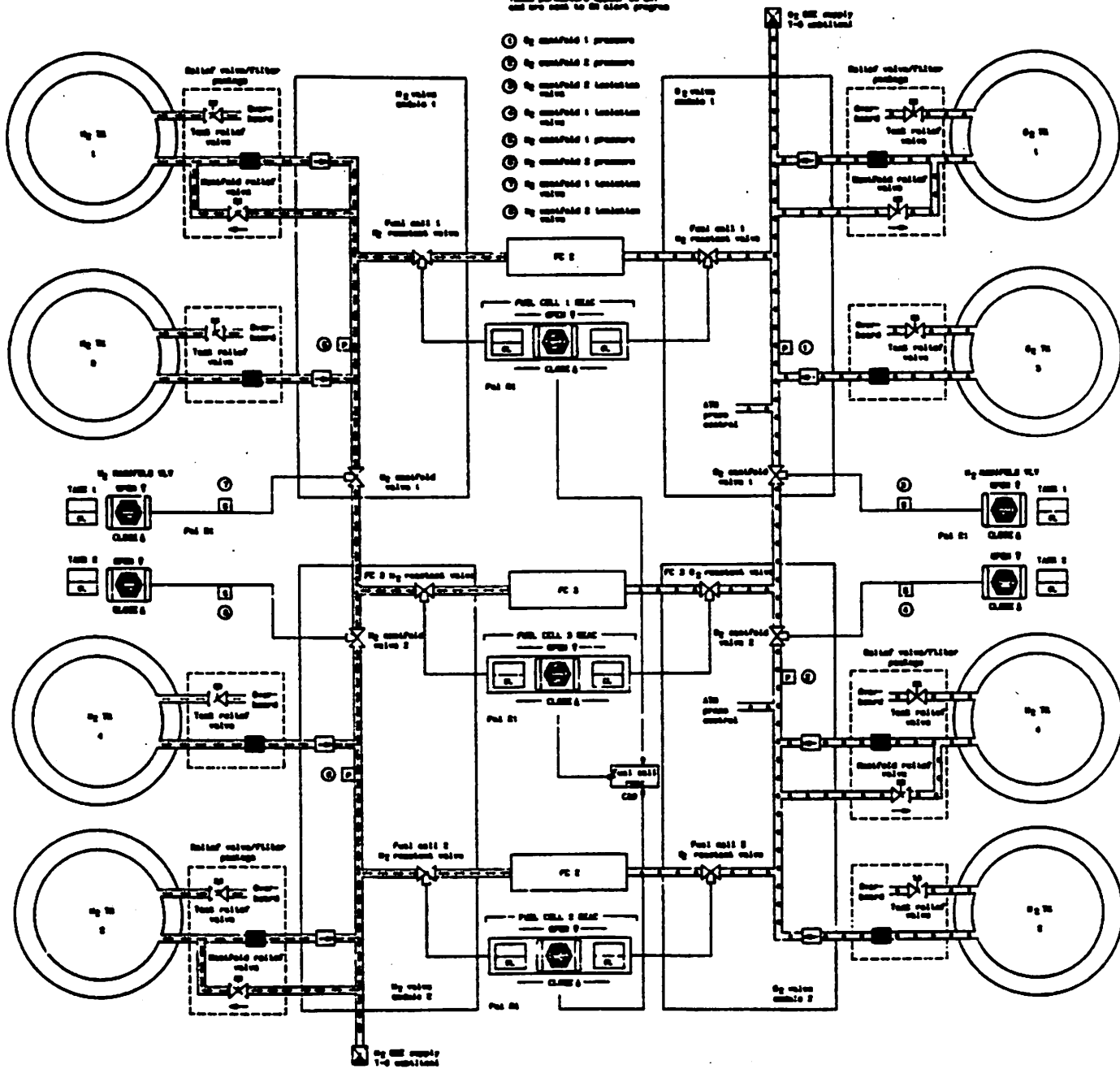


Figure 1-5.- Cryo / fuel cell interface.

C/W tone. A closed H₂ or O₂ manifold valve causes an SM ALERT to occur. The status of the manifold and fuel cell reactant valves are shown on the FUEL CELL CRT display; OP indicates an open valve, and CL and a down arrow (↓) indicate a closed valve. By closing the manifold valves, a crewmember can isolate one side of the reactant supply system if there is a malfunction and still be able to supply reactants to at least two of the fuel cells. The fuel cell reactant valves allow reactants to flow into the fuel cells from the manifold and can be used to isolate a malfunctioning fuel cell by closing it. The check valves prevent reactants from flowing from the manifold back into any tank in the event of a tank leak. The manifold relief valves are built-in safety devices used in the event of a manifold overpressure and a fuel cell reactant valve closure caused by a malfunction. The reactants trapped in the manifold lines will be heated up by the internal heat of the Orbiter and overpressurize. The manifold relief valves, which crack at 290 psig for the H₂ line and at 950 psig for the O₂ line, can relieve this built-up pressure by allowing the trapped reactants to flow back into the tanks.

The two pressure sensors located in both the H₂ and O₂ valve modules have their data displayed on the CRYO CRT display. This data is also sent to the SM computer, where its lower limit is checked. If the H₂ and O₂ manifold pressures are below 150 and 200 psia, respectively, an SM ALERT will occur.

1.3.4 Preflight

During preflight ground operations, the fuel cells are supplied by GSE reactants until approximately T-11 min. The GSE H₂ supply pressure is 300-320 psia and GSE O₂ supply pressure is 1000-1020 psia, which is higher than the PRSD supply pressure. The GSE supply valve will be closed by the ground to automatically transfer to internal reactants.

1.4 PRSD Controls And Displays

The controls and displays for the PRSD system are on flight deck panels R1, A11, O2, O13, O14, O15, O16, F7, and middeck panel ML86B. Figure 1-6 displays these panels and their relative positions on the flight deck and middeck.

The top right-hand portion of panel R1 contains the switches and talkbacks controlling reactant valves and manifold valves. The panel is in schematic form for easy understanding of the reactant distribution network. Below the reactant valves on panel R1 are the three-position (AUTO, OFF, ON) switches that control the H₂ and O₂ internal tank heaters and the O₂ heater TEST-RESET switch. Panel A11 contains the H₂ and O₂ tank 4 three-position heater switches and the O₂ tank heater 4 TEST-RESET switch. For increased power needs, tank 5 may be added. In this case, tanks 4 and 5 heater logic would be interconnected.

The circuit breakers for powering up the heater controllers, the quantity sensor for H₂ and O₂ tanks 1 and 2, and the O₂ heater current sensors for O₂ tanks 1 and 2 are on panels O13, O14, O15, and O16. The breakers for O₂ tanks 3 and 4 are on panel ML86B.

Panel O2 has meters which display H₂ tank pressure and quantity, O₂ tank pressure and quantity, and O₂ heater assembly temperature. Rotary select switches located directly underneath these dedicated displays allow selection of the tank parameters to be displayed on the meters.

A more complete description of each control and display pertaining to the PRSD system is given in table 1-1 which gives the panel number where the switch can be found, the type of crew control or display, the nomenclature that appears on the panel, and its function.

Panel F7 contains the C/W annunciation light matrix and the SM ALERT light. The lights pertaining to the PRSD system on the annunciator matrix are O₂ PRESS, H₂ PRESS, O₂ HEATER TEMP, and BACKUP C/W. The heater controllers sense the pressure in the tanks and hardwire this pressure signal to the C/W electronics. If this pressure is out of limits, the O₂ PRESS or H₂ PRESS light will come on. A different pressure sensor, located near the C/W pressure sensor, is used to drive the dedicated display on panel O2 which indicates O₂ and H₂ tank pressure. This pressure signal is also sent to the computers where the software checks its limits. If its signal is out of limits, the BACKUP C/W light will annunciate. Temperature sensors located on the O₂ tank heater assembly send a signal which drives the dedicated display located on panel O2, indicating heater assembly temperature. This same temperature signal is directly hardwired to the C/W electronics, where its limits are checked. If the signal is out of limits, the O₂ HEATER TEMP light on the annunciator matrix will annunciate. The temperature signal is also sent to the computers where the software checks its limits; if out of limits conditions exist, the BACKUP C/W light will annunciate. The computer software annunciated BACKUP C/W light is just as its name implies, a backup to the three hardwired lights. The upper and lower limits of the three hardwired lights (O₂ PRESS, H₂ PRESS, and O₂ HEATER TEMP) are the same as the software-annunciated BACKUP C/W light and the fault messages that will appear on the CRT screen when these lights come on. These figures also list the SM ALERT parameters that are applicable to the PRSD system.

The SM fault detection and annunciation (FDA), which consists of the SM ALERT and BACKUP C/W software, will be in general purpose computer (GPC) 5, the backup flight system (BFS) computer during ascent and descent phases of the mission. During on-orbit operations (OPS-2), the SM ALERT and BACKUP C/W software will be in GPC 4, a primary flight system computer.

Panel F7 also contains the three CRT screens where the crew can monitor the PRSD system performance. During on-orbit phases (OPS-2), PRSD parameters are displayed on the CRYO display (figure 1-9), and on the SM SYS SUMM 2 display (figure 1-10). During ascent and descent phases, the parameters are displayed on the SM SYS SUMM 2 display (figure 1-11). For a more complete description of the CRT displays, refer to SFOM Volume 14.

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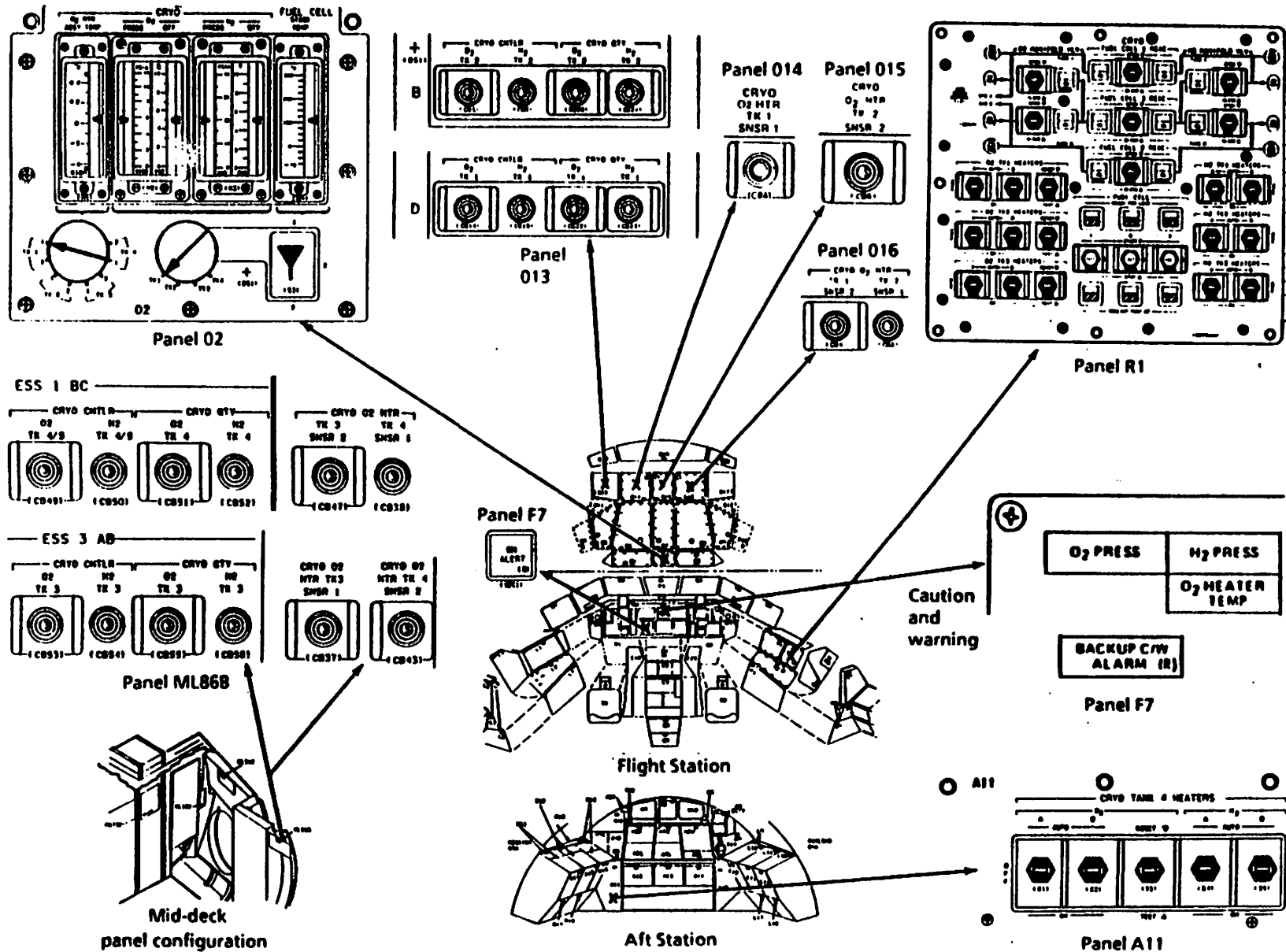


Figure 1-6.- PRSD displays and controls.

TABLE 1-1.- PRSD CONTROLS AND DISPLAYS

Panel	Type	Nomenclature	Function	Remarks
R1 R1 R1 A11	sw sw sw sw	O ₂ TK 1 (2,3,4) HEATER A AUTO OFF ON	Allows the A heater in O ₂ tank 1 (2,3,4) to turn on/off, based on tank pressure. No power directed to the A heater in O ₂ tank 1 (2,3,4) Applies power to the A heater in O ₂ tank 1 (2,3,4)	
R1 R1 R1 A11	sw sw sw sw	O ₂ TK 1 (2,3,4) HEATER B AUTO OFF ON	Allows the B heater in O ₂ tank 1 (2,3,4) to turn on/off, based on tank pressure. No power directed to the B heater in O ₂ tank 1 (2,3,4) Applies power to the B heater in O ₂ tank 1 (2,3,4)	
R1 R1 R1 A11	sw sw sw sw	O ₂ TK 1 (2,3,4) HEATERS RESET TEST	Resets the automatic tripping function of the current level detectors for O ₂ tank 1 (2,3,4) internal heaters. Tests the automatic tripping function.	
O13 O13 ML86B ML86B	cb cb cb cb	CRYO CNTL O ₂ TK 1 (2,3,4)	Provides ESS bus power to the O ₂ tank 1 (2,3,4) heater controllers.	
O15 O16 ML86B ML86B	cb cb cb cb	CRYO O ₂ HTR TK 1 (2,3,4) SNSR 1	Supplies MN bus power to current level detectors 1A and 1B.	
O16 O15 ML86B ML86B	cb cb cb cb	CRYO O ₂ HTR TK 1 (2,3,4) SNSR 2	Supplies MN bus power to current level detectors 2A and 2B.	

TABLE 1-1.- PRSD CONTROLS AND DISPLAYS (Continued)

Panel	Type	Nomenclature	Function	Remarks
O13 O13 ML86B ML86B	cb cb cb cb	CRYO QTY O ₂ TK 1 (2,3,4)	Supplies ESS bus power to the quantity measuring transducer.	
O2	sel	CRYO DISPLAY SELECTOR	Allows the selection of which of the four tanks pressure and quantity will be displayed on the meters.	
O2	ind	CRYO O ₂ PRESS/QTY	Displays the selected tank pressure and quantity on meters.	Pressure range of 0-1200 psia. Quantity range of 0-100%.
O2	sel	HEATER DISPLAY SELECTOR	Allows the selection of which heater elements assembly temperature will be displayed on the meter.	
O2	ind	CRYO O ₂ HTR ASSY TEMP	Displays the heater element temperature on a meter.	Temperature range of -400° to 400°F.
R1 R1	sw sw	O ₂ MANIFOLD VLV TK 1 (2)		
		OPEN	Opens the O ₂ manifold valve.	
		CLOSE	Closes the O ₂ manifold valve.	
R1	flag	O ₂ MANIFOLD VLV TK 1 (2)		
		OP	Indicates the O ₂ manifold valve is open.	
		CL	Indicates the O ₂ manifold valve is closed.	
R1 R1 R1 A11	sw sw sw sw	H ₂ TK 1 (2,3,4) HEATER A		
		AUTO	Allows the A heater in H ₂ tank 1 (2,3,4) to turn on/off, based on tank pressure.	
		OFF	No power directed to the A heater in H ₂ tank 1 (2,3,4).	
		ON	Applies power to the A heater in H ₂ tank 1 (2,3,4).	

TABLE 1-1.- PRSD CONTROLS AND DISPLAYS (Concluded)

Panel	Type	Nomenclature	Function	Remarks
R1 R1 R1 A11	sw sw sw sw	H ₂ TK 1 (2,3,4) HEATER B AUTO	Allows the B heater in H ₂ tank 1 (2,3,4) to turn on/off, based on tank pressure.	
		OFF	No power directed to the B heater in H ₂ tank 1 (2,3,4).	
		ON	Applies power to the B heater in H ₂ tank 1 (2,3,4).	
O13 O13 ML86B ML86B	cb cb cb cb	CRYO CNTRL H ₂ TK 1 (2,3,4)	Supplies ESS bus power to the H ₂ tank 1 (2,3,4) heater controllers.	
O13 O13 ML86B ML86B	cb cb cb cb	CRYO QTY H ₂ TK 1 (2,3,4)	Supplies ESS bus power to the quantity measuring transducer.	
O2	sel	CRYO DISPLAY SELECTOR	Allows the selection of which of the four tank's pressure and quantity will be displayed on the meters.	
O2	ind	CRYO H ₂ PRESS/QTY	Displays the selected tank pressure and quantity on meters.	Pressure range of 0-400 psia. Quantity range of 0-100%.
R1 R1	sw sw	H ₂ MANIFOLD VLS TK 1 (2)		
		OPEN	Opens the H ₂ manifold valve.	
		OFF	Closes the H ₂ manifold valve.	
R1	flag	H ₂ MANIFOLD VLV TK 1 (2)		
		OP	Indicates the H ₂ manifold valve is open.	
		CL	Indicates the H ₂ manifold valve is closed.	

BACKUP CW ALARM

CRT name	Units	Lower limit	Upper limit	Fault message	
H2 P	1,2,3,4	psia	153	293.8	S68 CRYO H2 PRES ↓ or ↑ 4 HH:MM:SS
O2 P	1,2,3,4	psia	540	985	S68 CRYO O2 PRES ↓ or ↑ 4 HH:MM:SS
O2 HTR T	1,2,3,4	°F		349	S68 CRYO O2 HTR ↑ 4 HH:MM:SS

SM ALERT

CRT name	Units	Lower limit	Upper limit	Fault message	
O2 TK P	1,2,3,4	psia	575	960	S68 CRYO O2 4 HH:MM:SS
O2 HTR CUR SNSR					
1A	event	TRIP			S68 CRYO O2 4 HH:MM:SS
2A	event	TRIP			S68 CRYO O2 4 HH:MM:SS
1B	event	TRIP			S68 CRYO O2 4 HH:MM:SS
2B	event	TRIP			S68 CRYO O2 4 HH:MM:SS
O2 MANF P	1,2	psia	200		S68 CRYO O2 4 HH:MM:SS
O2 MANF VLV	1,2	event	CLOSED		S68 CRYO O2 4 HH:MM:SS
H2 TK P	1,2,3,4	psia	165	283	S68 CRYO H2 4 HH:MM:SS
H2 HTR T	1,2,3,4	°F		210	S68 CRYO H2 4 HH:MM:SS
H2 MANF P	1,2	psia	150		S68 CRYO H2 4 HH:MM:SS
H2 MANF VLV	1,2	event	CLOSED		S68 CRYO H2 4 HH:MM:SS

Figure 1-7.— On-orbit alarms for PRSD system.

BACKUP CW ALARM

CRT name	Units	Lower limit	Upper limit	Fault message	
H2 P	1,2,3,4	psia	153	293.8	SM2 CRYO H2 PRES ↓ or ↑ 5 HH:MM:SS
O2 P	1,2,3,4	psia	540	985	SM2 CRYO O2 PRES ↓ or ↑ 5 HH:MM:SS
O2 HTR T1	1,2,3,4	°F		349	SM2 CRYO O2 HTR ↑ 5 HH:MM:SS

SM ALERT: NONE

Figure 1-8.— BFS alarms for PRSD system.

XXXX/XXX/068 CRYO SYSTEM XX X DDD/HH:MM:SS
 DDD/HH:MM:SS

	TK				
02	1	2	3	4	5
P	XXXXS	XXXXS	XXXXS	XXXXS	XXXXS
TK P	XXXXS	XXXXS	XXXXS	XXXXS	XXXXS
QTY	XXXS	XXXS	XXXS	XXXS	XXXS
T	+XXXXS	+XXXXS	+XXXXS	+XXXXS	+XXXXS
HTR T 1	+XXXXS	+XXXXS	+XXXXS	+XXXXS	+XXXXS
HTR T 2	+XXXXS	+XXXXS	+XXXXS	+XXXXS	+XXXXS
HTR 1A					
CUR 1B					
SNSR 2A					
SNSR 2B					
MANF P	XXXXS	XXXXS			
VLV	XXS	XXS			
H2					
P	XXXS	XXXS	XXXS	XXXS	XXXS
TK P	XXXS	XXXS	XXXS	XXXS	XXXS
QTY	XXXS	XXXS	XXXS	XXXS	XXXS
T	+XXXXS	+XXXXS	+XXXXS	+XXXXS	+XXXXS
HTR T	+XXXXS	+XXXXS	+XXXXS	+XXXXS	+XXXXS
MANF P	XXXS	XXXS			
VLV	XXS	XXS			

(XX)

3795. ART, 1
 Figure 1-9.- PRSD parameters on SM OPS 2 CRYO display.

XXXX/XXX/079 SM SYS SUMM 2 XX X DDD/HH:MM:SS
 DDD/HH:MM:SS

CRYO TK		1	2	3	4
H2 PRESS		XXXS	XXXS	XXXS	XXXS
O2 PRESS		XXXXS	XXXXS	XXXXS	XXXXS
HTR T1		+XXXXS	+XXXXS	+XXXXS	+XXXXS
T2		+XXXXS	+XXXXS	+XXXXS	+XXXXS

APU		1	2	3	HYD		1	2	3
TEMP EGT		XXXXS	XXXXS	XXXXS	PRESS		XXXXS	XXXXS	XXXXS
B/U EGT		XXXXS	XXXXS	XXXXS	RSVR T		XXXS	XXXS	XXXS
OIL IN		XXXS	XXXS	XXXS	QTY		XXXS	XXXS	XXXS
OIL OUT		XXXS	XXXS	XXXS	W/B				
SPEED %		XXXS	XXXS	XXXS	H2O QTY		XXXS	XXXS	XXXS
FUEL QTY		XXXS	XXXS	XXXS	BYP VLV		XXXS	XXXS	XXXS
PMP LK P		XXS	XXS	XXS					
OIL OUT P		XXXS	XXXS	XXXS					
AV BAY					THERM CNTL		1	2	
TEMP		XXXS	XXXS	XXXS	H2O PUMP P		XXXS	XXXS	
FAN AP		X.XXS	X.XXS	X.XXS	FREON FLOW		XXXXS	XXXXS	
					EVAP OUT T		XXXS	XXXS	

(XX)

1435. ART, 2
 Figure 1-10.- PRSD parameters on SM OPS 2 SYS SUMM CRT display.

XXXX/XXX/079

SM SYS SUMM 2

XX X DDD/HH:MM:SS
BFS DDD/HH:MM:SS

CRYO TK	1	2	3	4
H2 PRESS	XXXX	XXXX	XXXX	XXXX
O2 PRESS	XXXX	XXXX	XXXX	XXXX
HTR T1	±XXXX	±XXXX	±XXXX	±XXXX
T2	±XXXX	±XXXX	±XXXX	±XXXX

APU	1	2	3	HYD	1	2	3
TEMP EGT	XXXX	XXXX	XXXX	PRESS	XXXX	XXXX	XXXX
B/U EGT	XXXX	XXXX	XXXX	RSVR T	XXX	XXX	XXX
OIL IN	XXX	XXX	XXX	QTY	XXX	XXX	XXX
OUT	XXX	XXX	XXX	W/B			
SPEED %	XXX	XXX	XXX	H2O QTY	XXX	XXX	XXX
FUEL QTY	XXX	XXX	XXX	BYP VLV	XXX	XXX	XXX
PMP LK P	XXS	XXS	XXS	THERM CNTL		1	2
OIL OUT P	XXX	XXX	XXX	H2O PLMP P		XXX	XXX
AV BAY				FREON FLOW		XXXX	XXXX
TEMP	XXX	XXX	XXX	EVAP OUT T		XXX	XXX
FAN ΔP	X.XXS	X.XXS	X.XXS				

(XX)

1435. ART, 3

Figure 1-11.- PRSD parameters on BFS SM SYS SUMM.

1.5 PRSD Performance, Limitations, and Capabilities

1.5.1 Alarm Limits

	O ₂	H ₂
● Fluid critical pressure, psia	731.4	187.5
● Nominal tank operating pressures, psia	803-882	200-243
	(These numbers are maximum and minimum limits of the heater controllers.)	
● Maximum tank pressure, psia	1050	335
	(Maximum relief valve full flow pressure limits.)	
● Minimum tank pressure, psia	800	100
	(This pressure assures at least 100 psia at fuel cell interface.)	
● C/W high tank pressure limit, psia	985	293.8
	(Indicates tanks will start venting overboard if corrective action is not taken.)	
● C/W low tank pressure limit, psia	540	153
	(Indicates tanks are out of normal operating limits and some action should be taken.)	
● SM high tank pressure limit, psia	960	283
	(Indicates the tanks are venting overboard.)	
● SM low tank pressure limit, psia	575	165
	(This is the minimum tank pressure to insure minimum pressure at the fuel cell interface.)	
● Oxygen tank heater assembly maximum temperature limit for C/W	349°F	
	(The flash point of O ₂ and the teflon on the heaters is 700°F. A large safety margin brings the alarm limit to 340°F.)	

1.5.2 Consumables Profile

STS-11	O ₂	H ₂
● Total amount of reactants loaded, lb	3124.0	375.4
● Total reserves, residuals and measurement uncertainty, lb	295.6	37.3
● Total amount of reactants available, lb	2828.4	338.1

The delta between the total loaded and total available includes prelaunch requirements and tank residuals.

● Total required for STS-11, lb	1916.3	228.6
---------------------------------	--------	-------

Total required for O₂ includes electrical power generation, crew metabolic consumption and cabin pressure maintenance.

● Margin, lb	912.1	109.5
--------------	-------	-------

Margin allowances include 24-hour launch hold, flight planning dispersions, and two-day mission extension.

● kW hours required from required quantities for STS-11	14.1 kW	
---------------------------------------------------------	---------	--

1.5.3 Flow Characteristics

● Maximum continuous flow, lb/hr/tank	13.9	1.74
● Maximum flow for 2 min, lb/hr/tank	22.8	3.27
● Minimum flow, lb/hr/tank	0.618	0.070

One set of tanks can supply all three fuel cells with reactants.

1.5.4 Tank and Manifold Characteristics

● Tank spherical diameter, in.	33.4	41.5
● Tank fluid volume, ft ³	11.237	21.395
● Tank dry weight, lb	201	216
● Tank relief valve crack, psig	1005	302
reseat, psig	987	296
● Maximum flow through manifold relief valves, lb/hr/valve	60	5

Section 2: Fuel Cell System

2.1 Introduction

The fuel cell system produces all the electrical power required by the shuttle during all mission phases. The three fuel cells, through a chemical reaction, operate as independent electrical power sources, each supplying its own isolated, simultaneously operating, 28 V dc bus. The fuel cell, as a unit, consists of two sections—a power section where the chemical reaction occurs and an accessory section that controls and monitors the power section performance. The power section, where H₂ and O₂ are transformed into electrical power, water, and heat, consists of 96 individual small cells contained in three substacks. Manifolds run the length of these substacks and distribute hydrogen, oxygen, and coolant to these 96 small cells. The accessory section monitors the reactant flow, removes the

waste heat and water from the chemical reaction, and controls the temperature of the stack. The accessory section consists of the H₂ and O₂ flow system, fuel cell performance monitor, the coolant loop, and the electrical control unit (ECU).

The three fuel cells are located in the midbody area underneath the payload bay envelope (X₀582 to X₀693). (See figure 2-1.)

Fuel cell 1 is located on the left-hand side. Fuel cells 2 and 3 are located on the right-hand side. Right-hand and left-hand orientations of the fuel cells in the Orbiter vehicle midbody require right-hand and left-hand fuel cell configurations. Fuel cell configurations are identical except for water aspirator plumbing and startup heater wiring. As of this writing, the startup heater for fuel cell 1 is disabled.

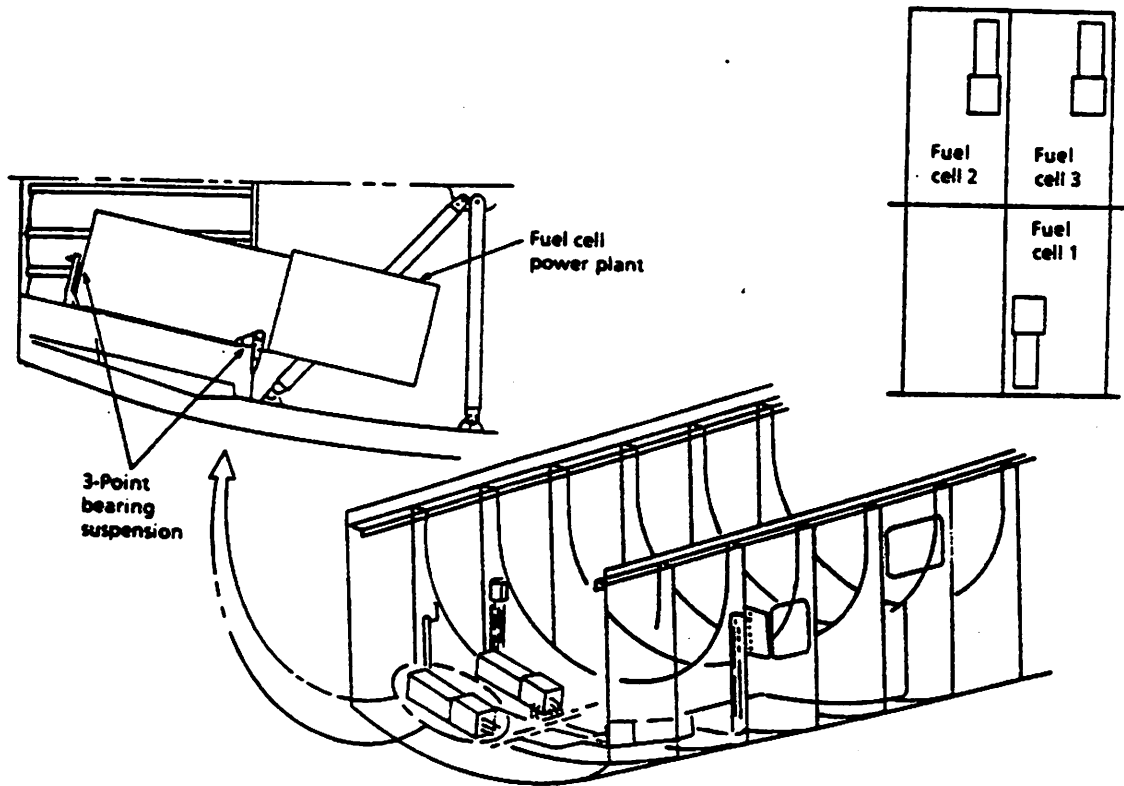


Figure 2-1.- Fuel cell installation.

2.2 Interfaces

The fuel cell system has interfaces as described below and shown in figure 2-2.

- A. PRSD - The fuel cells receive the cryogenic reactants of H_2 and O_2 which will be used for power generation.
- B. ECLSS - The fuel cells produce byproducts of heat and water. Heat is transferred through the fuel cell heat exchangers to the ECLSS Freon coolant loop. The potable water produced by the H_2/O_2 reaction is received by the water tanks.
- C. C/W - Sensor outputs are continuously checked for out of limits conditions.
- D. DPS - Sensor outputs are provided to the DPS for SM conditioning, monitoring, and display of fuel cell parameters on CRT displays.
- E. D&C - The fuel cells have dedicated meters which provide status information to the crew. Switches, circuit breakers, and talk-backs provide crew control and verification capability.
- F. INST - Sensor outputs are conditioned and telemetered.

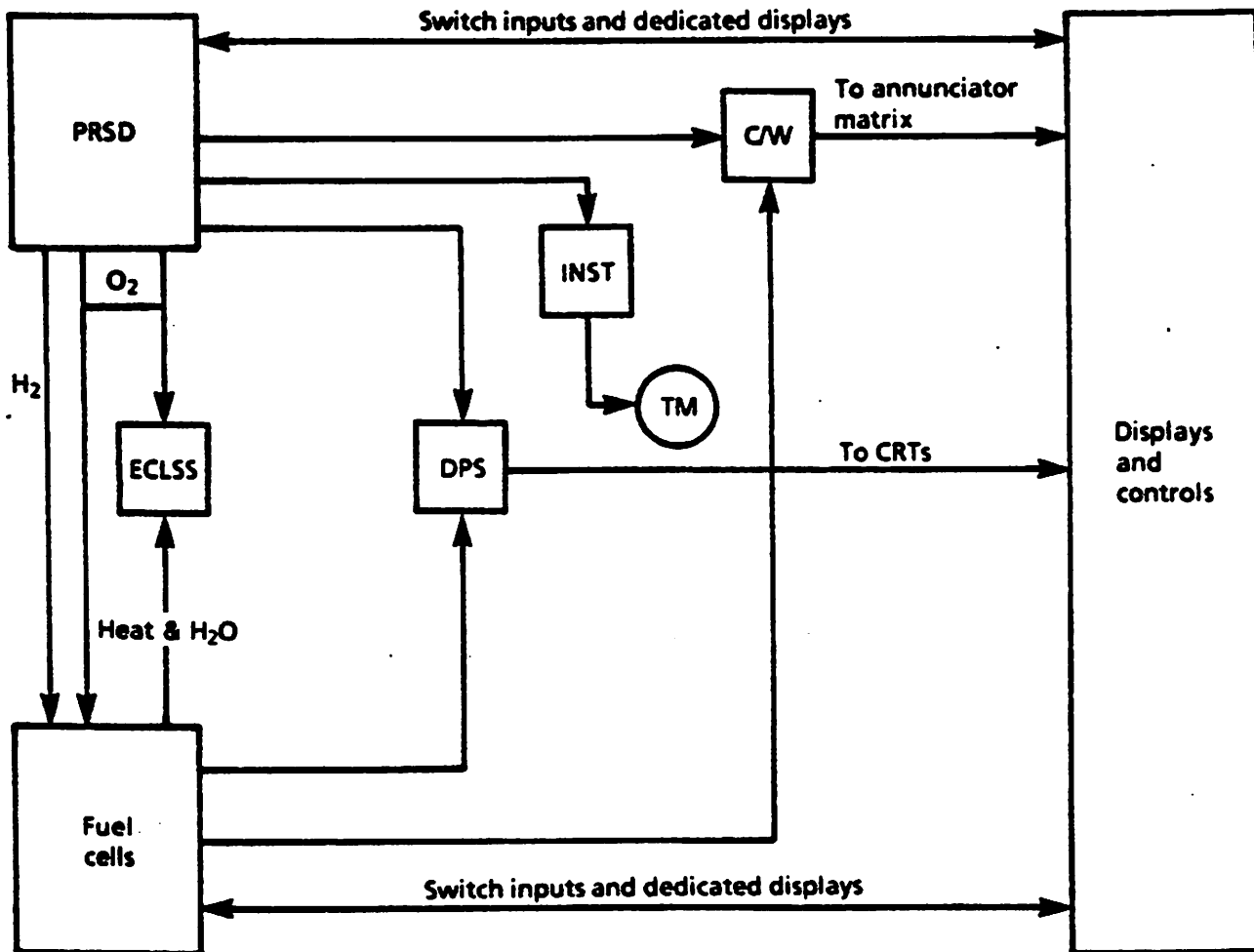


Figure 2-2.- Fuel cell interfaces.

2.3 Functional Description

The following will describe the individual components of the fuel cell system. Refer to figure 2-3 for a drawing of fuel cell 1 and figure 2-4 for the crew switches and displays.

2.3.1 H₂ and O₂ Flow

The cryogenic reactants, H₂ and O₂, are supplied from the PRSD in a single phase fluid state at a mass rate as demanded by the fuel cells. The three position, momentary (OPEN/CLOSE) FUEL CELL 1(2,3) REAC switches and accompanying talkbacks located on panel R1 allow for crew control of the reactant valves in the fuel cell feedlines. Because it is critically necessary to have reactants available at the fuel cell, the 40 light C/W annunciation matrix on panel F7 has a "FUEL CELL REAC" light dedicated to annunciate whenever any reactant valve is closed. This alerts the crew to the fact that the fuel cell will be inoperative within approximately 20-seconds for an H₂ valve closure and 130 seconds for an O₂ valve closure.

Reactant consumption is directly related to the 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 and current produced; an appreciable amount of excess reactants being used indicates a probable leak. (See 2.4.2 Reactant Usage, lb/hr.)

After entering the fuel cells, the reactants flow through a preheater (where they are warmed), a 5 micron filter, and a two-stage integrated dual gas module. The first stage of the regulator drops both the H₂ and O₂ pressure down to 130-150 psia; the second stage regulates the O₂ pressure at a level of 60 psia nominal and maintains the H₂ pressure at 4-6 psia below the O₂ pressure. The regulated O₂ line is connected to the accumulator which maintains an equalized pressure between the O₂ and the fuel cell coolant. In cases where the O₂ and H₂

pressures decrease for some reason, it is also necessary to decrease the coolant pressure to prevent a large differential pressure inside the stack that would crack the thin walls of the fuel cell which separates the coolant, H₂, and O₂, effectively destroying the fuel cell.

The O₂ from the dual gas regulator module flows directly through two ports into a closed end manifold in the fuel cell stack permitting optimum oxygen distribution in the cells. All oxygen that flows into the stack is consumed, except during purge operations.

Upon leaving the dual gas regulator module, the incoming hydrogen mixes with the hydrogen-water vapor exhaust from the fuel cell stack. This gas mixture is routed through a condenser where the temperature of the mixture is reduced below the boiling point of water, condensing the water. Liquid water is then separated from the hydrogen-water mixture by the H₂ pump/H₂O separator. Water removal will be discussed in more detail in section 2.3.2.

The H₂ pump circulates the H₂ gas back to the fuel cell stack where some of the H₂ is consumed in the reaction, while the remainder flows through the fuel cell stack, removing the product water by evaporation from the fuel cell. The hydrogen-water vapor mixture then combines with the regulated H₂ from the dual gas regulator module, and the loop described above begins again.

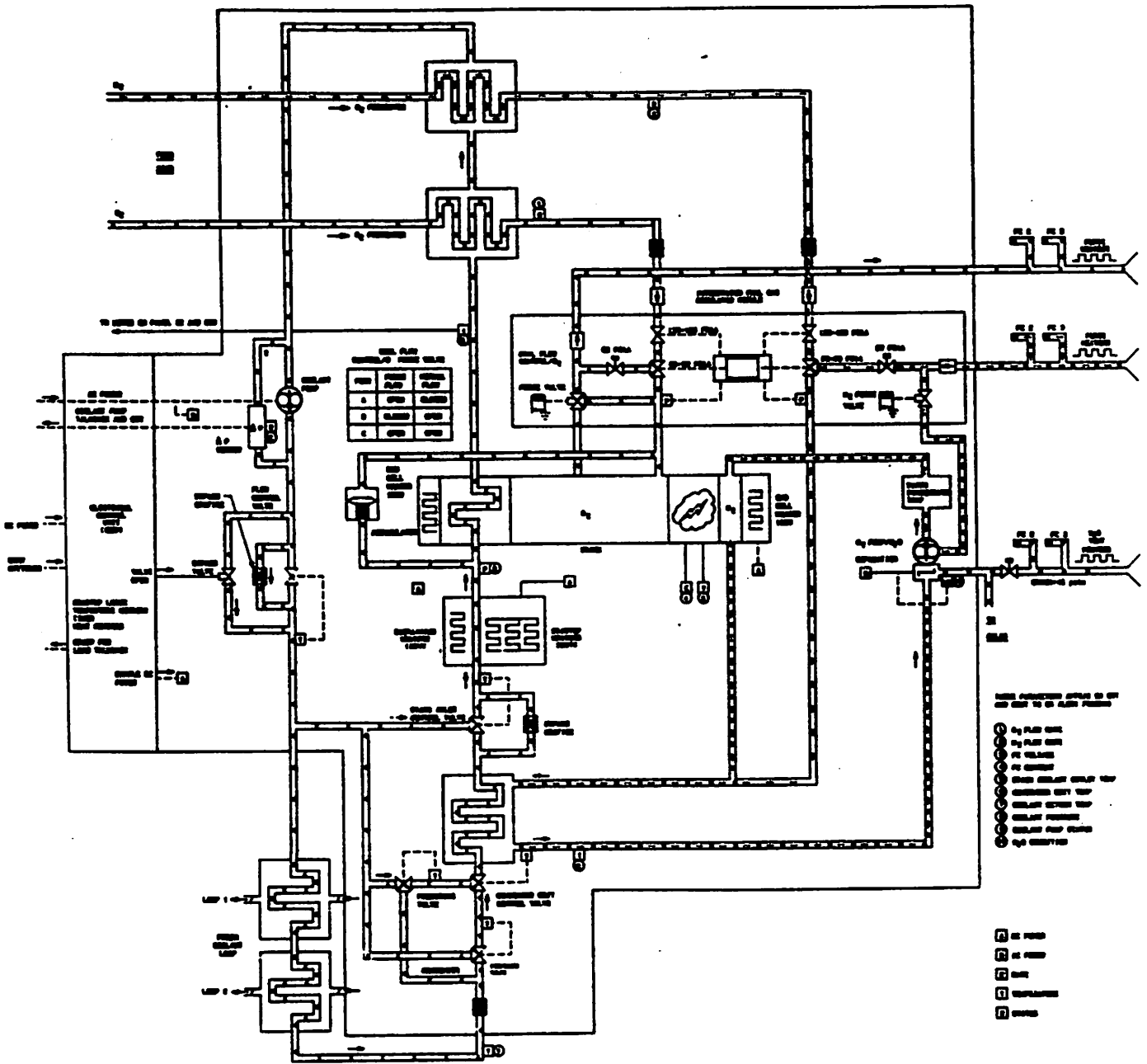


Figure 2-3.- Fuel cell 1.

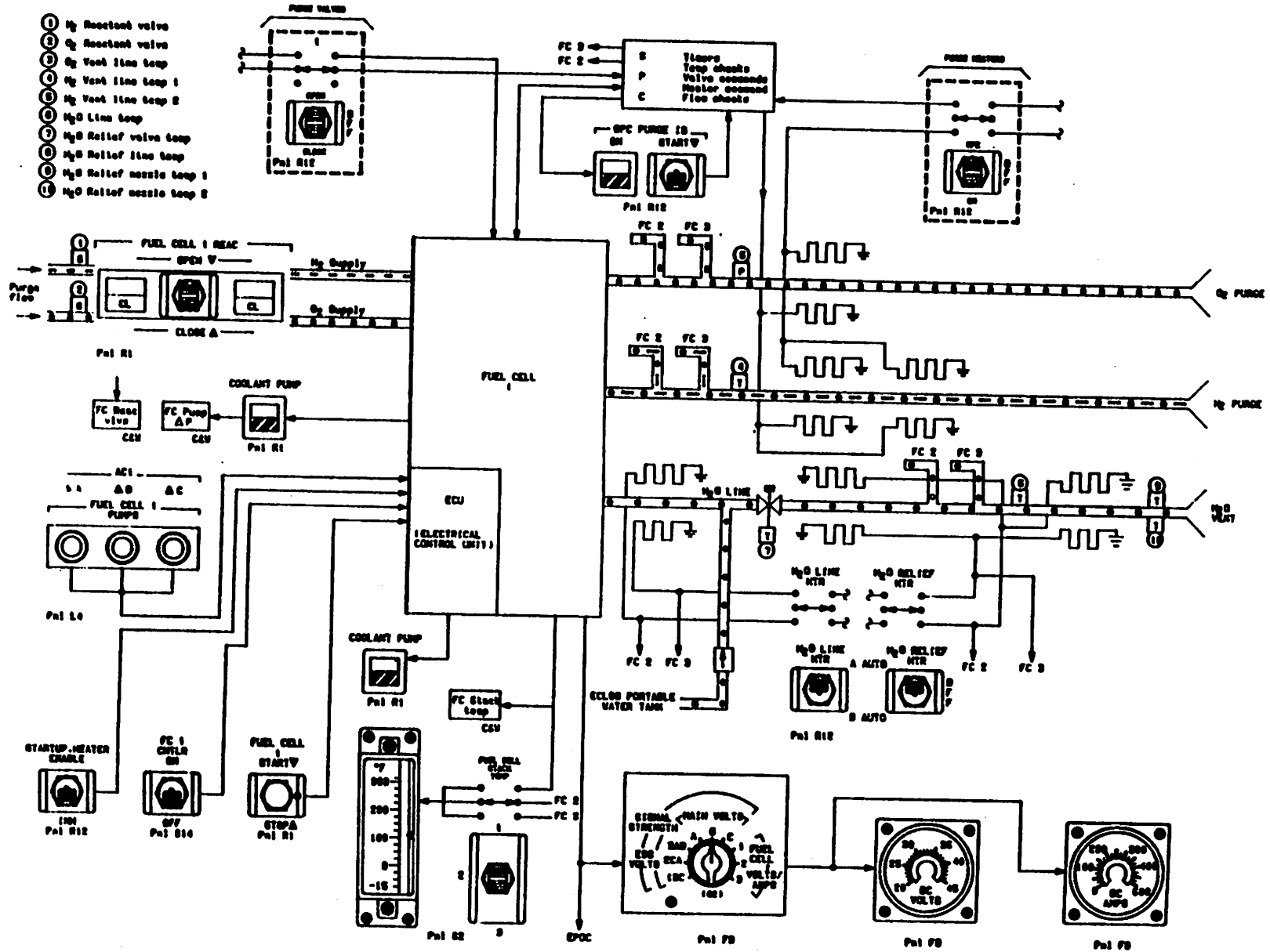


Figure 2-4.- Crew switches and displays.

2.3.2 Water Removal

Water and electricity are the products of the chemical reaction of oxygen and hydrogen that takes place in the fuel cells. This water must be removed or the stack will become saturated with water, causing decreased reaction efficiency. With an operating load of about 7 kW, it takes about 7 to 8 minutes to flood the fuel cell with produced water, thus effectively halting power generation. The H₂ is pumped through the stack, reacting with the oxygen and picking up and removing water vapor on the way. After being condensed, the liquid water is separated from the H₂ by the H₂ pump/H₂O separator and discharged from the fuel cell to be stored in the ECLSS potable water tanks.

A check valve in the water discharge line prevents a back pressure from the water tanks from flooding the fuel cells. If the water tanks are full or there is line blockage, the check valve will close and the water relief valve, which cracks at 45 psia, opens to allow the water to vent overboard through the H₂O relief line and nozzle.

For redundancy, there are two thermostatically actuated heaters wrapped around the discharge and relief lines to prevent line blockage caused by the formation of ice in the lines. Two switches on panel R12, H₂O LINE HTR and H₂O RELIEF HTR, provide the capability for the crew to select either A AUTO or B AUTO for the fuel cell water discharge line heaters and the water relief line and vent heaters, respectively. The A and B heaters are redundant to allow the other heater to be selected, should one fail. Displayed on the SM OPS 2 FUEL CELLS CRT display are the data from temperature sensors located on the fuel cell water discharge line, relief valve, relief line, and vent nozzle. The fuel cell uses a KOH catalyst in the stack. If the KOH migrates into the product water, a pH sensor, located just downstream of the H₂ pump/H₂O separator will sense the presence of the catalyst as a high pH and the crew will be alerted with an SM ALERT and a

down arrow (↓) on the OPS 2 S69 FUEL CELL display (figure 2-12).

2.3.3 Fuel Cell Purging

During normal fuel cell operation, the reactants, O₂ and H₂, are present in a closed loop system; i.e., 100 percent of the reactants are consumed in the production of electricity. Any inert gases or other contaminants present will slowly accumulate in and around the porous electrodes in the cells and reduce the reaction efficiency and load support capability. Therefore, fuel cell purges must be performed periodically during the mission to rid the fuel cell of contaminant buildup and to ensure proper voltage at the fuel cell terminals. The fuel cells will be purged on a schedule based on predicted load demand, with the maximum time of 8 hours between purges. Purges are usually performed pre- and post-sleep; however, because of flight planning constraints and conflicts, the intervals may be slightly shorter or longer. Additional purges will be required if a fuel cell degrades to 0.5 volts below its nominal V-I curve (figure 2-5). When a purge is initiated by opening the purge valves, the O₂ and H₂ become open-loop systems with increased flows allowing the reactants to circulate through the stack, pick up the contaminants, and blow them out overboard through the purge lines and vents. Electrical power is continually being produced throughout the entire purge sequence; although, due to increased reactant flows, no more than 10 kW or 350 amps should be required from the fuel cell. Although the capability exists for either manual or automatic control of the purge sequence by use of switches on panel R12, the basic purge sequence is the same.

Fuel cells will be purged using the automatic sequence, while the manual sequence will merely be a backup. However, one manual purge per mission will be performed.

The FUEL CELL CRT display contains the parameters, temperatures, and flow rates needed to monitor a fuel cell purge.

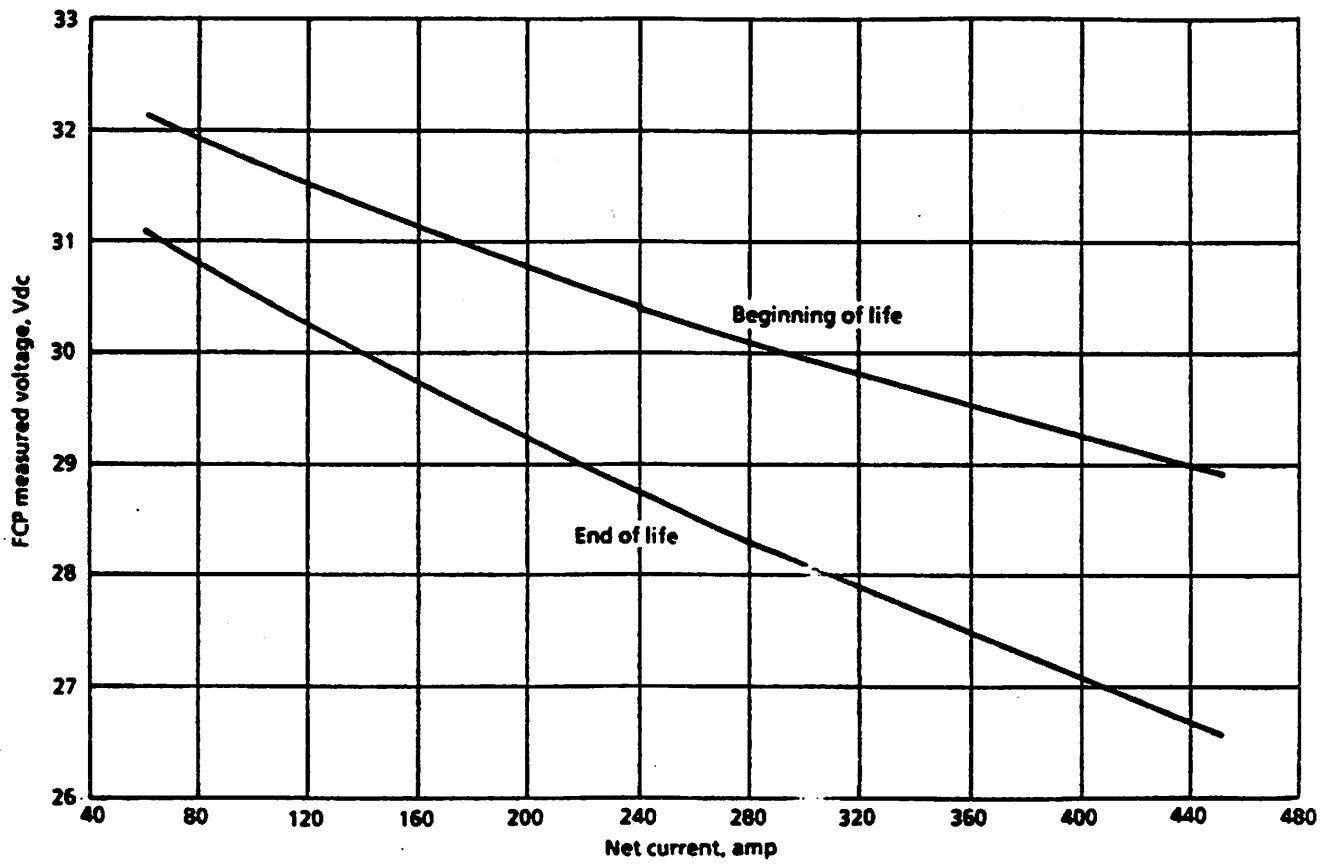


Figure 2-5.- FCP performance limits.

The auto purge is initiated by a crewmember, but the SM OPS 2 sequence automatically performs the purges, turning heaters ON/OFF and opening and closing purge valves. Before initiating a purge, the proper switch configuration must be verified.

Purge heater - GPC

Purge valves 1, 2, 3 - GPC

(If all three fuel cells are to be purged. If a fuel cell is not to be purged, that switch should be in the CLOSE position).

The crewmember holds GPC PURGE SEQ switch to START until GPC PURGE SEQ tb goes gray. The sequence is now started and no further action is required.

With sequence initiation, the purge line heaters are commanded on and a software timer is started. These heaters are needed to prevent condensate from freezing and thus blocking the lines. Three purge line temp. limits must be satisfied before the timer times out (27 minutes). These are the following:

O₂ vent line temp - 69°F

H₂ vent line temp 1 - 79°F

H₂ vent line temp 2 - 40°F

The expiration time for the timer satisfies the worst case vehicle thermal environment. If the timer times out and a limit is not satisfied, the sequence stops and an SM alert is indicated.

When all three temperature limits are satisfied, fuel cell purging is immediately started. The general purpose computer (GPC) checks the fuel cell 1 purge valve switch position. If the GPC position is selected, both purge valves (O₂ and H₂) are commanded open. The GPC then does a computation comparing actual reactant flow to calculated flow (fuel cell current x constant = reactant flow - lb/hr). If actual flow minus calculated flow is >0.9 lb/hr (O₂) and >0.3 lb/hr (H₂), the GPC is satisfied that the valves are opened. If either reactant check is not satisfied, the valves are commanded

closed, an SM alert is annunciated, and the sequence proceeds to the next fuel cell.

After a 2-minute purge time, the GPC commands the valves closed. Once again, the flow check is made. The actual flows should now equal the calculated flows within 0.9 lb/hr (O₂) and 0.3 lb/hr (H₂). If they do pass, the sequence proceeds with fuel cell 2 purging. If they do not pass, the sequence is stopped (heaters remain on) and an SM alert is annunciated. At the time of this writing, the purge valve open/close checks have been negated on OV102 and OV099.

The line heaters are not thermostatically controlled; however, some temperature fluctuations may be observed as the relatively cold reactants flow through the lines. After the fuel cells are purged, the line temperatures will increase steadily, perhaps > 300°F. The H₂ vent line T-2 may not increase much because the heat goes into ice vaporization and is dissipated. The O₂ vent line temperature may show little increase - perhaps, some decrease. If, during the sequence, a temperature indicates an uncharacteristic decreasing trend, a heater failure may have occurred. In this situation the auto purge capability is lost, and subsequent purges must be performed manually. The manual purge heaters must be used to bakeout the purge lines, which is accomplished by switching the heater configuration from AUTO to ON. Consideration may be given to extending the bakeout time for an extra accumulation of ice or water. If the failure occurred in the H₂ vent system, the bakeout time should be increased to 2 hours, which assures all ice removal in the line or at the port. Failures in the O₂ system are not as critical, since water and ice accumulation are not as likely. However, to be conservative, the 2-hour bakeout is recommended also.

If the fuel cell 2 purge valve switch is selected to GPC, fuel cell 2 is purged immediately after fuel cell 1 is completed.

If the fuel cell 3 purge valve switch is selected to GPC, fuel cell 3 is purged immediately after fuel cell 2 is completed. The

same procedure as described for fuel cells 1 and 2 is followed.

After fuel cell 3 has completed purging, the valves are closed; however, the sequence continues for an additional 55 minutes for purge line bakeout of all moisture. After 55 minutes, the GPC deactivates the heaters, and the sequence stops and recycles back to start. The GPC purge sequence start talkback will go barberpole when the sequence is completed.

The manual purge requires a crewmember to activate the heaters manually, monitoring temperatures on the S69 display (FUEL CELLS), opening and closing purge valves, and verifying proper purge flow. It is estimated that a manual purge will require about 20 to 25 minutes of a crewmember's time.

Continuous purging of a fuel cell should not exceed 20 minutes. Testing has shown that ice formation may occur shortly after 20 minutes, even with proper heater usage. If two fuel cells were simultaneously purged, purge duration should not exceed 11 minutes. (Purging two fuel cells simultaneously causes no damage.) The purge flow from each fuel cell is reduced, thus decreasing the effectiveness of the purge.

If ice does form in the purge lines, a 2-hour bakeout procedure should be performed. This consists of activating the heaters in the manual mode. Testing has shown that within 2 hours all ice plugging should be cleared.

If a fuel cell purge is performed with no prior preheating of lines, ice blockage may occur in the H₂ line during the purge. Ice blockage in the O₂ line may occur after the purge is completed but not while the purge flow is maintained.

Fuel cell voltage drops will occur between purges. Usually, the lowest voltage occurs just before a purge. The amount of the voltage drop depends on fuel cell usage during that 8-hour period – the more ampere-hours, the more ice build up, and more degradation. Purge intervals (8 hour) were established considering a lower fuel cell terminal voltage limit of 28.5 V dc. The

absolute specified lower limit is 27.5 V dc; however, a 1-V factor is figured in to allow for fuel cell to fuel cell variation around the nominal performance (0.5 V dc), transient load effects not considered in the steady-state performance (0.3 V dc), and the fact that perfect load sharing is not achieved between the three fuel cells (0.2 V dc). For example, the projected STS-1 power load profile and the purge schedule showed voltage degradation as much as 1.2 V from 29.71 V dc to 28.5 V dc. Inability of a fuel cell to purge properly will cause continued voltage degradation, requiring the fuel cell to be shut down.

Purging the O₂ reactant is more critical than H₂. O₂ inert buildup causes greater voltage degradation than H₂ for the same amount of time. Therefore, if a problem occurs in the H₂ purging (complete line blockage or just one fuel cell), the purge operations should be continued manually for all three fuel cells.

Between fuel cell purges, the fuel cell(s) may degrade at a faster rate than predicted. In the MCC, the actual fuel cell voltage will be compared to the predicted voltage, and if the actual is 0.5 V dc less than predicted, the fuel cell should be purged. Inert buildup in that fuel cell is occurring at a faster rate, and degradation should not be allowed to proceed to the lower limit of 28.5 V dc.

2.3.4 Coolant Loop

In order to cool the fuel cell stack during its operation, distribute heat during fuel cell startup, and warm up the cryogenic reactants entering the stack, the fuel cell circulates a coolant, fluorinated hydrocarbon (FC-40), throughout the fuel cell. The schematic of fuel cell 1 (fuel cells 1, 2, and 3 are identical) shows the coolant loop in the fuel cell and its interface with the ECLSS Freon coolant loops. (Refer to figure 2-3.)

At the coolant entrance to the fuel cell, the temperature of the coolant returning from the

ECLSS Freon loops is sensed just before it passes through a 75 micron filter. After the filter, there are two temperature-controlled premixing valves which allow some of the hot coolant (from the FC stack) to mix with the cool returning coolant from the vehicle to condition the temperature of the coolant flowing into the condenser exit control valve and prevent it from undergoing repeated oscillations. The condenser exit control valve adjusts the flow of the coolant through the condenser to maintain the H₂/H₂O vapor exiting the condenser at a temperature between 148°F and 153°F. The stack inlet control valve maintains the temperature of the coolant entering the stack between 181°F and 185°F by mixing coolant from the condenser (cold fluid) with coolant from the stack (hot fluid). The accumulator is the interface with the O₂ cryogenic reactant to maintain an equalized pressure between the O₂ and the coolant (O₂ and H₂ pressures are equalized at the dual gas regulator) to preclude a high pressure differential in the stack which could burst the thin walls of the cells. The pressure in the coolant loop is sensed right before the coolant enters the stack.

The coolant is circulated through the fuel cell stack to absorb the waste heat from the H₂/O₂ reaction occurring in the individual cells. After leaving the stack, the temperature of the coolant is sensed, with the data being sent to the GPC, the FUEL CELL STACK TEMP gage on panel O2, and STACK T section of the SM OPS 2 FUEL CELLS CRT display. The hot coolant just out of the stack flows through the O₂ and H₂ preheaters where it warms the cryogenic reactants before they enter the stack.

The coolant pump uses three-phase ac power to drive the coolant through its loop. The ΔP sensor senses a pressure differential across the pump to determine the status of the pump. Downstream of the pump is the flow control valve, which is a temperature-actuated valve. This valve adjusts the coolant flow to maintain the fuel cell coolant exit temperature between 196°F and 203°F. The stack inlet control valve and flow control valve have bypass orifices which allow coolant to flow through the coolant

pump and maintain some coolant flow through the condenser for water condensation even when the valves are fully closed.

The coolant (that which is not made to bypass) exits the fuel cell to interface with the ECLSS Freon loop fuel cell heat exchanger where it transfers its excess heat to the Freon to be dissipated somewhere else.

In addition to the thermal conditioning by means of the coolant loop, the fuel cell has internal startup, sustaining, and end cell heaters. The startup heater (3287 W) is only used during startup to warm the fuel cell up to its operational level. The two end cell heaters (160 W each) keep the cells at the end of the fuel cell stack at the same temperature as the cells in the middle of the stack. The sustaining heaters (1194 W) are normally used during low power periods to maintain the fuel cells at their operational temperature.

2.3.5 Electrical Control Unit

The electrical control unit (ECU) is the brain of the fuel cell. The ECU is an electrical module located within the fuel cell and contains the startup logic, heater thermostats, and 30-second timer. It is the interface with crew controls and displays for fuel cell startup, operation, and shutdown. The ECU controls the supply of ac power to the coolant pumps, H₂ pump/H₂O separator, and the pH sensor, as well as the dc power supplied to the flow control bypass valve (open only during startup), the internal startup, sustaining, and end cell heaters. The ECU also controls the status of the READY FOR LOAD and COOLANT PUMP ΔP talkbacks.

The D&C that interface with the ECU of fuel cell 1 (fuel cells 2 and 3 are identical) are shown in figure 2-4, and figure 2-6 shows their location in the flight deck. Located on panel L4:C are the nine circuit breakers that connect the three-phase ac power to the three fuel cells. The ECU receives its operating power from an essential bus through the FC1 CNTLR sw on panel O14.

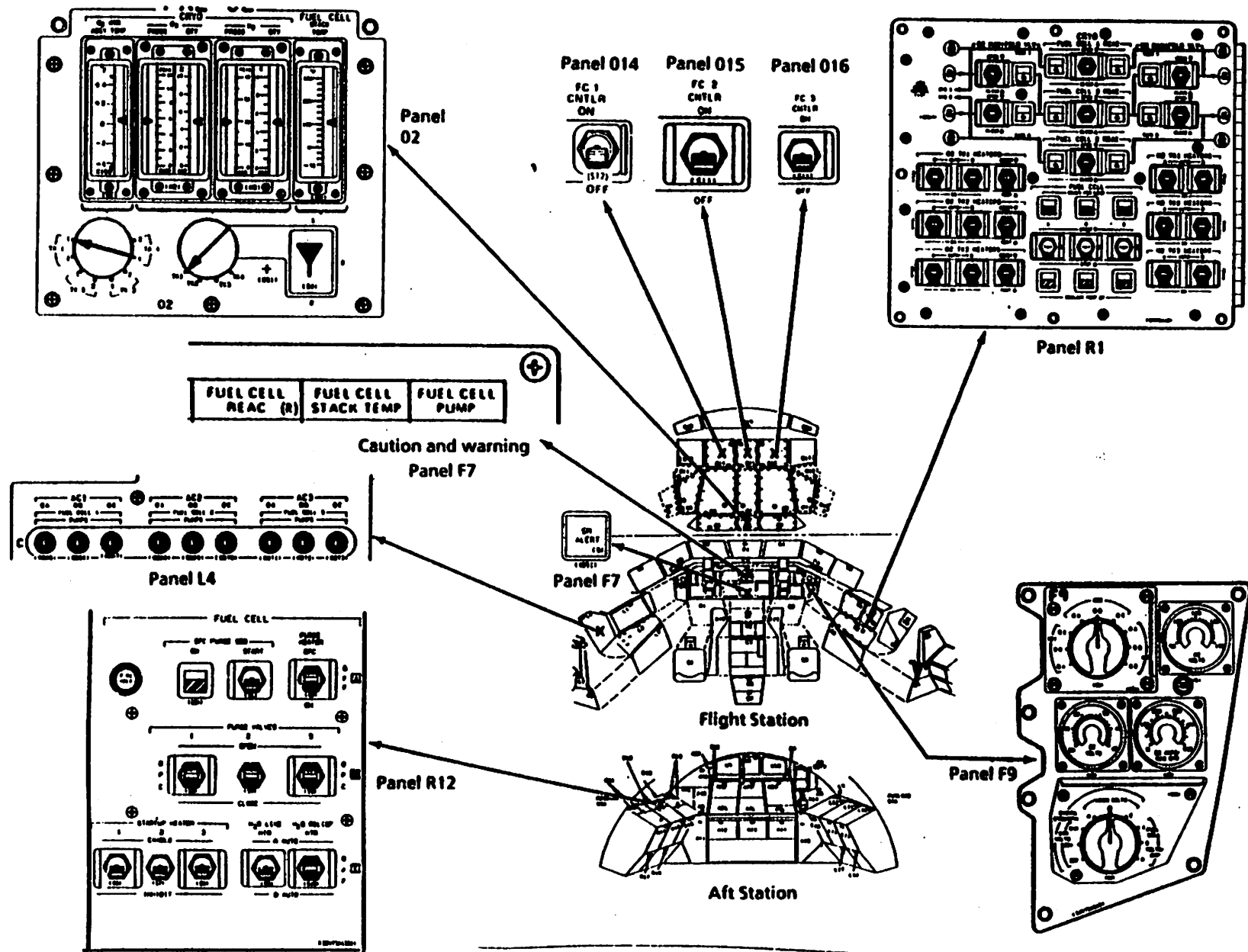


Figure 2-6.- Fuel cell controls and displays.

The **STARTUP HEATER ENABLE/INHIBIT** switch on panel R12 provides crew control of the startup heaters during fuel cell startup. The **INHIBIT** position allows the startup heaters to remain off, and, therefore, would be used only when starting an already warm fuel cell. The **FUEL CELL START/STOP** sw on panel R1 is used to initiate the start sequence or stop the fuel cell operation. When this switch is held in its momentary start position, the ECU connects the three-phase ac power to the coolant pump and H₂ pump/H₂O separator (allowing the coolant and the hydrogen-water vapor to circulate through their loops), and connects the dc power to the internal startup, sustaining and end cell heaters, and the flow control bypass valve. The **START/STOP** switch must be held in the start position until the **COOLANT PUMP ΔP** talkback turns gray, which should take approximately 3-4 seconds, or the pump will not be running. The **COOLANT PUMP ΔP** talkback, when gray, indicates that the coolant pump is functioning properly by creating a pressure differential across the pump; when barberpole, it indicates that the coolant pump is off. The **READY FOR LOAD** talkback will turn gray after the 30-second timer times out and the **STACK OUT TEMP** is above 187°F, which indicates that the fuel cell is up to the proper operating condition and is ready for the 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 depending on the initial temperature of the fuel cell. Once gray, the **READY FOR LOAD** talkback will remain gray until the **FUEL CELL START/STOP** switch is placed to **STOP**, the **FC CNTLR** sw is placed in **OFF**, or the **ESS** bus power is lost to the ECU.

At crew ingress the fuel cells will be on but in standby, and the Orbiter will be powered by the GSE. Just before lift-off (T - 20:00), GSE will be powered off and the fuel cells will take over the electrical loads. Indications of a switchover can be noted on the **SM SYS SUMM 1 CRT** display (figure 2-11) and the **DC AMP/SIG STR** meter on panel F9. The fuel cell current will rise to approximately 220 A; the O₂ and H₂ flow will

increase to approximately 4.0 lb/hr and 0.6 lb/hr, respectively; and the fuel cell stack temperature will increase slightly.

Fuel cell standby consists of removing the electrical loads, but continuing the operation of the fuel cell pumps controls, instrumentation, and valves, with the power being supplied from the other fuel cells. A small amount of reactants are used in this phase to generate power for the fuel cell internal heaters. A fuel cell shutdown, after standby, consists of stopping the coolant pump and H₂ pump/H₂O separator by placing the **START/STOP** switch to the **STOP** position. If the environment in the compartment beneath the payload bay where the fuel cells are located is lower than 40°F, the fuel cell should be left in standby instead of shutdown to keep it from freezing. There is no planned fuel cell standby or shutdown.

2.3.6 Cell Performance Monitor (CPM)

As fuel cell life increased with the introduction of the third substack, the likelihood of individual cell failures caused by "wearout" or "age" was increased. Consequently, the CPM was designed to detect individual cell performance problems or imminent failures such as cell crossover. (See figure 2-7.)

Crossover may be defined as an uncontrolled mixing of the reactants that result in the generation of excessive product heat. Hydrogen and oxygen in combination represent a mixture that requires little heat to explode. During normal FC operation, hydrogen and oxygen are diffusely mixed to produce electricity. A fibrous asbestos blotter device within each cell called the "matrix" allows this mixing to occur and, in addition, holds the potassium hydroxide (KOH) electrolyte. 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 occur at

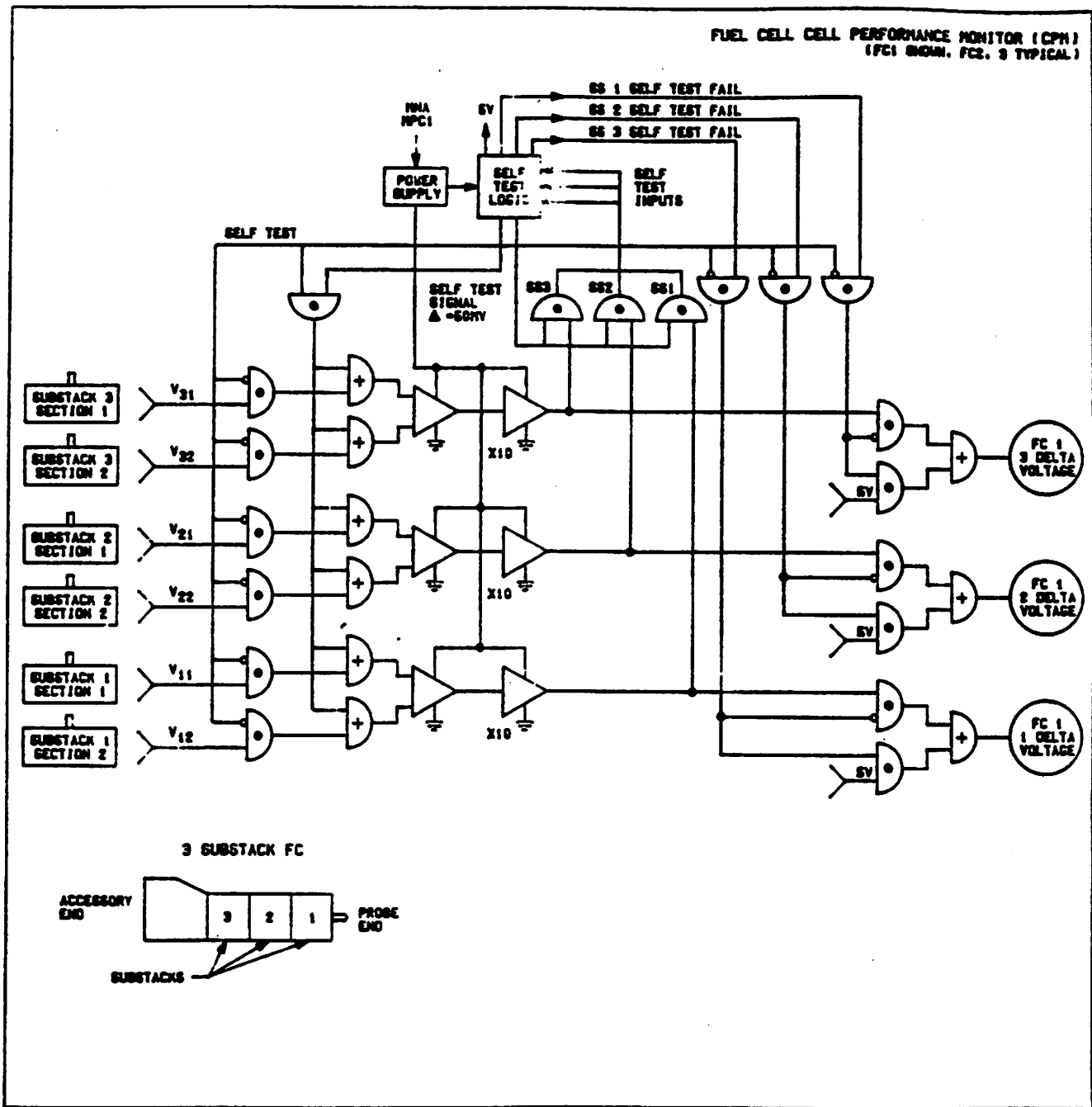


Figure 2-7.- Cell performance monitor (CPM).

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 may uncontrollably propagate possibly resulting in a violent explosion. A crossover may proceed rapidly or gradually. Before the introduction of the CPM 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 CPM basically compares each half substack voltage and extracts a delta volts measurement. By comparing both halves of a substack, the CPM can detect cell changes. Since all the cells in a substack are at the same current, both halves should be at approximately identical voltages, thus $\Delta V = 0$ (actually ± 50 mV). A significant voltage loss in any one cell will produce an identical change in the ΔV with 300 mV being a critical performance loss. ΔV can be either positive or negative, so the CPM 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 caution and warning limit is set at 150 mV. The output is then converted to a 0-5 V dc signal for telemetry and crew display systems by a 'times 10' amplifier. Calibration curves rescale this to EU (0-50 mV).

Every 7.5 minutes the CPM performs a self-test to insure data accuracy in order 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 575 to 425 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.

The CPM output is continuously varying within a few mV range as load, temperatures, concentration, and inert levels vary. Therefore, small changes are not unusual and should not be a cause of concern. Generally, a cell failure will show a continuing trend of increasing Δ 's, eventually exceeding the caution and warning alarm. It is not expected that a ΔV output voltage will suddenly jump to > 150 mV. This would be a suspect condition. Nominal readings for the CPM are on the order of 20 mV. The SM annunciates in the BFS and PFS at CPM delta volts of 150 mV. The devices are sampled in TM once per second. The measurements may be viewed on SYS SUMM 1 and SPEC 69 FUEL CELL DISPLAYS. The flight crew should plot the CPM values after each fuel cell purge to determine any slowly increasing trends.

The separate CPM units for each fuel cell run independently and begin whenever voltage from the midpower controllers is available, that is the FC 1 CPM is powered from MPC 1, FC 2 from MPC 2, FC 3 from MPC 3. The CPM unit draws ~ 150 mA and is protected by a 3-amp fuse. Loss of the fuse may be confirmed by simultaneous loss of the associated fuel cell hydrogen flow transducer.

2.3.7 Fuel Cell Controls and Displays

The D&C for the fuel cell system are on flight deck panels R1, R12, O2, O14, O15, O16, F7, F9, and L4. Figure 2-6 shows these panels and their relative positions on the flight deck.

The right-hand portion of panel R1 contains the switches and talkbacks for the fuel cell startup operation. These switches include the reactant valve switches (FUEL CELL 1(2,3) REAC), the start/stop switch (FUEL CELL

START/STOP), the ready for electrical load talkback (FUEL CELL READY FOR LOAD), and the coolant pump status talkback (COOLANT PUMP Δ P).

Panel R12 contains the startup heater switches STARTUP HEATER 1(2,3) ENABLE/NHIBIT and the H₂O discharge and vent line heater switches H₂O LINE HTR and H₂O RELIEF HTR, respectively. The rest of the switches on panel R12 deal with purging.

Panel L4 contains the nine circuit breakers that connect ac bus 1(2,3) three-phase power to the coolant pump, the H₂ pump/H₂O separator, and phase A power to the pH sensor.

Panel O2 contains a meter that indicates the temperature of the coolant exiting the fuel cell stack. This temperature closely relates to the actual temperature inside the fuel cell stack. A three-position switch directly below the meter allows selection of any one of three fuel cell stack temperatures to be displayed on the meter.

Panel F9 contains two meters, one to display fuel cell current and the other to display fuel cell voltage. A rotary select switch directly below these meters allows selection of any one fuel cell's current and voltage to be displayed on the meters.

The switches that supply power to the ECUs of fuel cells 1, 2, and 3 can be found on panels O14, O15, and O16, respectively.

A more complete description of each display or control pertaining to the fuel cell system is given in table 2-1, which gives the panel number where the switch can be found, the type of crew control or display, the nomenclature that appears on the panel, and each control's function.

Panel F7 contains the C/W annunciator light matrix and the SM ALERT light. The lights pertaining to the fuel cell system on the annunciator matrix are FUEL CELL REAC, FUEL CELL STACK TEMP, FUEL CELL PUMP, and BACKUP C/W. The FUEL CELL REAC light will annunciate whenever a reactant valve is in

the closed position. The signal that is sent to the FUEL CELL STACK TEMP meter on panel O2 is also hardwired to the C/W electronics where, if the signal is out of limits, the FUEL CELL STACK TEMP light will annunciate. This same signal is also sent to the computers where its limits are checked; if the signal is out of limits, the BACKUP C/W light will annunciate. The signal that is sent to the COOLANT PUMP Δ P talkback on panel R1 is also hardwired to the C/W electronics. If this signal indicates the pump is off, the FUEL CELL PUMP light will annunciate. This same signal is also sent to the computers and will light up the BACKUP C/W light if the pump signal indicates an OFF position.

The computer software detected BACKUP C/W light is just as its name implies, a backup to the three hardwired lights: FUEL CELL STACK TEMP, FUEL CELL PUMP, and FUEL CELL REAC. The upper and lower limits of the three hardwired lights are exactly the same as the software detected BACKUP C/W light. Figures 2-8 and 2-9 list the upper and lower limits for the three hardwired lights and the software detected BACKUP C/W light, along with the fault message that will appear on the CRT screen when one of these lights annunciate. These figures also list the SM ALERT parameters that are applicable to the fuel cells.

The SM FDA, which consists of the SM ALERT and BACKUP C/W software, will be in GPC 5, the BFS computer during ascent and descent phases of the mission. During on-orbit operations (OPS-2), the SM ALERT and BACKUP C/W software will be in GPC 4, a primary flight system computer.

Panel F7 also contains the three CRT screens where the crew can monitor the fuel cell performance. During on-orbit phases (OPS-2), fuel cell parameters are displayed on the FUEL CELL display (figure 2-12) and on the SM SYS SUMM 1 display (figure 2-10). During ascent and entry phases, the parameters are displayed on the SM SYS SUMM 1 display (figure 2-11). For a more complete description of CRT displays, refer to SFOM Volume 14.

TABLE 2-1.- FUEL CELL DISPLAYS AND CONTROLS

Panel	Type	Nomenclature	Function	Remarks
R12	sw	FUEL CELL 1(2,3) STARTUP HEATER		Startup heater disable for FC1
		ENABLE	Allows the startup heater to turn on during a fuel cell-startup.	
		INHIBIT	The startup heater will not be on during a fuel cell startup.	
O14 O15 O16	sw sw sw	FC 1(2,3) CNTLR		
		ON	Connects ESS bus power to fuel cell 1,(2,3) ECU for startup and heater operations.	
		OFF	No power supplied to fuel cell 1(2,3) ECU.	
R12	sw	FUEL CELL 1(2,3) PURGE VALVES		
		OPEN	Opens fuel cell 1(2,3) H ₂ and O ₂ purge valves.	
		GPC	Fuel cell 1(2,3) H ₂ and O ₂ purge valves. Open and close on command from the GPC.	
		CLOSE	Closes fuel cell 1(2,3) H ₂ and O ₂ purge valves.	
R12	sw	FUEL CELL GPC PURGE SEQ		
		START	Sends signal to the GPC to begin purging sequence.	
R12	flag	FUEL CELL GPC PURGE SEP		
		gray	Computer-controlled purging sequence on.	
		barberpole	Purging sequence off.	

TABLE 2-1.- FUEL CELL DISPLAYS AND CONTROLS (Continued)

Panel	Type	Nomenclature	Function	Remarks
R12	sw	FUEL CELL PURGE HEATER		
		GPC	Enables power to the set of heater elements which are turned on and off by GPC commands.	
		OFF	No power is connected to any purge line heaters.	
R12	sw	FUEL CELL H ₂ O LINE HTR		
		A AUTO	Allows the A heaters in fuel cell 1(2,3) H ₂ O discharge line to the water supply system to turn on and off automatically.	
		OFF	No power connected to fuel cell 1(2,3) H ₂ O discharge line heaters.	
R12	sw	FUEL CELL H ₂ O RELIEF HTR		
		A AUTO	Allows the A heaters in the H ₂ O relief vent line to turn on and off automatically.	
		OFF	No power connected to the H ₂ O relief vent line heaters.	
R12	sw	B AUTO	Allows the B heaters in fuel cell 1(2,3) H ₂ O discharge line to turn on and off automatically.	
		B AUTO	Allows the B heaters in the H ₂ O relief vent line to turn on and off automatically.	
F9	sel	FUEL CELL DISPLAY SELECT	Selects fuel cell 1, 2, or 3 voltage and current to be displayed on the DC VOLTS meter and DC AMPS/SIG STR meter.	

TABLE 2-1.- FUEL CELL DISPLAYS AND CONTROLS (Continued)

Panel	Type	Nomenclature	Function	Remarks
F9	ind	DC AMPS/SIG STR	Displays fuel cell 1, 2, or 3 current on a meter.	Range of 0 to 500 A.
F9	ind	DC VOLTS	Displays fuel cell 1, 2, or 3 voltage on a meter.	Range of 20 to 45 V.
O2	sw	FUEL CELL 1(2,3) DISPLAY SELECT	Selects fuel cell 1, 2, or 3 stack temperature to be displayed on the meter.	
O2	ind	FUEL CELL 1(2,3) STACK TEMP	Displays fuel cell 1, 2, or 3 stack temperature on a meter.	Range of -74° to 300°F.
L4	cb cb cb cb	FUEL CELL 1 PUMP AC1φA AC1φB AC1φC	Provides three-phase ac power for fuel cell 1 coolant pump, H ₂ pump/H ₂ O separator, and φA to the pH sensor.	
L4	cb cb cb cb	FUEL CELL 2 PUMP AC2φA AC2φB AC2φC	Provides three-phase ac power for fuel cell 2 coolant pump, H ₂ pump/H ₂ O separator, and φA to the pH sensor.	
L4	cb cb cb cb	FUEL CELL 3 PUMP AC3φA AC3φB AC3φC	Provides three-phase ac power for fuel cell 3 coolant pump, H ₂ pump/H ₂ O separator, and φA to the pH sensor.	
R1	sw	FUEL CELL 1(2,3) REAC OPEN CLOSE	Opens the H ₂ and O ₂ reactant valves, allowing reactants to flow from the manifold into fuel cell 1(2,3). Closes the H ₂ and O ₂ reactant valves, shutting off reactant flow from the manifold to fuel cell 1(2,3).	
R1	flag	FUEL CELL 1(2,3) REAC OP CL	Indicates the H ₂ and O ₂ reactant valves are open. Indicates the H ₂ and O ₂ reactant valves are closed.	

TABLE 2-1.- FUEL CELL DISPLAYS AND CONTROLS (Concluded)

Panel	Type	Nomenclature	Function	Remarks
R1	sw	FUEL CELL 1(2,3) START	Sends signal to fuel cell 1(2,3) ECU to begin the start sequence.	
		STOP	Sends signal to fuel cell 1(2,3) ECU to stop operation.	
R1	flag	FUEL CELL 1(2,3) READY FOR LOAD		
		gray	Fuel cell 1(2,3) is ready to be connected to MNA (B,C) and ESS 1BC (2CA, 3AB).	
		barberpole	Fuel cells are not ready for electrical loads to be connected.	
R1	flag	COOLANT PUMP 1(2,3) ΔP		
		gray	Coolant pump 1(2,3) on.	
		barberpole	Coolant pump 1(2,3) off.	

**BACKUP CW
ALARM**

CRT name	Units	Lower limit	Upper limit	Fault message
PUMP	1,2,3	event	OFF	S69 FC PUMP 1,2,3 ↓ 4 HH:MM:SS
REAC O2	1,2,3	event	CLOSE	S69 FC REAC 1,2,3 ↓ 4 HH:MM:SS
REAC H2	1,2,3	event	CLOSE	S69 FC REAC 1,2,3 ↓ 4 HH:MM:SS
STACK T	1,2,3	°F	172.5 243.7	S69 FC STACK T 1,2,3 ↑ or ↓ 4 HH:MM:SS

**SM
ALERT**

CRT name	Units	Lower limit	Upper limit	Fault message
FC VOLTS	1,2,3	V dc	27.5 32.5	S69 FUEL CELL 4 HH:MM:SS
AMPS	1,2,3	amps	54.0 360.0	S69 FUEL CELL 4 HH:MM:SS
FLOW O2	1,2,3	lb/hr	10.0	S69 FUEL CELL 4 HH:MM:SS
FLOW H2	1,2,3	lb/hr	1.6	S69 FUEL CELL 4 HH:MM:SS
STACK T	1,2,3	°F	175 212	S69 FC STACK T 1,2,3 4 HH:MM:SS
STACK T	1,2,3	°F	185 222	S69 FC STACK T 1,2,3 4 HH:MM:SS
STACK T	1,2,3	°F	195 238	S69 FC STACK T 1,2,3 4 HH:MM:SS
EXIT	1,2,3	°F	131 170	S69 FUEL CELL 4 HH:MM:SS
COOL P	1,2,3	psia	50.1 75	S69 FUEL CELL 4 HH:MM:SS
H2O LNT	1,2,3	°F	45 185	S69 FUEL CELL 4 HH:MM:SS
H2O VLV T	1,2,3	°F	60 150	S69 FUEL CELL 4 HH:MM:SS
PH	1,2,3	event	ON	S69 FUEL CELL 4 HH:MM:SS
H2O RLF LNT		°F	60 150	S69 FUEL CELL 4 HH:MM:SS
NOZ T A,B		°F	100 425	S69 FUEL CELL 4 HH:MM:SS
PURGE LN O2 T		°F	380	S69 FUEL CELL 4 HH:MM:SS
PURGE LN H2 T 1,2		°F	380	S69 FUEL CELL 4 HH:MM:SS
V SS 1,2,3		mVdc	150	S69 FC DELTA V 1,2,3 4 HH:MM:SS
END HTR A,B		event	ON	S69 FC END HTR 4 HH:MM:SS

Figure 2-8.- On-orbit fuel cell alert parameters.

**BACKUP CW
ALARM**

CRT name	Units	Lower limit	Upper limit	Fault message
PUMP	1,2,3	event	OFF	SM1 FC PUMP 1,2,3 ↓ 5 HH:MM:SS
REAC O2	1,2,3	event	CLOSE	SM1 FC REAC 1,2,3 ↓ 5 HH:MM:SS
REAC H2	1,2,3	event	CLOSE	SM1 FC REAC 1,2,3 ↓ 5 HH:MM:SS
STACK T	1,2,3	°F	172.5 243.7	SM1 FC STACK T 1,2,3 ↑ or ↓ 5 HH:MM:SS

**SM
ALERT**

CRT name	Units	Lower limit	Upper limit	Fault message
FC AMPS	1,2,3	amps	54 410	SM1 FC AMPS 1,2,3 5 HH:MM:SS
STACK T	1,2,3	°F	175 212	SM1 FC STACK T 1,2,3 5 HH:MM:SS
STACK T	1,2,3	°F	185 221.6	SM1 FC STACK T 1,2,3 5 HH:MM:SS
STACK T	1,2,3	°F	195 237.4	SM1 FC STACK T 1,2,3 5 HH:MM:SS
DC VOLT FC	1,2,3	V dc	27.5 32.5	SM1 DC VOLT FC 1,2,3 5 HH:MM:SS
COOL P	1,2,3	psia	50.1 75	SM1 VC COOL P 1,2,3 5 HH:MM:SS
EXIT T	1,2,3	°F	131 169.7	SM1 FC EXIT T 1,2,3 5 HH:MM:SS
ΔV SS	1,2,3	mVdc	150	SM1 FC DELTA V 1,2,3 5 HH:MM:SS
END HTR	A,B	event	ON	S MO FC END HTR 5 HH:MM:SS

Figure 2-9.- BFS fuel cell alert parameters.

2011/094/078				SM SYS SUMM 1			3 000/02: 48: 16		
							000/00: 00: 00		
EMERGENCY									
SMOKE	1/A	2/B		DC VOLTS	1/A	2/B	3/C		
AV BAY	1-	0.0	0.0	FC	31.4	31.4	31.2		
	2-	0.0	0.0	MAIN	31.2	31.1	31.3		
	3-	0.0	0.0	CNTL	AB	30.1	30.1	30.0	
dP/dT	±.00				BC	30.0	30.0	30.0	
					CA	30.0	30.0	30.0	
CABIN				ESS	29.9	30.0	30.0		
PRESS	14.9			AC					
PPO2	3.04	3.04		VOLT	Φ A	117	117	117	
FAN ΔP	6.43				Φ B	117	117	117	
HX OUT T	53				Φ C	117	117	117	
O2 FLOW	0.0L	0.0L		AMPS	Φ A	2.2	3.0	2.4	
N2 FLOW	0.0L	0.0L			Φ B	2.2	3.2	2.4	
					Φ C	2.2	3.2	2.1	
IMU FAN	A	B*	C	FUEL CELL					
ΔV	FC1	FC2	FC3	AMPS	156	158	148		
SS1	23	26	26	REAC VLV	OP	OP	OP		
SS2	18	22	13	STACK T	+202	+300H	+202		
SS3	9	13	13	EXIT T	151	151	151		
TOTAL AMPS	463			COOL P	61	61	61		
	KW	14		PUMP					
SYS SUMM									

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Figure 2-10.- Fuel cell parameters on SM OPS 2 SYS SUMM 1 CRT display.

2011/094/078				SM SYS SUMM 1			3 000/02: 48: 16		
							BFS 000/00: 00: 00		
EMERGENCY									
SMOKE	1/A	2/B		DC VOLTS	1/A	2/B	3/C		
AV BAY	1-	0.0	0.0	FC	31.4	31.4	31.2		
	2-	0.0	0.0	MAIN	31.2	31.1	31.3		
	3-	0.0	0.0	CNTL	AB	30.1	30.1	30.0	
dP/dT	±.00				BC	30.0	30.0	30.0	
					CA	30.0	30.0	30.0	
				ESS	29.9	30.0	30.0		
CABIN				AC					
PRESS	14.9			VOLT	Φ A	117	117	117	
PPO2	3.04	3.04			Φ B	117	117	117	
FAN ΔP	6.43				Φ C	117	117	117	
HX OUT T	53			AMPS	Φ A	2.2	3.0	2.4	
O2 FLOW	0.0L	0.0L			Φ B	2.2	3.2	2.4	
N2 FLOW	0.0L	0.0L			Φ C	2.2	3.2	2.1	
IMU FAN	A	B*	C	FUEL CELL					
ΔV	FC1	FC2	FC3	AMPS	156	158	148		
SS1	23	26	26	REAC VLV	OP	OP	OP		
SS2	18	22	13	STACK T	+202	+300H	+202		
SS3	9	13	13	EXIT T	151	151	151		
TOTAL AMPS	463			COOL P	61	61	61		
	KW	14		PUMP					
SYS SUMM									

1436. ART, 5

Figure 2-11.- Fuel cell parameters on BFS SM SYS SUMM 1 CRT display.

0001/	/	THERMAL				XX X DDD/HH: MM: SS			
						BFS SSS/HH: MM: SS			
HYD SYS TEMP	BDYFLP RD/SB	L OB	L IB	R IB	R OB				
	ACTR	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
	PRIME	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
	STBY 1	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
	STBY 2	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
HTR TEMP	L/A	R/B	FREON LOOP			1	2		
PRPLT			ACCUM QTY	XXXX	XXXX				
POD	SSSSSSS	SSSSSSS	RAD IN T	XXXX	XXXX				
OMS CRSFD	SSSSSS								
EVAP			H2O						
HI LOAD	SSS		SUPPLY P	XXXX					
TOP DUCT	SS								
	NOZ	S							
FDLN	SSSS	SSSS							
HYD BLR/HTR	S	S							
APU									
GG/FU PMP HTR	SSSS	SSSS							
TK/FU LN HTR	SSSSSSSSS	SSSSSSSSS							
PUMP/VLV COOL	SS	SS							
FC END HTR A/B	XXXX/XXXXX	XXXX/XXXXX	XXXX/XXXXX						(XX)

4276. ART, 1

Figure 2-12.- Fuel cell parameters on SM OPS 2 FUEL CELL CRT display.

XXXX/XXX/069	FUEL CELLS			XX X DDD/HH: MM: SS				
				DDD/HH: MM: SS				
	FC							
	1	2	3					
VOLTS	XX.XS	XX.XS	XX.XS	H2O RLF LINE T		XXXX		
AMPS	XXXX	XXXX	XXXX	NOZ T A		XXXX		
				B		XXXX		
FLOW O2	XX.XS	XX.XS	XX.XS	PURGE LN O2 T		XXXX		
H2	X.XS	X.XS	X.XS	H2 T1		XXXX		
REAC O2	XXS	XXS	XXS	T2		XXXX		
H2	XXS	XXS	XXS					
STACK T	±XXXX	±XXXX	±XXXX					
EXIT T	XXXX	XXXX	XXXX					
COOL T	XXXX	XXXX	XXXX					
P	XXXX	XXXX	XXXX					
PUMP	XXS	XXS	XXS	PH				
				ΔV				
H2O LN T	XXXX	XXXX	XXXX	SS1	1	2	3	
VLV T	XXXX	XXXX	XXXX	SS2	XXS	XXS	XXS	
END HTR				SS3	XXXX	XXXX	XXXX	
	A	XXXXX	XXXXX	XXXXX				
	B	XXXXX	XXXXX	XXXXX				

Figure 2-13.- Fuel cell parameters on BFS THERMAL CRT display.

4275. ART, 1

2.4 Fuel Cell Performance, Limitations, and Capabilities

2.4.1 Fuel Cell Power Outputs

- 2 kW minimum (any power output below this and voltage may exceed design limit of 32.5 V)
- 7 kW continuous
- 10 kW one hour maximum
- 12 kW fifteen minutes maximum every 3 hours
- 15 kW maximum power in an emergency situation for 12 minutes (voltage may drop below 27.5 V)
- 16 kW overload capacity (10 minutes maximum at 26.5 Vdc). Exceeds design capability. Possible fuel cell damage.

2.4.2 Reactant Usage, lb/hr

<u>Power</u>	<u>O₂</u>	<u>H₂</u>
2 kW	1.372 lb/hr	.1728 lb/hr
7 kW	5.026 lb/hr	.6335 lb/hr
10 kW	7.43 lb/hr	.935 lb/hr
12 kW	9.072 lb/hr	1.145 lb/hr

Reactant consumption is directly related to the current produced by the fuel cell.

2.4.3 Water Production, lb/hr

<u>Power</u>	<u>lb/hr</u>
2 kW	1.7
7 kW	5.9
10 kW	8.4
12 kW	10.0

2.4.4 Fuel Cell Nominal Ranges

Current	140 - 350 A
Stack out temperature	190° - 210°F
Condenser exit temperature	140° - 160°F
Coolant return temperature	70° - 140°F
Water line temperature	130° - 155°F
Water relief valve temperature	70° - 100°F
Coolant pressure	55 - 65 psia

2.4.5 Fuel Cell Purging

- Each fuel cell must be purged a minimum of 2 minutes every 8 hours or its efficiency will drop off
- Power output of a fuel cell should not exceed 10 kW (350 A) since this may cause the dual gas regulator to freeze.
- Only one of the three fuel cell reactants may be purged at one time, due to purge line sizing.
- O₂ purge flow is 3.3 lb/hr.
- H₂ purge flow is 0.6 lb/hr.

2.4.6 Fuel Cell Temperature Limits

	<u>Minimum Operating Temperature</u>	<u>Maximum Operating Temperature (long term)</u>
Stack (external)	40°F	170°F
Coolant lines	40°F	140°F
Water lines	40°F	120°F
Coolant exit temperature	180°F	230°F
H ₂ O pressure relief valves	40°F	220°F

2.4.7 Manifold - Fuel Cell Interface Reactant Pressure and Temperatures

H ₂ maximum pressure	335 psia
minimum pressure	100 psia
H ₂ maximum temperature	170°F
minimum temperature	-402°F
O ₂ maximum pressure	1050 psia
minimum pressure	100 psia
O ₂ maximum temperature	170°F
minimum temperature	-260°F

2.4.8 Fuel Cell Start/Stop Capability

Maximum time to obtain full capability	25 min
Maximum time for shutdown	1 min
Start/stop cycles during 2000 hr life	50
Start/stop cycles during 5000 hr life	125

2.4.9 Fuel Cell Heaters

Startup heaters:	activation	automatic with startup	
	deactivation	$183^{\circ} \pm 2.5^{\circ}\text{F}$	stack coolant exit temperature
		or	
		$212^{\circ} \pm 2.5^{\circ}\text{F}$	stack coolant inlet temperature
Sustaining heaters:	activation	$183^{\circ} \pm 2.5^{\circ}\text{F}$	stack coolant exit temperature
	deactivation	2°F above activation temperature	
End cell heaters:	activation	$187^{\circ} \pm 2.5^{\circ}\text{F}$	
	deactivation	2°F above activation temperature	

2.4.10 Degradation

- If the H₂ pump/H₂O separator fails, the fuel cell will have to be shut down in 7 minutes.
- If the coolant pump fails, the fuel cell will exceed the design temperature limits in 6 minutes.

2.4.11 Fuel Cell Performance Characteristics

- See figure 2-14.

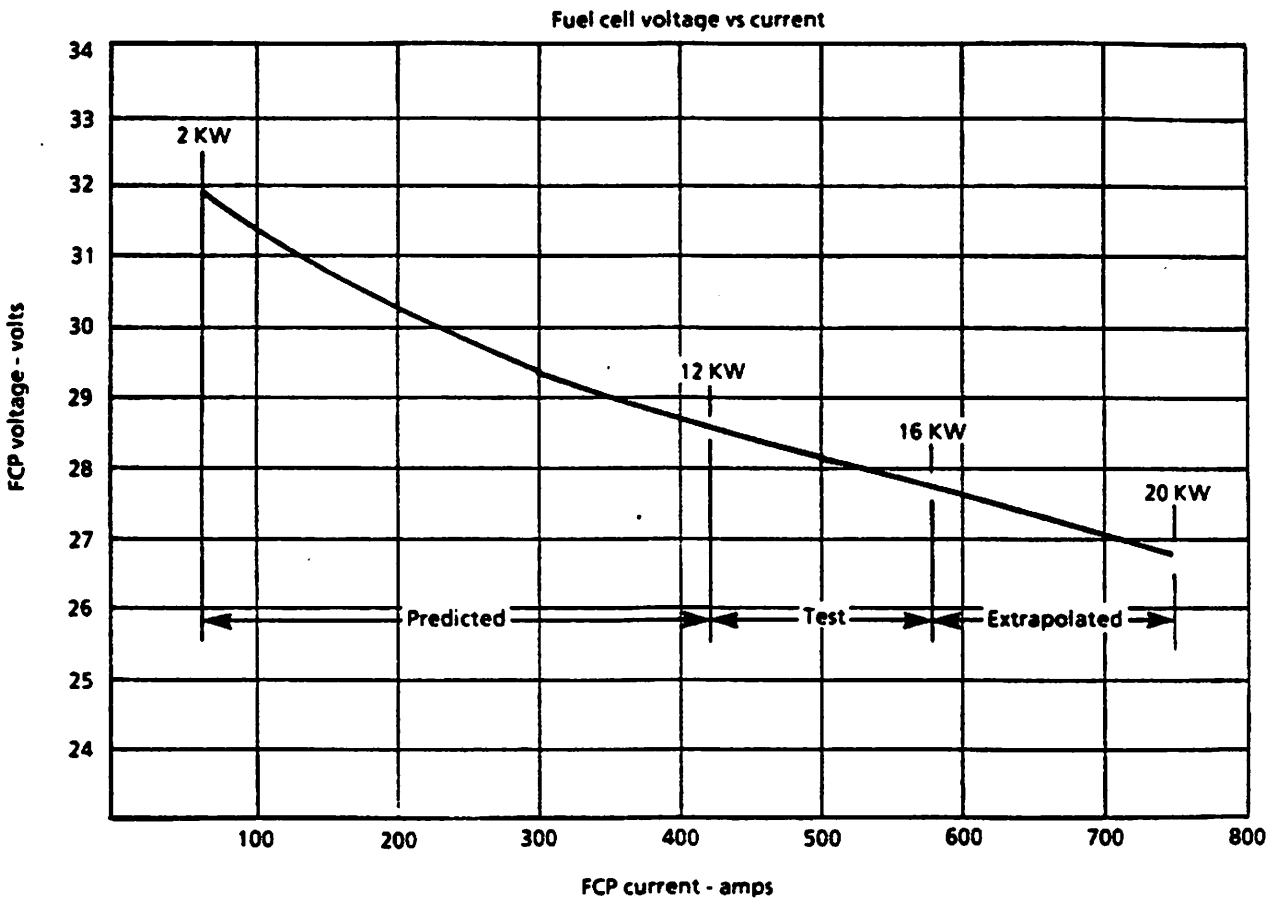


Figure 2-14.- Fuel cell performance characteristics.

2.4.12 Fuel Cell System

- **Fail operational/fail safe**
 - Three fuel cells.
 - With loss of one fuel cell, mission can be completed.
 - With loss of two fuel cells, Orbiter can return home safely in a powered down mode.
- **Features that enhance fuel cell reliability**
 - Developed, demonstrated, and tested technology.
 - Cell design and accessory section components.
- **Simple startup and shutdown procedures**
 - **Startup:** Apply 6 kW internal load to FCP.
Heat up from 40° to 187° F in 15 minutes.
 - **Shutdown:** Deactivate pumps, heaters, and control circuits.
- **Water removal system**
 - Essentially same as Apollo (proven zero-g performance).
- **Component**
 - Developed and tested (JSC technology program).

Section 2.5 gives an in-depth study of the fuel cells. Sufficient material was given in the previous section to give the student a thorough knowledge of the fuel cells.

2.5 Fuel Cell Powerup

Fuel cell powerup is initiated on the pilot side of the cockpit. Basically, the procedure consists of three parts – several preactivation steps, starting the fuel cell, and then monitoring progress of the activation. The only action required from the cockpit is to set the switches for the preactivation phase, and then to hold the start switch to START. From then on, the activation is automatic with the fuel cell controlling the temperature, internally powering the startup heaters, and monitoring the temperature rise. Activation of the fuel cell should require approximately 8 to 15 minutes (worst case start time is starting from a cold environment of 40°F). During activation, the fuel cell will produce about 4400 W required to power the internal startup and sustaining heaters. If desired, the startup heater (3287 W) can be inhibited during the activation – the only effect will be to increase the activation time. Also, if absolutely required, the fuel cell can be connected to its respective main and essential bus during activation. Should this be done, caution should be taken to ensure that a low bus voltage condition does not occur. Bus voltage will improve as the activation nears completion. Normally, the startup heater will be enabled and the buses disconnected.

The preactivation phase consists of the following:

- Closing the fuel cell pump ac cb's
- Connecting power to the fuel cell electrical control unit (ECU)
- Enabling startup heater
- Main and essential buses off
- Reactant valves open

Fuel cell activation is initiated by holding the START/STOP switch to the START position

for 3 to 4 seconds. This applies dc essential bus power to the ECU, which in turn provides ac power to pumps and fuel cell internal power to heaters. When the coolant pump ΔP tb goes gray (indicates coolant pump working properly), the START switch can be released. Fuel cell activation will continue automatically with no further cockpit action required.

At initiation of startup, several parameters should change. The coolant pump ΔP should indicate ON, and O₂ and H₂ flow should indicate some flow. Stackout temperature and condenser exit temperature will indicate ambient temperature at initiation. Fuel cell voltage will indicate ~30 V and will show a gradual increase through activation.

As the activation continues, temperatures will reflect the progress. The stackout temperature will increase about 15°F/min, with the rate decreasing somewhat as it approaches its upper limit of 187°F. The condenser exit temperature will increase about 10°F/min up to its normal value of 140° to 150°F. During startup, no change will be noticed in the coolant return temperature, since most of the fuel cell coolant flow is recirculated through the stack.

Fuel cell activation is complete when stackout temperature reaches approximately 187°F. Heaters turn off and the ready for load flag is set to gray. Reactant flows will go to zero, indicating no current, and fuel cell voltage will indicate approximately 36 V dc (OCV).

Prelaunch activation time will require 7 to 8 minutes. On-orbit activation (if required) will take slightly longer if the fuel cell is allowed to cool to payload bay temps.

If the fuel cell remains disconnected from the bus or is lightly loaded (< 100 A), it will cool to 183°F (stackout temperature). At this point, the sustaining heater will cycle on, driving the temperature back up to 187°F where it will cycle off. Prelaunch duty cycle is estimated 2 minutes on, 4 to 5 minutes off. Reactant flows and fuel cell voltage will indicate heater cycling.

A. Fuel Cell Startup Failure Recognition

- 1. ΔP sensor failure or coolant pump failure – If the coolant ΔP tb does not indicate gray in 3 to 4 seconds, the failure could be the coolant pump or the sensor itself. The procedure calls out holding the switch for a maximum of 10 seconds in the START position. Once the switch is released, the ECU will deactivate and the startup will not continue if the tb is not set to gray. The only method to determine which has failed is for the crew to override with the timer by holding to START for 32 seconds. Once the timer times out, power will be maintained in the ECU. If the sensor has failed, the activation will continue normally – temperatures will respond appropriately. If the coolant pump has failed, the stackout temperature will not respond as it should. Once this is realized, the switch should be placed to STOP. Overriding the ΔP sensor should not be done unless the fuel cell is required and there is no reason to suspect a coolant pump failure.**
- 2. Failure of ready for load flag to go gray – If the ready for load flag stays barberpole, this might indicate that the startup heater has failed on or the ECU timer has failed. After the fuel cells are connected to the buses, load sharing should indicate the heater failure. If the suspect fuel cell is carrying 25 to 30 A less than the other fuel cells, the sustaining heater is probably failed ON. If the load sharing indicates about equal, the tb has probably failed.**

If the ECU timer circuit failed, the fuel cell should still function

properly since the coolant pump ΔP switch has closed.

- 3. Inadequate voltage after completing activation – If the fuel cell terminal voltage does not achieve nominal open circuit voltage (~ 36.5 V dc) after activation, the fuel cell should be purged. Purge time can be extended beyond 2 minutes if required; however, purge time should not exceed 20 minutes. (Freezing may occur in the H_2 purge line after 20 minutes continuous purge flow.)**

B. Fuel Cell Standby/Shutdown

Fuel cell standby/shutdown description – Discontinuing use of a fuel cell falls into two categories: standby or shutdown. The standby condition simply disconnects the essential bus and the main bus from the fuel cell. The fuel cell remains activated (pumps are running and heaters are enabled), but the buses are disconnected. Heaters will cycle on to maintain fuel cell temperature. The MCC can recognize a fuel cell in standby by observing the reactant flows and fuel cell voltage. The reactant flows will cyclically read zero, and voltage will cycle between 36 V dc (OCV) and 30 V dc with heater loads.

The standby mode will be used to manage fuel cell usage from a power conservation fuel cell lifetime standpoint. Standby is not planned during operational flight.

Shutdown of a fuel cell involves disconnecting essential and main buses and stopping the fuel cell. Stopping the fuel cell is accomplished by moving the FC START/STOP switch to STOP and holding for 1 second. The pumps and the heaters are deactivated and power to the ECU is removed. The reactant valves will normally remain open. This allows

the fuel cell to cool in a normal pressurized condition. It assures that the O₂, H₂, and coolant magnesium plates remain at the same pressure during cooling, thus minimizing thermal stressing. They will only be closed if a reactant leak is suspected downstream of the valves. When the fuel cell is stopped, the ready for load tb and the coolant pump ΔP tb go barberpole. The stackout temperature will begin decreasing - dropping off rapidly for the first 30 minutes and then at a slower rate. The fuel cell will eventually cool to ambient over several hours. In a shutdown condition, the fuel cell is still functional. It can be compared to a battery, and, depending on temperature, it can provide some power without a start procedure or pumps running. Simply connecting the fuel cell to a bus will provide the power. (This should be considered only in absolute emergency situations.)

C. Fuel Cell Standby/Shutdown Failure Recognition

1. Failure to respond to STOP signal
 - (a) Coolant pump ΔP tb fails to go barberpole and the ready for load tb remains gray, indicative of STOP driver failure. The fuel cell may be stopped by placing the fuel cell controller switch to OFF.
 - (b) Coolant pump ΔP tb fails to go barberpole; the ready for load tb goes barberpole. The fuel cell should be allowed to cool down. If the sustaining heaters come on (indicated by the flow rates), the fuel cell is not shut down. In this case, the fuel cell switch should be placed to OFF. However, if the heaters do not come on, the tb has probably failed.

2.6 Fuel Cell Status Monitoring

A. Fuel Cell Load Sharing

Because of the Orbiter dioded loads, FCs will tend to share equally the entire load of the vehicle. For example, if the entire vehicle load was 1000 amperes, each FC would carry 320 - 340 amperes. This equal load sharing assumes that all three FCs are about the same age and condition, and have about the same volt-ampere curve characteristics. If one of the three FCs is a newer FC or is more efficient (has a better volt-ampere performance curve), it will carry a higher percentage of the vehicle load. Conversely, an older or less efficient fuel cell will share less of the load. FC load sharing predictions will be made preflight. Preflight FC operating characteristics can be used to accurately predict how the FCs will load share. This performance standard will be used in flight to evaluate the FC. As long as the load sharing between FCs is relatively the same as prelaunch, it can be assumed that from a voltage-current performance standpoint, the FCs are performing normally. If a FC begins to digress from this nominal load sharing plan, a closer examination should be made to determine the reason. Apparent load sharing differences can be caused by the following circumstances:

1. A contaminated FC - As time from the last FC purge increases, the FCs will continue to degrade, perhaps at different rates. If one FC degrades at a slower rate than the other two, it will proportionately carry more of the load.
2. A hot FC - If one FC is running hotter than the other two (i.e., its STACK TEMP is higher than the others), it will carry more of the total load. It is very difficult to quantify this performance increase with temperature increase.

3. A degraded FC – A degraded FC can be caused by several problems internal to the FC. This includes individual cell problems, KOH concentration changes, thermal control valve shifts, etc.
4. A degraded sensor – The FC volt and amp sensors are used to calculate the power output of the FC; however they, like the FC, are subject to failure.

The FC voltmeter may be compared with the sub bus voltmeters after history data has been examined to determine the nominal differences due to I-R losses between the FC connectors and the pertinent buses. If the comparison fails, an appropriate sub bus voltmeter may be used to approximate FC volts.

The FC ammeter failure is somewhat more elusive to detection because of the following considerations:

- a. Some sub-buses are not current-instrumented; therefore, the sum of the sub-bus current TM will not be equal to the FC current output.
- b. Reactant flow meters are (worst case) accurate to ~7 percent. Therefore history data of reactant flows versus FC current output should be studied to compare FC amps – reactant flow agreement prior to the time of the suspected failure.

B. Fuel Cell KOH Concentration

Fuel cell KOH concentration should be monitored to verify that the fuel cell is operating within the acceptable range of average KOH concentration (48 percent to 27 percent). The fuel cells thermal control valves will normally ensure acceptable thermal status within the stack so that the proper amount of water mixes with the solid

KOH to provide adequate KOH concentration levels.

In general, the Δ temperature between the FC stack (STACK T) and the condenser exit (TCE) should be between 50° to 55°F assuming a total on-orbit load of 15kW and a relatively steady state load situation. Any excursion beyond this range demands investigation. A larger Δ temp indicates that too much water is being removed and the stack may be "drying out." A smaller Δ temp indicates that the stack may be flooding, i.e., not enough water is being condensed out. Both conditions merit careful attention since if the condition continues to FC failure, the failure may not be "benign" and the FC may thus become dangerous.

It should be emphasized that in both situations, if the KOH concentration ultimately causes the FC performance to fail, the fuel cell is lost and will require total stack refurbishment on the ground. Therefore, consideration may be given to removing the errant fuel cell from the bus and saving it for entry if required.

If the luxury of vehicle operation on two FCs does not exist, the following suggestions may prove to be helpful. If a fuel cell is running wet, the situation may be alleviated by initiating a vehicle powerdown. The smaller the load, the less water is produced by the fuel cell. This will have to be a "cut and try" procedure utilizing the approved priority powerdowns. After the powerdown has been performed, steady state KOH concentration must be determined to see if further powerdowns are required.

Another option is to perform a continuous or extended purge on the fuel cell. The purge will remove an additional 5 percent of the product water. Finally the fuel cell may be removed from the bus while undergoing the continuous purge. The concentration should be allowed to increase to approximately 32 percent, at which time

the fuel cell may be reconnected to the bus. A stop command should not be applied to a wet fuel cell unless absolutely necessary since a subsequent start after the FC cools down produces increased wetting of the KOH, compounding the excess water problem. The above purge procedures are acceptable as long as the pH high bi-level is not set. If the bi-level is set and confirmed via the malfunction procedures, the fuel cell should be shut down and safed.

The safing procedure consists of removing the errant fuel cell from its bus, closing its reactant valves, allowing it to cool down and then performing a start until the fuel cells internal heater operation consumes the H₂ reactants trapped in the lines downstream of the reactant valves.

The rationale here is that if a fuel cell has expelled KOH into the H₂ vapor stream, a KOH-H₂O mixture may short across several cells in the hydrogen gas manifold. The water may begin to electrolyze causing oxygen to be present in the hydrogen manifold. A 4 percent concentration of O₂ in the manifold is considered unacceptable. Purging a fuel cell that has expelled KOH should not be done unless the spacecraft is on a reentering trajectory. KOH in the hydrogen stream may solidify out in the common O₂ or H₂ purge line precluding purge capability on the other fuel cells.

A dry fuel cell represents a more difficult operational situation. Inadvertent operation of the STARTUP heater (~3500 watts) may cause the fuel cell to dry out. To verify that this heater is on, observe FC amps and flows. If the Δ amps between the "dry" FC and the others is about 80 amperes, with the dry FC showing a lower current and its O₂ (H₂) flow is greater than the reactant demand calculated from its ammeter reading by approximately 2.6 (0.3) pounds per hour, then the startup heater may be failed on. Another confirming cue of this failure may be the RDY tb = bp. The STARTUP HEATER switch on panel R12 should be moved to the INHIBIT position. If the flows and amperes

do not return to a normal state, then a FC stop should be issued after the fuel cell has been removed from the main and essential buses. At this time, FC volts should be observed as a double check. An open circuit voltage (OCV)* less than 32.5 volts confirms that the heater has failed on. The fuel cell is lost and the reactant valves on this fuel cell must be closed. It should be noted that a failed-on sustaining heater will not cause the fuel cell to be lost as the thermal control system should adjust to compensate for the increased heat load. With a failed-on sustaining heater, the FC OCV will be less than 32.5 V dc and the current Δ will be low by about 26 amperes.

If the FC OCV is greater than 32.5 volts, the problem must be in the fuel cells thermal control system (thermal control valves or pump package). Consideration may be given to saving the fuel cells' remaining capability for entry. Some capability may be regained by performing a FC start after letting the fuel cell cool down but terminating the sequence with a stop prior to the RDY talkback going gray. A start sequence tends to make the fuel cell run "wet" until proper thermal conditions are established to condense out water. Another way to "wet up" a fuel cell is to allow it to run while connected to the buses for up to 6 minutes after performing a FC stop. Operationally, this represents a less acceptable approach.

C. FC Coolant Pressure

The FC coolant pressure parameter is an extremely important parameter. Recall that the dual gas regulator conditions the O₂ pressure in the stack to 60-62 psia. The fuel cells coolant loop is pressurized by the O₂ chambers' pressure exerted against a coolant

*The flow meters cannot be used to verify that the fuel cells' heater has failed on in this situation since the flow meters receive operating power from the main bus. If a bus tie is performed, the flow meters will read properly.

accumulator bladder. Also remember that the dual gas regulator regulates the H₂ pressure to approximately 4-6 psia less than the O₂ pressure. Therefore the COOL P parameter can give insight into the operation of the dual gas regulator and the integrity of the coolant loop.

For instance, normal coolant pressure readings will be in the neighborhood of 60 to 65 psia. Assume that COOL P begins to decrease. Now, if the COOLANT PUMP ΔP indication begins to "chatter" or go low, then it can be assumed that the coolant loop has developed a leak which will ultimately render the fuel cell useless. The fuel cell should be shut down. If, however, COOL P is seen to shift low concurrent with an increase in the vent line temperatures (either O₂ or H₂) and reactant flow is greater than required by the load, then anomalous gas flow to the regulator or fuel cell operation may be surmised. In general, for this situation fuel cell operation may remain essentially unchanged until the COOL P reaches approximately 20 psia, at which point fuel cell operation will be drastically affected and V-I performance will rapidly decrease. The increase in purge vent line temperature previously mentioned represents the regulators attempt to maintain an approximate 4-6 psia O₂ overpressure by relieving excess pressure overboard through the purge line.

The COOL P high alert is set at 75 psia. If the COOL P is indeed high, increased reactant pressure in the stack will be manifested by an increase in performance. (This performance increase may be masked by various conditions such as operation of single bus loads, individual fuel cell performance, etc.) Historical evaluation of the FC's previous performance up to the time of the apparent increase will give a clue as to the validity of the indication.

Refer to the SSSH fuel cell drawing 3.4, N Z 7,8 and notice the H₂ and O₂ preheaters. Recall that the reactants going to the dual gas regulator are thermally conditioned to at least -40°F by hot coolant coming out of the fuel cell stack. Also notice that each fuel cell's coolant loop passes through a heat

exchanger interfacing with both Orbiter Freon coolant loops. Now, assume that a leak develops in the O₂ preheater such that the O₂ reactant at reactant tank pressure (~800 psi) begin to pressurize the fuel cells coolant loop. If a violent "blowout" occurs in the fuel cell heat exchanger where the other two fuel cell coolant loops also dump their waste heat it is conceivable that it could simultaneously damage the coolant loops of the other two fuel cells, thereby ultimately terminating all electrical power. These are, of course, worse case assumptions. The FC heat exchanger has a burst pressure of about 2400 psi. Assuming a failed on heater in the O₂ cryo tank, worse case pressures in the O₂ lines would be on the order of 1000 psi; however, since loss of the FC heat exchanger has such horrendous consequences, a fuel cell with a pre-heater leak should be shut down. A confirming cue indicating the presence of cryo gas bubbles in the fuel cells' coolant loop is "chattering" of the FC PUMP ΔP talkback. If this situation develops, the FC should be shut down and its reactant valves closed.

FC COOL P may also be used as a confirming cue that the FC coolant pump has failed. The prime indication of such a failure is, of course, FC PUMP ΔP talkback going barberpole. If only the coolant pump has failed, condenser exit temperature will begin to approach STACK TEMP; however, if ac power to both pumps is lost the two sensors (STACK T and TCE) will decrease, but the decrease may or may not be highly obvious. (This is because the temperature sensors require flow by them to accurately measure temperature. If the flow ceases, the sensors will tend to decrease very slowly. COOL P becomes a tie breaker since as the coolant pump no longer circulates hot coolant through the pre-heaters to condition the cryos entering the dual gas regulator, the regulator will begin to fail and probably lose control of pressure regulation of the gases into the stack. Therefore, the fuel cell should be shut down if COOL P begins to change, indicating regulator failure.

D. STACK TEMP/TCE

These two parameters may be used to assess thermodynamic conditions existing within the fuel cell. The values of each parameter and their difference (ΔT) are very important in determining the overall health of the fuel cell.

Refer to the SSSH drawing 3.4 N Z 7 and note the location of the STACK COOL OUT TEMP sensor. Note that it measures the temperature of the FC 40 coolant as it exits the fuel cell power stack.

In essence, the actual internal temperature of the fuel cell stack is not measured; however, the temperature of the coolant exiting the stack approximates closely the internal temperature of the stack.

The fuel cell thermal control valves are designed to maintain proper STACK-TCE relationships over a range of 40° to 140°F coolant return temperature. (This is the temperature of the FC 40 coolant as it leaves the fuel cell heat exchanger after dumping waste heat into the Orbiter Freon loops.) As previously mentioned, the STACK-TCE relationship is important in establishing proper KOH concentrations in the fuel cells.

At zone N Z 5 there is a second stack temperature sensor that is not visible via TM. This sensor is used to activate the sustainer heater when stack temperature decreases to 184°F. (The startup heater utilizes this sensor in addition to another temperature sensor at the inlet of the stack).

Stack temp is used in conjunction with the fuel cell ammeter and voltmeter in the FC performance monitor routine. Basically, this routine is a KOH concentration monitor. The routine calculates fuel cell kilowatts and compares them with stack temp. In the SM and the BFS the upper limits are tested, but in the SM the lower limit is also tested. The crew is alerted (class 3) if the stack temperature violates limits established over 3 load ranges. Table 2-2 gives the applicable limits.

TABLE 2-2.- STACK TEMP ACCEPTABLE LIMITS

<u>KW</u>	<u>STACK TEMP (°F)</u>
≥3.5	212 < T < 175
>3.5	222 < T < 185
≥7.5	238 < T < 195

E. Purging the Fuel Cells

The fuel cells must be purged periodically to maintain their V-I performance. Examination will show that the oxygen chambers in the sub cells are "dead headed," which means that the flow of oxygen into the chambers is not circulated out during non-purging conditions. It should also be noted that the hydrogen chambers experience circulative flow since the hydrogen is used as the vehicle to transport water produced by the reaction out of the subcells. As can be imagined then, the purge of the fuel cells O₂ chambers is especially critical.

The purge itself consists of nothing more than increasing the reactant flow over and above the flow required by the fuel cell load.

Both sets of reactant chambers are simultaneously purged. Purge valves in the dual gas regulator are activated, allowing the additional reactant flow (O₂: 2.2 lb per hour max; H₂: 0.6 lb per hour max). Normally, the fuel cells are purged serially for 2 minutes each.

The purge flow simply flushes inert gas (which displaces active O₂ or H₂ molecules) out of the reaction chambers. The rate of inert buildup is directly related to the kilowatt hours (kWh) or energy being demanded and to the purity of the reactants supplied.

In general, a fuel cell should not be purged if it is producing 350 amperes (approximately 10 kW). This is because the fuel cell preheaters that thermally condition the cryogenic reactants up to at least -40°F are sized to provide the desired thermal conditioning for load plus purge flows of less than 10 kW equivalent. The -40°F temperature constraint is levied by the fuel cells dual gas regulator operation. Below

this temperature seals/seats in the regulator may begin to harden and/or differential expansion of close tolerance components may cause the regulator to bind.

If it is absolutely necessary to purge at loads greater than 350 amperes, consideration may be given to purging the fuel cell for less than 2 minutes continuously. There are several options available such as pulse purging (10 seconds open, 10 seconds close for a total open time of 2 minutes) and purging for only 60 seconds.

Each fuel cell has a separate O₂ and H₂ purge line. The O₂ lines from the three fuel cells are manifolded into one line that terminates in a nozzle on the port side of the vehicle. Similarly, the H₂ lines are manifolded into a single line terminating in a nozzle on the starboard side of the spacecraft. It should be noted at this point that the purge lines are also the vent lines for the dual gas regulators. If for some reason the dual gas regulator must vent reactant to maintain the proper ΔP relationship between O₂ and H₂ within the stack, the excess reactant(s) are relieved overboard through these lines.

The purge lines are thermally conditioned by either a manual or automatic set of heaters. Although the gas exiting the fuel cell is on the order of 150° to 160°F or perhaps higher, the high water vapor content (especially of the H₂) and the rapid expansion of the gas into the line vacuum may cause a plug of ice to form terminating flow. A plugged purge line is an extremely serious situation (especially a constricted O₂ purge line for reasons previously stated).

For normal on-orbit operations, the fuel cells, in general, should be purged once every 8 hours, although purges may be required at different intervals depending upon the loads and the reactant purity. At least once a rev, the delta volts between actual and predicted performance should be checked by the EPS controller. When the program indicates an 0.5 volt performance drop, the fuel cell should be purged.

There are two means by which the fuel cells may be purged - manually or automatically.

The auto purge routine resides in the SM program only and may be invoked in OPS 201. To prepare for an auto purge the following switches on panel R12 must be configured as follows:

- FUEL CELL PURGE HEATER - GPC
- FUEL CELL PURGE VALVES 1 (2, 3) - GPC.

To start the purge, the FUEL CELL PURGE SEQ switch (R12) is moved to the START position. The GPC PURGE SEQ ON talkback should go to gray, indicating that the GPC purge heaters have been energized. If the talkback fails to toggle, the following parameters should be observed on SPEC 69 to see if they are increasing to 79°, >40°, and >69°F, respectively (H₂ PURGE LINE TEMP 1, H₂ PURGE NOZZLE TEMP 2, O₂ PURGE LINE TEMP 1). If they are increasing to these values the talkback has probably failed; however, the reactant flow parameters on the first fuel cell selected for the automatic purge should be observed for an increase in flow. If the flow does not increase or the SM program issues the message FC PURGE SEQ to the crew, then the AUTO purge sequence is lost and only manual purges may be accomplished.

If the GPC PURGE SEQ talkback goes gray but the temperatures do not increase or fail to increase at a rate that will allow the previously mentioned temperature parameters to satisfy their limits within 27 minutes after the talkback went gray, then the FC PURGE TEMP message will terminate the sequence. Two options are available. One is to perform manual purges; a second option would be to tell the crew to select the manual purge heaters, allow the temperatures to reach their acceptable limits, then reselect the GPC position on the purge heater switch and perform a GPC PURGE SEQ start. The flows should be observed to ensure that they increase for 2 minutes and

then decrease back to normal load only levels.

The routine will sequentially purge the fuel cells selected for an auto purge. If a fuel cell's flow meter fails to indicate that the fuel cells purge valve did not open 10 seconds after the GPC has issued the open command, then the message FC PURGE 1 (2, 3) will be issued for that fuel cell and the routine will move on to the next fuel cell to be purged. The routine should be allowed to complete the purge of the other fuel cells. When the purge is completed, a manual purge should be attempted on the unpurged cells, while carefully observing the flows. If the O₂ flow does not increase and the attempted post-purge Δvolts computation does not indicate zero or a positive margin, then this fuel cells main bus may be tied and the fuel cell taken off-line (off both main and essential buses) in an attempt to save its remaining capability for entry. If the H₂ flow meter reading is not seen to increase and the Δ volts computation does not indicate a zero or positive margin after the attempted purge a conservative estimate of the cumulative degradation up to vehicle landing must be made by the EPS controller. This is accomplished by utilizing plots of FC kWh provided between purges at different amperage levels versus Δ volts degradation between purges for various reactant impurity levels.* The H₂ degradation and O₂ degradation should be summed. If the projected degradation based on load estimate and no H₂ purging until landing is greater than 0.5 volts, steps should be taken to either reduce vehicle loads or set a duty cycle on this fuel cell so that it can adequately support entry power demands.

The FC PURGE 1 (2, 3) message is likewise issued for the situations where the SM routine detects that the purge valves were not closed 10 seconds after they were commanded closed by SM. The message FC PURGE 1 and the message FC 1 indicating purge flow are indicative of a stuck open

*The purity level of the reactants are provided by the Cape prior to lift-off.

purge valve. The AUTO purge routine will not advance to purge the next fuel cell in this situation. If the same message appeared while FC 2 or 3 was purging, then the problem was a purge valve stuck closed on FC 1 and the routine has moved ahead to purge the other FCs selected.

The SM message FC PURGE 1, FC PURGE 2, FC PURGE 3 is indicative of a constriction in a purge line downstream of the manifolded exit lines from each fuel cell. Which line has been plugged may be ascertained by observing playbacks of the flows during the purge. A plugged O₂ line is the most serious situation and an immediate powerdown of the vehicle should be performed. (Early mission termination should also be considered if the following procedure fails to clear the line.) Selection of the manual heaters followed by an extended bakeout (2 hours) should be performed. Simultaneously, the purge valves of one of the fuel cells should be placed to the open position, in hopes that the reactant pressure plus the heat from the manual purge heaters will "break loose" whatever has caused the line to block.

F. Fuel Cell Water Relief System

The fuel cell must remove just the right amount of water to maintain the proper KOH concentration within the cell. The excess water is manually purged into water tanks by the pressure developed by the H₂/H₂O separator pump.

The water tanks are normally pressurized at the cabin atmospheric pressure. As long as the tanks are not full and are not pressurized above ~30 psi, water will flow into them.

Refer to drawing 3.4 F Z 3 (see the SSSH) and notice the check valves that prevent any back flow of water into the fuel cells. These valves crack at approximately 0.5 PSID. At E Z 4, 5, 6 notice the three relief valves that allow FC water to pass through the H₂O vent line in the event that the potable tank lines become blocked.

Indications that water is relieving through this system are as follows:

- H₂O relief valve temp will increase as water flows through the valve.
- H₂O relief line temp will increase as water enters the relief line. **NOTE:** Water will traverse the distance between the check valve and the exit nozzle in less than 30 seconds.
- The relief nozzle temperatures A and B will begin to oscillate from about 170° to 200°F.

The oscillation of the nozzle temperature is positive proof of water relieving through the system. This situation requires immediate investigation.

G. AC Phases

The fuel cell pump package (H₂ and coolant pump) are three phase ac pumps. Fuel cell 1 draws its pump power from AC1 - fuel cell 2 from AC2, fuel cell 3 from AC3. The ac traces can provide valuable information on the health of the pump system.

During fuel cell purge flow, the ac bus currents to the pump package of the fuel cell being purged should be carefully examined. Any change in the ac signatures during the period of purge flow may be indicative of a hydrogen pump in distress (the H₂ purge flows through the H₂ pump). STS-2 experience revealed that due to a plugged H₂ pump rim aspirator, the pump became overloaded and ultimately caused fuel cell flooding. Recall that the H₂ pump is a vapor pump and as such, cannot function properly if standing water is in it. The purge flow causes some of the water to be blown out of the pump, hence the ac (all 3 phases) decreased approximately 400 mA during the purge as some of the excess water in the pump was blown out through the purge port.

If such a signature is observed and the fuel cell has not set its pH high discrete, consideration should be given to either shutting down the fuel cell and saving it for

entry or performing more frequent and/or extended purges on it. A purge should not be attempted if the water out into the common purge line exists. This might cause common purge line blockage when KOH solidifies, thus precluding a purge of all 3 fuel cells.

The ac may also be utilized to verify an intermittent coolant pump ΔP tb. If the ac is seen to decrease during the period of time that the coolant pump ΔP tb goes bp, then faulty coolant loop operation may be surmised. Consideration may be given to shutting down the fuel cell and saving it for entry.

NOTE

Fuel cell currents (3) should be displayed continuously to maintain glitch detection.

After sequence starts, the O₂ vent line temperature and the H₂ vent line temperatures 1 and 2 should be verified above or approaching minimum limits of 69°F, 79°F, and 40°F, respectively.

When all three temperature limits are satisfied, fuel cell 1 (2, 3) purge valves should be verified open by comparing O₂ and H₂ reactant flow with calculated flow. If the valves have opened, the difference should be >0.9 and >0.3 lb/hr, respectively.

As each fuel cell is purged, purge valve closing should be verified by comparing actual vs calculated reactant flow.

After each fuel cell is purged, increased fuel cell voltage should be verified.

Bakeout period complete and decreasing line temperatures should be verified.

2.7 Fuel Cell Contingency Powerup

There are failures that can cause loss of ac power to the fuel cell H₂/water separator and coolant pumps. This, of course, will result in loss of the fuel cell. For some of these failures it will

be possible to implement an in-flight maintenance (IFM) procedure to regain ac power to the fuel cell pump package. This procedure takes advantage of a circuit in the electronic control unit (ECU) used to check the pump package preflight. (See figure 2-15.) This is accomplished by fabricating two cables, one using a 16mm camera power cable, 4 feet of 22-gage wire, and a 22-gage pin and socket. The first cable is connected between a dc utility outlet and the F10 fuse receptacle on a FWD POWER CONTROLLER (FPC). This connection will supply 28 V dc power to the fuel cell pump check load driver in a MID POWER CONTROLLER (MPC) through the PRE-FLT TEST 1 bus. The

second cable is connected between another dc utility outlet and the appropriate harness connector pin from launch MDM LF 1. This connection will supply 28 V dc power to the enable input of the same pump check load driver. This final connection will cause relay K7 in the ECU to operate applying ac power to the pump package.

The types of failures that can result in taking this IFM action are the following: short to ground in the ECU on the circuit noted in heavy lines in figure 2-15, or in the fuel cell control power load driver circuit causing the 3-A fuse to blow; fuel cell control power switch

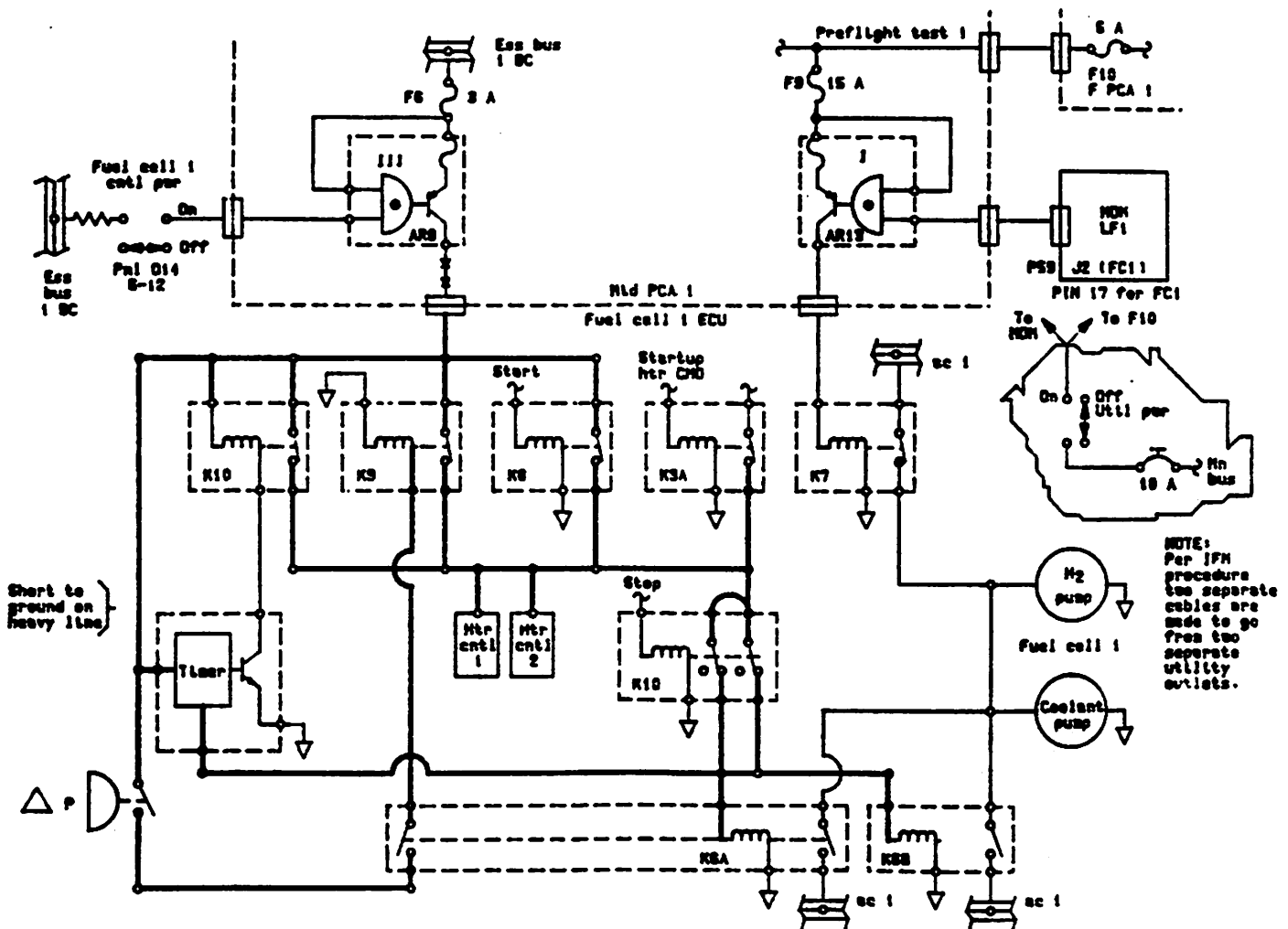


Figure 2-15.- Fuel cell contingency powerup circuit (fuel cell 1 shown).

failure; and loss of the ESS bus in the MPC or in the flight deck (FD). For any of these failures where the fuel pumps can be restarted with the IFM procedure, it is mandatory that the fuel cell be shut down immediately once the failure is confirmed. The signature (for fuel cell parameters) of the failures mentioned above would be COOLANT PMP ΔP tb and READY FOR LOAD tb both bp with a FUEL CELL PUMP caution and warning (C&W) and systems management (SM) alert message. Mission Control Center (MCC) would also receive these indications. Also, the appropriate ac 3-phase loading would decrease by 0.8 A per phase. If the ESS MPC or FD sub bus failed, other indications would be observed as listed in the malfunction bus loss SSRs.

2.7.1 Procedure

- A. Confirm failure and have fuel cell shut down immediately.**
- B. Schedule IFM procedure with flight activities officer (FAO). It should be performed before stack cools down to 183°F (within 3 hours - below 183°F, stack end cell heaters are required but will be inoperative). Time required to accomplish the procedure in the 1-g trainer was 30 minutes.**
- C. Have crew perform IFM procedure.**
- D. Attach fuel cell to the bus (keep bus tied).**
- E. When fuel cell stack temperature gets above 191°F, buses can be untied and the fuel cell can be allowed to take the load.**
- F. Maintain load on fuel cell above 4.5 kW. This will maintain proper thermal conditioning of the stack since end cell heaters will no longer function.**

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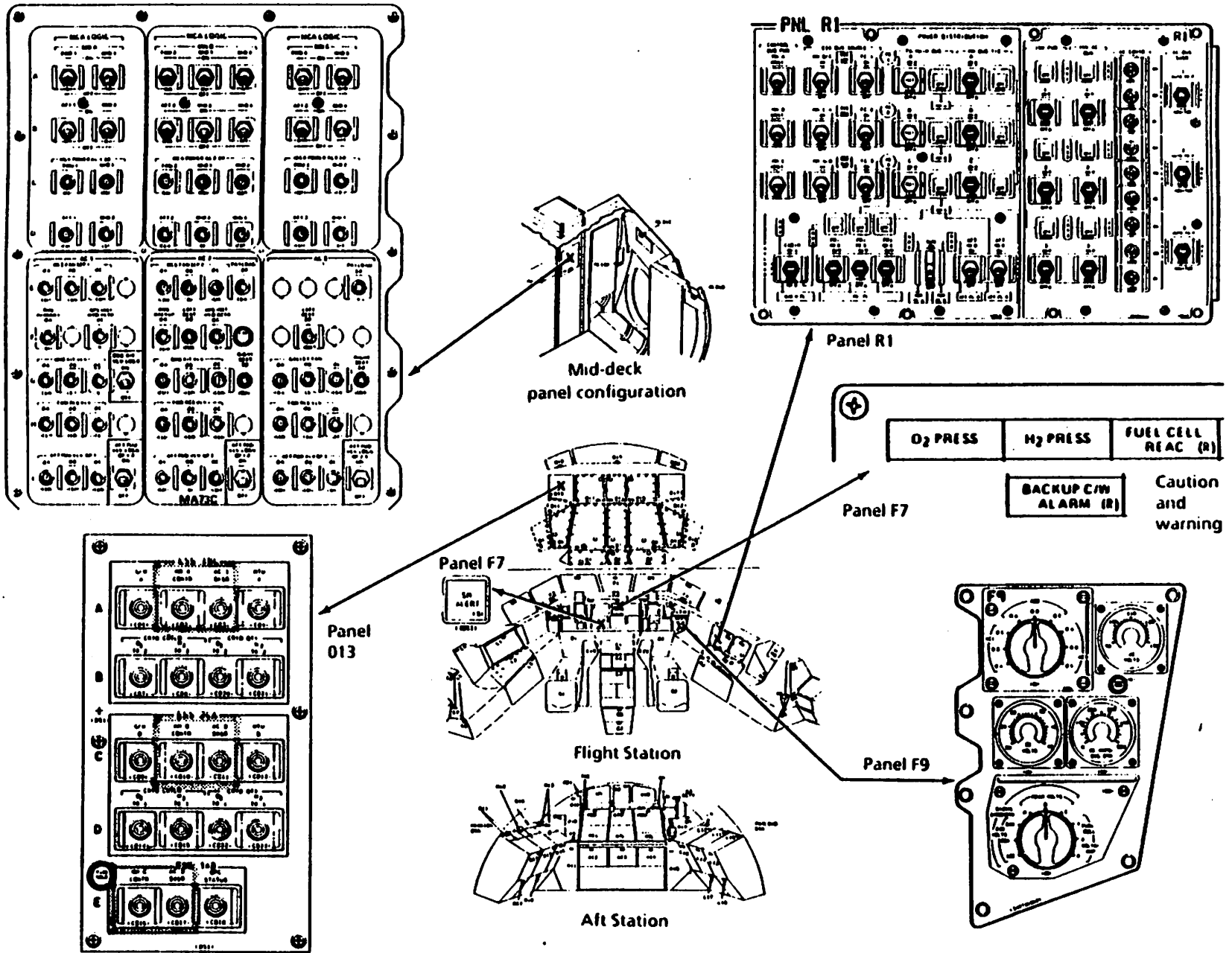


Figure 3-1.- EPDC displays and controls.

Section 3: Electrical Power Distribution and Control

3.1 Introduction

The electrical power distribution and control system (EPDC) distributes direct current (dc) and generates and distributes alternating current (ac) to all the Shuttle system's electrical equipment throughout all mission phases. To perform the above functions, the EPDC consists of a three-bus system which distributes electrical power to the forward, mid, and aft sections of the Orbiter for equipment use in these areas. The buses used on the Orbiter are as follows. Three main dc buses (MNA, MNB, MNC) are the main or prime source of dc power to the Orbiter's electrical loads. Each main bus is the most important element in its power bus string. Three ac buses (AC1, AC2, AC3) are used to supply ac power to the ac loads. Three essential buses (ESS1BC, ESS2CA, ESS3AB) are used to supply control power to selected crew controls and operational power to electrical loads which are deemed essential. Nine control buses (CNTLAB1,2,3; CNTLBC1,2,3; and CNTLCA1,2,3) are used only to supply control power to crew controls. Two preflight buses (PRFLT 1, PRFLT2) are used only during ground operations for ground usage.

Use figure 3-2 during the following discussion. Electrical power is controlled and distributed by the use of assemblies. Each assembly is a line replaceable unit (LRU) and is used to distribute bus power to system loads. Each assembly (main distribution assembly, power controller assembly, load controller assembly, and motor controller assembly) is an electrical equipment storage container or box. The electrical equipment consists of buses, resistors, fuses, diodes, and remote switching devices. The types of remote switching devices used on the Orbiter are remote power controllers (RPC), hybrid circuit drivers, power contactors, relays, and hybrid relays. Each main dc distri-

bution assembly receives power from a fuel cell, and its only function is to distribute main bus power to the forward, mid, and aft power controllers, and to flight and middeck panel buses. The only switching devices in the distribution assemblies are power contactors. The power controller assemblies and load controller assemblies distribute dc power to all the system loads using remote switching devices. The difference between a power controller assembly and a load controller assembly is simply the type of remote switching devices located in them. Power controller assemblies contain the RPCs and relays. Load controller assemblies contain hybrid circuit drivers. In the midbody area, there are no load controller assemblies; therefore, the power controller assemblies contain RPCs, relays, and hybrid circuit drivers. Power from the forward, mid, and aft power controllers is routed to forward, mid, and aft motor controllers, respectively. The motor controller assemblies distribute ac power to ac motors through the use of hybrid relay drivers.

The ac bus generation and distribution assemblies contain the ac inverters for dc to ac conversion, the ac buses, and the ac bus sensor. All ac power is distributed to the flight and middeck panels (L4, MA73C, R11A2).

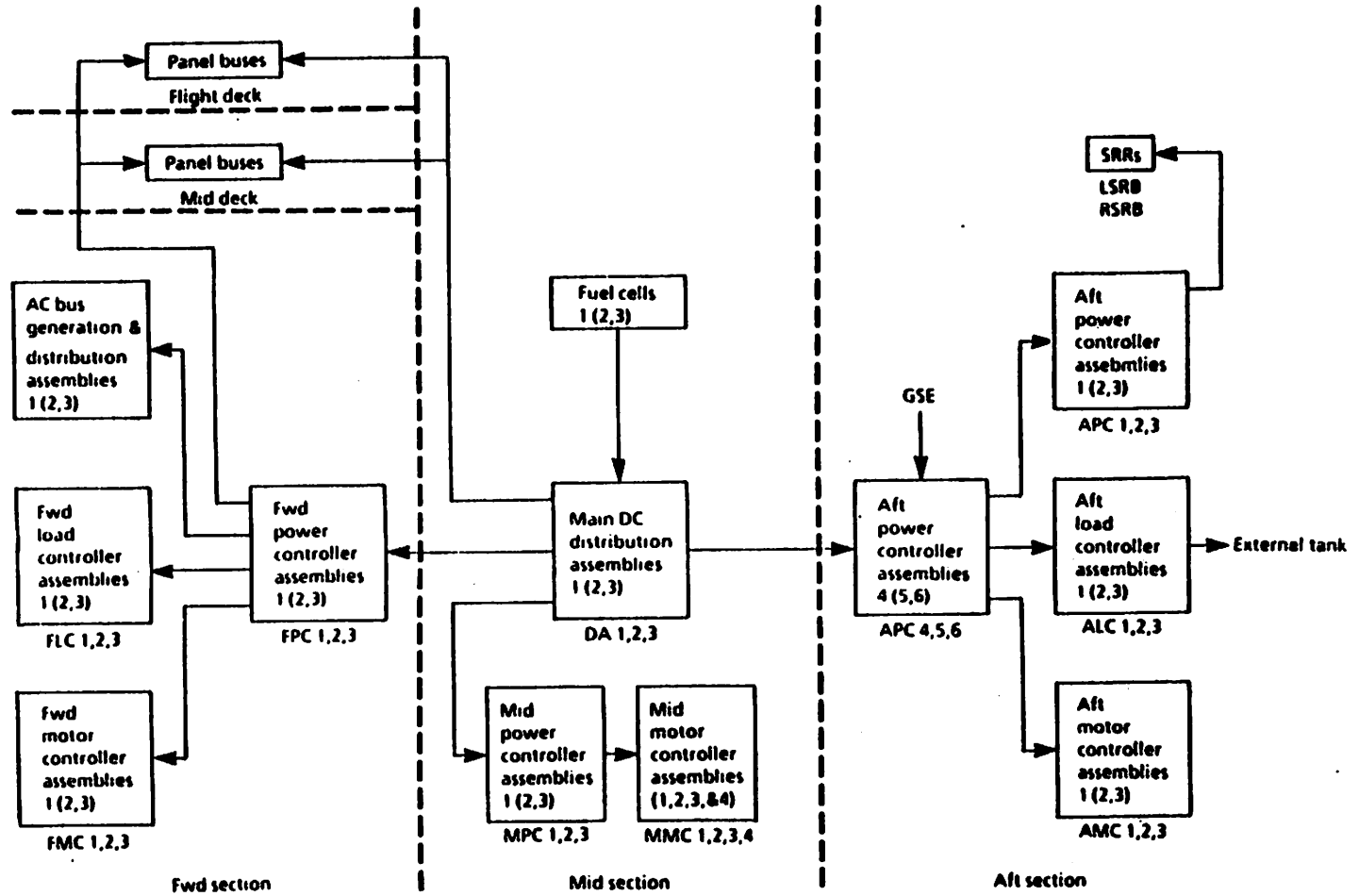


Figure 3-2.- Electrical power distribution block diagram.

3.2 Interfaces

EPDC interfaces with the Orbiter systems are listed below and illustrated in figure 3-3.

- A. ECLSS - The EPDC controller assemblies transfer heat to the water and Freon coolant loops.
- B. C/W - Bus voltages, current, and overload sensors are continuously checked for out-of-limit conditions.
- C. INST - Sensors' output are provided for conditioning and telemetering.
- D. Onboard D&C - EPDC has dedicated displays, switches, and meters to provide control capability and status information to the crew.
- E. DPS - Receives sensors' output for SM conditioning and monitoring of EPDC on the CRT display.

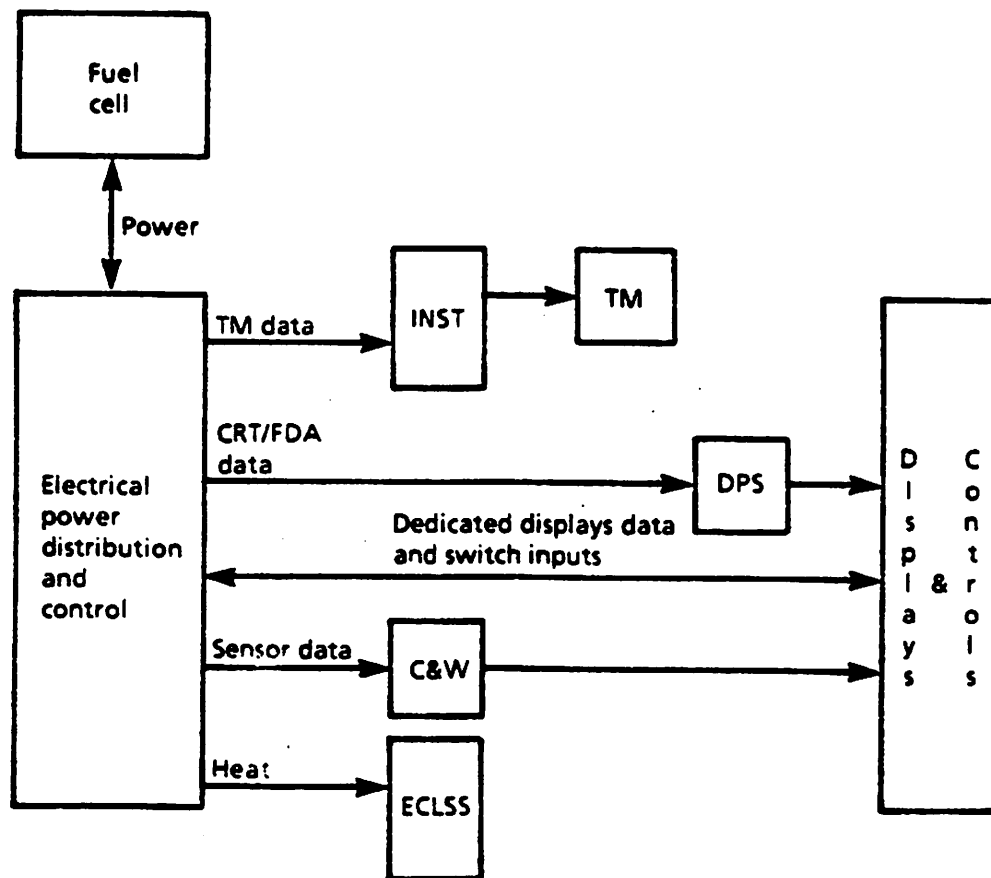


Figure 3-3.- EPDC interfaces.

3.3 Functional Description

3.3.1 DC Distribution

Refer to figure 3-4 during this discussion. The dc power generated by the three fuel cells is routed to main buses and essential buses, located in the distribution assemblies and controller assemblies. Each fuel cell is dedicated to a specific main bus: fuel cell 1 to main bus A (MNA), fuel cell 2 to main bus B (MNB), and fuel cell 3 to main bus C (MNC). Each fuel cell is also dedicated to an essential bus: fuel cell 1 powers essential bus 1BC (ESS1BC), fuel cell 2 powers

essential bus 2CA (ESS2CA), and fuel cell 3 powers essential bus 3AB (ESS3AB). All the number 1 assemblies go with fuel cell 1/MNA, all number 2 assemblies go with fuel cell 2/MNB, and all number 3 assemblies go with fuel cell 3/MNC. Note that the Orbiter has aft power controller Assemblies 4, 5, and 6. These assemblies had to be added for additional electrical loads in the aft section. Assemblies 4, 5, and 6 go with fuel cell 1/MNA, fuel cell 2/MNB, and fuel cell 3/MNC, respectively. The mid motor controller assemblies 1, 2, 3, and 4 are an exception to the above rules and will be discussed later.

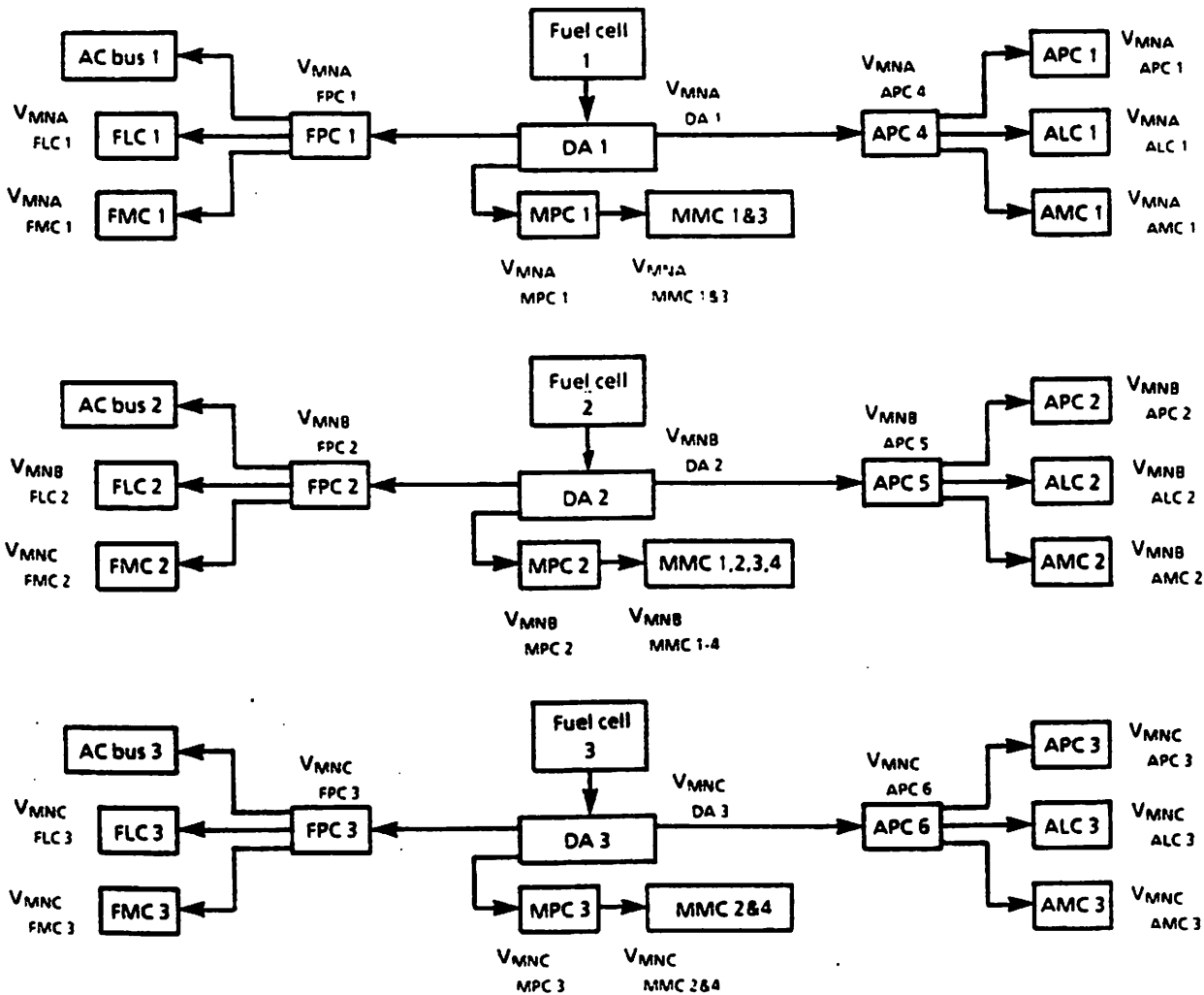


Figure 3-4. - DC power distribution block diagram.

3.3.1.1 Main DC Bus Distribution.

Refer to figure 3-5 during this discussion. If a picture of panel R1 is needed, refer to figure 3-6. The FC/MAIN BUS A switch is used to connect fuel cell 1 to MNA in distribution assembly 1 (DA 1). Note the standard bus acronyms used in each assembly. For example, forward power controller is FPC, forward load controller is FLC, etc. When fuel cell 1 is connected to MNA, MNA buses throughout the vehicle are powered up through fuses. The MN BUS TIE A switch can be used to tie MNA to MNB or MNC. The main A controller circuit breaker (panel O13), which is part of the central 1BC, and the main A controller circuit breaker (panel O15), which is powered by main B, provide redundant control power to the fuel cell main bus A and the main bus tie A switches. If essential bus power is lost, the capability to bus tie and to disconnect the main bus from the fuel cell still exists. The MNB and MNC distribution buses are essentially the same. The position of sensors whose parameters are used for CRT displays, dedicated meters, C/W, and FDA are shown in figure 3-5. The letter V indicates voltage; I indicates current; and E indicates event. MAIN BUS UNDERVOLTS C/W light is set at 26.4 V dc, informing the crew that the minimum equipment operating voltage of 24 V dc is being exceeded. A BACKUP C/W light will also annunciate when the voltage drops to 26.4 V dc. This light uses a different sensor and is a backup to the MAIN BUS UNDERVOLTS light. An SM ALERT light will annunciate at a voltage less than or equal to 27.0 V dc, alerting the crew to the possibility of a future low voltage problem. The BACKUP C/W and SM ALERT lights are software driven out of the SM FDA program, which is located in GPC 4 for on-orbit phases and GPC 5 for launch/entry phases. CRT fault messages for BACKUP C/W and SM ALERT lights and CRT displays are covered in section 3.4, Displays and Controls. Fuel cell voltage, current, and main bus voltage are also displayed on dedicated meters on panel F9.

The only difference between main bus A, B, and C distribution is in the panel bus distribution. In general, a bus is distributed to a panel

only if there is a requirement for that bus to be used at that panel. Panel buses are used to supply control power to switches on their respective panels.

Main buses are the preferred primary source of power for all Orbiter electrical equipment. Depending upon the criticality of the 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.

3.3.1.2 Essential Bus Distribution.

Refer to figure 3-7 during this discussion and figure 3-6 for a picture of panel R1. Essential 1BC receives power from three redundant sources, fuel cell 1 through the ESS BUS SOURCE FC1 switch, and main bus B and C through RPCs which are controlled by the ESS BUS SOURCE MN B/C switch. The nomenclature 1BC implies fuel cell 1 and MNB and MNC; 2CA implies fuel cell 2 and MNC and MNA; 3AB implies fuel cell 3 and MNA and MNB. From the essential bus in DA 1, power is distributed through fuses to the controller assemblies and to the flight and middeck panels. The crew has a dedicated meter on panel F9 and the CRT displays for essential bus voltage. An SM ALERT will annunciate to inform the crew when the voltage is less than 25.0 V dc.

Essential buses are used for supplying control power to the switches which are necessary to restore power to a failed main or ac bus and to essential non-EPS electrical loads and switches. In some cases, essential buses are used for switching discrettes to MDMs. Some of the selected crew switches and loads are EPS system switches, GPC switches, tacan mode switches, radar altimeter and microwave scanning beam landing system (MLS) power switches, C/W system, emergency lighting, audio control panel, and master timing unit (MTU), to name a few.

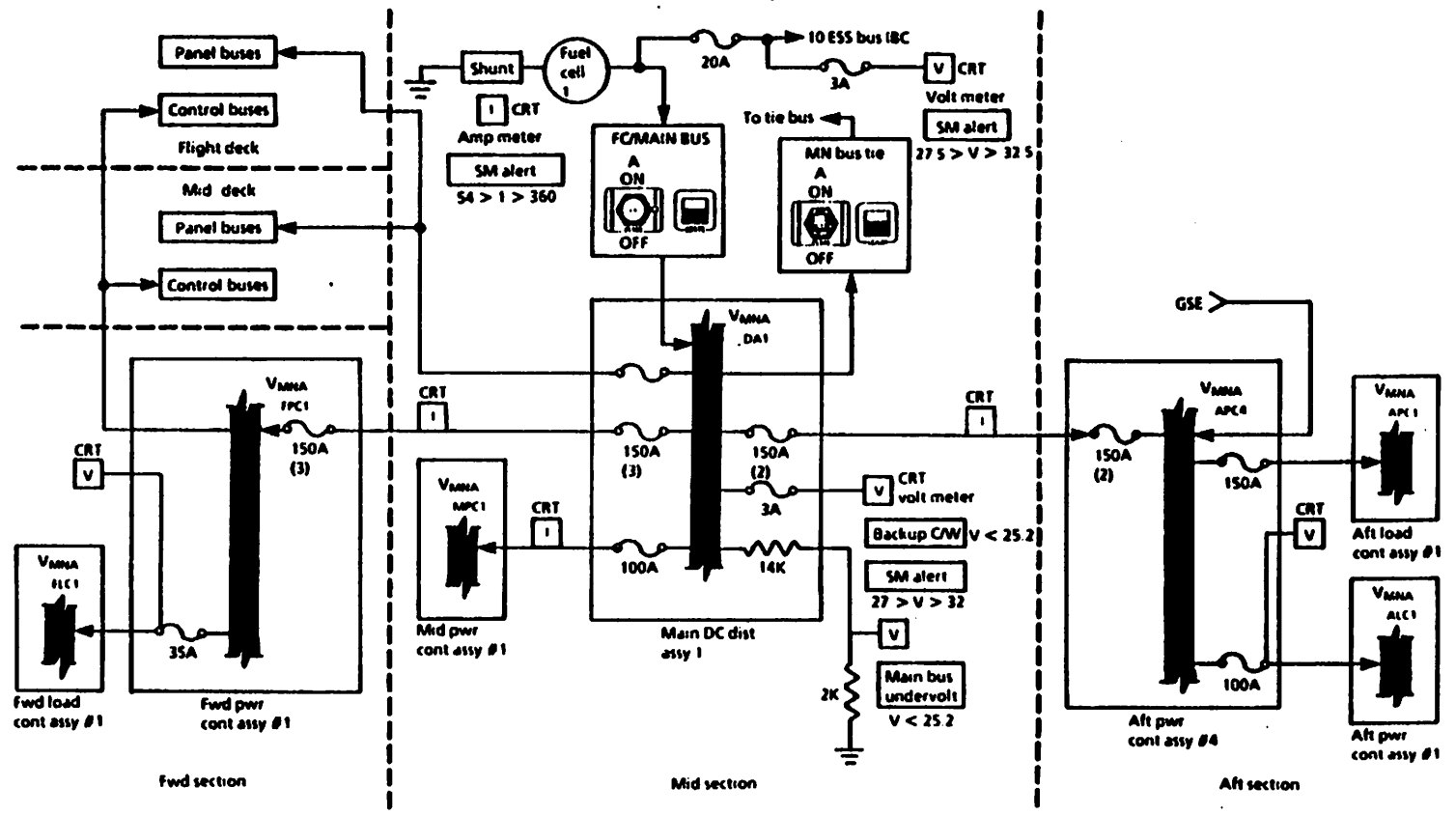


Figure 3-5.- Main bus A distribution.

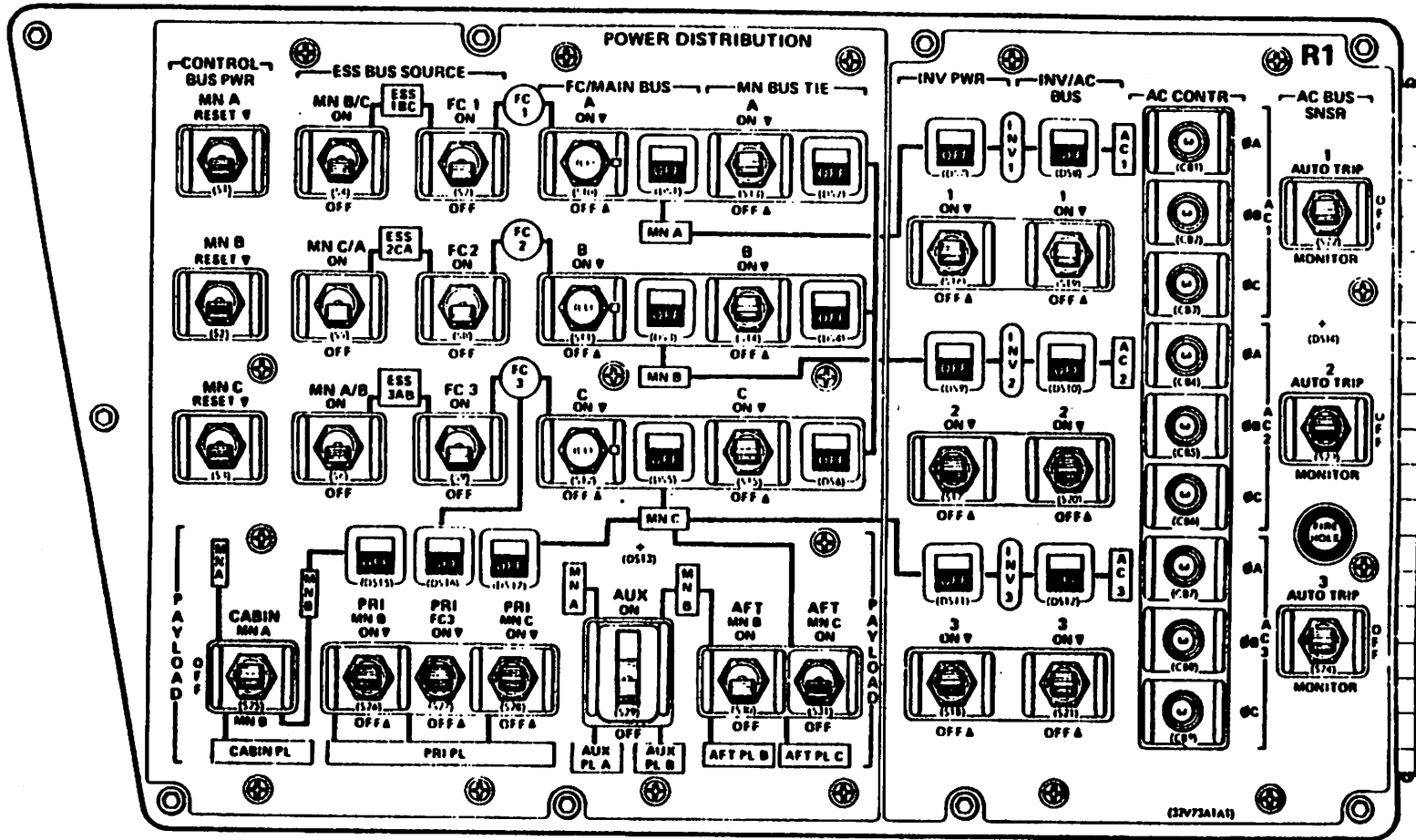


Figure 3-6.- Panel R1.

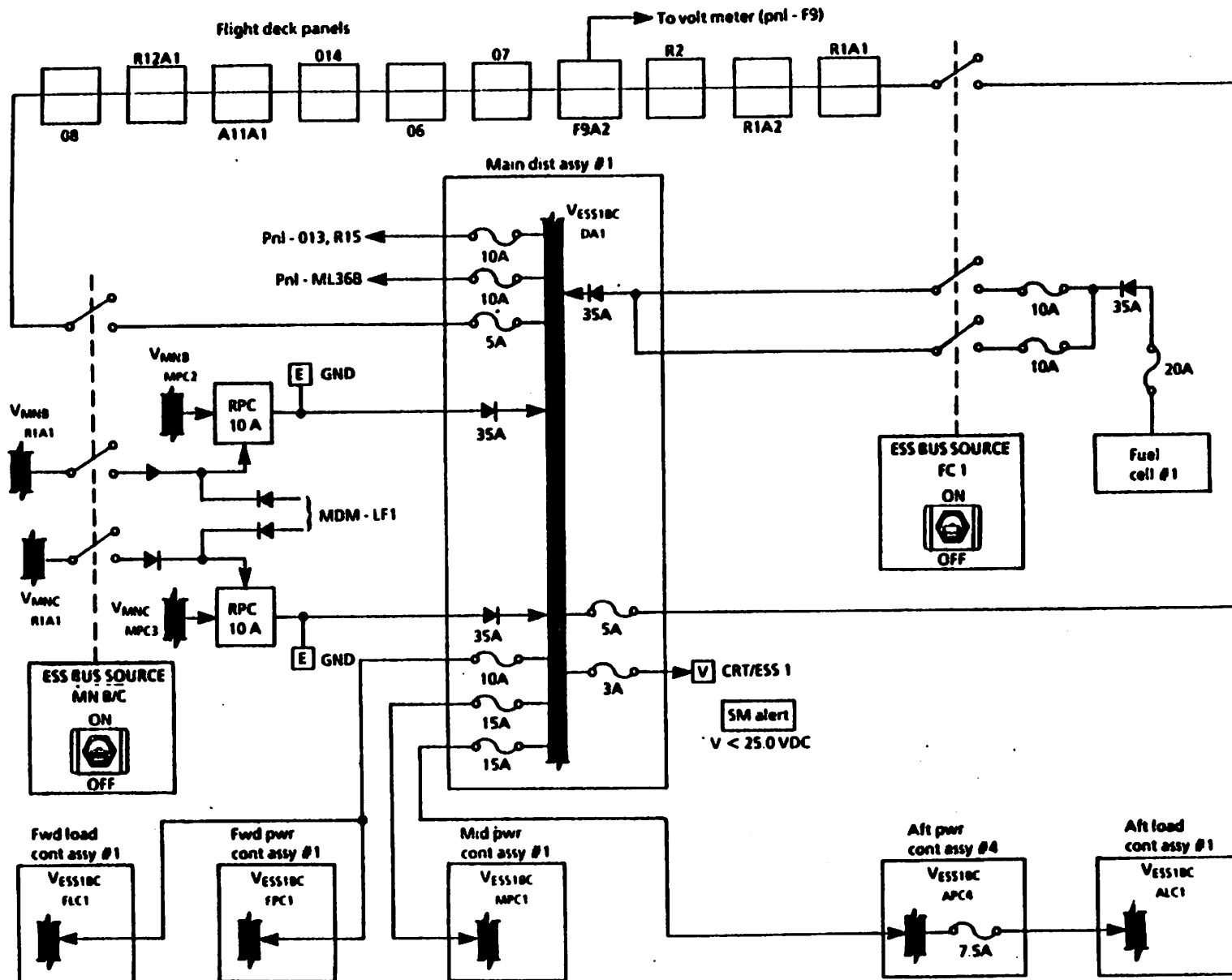


Figure 3-7.- Essential bus 1BC distribution.

3.3.1.3 Control Bus Distribution. Use figures 3-6 and 3-8 during this discussion. Main buses located in the FPC assemblies are connected through RPCs and diodes to nine control buses. The RPCs are continuously powered by the circuit drivers, unless the CONTROL BUS PWR switch is placed to the momentary RESET position, which turns the RPC off and resets the RPC if it has been "tripped out." In the normal switch configuration, when a fuel cell is connected to a main bus, the control buses receiving power from that main bus are also powered up. Each control bus receives power from three main buses for system reliability. For example, control bus AB1 receives power from MNA and MNB through RCSs. The third main bus, main C, provides power through a circuit breaker which is located on panel R15. The 1, 2, or 3 implies the number of the bus and not a fuel cell, as is the case for essential bus nomenclature. Each control bus voltage is available on the CRT display, and an SM ALERT will occur for voltages less than 24.5 V dc. Mission Control Center (MCC) also has the capability to monitor the status of each RPC, in order to check for a "tripped out" RPC.

Control buses are located only in the flight and middeck areas behind the D&C panels. Control buses are only behind panels where there is a requirement or need and are used only for control power to D&C panel switches. A control bus does not supply operational power to any system loads.

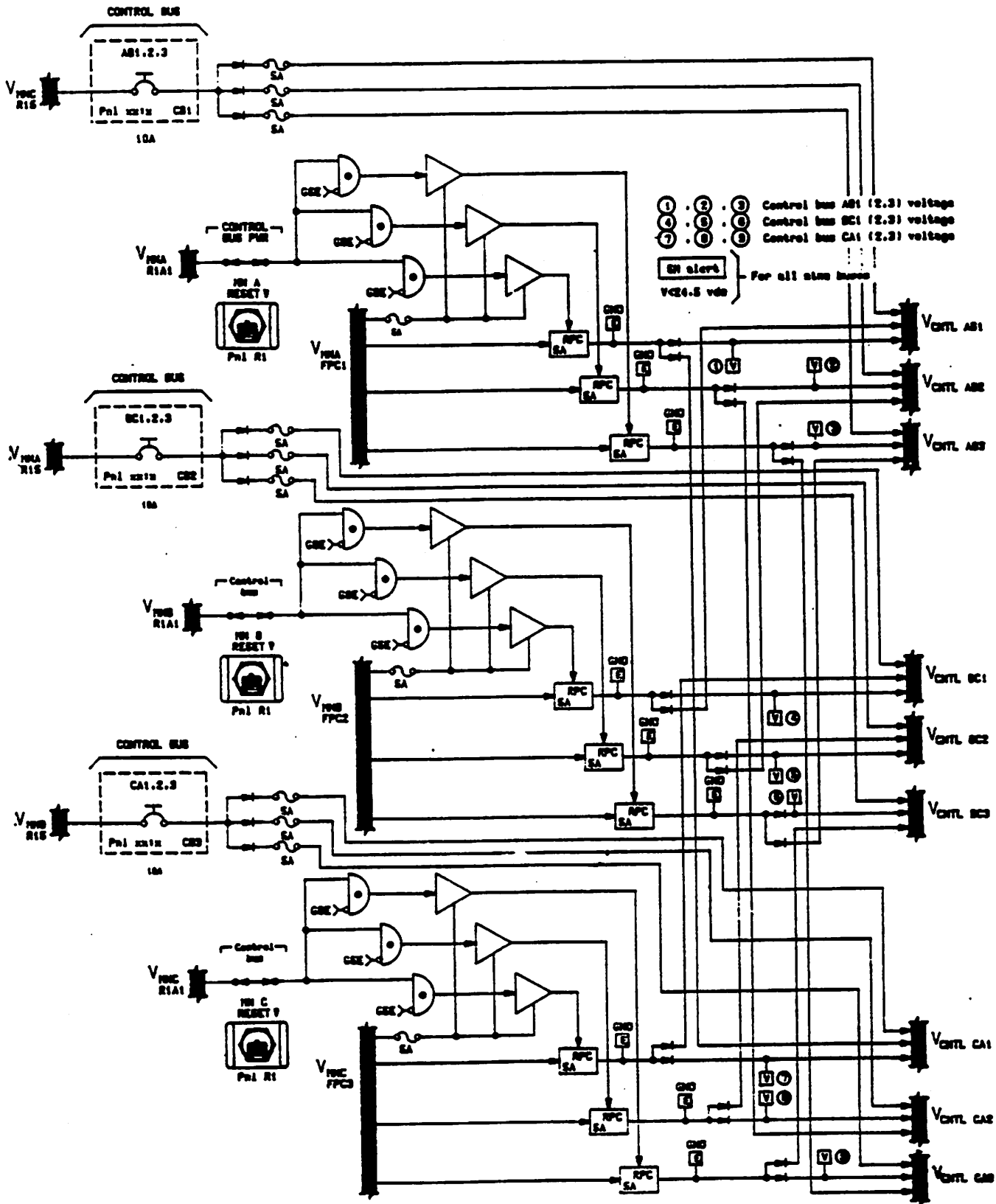


Figure 3-8.- Control buses .

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3.3.2 AC Bus Distribution

AC power is generated and made available to system loads by the EPDC, using three independent ac buses. Each ac bus consists of three separate phase buses connected in a three-phase array. Nine static inverters (one for each phase bus) located in the forward avionics bays are used to convert dc power into ac power. Each inverter is rated at 750 VA (volt amps) and has an output voltage of $117 \pm 3, -1$ V rms (root mean square) at 400 ± 2 Hz (with MTU sync) with a power factor range of 0.7 lagging to 0.9 leading. The inverter efficiency is approximately 76.5 percent.

The ac system is used to power single-phase loads such as panel lights, as well as three-phase ac loads, including the fuel cell pumps and H₂O loop pumps. Use figure 3-9 during this discussion and figure 3-6 for a picture of panel R1. Figure 3-9 is a schematic for ac bus 1 only. AC buses 2 and 3 are identical. The three phase inverters for AC1 receive power only from MNA, AC2 from MNB, and AC3 from MNC. The INV PWR 1 switch on panel R1 is used to apply main bus power to the inputs of each phase inverter. The INV/AC BUS 1 switch is used to apply each inverter output to the respective ac phase bus. Both of these switches must have control power from the AC CONTR circuit breakers in order to operate. Once ac power has been established, these circuit breakers are opened to prevent any inadvertent disconnection, either by switch failure or accidental movement of the INV PWR or INV/AC BUS switches. Each of these switches has an ON/OFF talkback to indicate the status of the switch, and in order for the INV PWR switch talkback to indicate ON, all three inverters must be on, and all three inverters must be connected to their respective ac buses for the INV/AC bus talkback to display ON.

There are two voltage sensors for each ac bus. One sensor sends its data to the BFS FDA (ascent and entry) or SM OPS 2 FDA (on-orbit), to the voltage readouts on the CRT, to the

voltage meter on panel F9, and to drive the BACKUP C/W light. The other sensor is the ac bus sensor which provides circuit protection and crew statusing for over/under voltage and inverter overload conditions. Each ac bus sensor has a switch and circuit breaker for crew control. The AC 1 SNSR circuit breaker applies essential bus power to the AC BUS SNSR 1 switch and operational power to the INV/AC BUS switch talkback. The AC BUS SNSR 1 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 an over/under voltage, and each phase inverter for an overload signal. The limits are as follows:

- Overvoltage – bus voltages greater than 123 to 127 V ac for 50 to 90 msec.
- Undervoltage – bus voltages less than 102 to 108 V ac for 6.5 to 8.5 sec.
- Overload – any ac phase current greater than 14.5 A for 10 to 20 sec, or greater than 17.3 to 21.1 A for 4 to 6 sec.

If the AC BUS SNSR switch is selected to the AUTO TRIP position and an over-voltage or overload condition exists, the ac bus sensor will light the corresponding C/W light and trip out (disconnect) the inverter from its respective phase bus for the bus/inverter causing the problem. If an undervoltage exists, the AC VOLTAGE C/W light will annunciate but the inverter will not be tripped out from its phase bus. In the OFF position, the ac bus sensor is operational and all C/W and trip out capability is inhibited. In the MONITOR position, the ac bus sensor will monitor for an overload and over/under voltage and annunciate the C/W but it will not trip out the phase bus/inverter causing the problem. It should be noted that there is only one AC OVERLOAD and AC VOLTAGE C/W light, and all nine inverters/ac phase buses can annunciate the lights; therefore, the voltage meter on panel F9 or the CRT display should be used to determine which

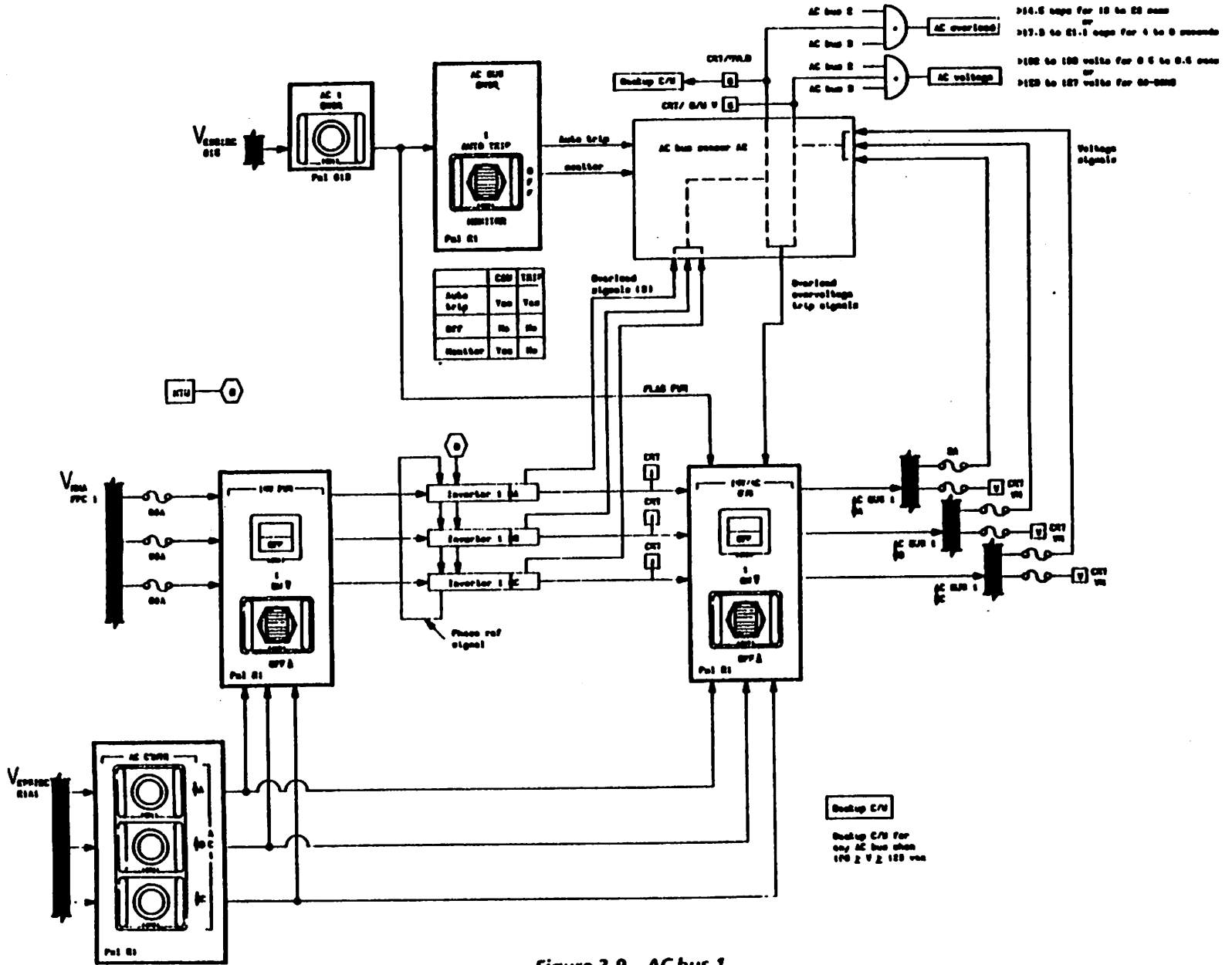


Figure 3-9.- AC bus 1.

inverter or phase bus caused the C/W light. If the AUTO TRIP position is selected and an overload or overvoltage occurs, the AC OVERLOAD or AC VOLTAGE C/W lights will annunciate and the phase bus voltages causing the problem will be zero amps because power has been disconnected (tripped) from the bus.

Because of the various three-phase motors throughout the vehicle there will be a small induced voltage on the phase bus if there is only one phase which has lost power. Before power can be restored to the tripped bus, the trip signal to the INV/AC BUS switch must be removed by cycling the AC BUS SENSOR switch to OFF and then back to the desired position, which will also cause the C/W light to extinguish. The INV/AC BUS switch is then placed to ON, restoring power to the failed bus. If the problem is still present, the C/W lights will annunciate again.

A BACKUP C/W light will occur for an overload or over/under voltage condition. Also, an SM ALERT light will occur for an over/under voltage condition. The limits and CRT fault messages for these conditions are covered in section 3.4, EPDC Displays and Controls. The CRT displays showing ac parameters are also in this section.

3.3.2.1 AC Power Transfer Cable

A. General Information

Recall that the ac system is composed of nine inverters which power three independent 3 ϕ buses.

1. AC1, composed of AC1 ϕ A, AC1 ϕ B, AC1 ϕ C
2. AC2, composed of AC2 ϕ A, AC2 ϕ B, AC2 ϕ C
3. AC3, composed of AC3 ϕ A, AC3 ϕ B, AC3 ϕ C

DC power input for the three AC1 inverters is MNA FPC1, for AC2 inverters is MNB FPC2, and for AC3 inverters is MNC FPC3.

If one inverter of a 3 ϕ ac bus system is lost (e.g., AC1 ϕ A), the 3 ϕ loads will continue to operate on the two remaining phases. (The only 3 ϕ equipment switched for this case is the H₂O loop pump and the Freon pump to gain higher performance.) If two inverters of a 3 ϕ ac bus system are lost (e.g., AC1 ϕ A and AC1 ϕ C), none of the 3 ϕ loads powered by that ac bus will operate. This causes loss of a fuel cell due to loss of pumps, which necessitates tying main buses and disconnecting and stopping the fuel cell to prevent thermal damage.

To prevent losing a fuel cell and redundancy in other systems by such a failure, an ac power transfer cable (AC PTC) is stowed onboard the Orbiter in locker MF57M. Using the AC PTC, a crewmember may repower a failed 3 ϕ ac bus by connecting it to one of the two remaining 3 ϕ ac buses. The AC PTC will not be used to repower an ac bus that has a shorted phase(s). It may be used whenever the following conditions occur:

1. Two or three inverters of a 3 ϕ ac bus fail.

2. DC power to the inverters of a 3 ϕ bus is lost.

B. Physical Description

The AC PTC is 15 feet long and contains two twisted wire pairs; ϕ A and ϕ B wires are twisted together and ϕ C and ac neutral are twisted together. The plug is compatible with the Orbiter ac utility outlet sockets for the AC1 panel M052J) and AC3 (panel M013Q), and with the AC2 socket on the payload station patch panel (J37). (There are no AC2 utility outlets.) The four wires of the AC PTC are connected to plug pin A (ϕ A), pin B (ϕ B), pin C (ϕ C), and pin J (ac neutral).

Procedures

Because of possible differences in phase relationship between two 3 ac buses, all three inverters of a failed ac bus must be disconnected from the bus before connecting the AC PTC (i.e., one remaining operational inverter from the failed 3 ϕ ac bus may not be used). Also, if an unpowered inverter remained connected to the ac bus, it would draw current and provide an unnecessary load.

The onboard procedures for connecting the AC PTC are contained in the In-Flight Maintenance (IFM) Checklist. Figures 3-10 through 3-12 illustrate the controls and connections for tying AC1 to AC2, AC1 to AC3, and AC2 to AC3. The total load capability of an AC bus repowered via the AC PTC is 3 amperes per phase, limited by the 3 ϕ circuit breakers.

The ac bus that repowers a failed ac bus must supply current to its own loads plus up to 3 amperes per phase to the repowered bus. Care must be taken not to exceed each inverter's limit of 6.41 amperes (100 percent) continuous, 9.62 amperes (150 percent) for 30 minutes, or 12.8 amperes (200 percent) for two minutes. (An inverter's output capacitors allow higher bus currents for inductive loads. The bus current

limits may be calculated based on the load power factor.)

To connect one end of the AC PTC to AC1 or AC3, it is simply connected to the ac utility outlet jack on panel M052J (AC1) or M013Q (AC3). To connect one end to AC2, it is necessary to remove panel cover L17 at the payload station to gain access to the payload station patch panel and to connect the AC PTC to jack J37. Also, if necessary, a seated commander (CDR) could reset the AC1 or AC3 power circuit breaker on panel L4, but the AC2 power circuit breaker is located on middeck panel MA73C. Therefore, it is not desirable procedurally to use AC2 to repower AC1 or AC3, although it may be necessary to do so to balance loads between the two remaining ac inverter systems.

The procedures for systems reconfiguration and AC PTC connection following a forward power control assembly dc bus loss is contained in the malfunction procedures bus loss SSRs in section 7. Following the MNA FPC1 loss, which causes the loss of AC1, MNA is tied to MNB, fuel cell 1 is shut down, and the AC1 inverters are isolated from the dc power source and from the AC1 bus. Before connecting the AC PTC, AC1 loads are isolated by opening all the AC1 circuit breakers on panels L4, R11, and MA73C. After repowering AC1 from AC3, the fuel cell is regained, and other AC1 equipment listed in the shopping list may be regained; but the AC1 loads may not exceed 3 amperes per phase to avoid tripping the AC1 or AC3 utility power circuit breaker on panel L4. Also, AC3 must power its own loads plus the repowered AC1 loads.

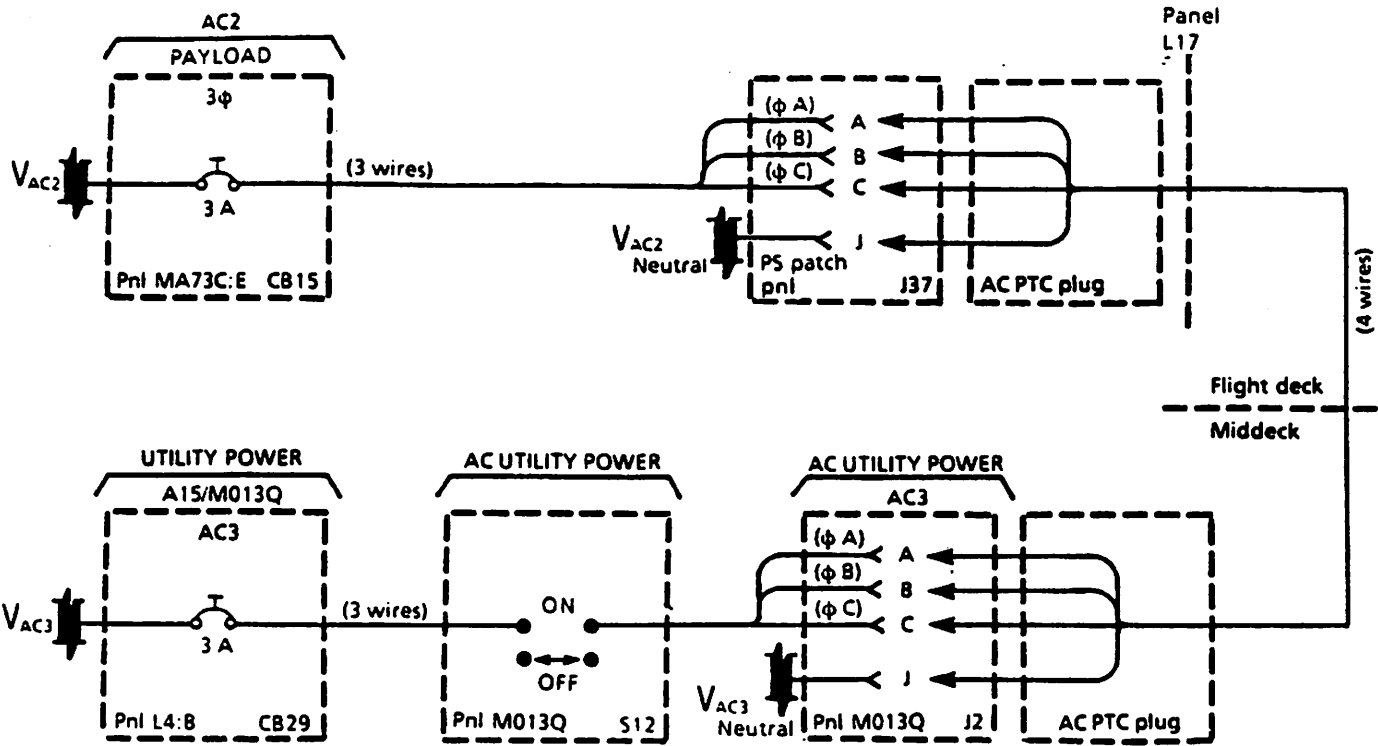


Figure 3-10.- AC2 to AC3 power transfer cable connection.

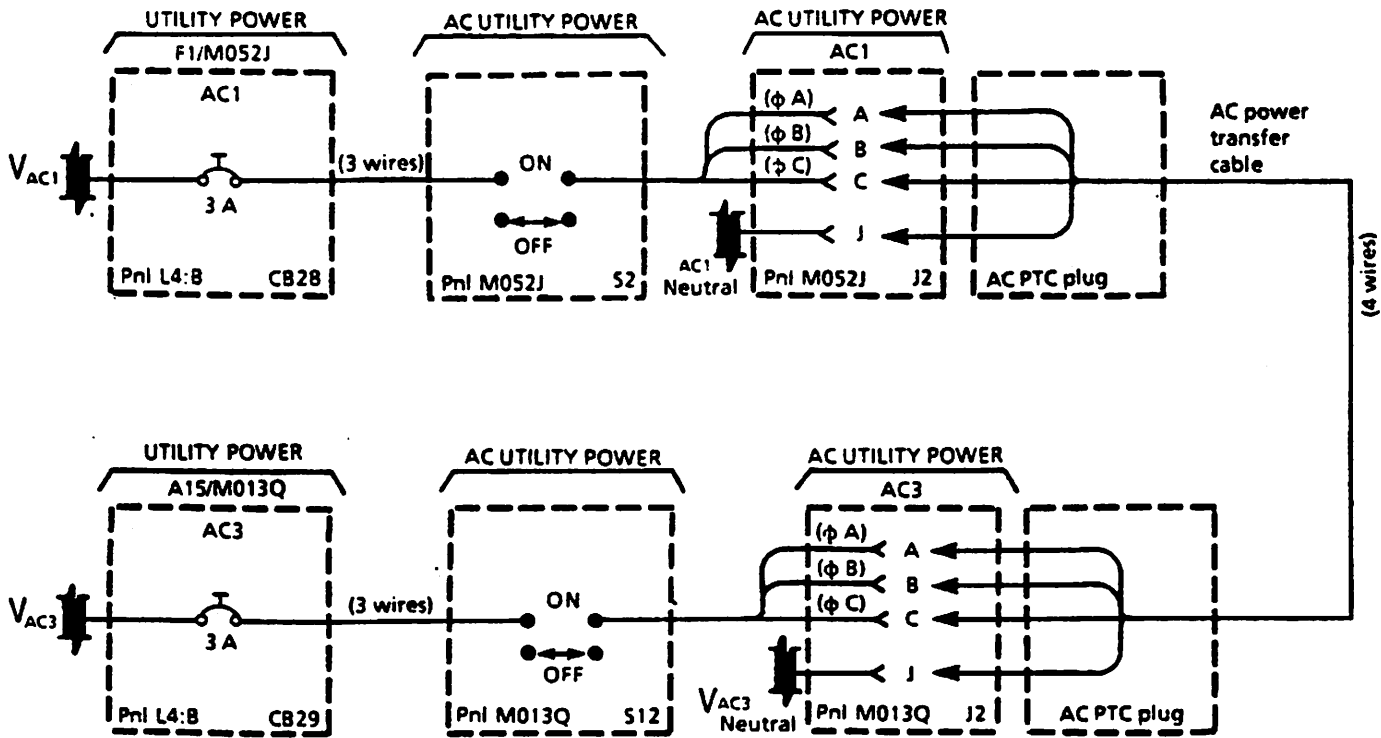


Figure 3-11.- AC1 to AC3 power transfer cable connection.

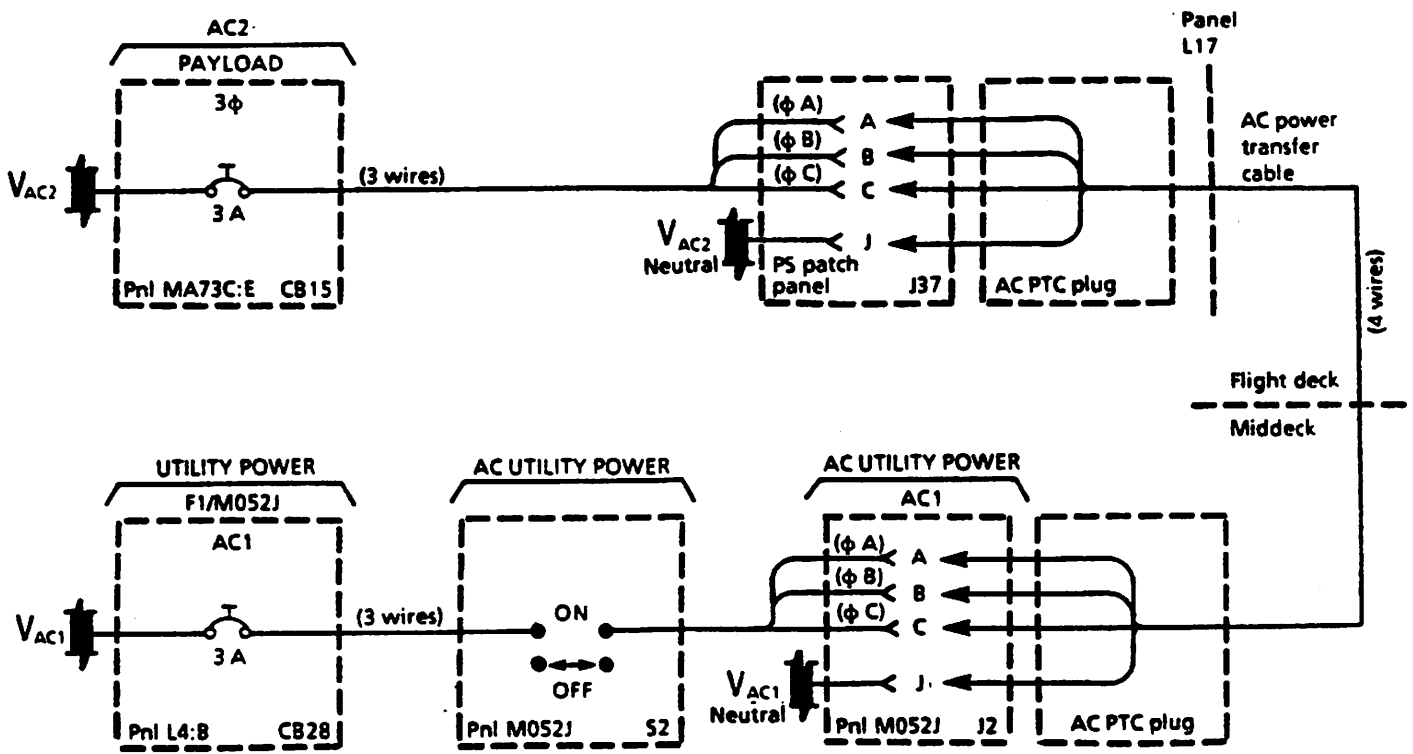


Figure 3-12.- AC2 to AC1 power transfer cable connection.

3.3.3 Motor Control Assembly Power Distribution

There are ten motor control assemblies used on the Orbiter: three in the forward area, four in the midbody area, and three in the aft area. Their only function is to supply ac power to noncontinuous ac loads such as: orbital maneuvering subsystem/reaction control system (OMS/RCS) valves, vent doors, air data probe deployment, and star tracker doors from the forward motor control assemblies (FMCs); vent doors, payload bay doors, Freon radiator deployment, RMS retention, payload retention, and Ku-band (rendezvous radar) deployment from the mid-motor control assemblies (MMCs); and vent doors, external tank (ET) umbilical doors, and OMS/RCS valves from the aft motor control assemblies (AMCs).

Motor control assemblies contain main buses, ac buses, and hybrid relays, which are the remote switching devices for switching the ac power to the electrical loads. The main buses are used only to supply control or logic power to the hybrid relays, so that ac power can be switched on/off. 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 MCA main bus.

It should be noted that some motors have a circuit breaker per phase and some do not. Theoretically, those with three separate breakers are motors that can operate on two phases. Thus if one phase were to short, only the breaker on that phase would pop and the motor would continue to operate. However, the short would most likely feed back through the motor windings and pop the two remaining breakers.

Except for OMS/RCS, all functions powered from the MCAs are redundant, in that loss of an MCA will result in loss of only one of two motors for a given system.

3.3.3.1 Forward Motor Controllers.

The three forward motor control assemblies 1, 2,

and 3 (FMC-1, FMC-2, FMC-3) correspond to MNA/AC bus 1, MNB/AC bus 2, and MNC/AC bus 3, respectively. Use figure 3-13 for a schematic of FMC-1 and figure 3-14 for a picture of panel MA73C. FMC-2 and FMC-3 are similar to FMC-1. Each forward motor control contains a main bus, an ac bus, and an RCS ac bus. The main bus is used to supply control or logic power to the hybrid relays associated with both the ac bus and the 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 probe left and right doors. The RCS ac bus supplies power to the forward RCS manifold and tank isolation valves.

3.3.3.2 Aft Motor Controllers.

The aft motor control assemblies 1, 2, and 3 (AMC-1, AMC-2, AMC-3) correspond to MNA/AC bus 1, MNB/AC bus 2, and MNC/AC bus 3, respectively. Use figure 3-15 for a schematic of the AMC-1 and figure 3-14 for a picture of panel MA73C. AMC-2 and AMC-3 are similar to AMC-1. Each aft motor control assembly contains a main bus and its accompanying ac bus, and also a main OMS/RCS bus and its corresponding OMS/RCS ac bus. Both main buses are used for control or logic power for the hybrid relays. The ac bus is used by the aft vent doors, external tank centerline latches and doors, etc. The OMS/RCS ac bus is used by the aft OMS/RCS manifold, tank isolation and crossfeed valves.

3.3.3.3 Mid Motor Controllers.

Each of the mid motor control assemblies (MMC-1, MMC-2, MMC-3, MMC-4) contain two main buses and the corresponding ac bus. Use figure 3-16 for a schematic of MMC-1 and figure 3-14 for a picture of panel MA73C. MMC-2, MMC-3 and MMC-4 are similar to MMC-1. MMC-1 contains main bus A and B and their corresponding ac buses, ac bus 1 and ac bus 2. MMC-2 contains main buses B and C and their corresponding ac buses, ac bus 2 and ac bus 3. MMC-3 and MMC-4 contain the same respective buses as MMC-1 and MMC-2. There is no

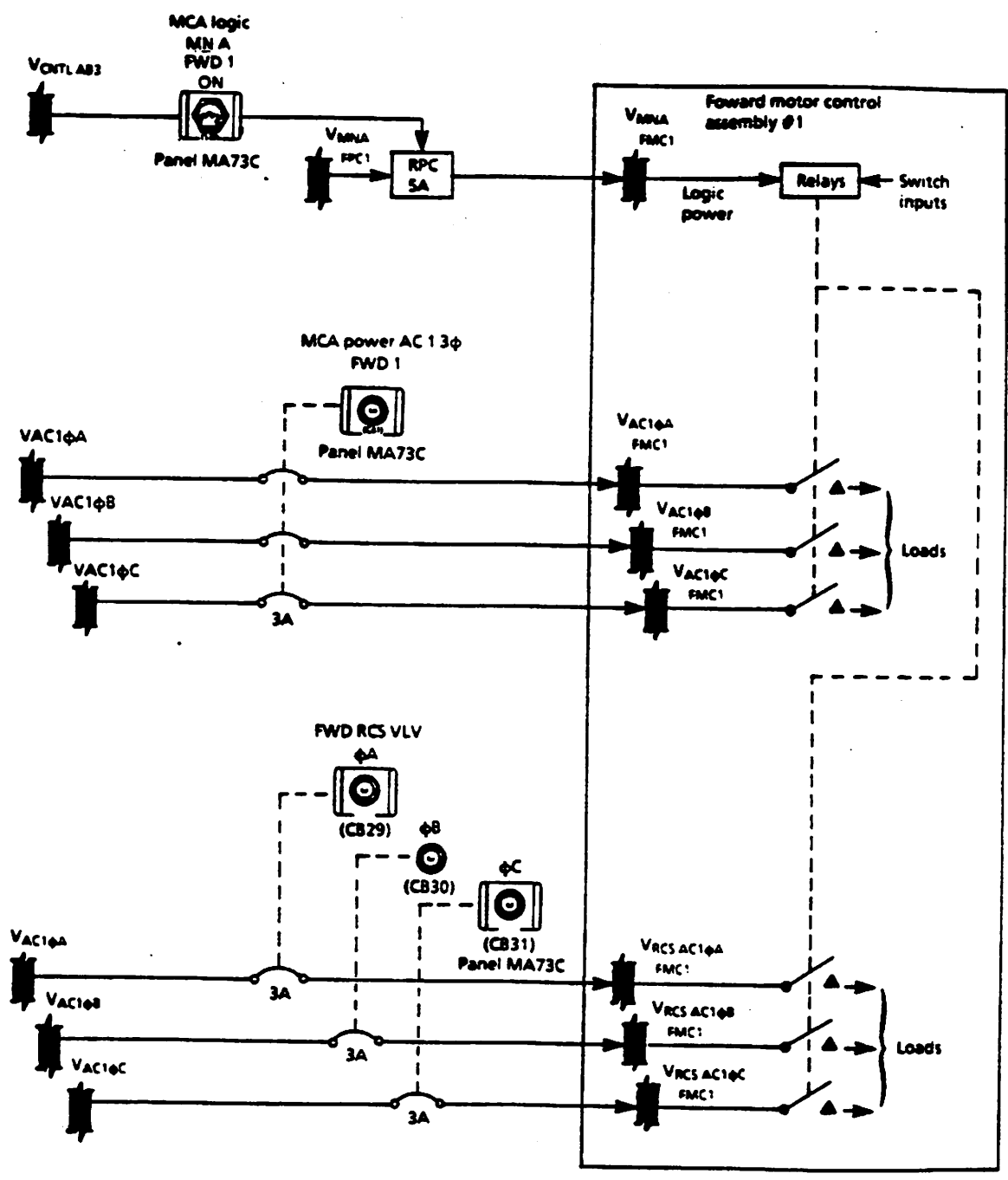


Figure 3-13.- Forward motor control assembly 1.

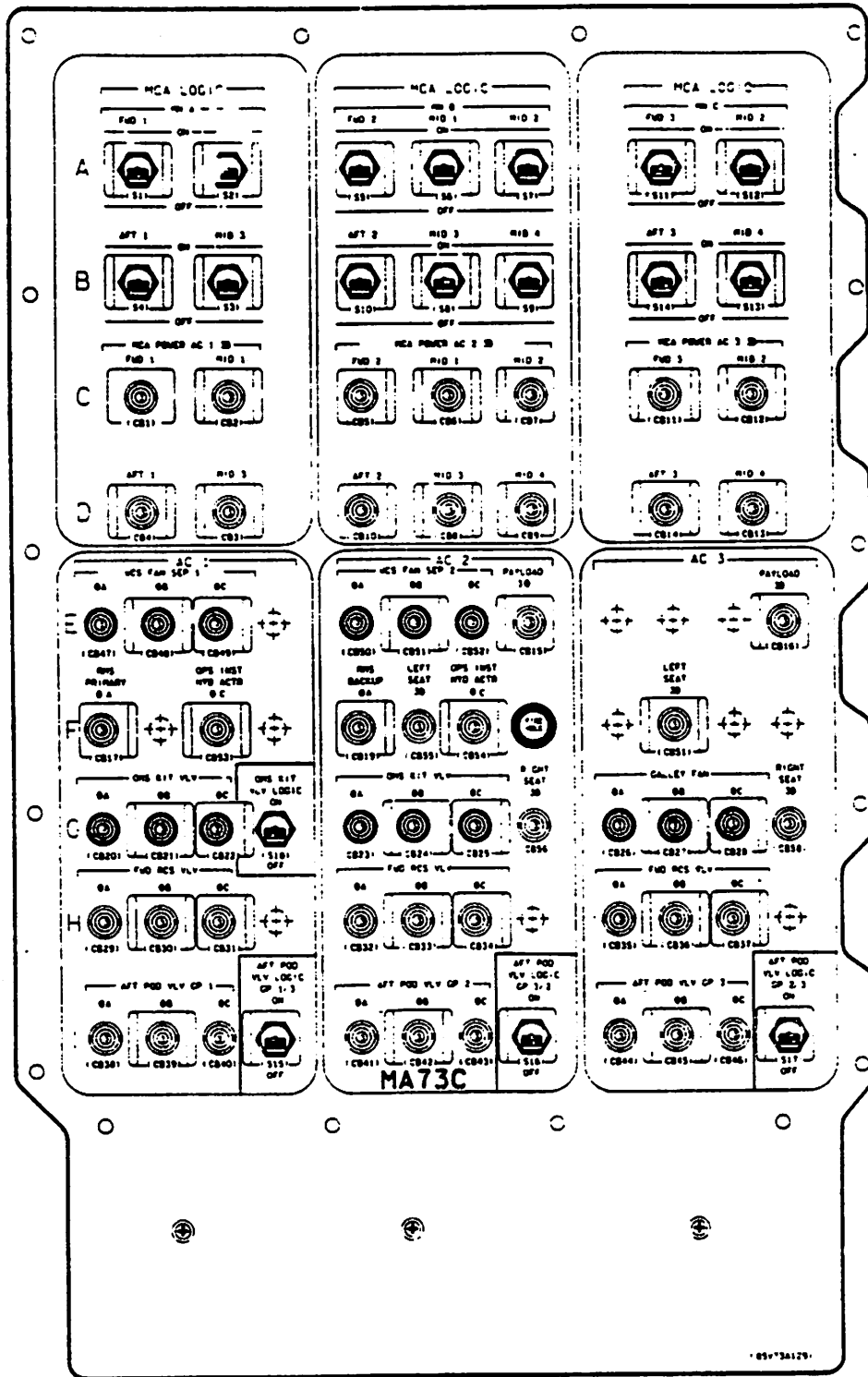


Figure 3-14.- Panel MA73C.

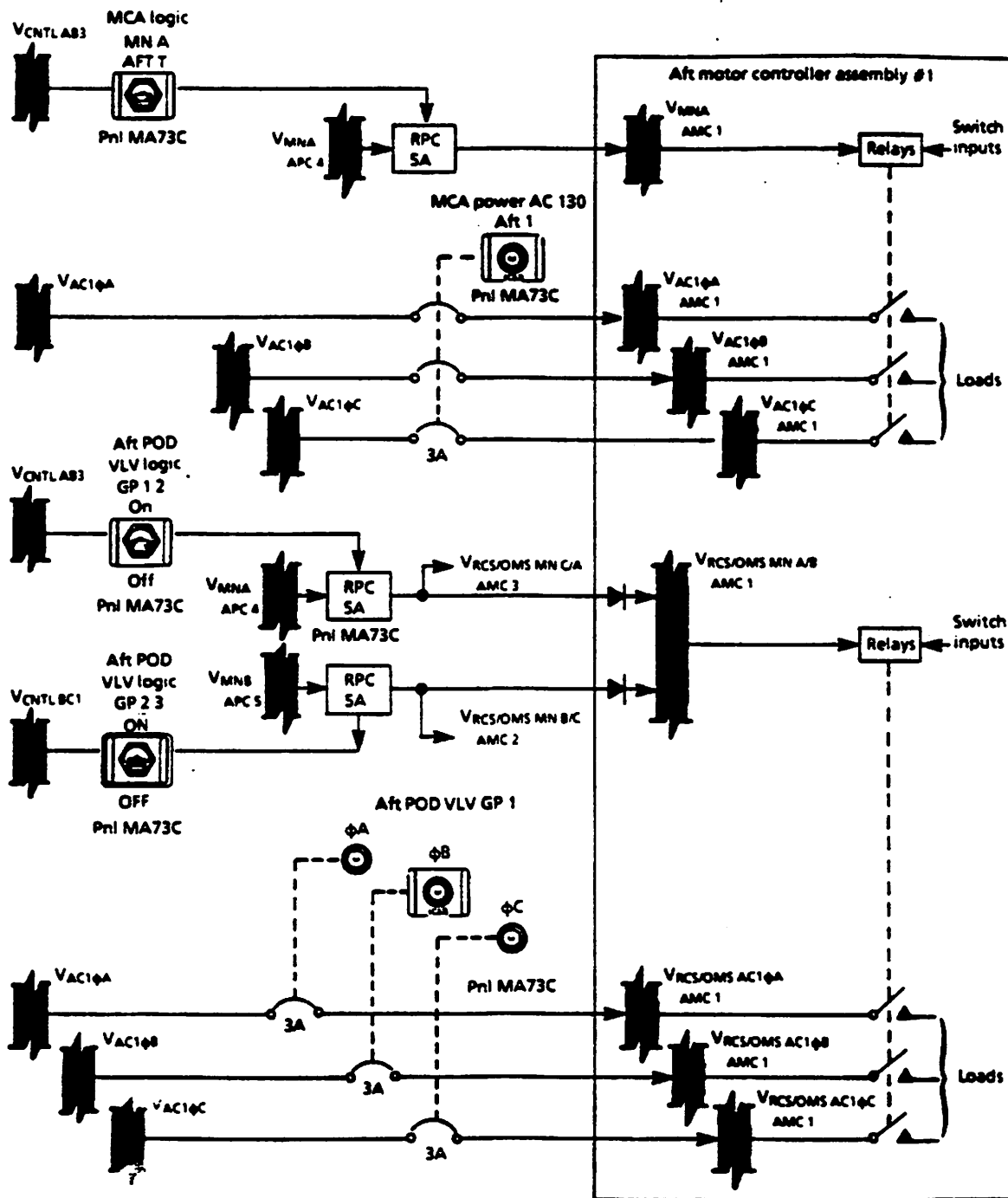


Figure 3-15.- Aft motor control assembly 1.

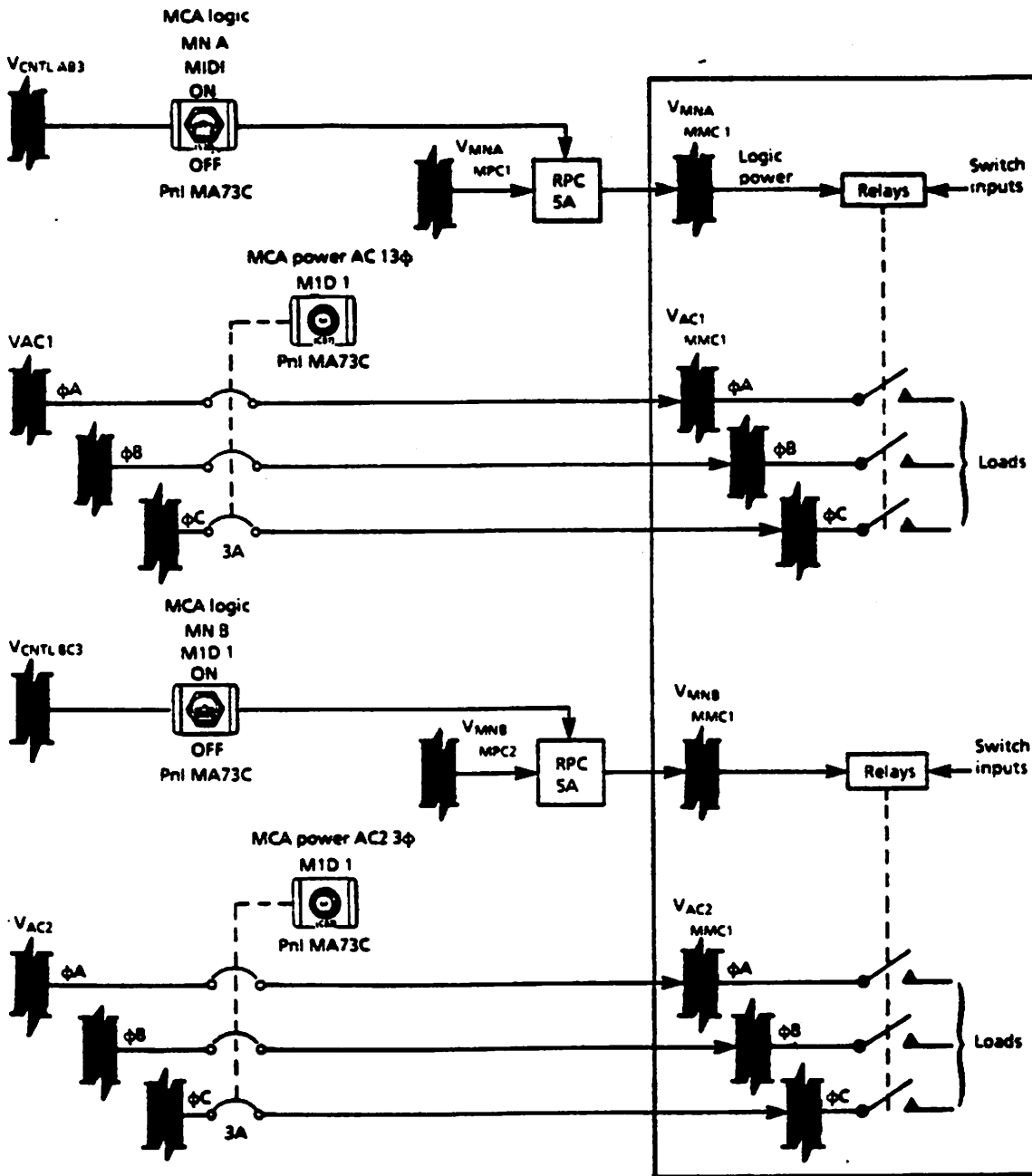


Figure 3-16.- Mid motor control assembly 1.

distinction for the mid motor controller assemblies as there were in the forward and aft motor control assemblies. Typical loads for both main buses/ac buses are vent doors, payload bay door and latches, radiator panel deployment actuators and latches, payload retention latches, etc.

3.3.4 Payload Power Distribution

Use figure 3-17 during this discussion. If a picture of panel R1 is needed, use figure 3-6. The EPDC provides primary and emergency power to payloads and experiment equipment. The primary electrical interface, which is located at X₀645 in the forward section, is the primary payload bus (PRI PL bus). The EPDC is capable of distributing 7 kW maximum continuous (12 kW peak) power at 28 V dc from fuel cell 3, which is dedicated to the payloads. The dedicated fuel cell mode can occur only when the following conditions are met: all three fuel cells are operating, and the payload bay doors are fully opened. As a backup to the dedicated fuel cell mode, there is a primary electrical interface 5 kW maximum (8 kW peak) of power from either MAIN B or MAIN C buses.

A backup interface to the primary interface, the secondary payload bus (SEC PL bus), can be used by installation of an Orbiter-furnished kit. This SEC PL bus can transfer 5 kW of power directly from MNB. If the SEC PL bus is used, the ability to connect main B to the PRI PL bus is lost. If payload equipment requiring electrical power from two separate Orbiter sources is required, this backup interface would be used.

There are two additional primary interfaces in the aft section (X₀1307) of the payload bay (AFT PL B bus and AFT PL C bus). Each bus can transfer 1.5 kW of power and a peak of 2 kW at a minimum of 24 V dc. These buses are used by payloads located in the aft section of the payload bay.

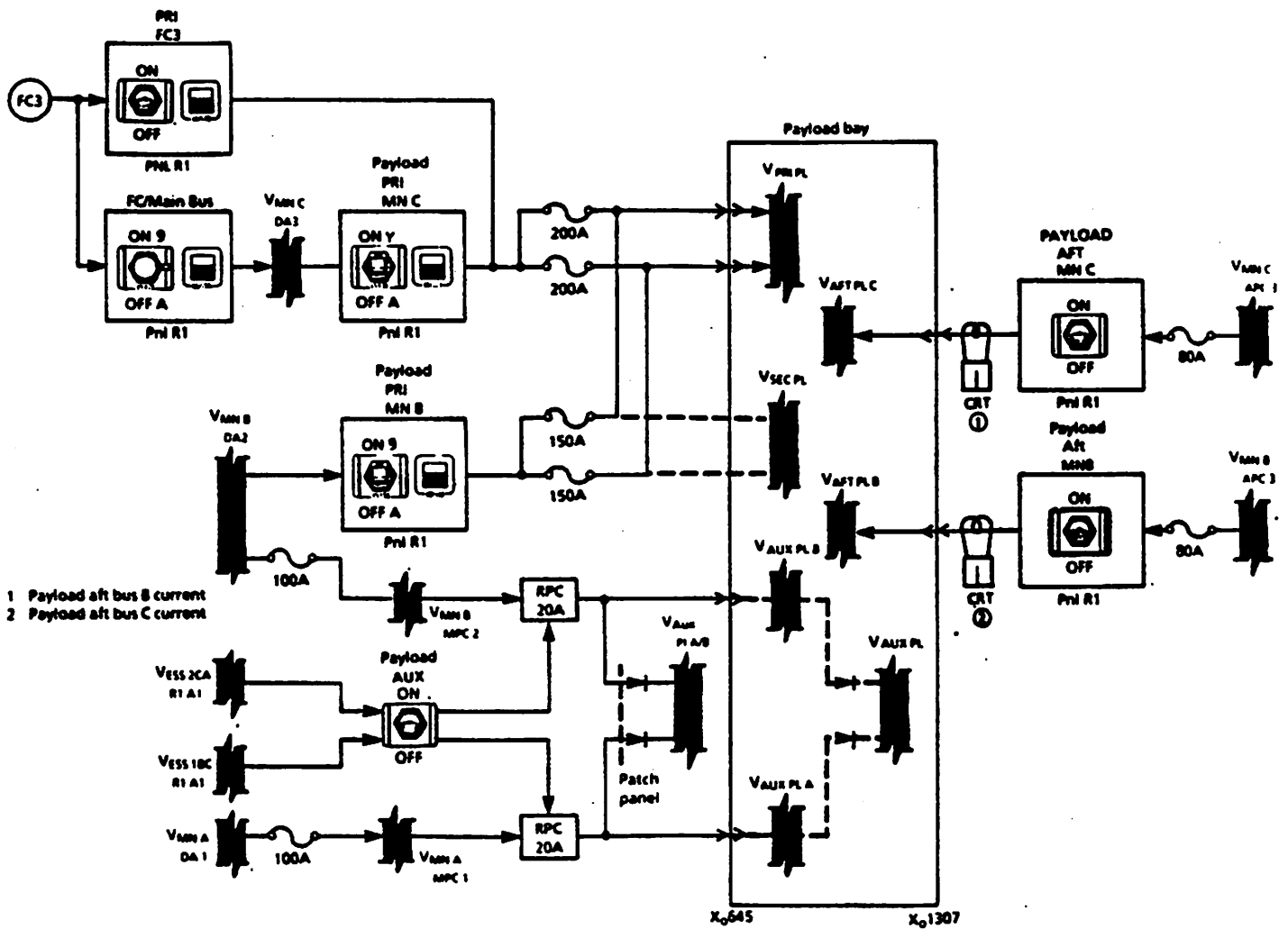
Two other interfaces, the auxiliary payload main A bus (AUX PL A) and the auxiliary

payload main B bus (AUX PL B), located adjacent to the primary and secondary buses in the mid payload bay area (X₀645), can supply a total of 0.4 kW from main A and main B buses. Two auxiliary payload buses (AUX PL A and AUX PL B) may be dioded together to form one bus (AUX PL A/B), redundantly powered by two sources. The general plan is for the auxiliary buses in the payload bay to be used for emergency equipment functions only.

Two or more power feeders to the payload may be used simultaneously, but two Orbiter power sources may not be tied directly within the payload. Any payload equipment requiring electrical power from two separate Orbiter sources shall make provisions that assure isolation of these power sources, so that no single failure in a load, succession or propagation of failures in a load will allow a paralleling of power sources, which will cause an out of limit condition to exist on the Orbiter vehicle subsystem equipment on more than one bus.

The PAYLOAD CABIN switch (figure 3-18) provides MNA or MNB power to patch panels located under the on-orbit, payload specialist, and mission specialists stations located in the aft flight deck. The purpose of these patch panels is to supply power to payload-related equipment located on panels at these stations.

On panel MA73C, two three-phase circuit breakers, AC 2 CABIN PL 3 ϕ and AC 3 CABIN PL 3 ϕ , provide ac power to the patch panels.



- 1 Payload aft bus B current
- 2 Payload aft bus C current

Figure 3-17.- Orbiter/payload power interface schematic.

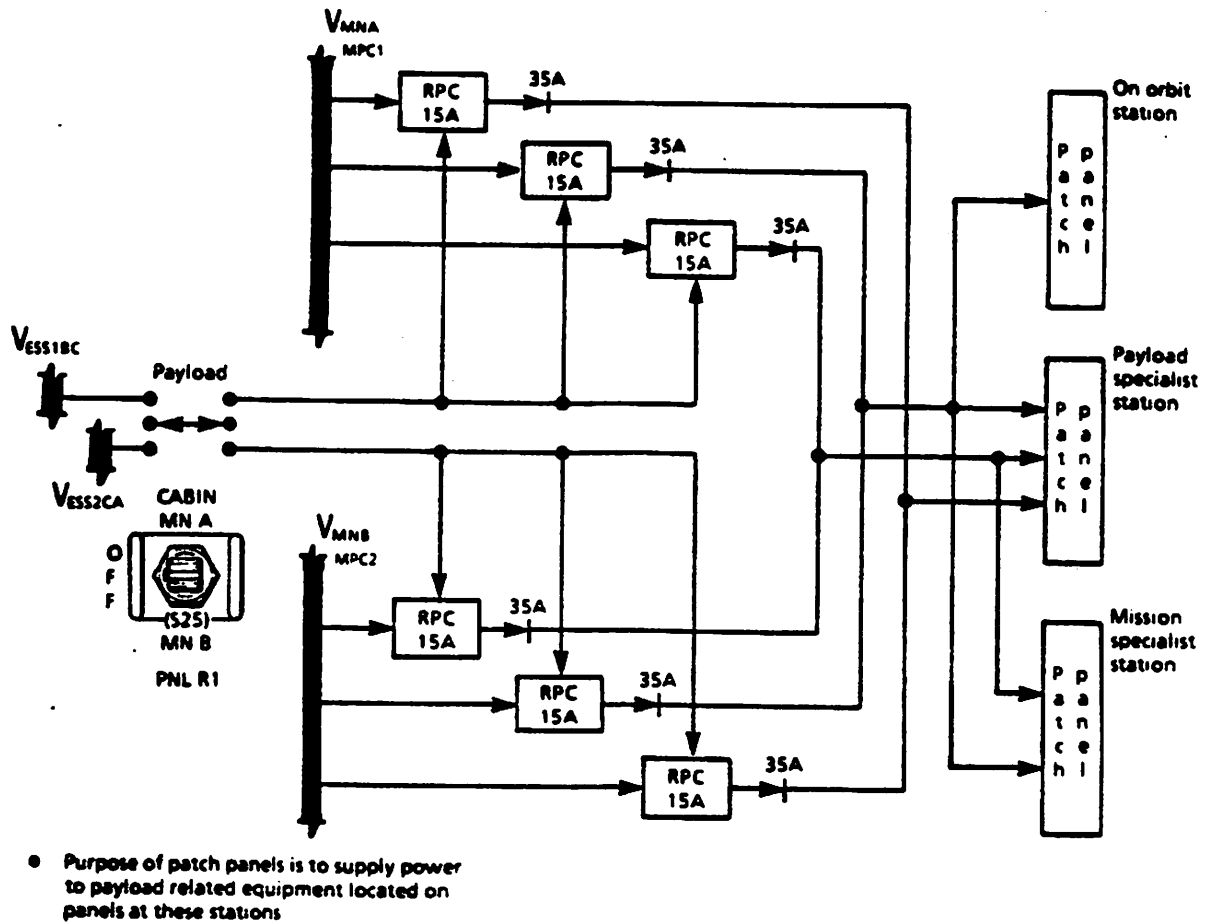


Figure 3-18.- PAYLOAD CABIN switch.

3.3.5 Preflight Power

Refer to figure 3-19 throughout this discussion. Until a few minutes before lift-off, power to the Orbiter is supplied by GSE, even though the fuel cells are on and capable of supplying power. Main bus power is supplied through the T-O umbilicals, main A through the left side, and main B and C through the right side to APC 4, 5 and 6. From APC 4, 5 and 6 the GSE power is directed up to the distribution assemblies, where the power is distributed throughout the vehicle, as has already been described. The power for the preflight test bus

(PRFLT) is also supplied through the T-O umbilical. These test buses are scattered throughout the Orbiter and are used for GSE related functions, although they also power up the essential buses in the aft power controllers when on GSE. As in main bus distribution, essential bus power from the APCs is directed to the distribution assemblies and then distributed throughout the vehicle. No crew action is needed in switching from GSE power to fuel cell power. The ground turns off GSE power, disconnects the lines from the T-O umbilical, and the fuel cells automatically pick up the load.

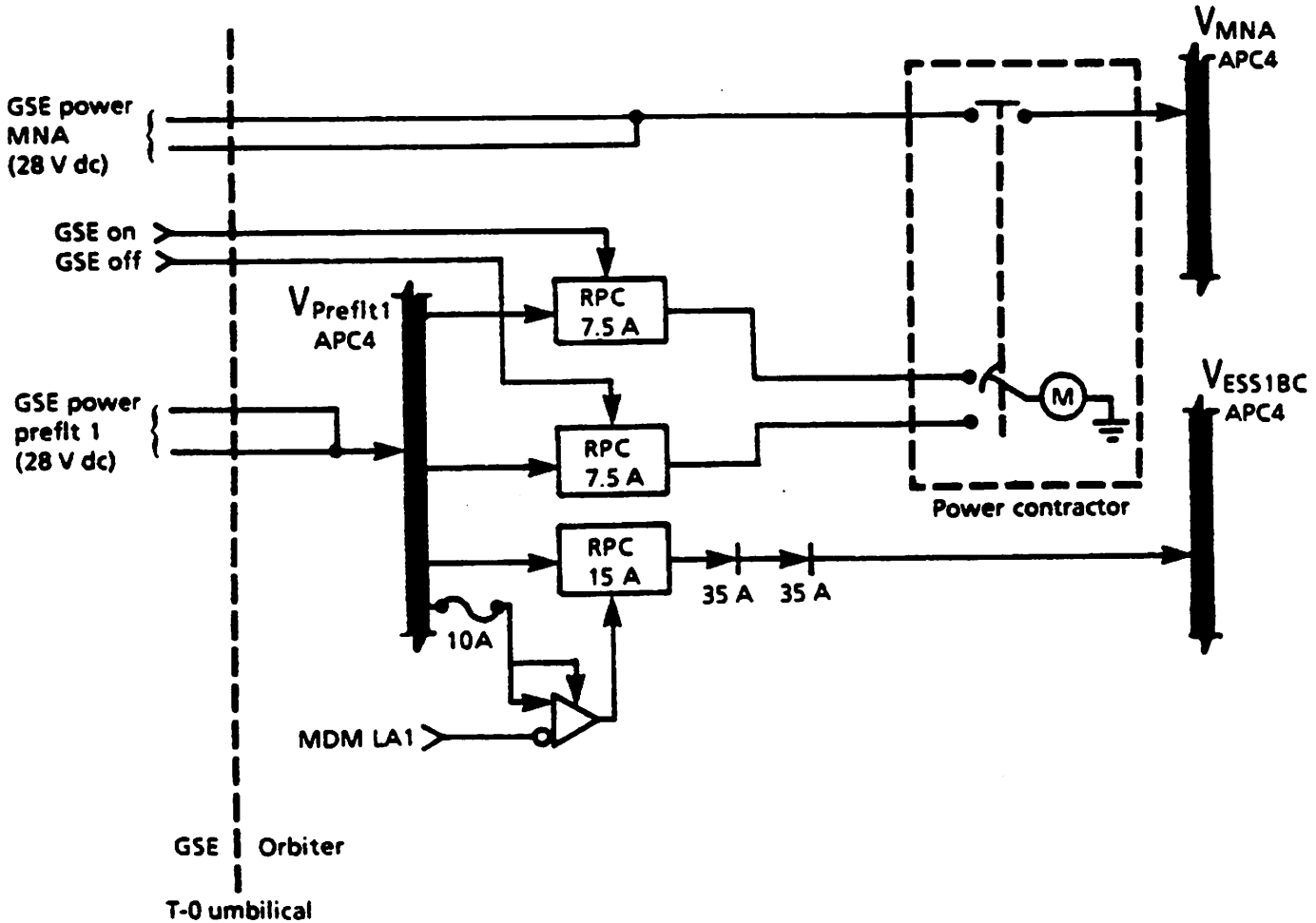


Figure 3-19.- Orbiter: GSE power interface (MNA only).

3.4 EPDC Displays and Controls

The displays and controls for the EPDC on flight deck panels R1, O13, F7, F9, O14, O15, O16, R15, and middeck panel MA73C. Figure 3-1 shows the panels and their relative positions in the flight deck station and middeck area. Panel R1 contains the switches and accompanying talkbacks for connecting fuel cell power to the main and essential buses, for connecting main bus power to the payloads, and for connecting dc power through the inverters to the ac buses. Panel O13 contains the MNA (B,C) CONTR and AC 1 (2,3) SNSR circuit breakers that supply control power to many of the switches on panel R1. Panels O14, O15, and O16 contain additional controller circuit breakers. Panel R15 contains circuit breakers which apply main bus power to control buses. Panel F7 has meters that display main and essential bus voltage and ac bus voltage. Rotary select switches located next to these dedicated displays allow selection of which main, essential, or ac bus data is to be displayed. Panel MA73C contains the switches and circuit breakers for applying power to the MCA buses.

A more complete description of each control or display pertaining to the EPDC system is given in table 3-1. This table gives the panel number where the control or display can be found the type of control or display, the nomenclature that appears on the panel, and the control function.

Panel F7 contains the C/W annunciator light matrix and the SM ALERT light. The C/W lights pertaining to the EPDC system are MAIN BUS UNDERVOLTS, AC OVERLOAD, AC VOLTAGE, and BACKUP C/W. The MAIN BUS UNDERVOLTS light has been described in section 3.3.1.1, and the AC OVERLOAD and AC VOLTAGE lights have been described in section 3.3.2. The sensors for these three lights are hardwired directly to the C/W electronics, where their limits are checked. The BACKUP C/W light is just as its name applies, a backup to the

hardwired C/W lights. Sensors send their signal to the computer, where the limits are checked. If an out-of-limits condition exists, the BACKUP C/W light will come on. The limits of the three hardwired lights are the same as the software detected BACKUP C/W light. Figures 3-20 through 3-23 list the upper and lower limits for the three hardwired lights and the software detected BACKUP C/W light, along with the fault message that will appear on the CRT screen when these lights come on. These figures also list the SM ALERT parameters that are applicable to the EPDC system.

The SM FDA, which consists of the SM ALERT and BACKUP C/W software program, will be in GPC 5, the BFS computer during ascent and descent phases of the mission. During on-orbit operations (OPS-2), the SM ALERT and BACKUP C/W software will be in GPC 4, a primary flight system computer.

Panel F7 also contains the three CRT screens with which the crew can monitor the EPDC system performance. During on-orbit phases (OPS-2), EPDC parameters are displayed on the ELECTRIC display (figure 3-24), and on the SM SYS SUMM 1 (figure 3-25). During ascent and descent phases, the parameters are displayed on the BFS SM SYS SUMM 1 display (figure 3-26). For a more complete description of the CRT displays, refer to SFOM Volume 14.

TABLE 3-1.- EPDC CONTROLS AND DISPLAYS

Panel	Type	Nomenclature	Function	Remarks
R1	sw	ESS BUS SOURCE FC 1(2,3)	ON	Applies fuel cell power to essential bus 1BC (2CA,3AB).
			OFF	Removes fuel cell power from essential buses.
R1	sw	ESS BUS SOURCE MN BC (CA,AB)	ON	Applies MN bus power to essential bus 1BC (2CA, 3AB)
			OFF	Removes MN bus power from the essential buses.
R1	sw	FC/MAIN BUS A (B,C) BUS	ON	Applies fuel cell 1 (2, 3) power to MN bus A (B,C).
			OFF	Removes fuel cell power from the MN buses.
R1	flag	FC/MAIN BUS A (B,C) BUS	ON	Indicates MN bus A (B,C) is connected to fuel cell 1 (2,3).
			OFF	Indicates MN bus A (B,C) is not connected to fuel cell 1 (2,3).
R1	sw	MN BUS TIE A (B,C)	ON	Applies MNA (B,C) to tie bus.
			OFF	Removes MNA (B,C) from tie bus.
R1	flag	MN BUS TIE A (B,C)	ON	Indicates MNA (B,C) is connected to the tie bus.
			OFF	Indicates MNA (B,C) is not connected to the tie bus.

TABLE 3-1.- EPDC CONTROLS AND DISPLAYS (Continued)

Panel	Type	Nomenclature	Function	Remarks
O15	cb	MNA CONTR	For OV099/OV103 only, applies MN B power to the FC/MAIN A BUS and MN A BUS TIE switches on panel R1.	
O16	cb	MNB CONTR	For OV099/OV103 only, applies MN C power to the FC/MAIN B BUS and MN B BUS TIE switches on panel R1.	
O17	cb	MNC CONTR	*For OV099/OV103 only, applies MN A power to the FC/MAIN C BUS and MN C BUS TIE switches on panel R1.	
R1	sw	CONTROL BUS PWR MN A (B,C) RESET RESET	Resets a tripped control bus RPC.	
O13	cb	MN A CONTR	Applies essential bus power to the FC/MAIN A BUS and MN A BUS TIE switches on panel R1.	
O13	cb	MN B CONTR	Applies essential bus power to the FC/MAIN B BUS, MN B BUS TIE, PAYLOAD PRI MN B, and PAYLOAD AFT MN B switches on panel R1.	
O13	cb	MN C CONTR	Applies essential power to the FC/MAIN C BUS, MN C BUS TIE, PAYLOAD PRI MN C, PAYLOAD AFT MN C, and PAYLOAD PRI FC 3 switches on panel R1.	
R1	sw	PAYLOAD PRI MN B ON OFF	Applies MN B bus power to the PRI PL bus. Removes MN B bus power from the PRI PL bus.	

TABLE 3-1.- EPDC CONTROLS AND DISPLAYS (Continued)

Panel	Type	Nomenclature	Function	Remarks
R1	flag	PAYLOAD PRI MN B	ON	Indicates MNB is connected to the PRI PL bus.
			OFF	Indicates MNB is not connected to the PRI PL bus.
R1	sw	PAYLOAD PRI FC 3	ON	Applies fuel cell 3 power to the PRI PL bus.
			OFF	Removes fuel cell 3 power from the PRI PL bus.
R1	flag	PAYLOAD PRI FC 3	ON	Indicates fuel cell 3 is connected to the PRI PL bus.
			OFF	Indicates fuel cell 3 is not connected to the PRI PL bus.
R1	sw	PAYLOAD PRI MN C	ON	Applies MNC bus power to the PRI PL bus.
			OFF	Removes the MNC bus power from the PRI PL bus.
R1	flag	PAYLOAD PRI MN C	ON	Indicates MNC is connected to the PRI PL bus.
			OFF	Indicates MNC is not connected to the PRI PL bus.
R15	cb	CONTROL BUS AB1/2/3	Applies MNC power to CNTL AB 1/2/3	
R15	cb	CONTROL BUS BC1/2/3	Applies MNA power to CNTL BC 1/2/3	
R15	cb	CONTROL BUS CA1/2/3	Applies MN B power to CNTL CA 1/2/3.	
R1	sw	PAYLOAD AUX	ON	Applies MNA or MNB bus power to the AUX PL A/B bus,
			OFF	Removes MNA or MNB bus power from the AUX PL A/B bus.

100

TABLE 3-1.- EPDC CONTROLS AND DISPLAYS (Continued)

Panel	Type	Nomenclature	Function	Remarks
R1	sw	PAYLOAD AFT MN B	<p>ON Applies MNB bus power to the AFT PL B bus.</p> <p>OFF Removes MNB bus power from the AFT PL B bus.</p>	
R1	sw	PAYLOAD AFT MN C	<p>ON Applies MNC bus power to the AFT PL C bus.</p> <p>OFF Removes MNC bus power from the AFT PL C bus.</p>	
R1	sw	PAYLOAD CABIN	<p>MN A Applies MNA bus power to the payload-related aft flight deck panels.</p> <p>OFF No power supplied to the payload-related aft flight deck panels.</p> <p>MN B Applies MNB bus power to the payload-related aft flight deck panels.</p>	
MA73C	cb	AC 2 CABIN PL 3 ϕ	Applies AC bus 2 power to payload-related aft flight deck panels.	
MA73C	cb	AC 3 CABIN PL 3 ϕ	Applies AC bus 3 power to payload-related aft flight deck panels.	
F9	sel	DC DISPLAY SELECT	Allows selection of MN and ESS bus voltage to be displayed on the DC VOLTS meter and DC AMPS/SIG STR meter.	
F9	ind	DC/AMPS/SIG STR	Indicates MN and ESS bus on amp meter.	Range of 0 to 500 A.
F9	ind	DC VOLTS	Indicates MN and ESS bus voltage on a volt meter.	Range of 20 to 45 V.
MA73C	sw	MCA LOGIC MN A FWD 1 MID 1,3 AFT 1	<p>ON Applies MNA power to MCA main buses.</p> <p>OFF Removes MNA power from MCA main buses.</p>	

TABLE 3-1.- EPDC CONTROLS AND DISPLAYS (Continued)

Panel	Type	Nomenclature	Function	Remarks
MA73C	sw	MCA LOGIC MNB FWD 2 MID 1,2,3,4 AFT 2	ON Applies MNB power to MCA main buses. OFF Removes MNB power from MCA main buses.	
MA73C	sw	MCA LOGIC MNC FWD 3 MID 2,4, AFT 3	ON Applies MNC power to MCA main buses. OFF Removes MNC power from MCA main buses.	
MA73C	cb	MCA LOGIC MCA POWER AC 1 3 ϕ FWD 1 MID 1,3 AFT 1	Applies ac bus 1 (three phases) power to the ac bus 1 in MCAs.	
MA73C	cb	MCA LOGIC MCA POWER AC 2 3 ϕ FWD 2 MID 1,2,3,4 AFT 2	Applies ac bus 2 (three phases) power to ac bus 2 in MCAs.	
MA73C	cb	MCA LOGIC MCA POWER AC 3 3 ϕ FWD 3 MID 2,4 AFT 3	Applies ac bus 3 (three phases) power to ac bus 3 in MCAs.	
MA73C	cb	AC 1 FWD RCS VLV ϕ A, ϕ B, ϕ C	Applies ac bus 1 phase bus power to RCS ac bus 1 in FWD MCA 1.	
MA73C	cb	AC 2 FWD RCS VLV ϕ A, ϕ B, ϕ C	Applies ac bus 2 phase bus power to RCS ac bus 2 in FWD MCA 2.	
MA73C	cb	AC 3 FWD RCS VLV ϕ A, ϕ B, ϕ C	Applies ac bus 3 phase bus power to RCS ac bus 3 in FWD MCA 3.	
MA73C	cb	AC 1 AFT POD VLV GP 1 ϕ A, ϕ B, ϕ C	Applies ac bus 1 phase bus power to OMS/RCS ac bus 1 in AFT MCA 1.	

TABLE 3-1. - EPDC CONTROLS AND DISPLAYS (Continued)

Panel	Type	Nomenclature	Function	Remarks
MA73 C	cb	AC 2 AFT POD VLV GP 2 φA, φB, φC	Applies AC Bus 2 phase bus power to OMS/RCS ac bus 2 in AFT MCA 2.	
MA73 C	cb	AC 3 AFT POD VLV GP 3 φA, φB, φC	Applies AC Bus 3 phase bus power to OMS/RCS ac bus 3 in AFT MCA 3.	
MA73 C	sw	AFT POD VLV LOGIC GP 1/3	ON Applies MN A power to the OMS/RCS MNA/B bus in AFT MCA 1, and to the OMS/RCS MNC/A bus in AFT MCA 3. OFF Removes MN bus A power to above buses.	
MA73 C	sw	AFT POD VLV LOGIC GP 1/2	ON Applies MN B power to the OMS/RCS MNA/B bus in AFT MCA 1, and to the OMS/RCS MNB/C bus in AFT MCA 2. OFF Removes MN B power to above buses.	
MA73 C	sw	AFT POD VLV LOGIC GP 2/3	ON Applies MN C power to the OMS/RCS MNC/A bus in AFT MCA 1, and to the OMS/RCS MNB/C bus in AFT MCA 2. OFF Removes MN C power to above buses.	
R1	sw	INV PWR 1 (2,3)	ON Applies MNA (B,C) bus power to inverters 1 (2,3). OFF Removes MNA (B,C) bus power from inverters 1 (2,3).	

TABLE 3-1.- EPDC CONTROLS AND DISPLAYS (Continued)

Panel	Type	Nomenclature	Function	Remarks	
R1	flag	INV PWR 1 (2,3)	ON OFF	Indicates MNA (B,C) bus power is connected to inverters 1 (2,3). Indicates MNA (B,C) bus power is not connected to inverters 1 (2,3).	
R1	sw	INV/AC BUS 1 (2,3)	ON OFF	Applies inverter 1 (2,3) power to ac bus 1 (2,3). Removes inverter 1 (2,3) power from ac bus 1 (2,3).	
R1	flag	INV/AC BUS 1 (2,3)	ON OFF	Indicates inverter 1 (2,3) is connected to ac bus 1 (2,3). Indicates inverter 1 (2,3) is not connected to ac bus 1 (2,3).	
R1	cb	AC CONTR AC 1 ϕ A,B,C AC 2 ϕ A,B,C AC 3 ϕ A,B,C		Connects ESS bus power to the INV PWR and INV/AC BUS switches.	
R1	sw	AC BUS 1 (2,3) SNSR AUTO TRIP		Allows the ac bus sensor to disconnect AC ϕ A, ϕ B, or ϕ C bus from its inverter for an overload or overvoltage condition and gives a primary and backup C/W alarm for an over/under voltage and overload.	
		OFF		Removes power from the ac bus sensor, however, still gives a backup C/W alarm for an ac failure of any type.	
		MONITOR		The ac bus sensor does not have the disconnect ability but still gives a primary and backup C/W alarm for over/under voltage or overload.	

TABLE 3-1.- EPDC CONTROLS AND DISPLAYS (Concluded)

Panel	Type	Nomenclature	Function	Remarks
O13	cb	AC 1 (2,3) SNSR	Applies ESS bus power to the AC BUS SNSR switch and the INV/AC BUS flag.	
F4	sel	AC DISPLAY SELECT	Allows the selection of a particular phase of one of the three ac buses to be displayed on the AC VOLTS meter.	
F9	ind	AC VOLTS	Displays the voltage of one phase of a particular ac bus on a voltmeter.	Range of 90-130 V ac.

**BACKUP CW
ALARM**

CRT name	Units	Lower limit	Upper limit	Fault message
DC VOLTS MN A	V dc	26.4		S67 MAIN BUS V A ↓ 4 HH:MM:SS
DC VOLTS MN B	V dc	26.4		S67 MAIN BUS V B ↓ 4 HH:MM:SS
DC VOLTS MN C	V dc	26.4		S67 MAIN BUS V C ↓ 4 HH:MM:SS

**SM
ALERT**

CRT name	Units	Lower limit	Upper limit	Fault message
DC VOLTS MN A	V dc	27.0	32.0	S67 MAIN BUS V A 4 HH:MM:SS
DC VOLTS MN B	V dc	27.0	32.0	S67 MAIN BUS V B 4 HH:MM:SS
DC VOLTS MN C	V dc	27.0	32.0	S67 MAIN BUS V C 4 HH:MM:SS
DC VOLTS ESS 1,2,3	V dc	25.0		S67 CNTL/ESS V 4 HH:MM:SS
CNTL AB 1,2,3	V dc	24.5		S67 CNTL/ESS V 4 HH:MM:SS
CNTL BC 1,2,3	V dc	24.5		S67 CNTL/ESS V 4 HH:MM:SS
CNTL CA 1,2,3	V dc	24.5		S67 CNTL/ESS V 4 HH:MM:SS
DC VOLTS FC 1,2,3	V dc	27.5	32.5	S69 FUEL CELL 4 HH:MM:SS
AMPS FC 1,2,3	amp dc	54.0	360.0	S69 FUEL CELL 4 HH:MM:SS

Figure 3-20.- SM OPS 2 class 2 and 3 alarms for dc system.

**BACKUP C/W
ALARM**

CRT name	Units	Lower limit	Upper limit	Fault message		
ACV ϕ A 1	V ac	108	123	S67 AC VOLT 1	↓ or ↑	4 HH:MM:SS
ACV ϕ A 2	V ac	108	123	S67 AC VOLT 2	↓ or ↑	4 HH:MM:SS
ACV ϕ A 3	V ac	108	123	S67 AC VOLT 3	↓ or ↑	4 HH:MM:SS
ACV ϕ B 1	V ac	108	123	S67 AC VOLT 1	↓ or ↑	4 HH:MM:SS
ACV ϕ B 2	V ac	108	123	S67 AC VOLT 2	↓ or ↑	4 HH:MM:SS
ACV ϕ B 3	V ac	108	123	S67 AC VOLT 3	↓ or ↑	4 HH:MM:SS
ACV ϕ C 1	V ac	108	123	S67 AC VOLT 1	↓ or ↑	4 HH:MM:SS
ACV ϕ C 2	V ac	108	123	S67 AC VOLT 2	↓ or ↑	4 HH:MM:SS
ACV ϕ C 3	V ac	108	123	S67 AC VOLT 3	↓ or ↑	4 HH:MM:SS
OVLD 1	event	OVERLOAD		S67 AC OVLD 1	↓	4 HH:MM:SS
OVLD 2	event	OVERLOAD		S67 AC OVLD 2	↓	4 HH:MM:SS
OVLD 3	event	OVERLOAD		S67 AC OVLD 3	↓	4 HH:MM:SS

SM
ALERTS

NONE

Figure 3-21.- SM OPS 2 class 2 alarms for ac system.

**BACKUP CW
ALARM**

CRT name	Units	Lower limit	Upper limit	Fault message
DC VOLTS MN A	V dc	26.4		SM1 MAIN BUS V A ↓ 5 HH:MM:SS
DC VOLTS MN B	V dc	26.4		SM1 MAIN BUS V B ↓ 5 HH:MM:SS
DC VOLTS MN C	V dc	26.4		SM1 MAIN BUS V C ↓ 5 HH:MM:SS

**SM
ALERT**

CRT name	Units	Lower limit	Upper limit	Fault message
DC VOLTS MN A	V dc	27.0	32.0	SM1 MAIN BUS V A 4 HH:MM:SS
DC VOLTS MN B	V dc	27.0	32.0	SM1 MAIN BUS V B 4 HH:MM:SS
DC VOLTS MN C	V dc	27.0	32.0	SM1 MAIN BUS V C 4 HH:MM:SS
DC VOLTS ESS	1,2,3 V dc	25.0		SM1 CNTL/ESS V 4 HH:MM:SS
CNTL AB	1,2,3 V dc	24.5		SM1 CNTL/ESS V 4 HH:MM:SS
CNTL BC	1,2,3 V dc	24.5		SM1 CNTL/ESS V 4 HH:MM:SS
CNTL CA	1,2,3 V dc	24.5		SM1 CNTL/ESS V 4 HH:MM:SS
DC VOLTS FC	1,2,3 V dc	27.5	32.5	SM1 FUEL CELL 4 HH:MM:SS
AMPS FC	1,2,3 amp dc	54.0	360.0	SM1 FUEL CELL 4 HH:MM:SS

Figure 3-22.- BFS class 2 and 3 alarms for dc system.

BACKUP CW
ALARM (R)

CRT name	Units	Lower limit	Upper limit	Fault message		
ACV ϕ A 1	V ac	108	123	SM1 AC VOLT 1	↓ or ↑	5 HH:MM:SS
ACV ϕ A 2	V ac	108	123	SM1 AC VOLT 2	↓ or ↑	5 HH:MM:SS
ACV ϕ A 3	V ac	108	123	SM1 AC VOLT 3	↓ or ↑	5 HH:MM:SS
ACV ϕ B 1	V ac	108	123	SM1 AC VOLT 1	↓ or ↑	5 HH:MM:SS
ACV ϕ B 2	V ac	108	123	SM1 AC VOLT 2	↓ or ↑	5 HH:MM:SS
ACV ϕ B 3	V ac	108	123	SM1 AC VOLT 3	↓ or ↑	5 HH:MM:SS
ACV ϕ C 1	V ac	108	123	SM1 AC VOLT 1	↓ or ↑	5 HH:MM:SS
ACV ϕ C 2	V ac	108	123	SM1 AC VOLT 2	↓ or ↑	5 HH:MM:SS
ACV ϕ C 3	V ac	108	123	SM1 AC VOLT 3	↓ or ↑	5 HH:MM:SS
OVLD 1	event	OVERLOAD		SM1 AC OVLD 1	↓	5 HH:MM:SS
OVLD 2	event	OVERLOAD		SM1 AC OVLD 2	↓	5 HH:MM:SS
OVLD 3	event	OVERLOAD		SM1 AC OVLD 3	↓	5 HH:MM:SS

SM
ALERTS

NONE

Figure 3-23.- BFS class 2 alarms for ac system.

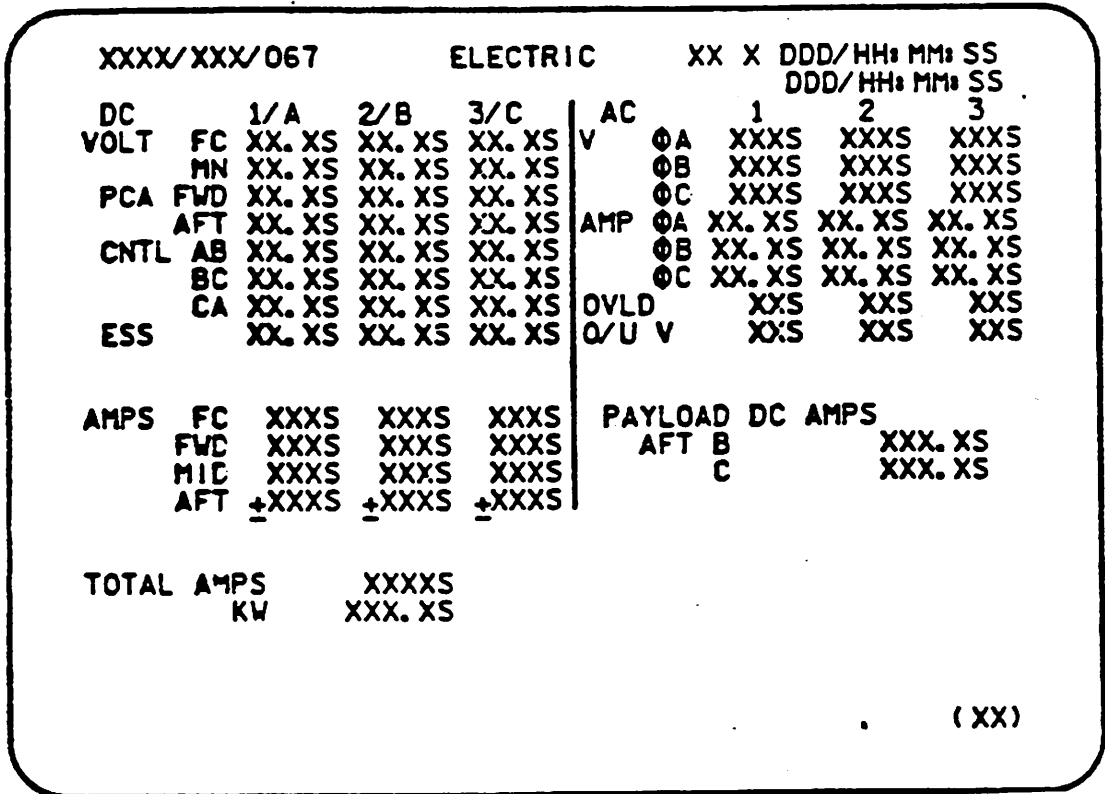


Figure 3-24.- SM OPS 2 ELECTRIC CRT display.

1439. ART, 1

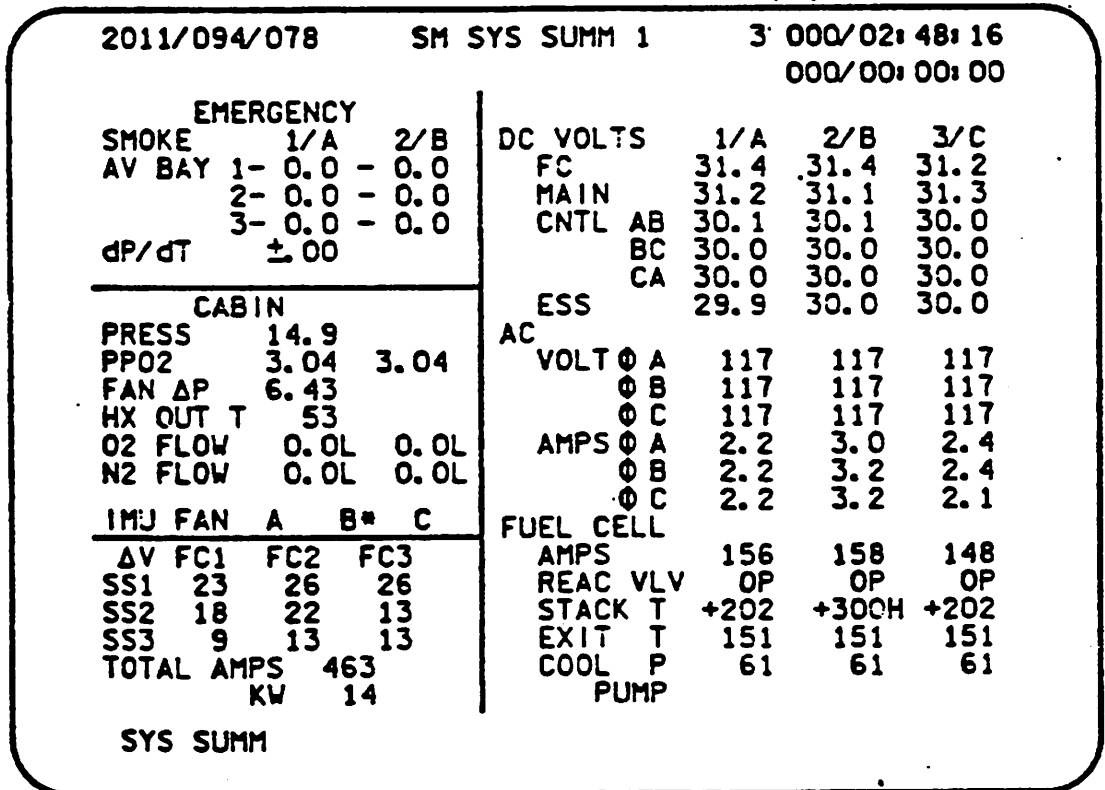


Figure 3-25.- EPDC parameters on SM OPS 2 SYS SUMM 1 CRT display.

1436. ART, 4

2011/094/078

SM SYS SUMM 1

3 000/02: 48: 16

BFS 000/00: 00: 00

EMERGENCY		
SMOKE	1/A	2/B
AV BAY 1-	0.0	0.0
	2-	0.0
	3-	0.0
dP/dT	±.00	
	BU ±.XXS	

CABIN		
PRESS	14.9	
PPO2	3.04	3.04
FAN ΔP	6.43	
HX OUT T	53	
O2 FLOW	0.0L	0.0L
N2 FLOW	0.0L	0.0L

IMU FAN	A	B*	C
ΔV FC1	FC2	FC3	
SS1	23	26	26
SS2	18	22	13
SS3	9	13	13
TOTAL AMPS	463		
	KW	14	

DC VOLTS	1/A	2/B	3/C
FC	31.4	31.4	31.2
MAIN	31.2	31.1	31.3
CNTL AB	30.1	30.1	30.0
BC	30.0	30.0	30.0
CA	30.0	30.0	30.0
ESS	29.9	30.0	30.0

AC			
VOLT @ A	117	117	117
@ B	117	117	117
@ C	117	117	117
AMPS @ A	2.2	3.0	2.4
@ B	2.2	3.2	2.4
@ C	2.2	3.2	2.1

FUEL CELL			
AMPS	156	158	148
REAC VLV	OP	OP	OP
STACK T	+202	+202	+202
EXIT T	151	151	151
COOL P	61	61	61
PUMP			

SYS SUMM

1436. ART, 5

Figure 3-26.- EPDC parameters on BFS SM SYS SUMM 1 CRT display.

3.5 EPDC Performance, Limitations, and Capabilities

3.5.1 Bus Voltage Limits

● Minimum steady state (all dc buses)	24 V dc
● Max steady state	
Main and control buses	32 V dc
Essential buses	38.5 V dc
● Nominal values for	
Fuel cell voltage	29 – 32 V dc
Main bus voltage	29 – 32 V dc
Forward power controllers voltage	29 – 32 V dc
Aft power controllers voltage	29 – 32 V dc
Control bus voltages	28 – 30 V dc
Essential bus voltages	28 – 30 V dc
Fuel cell current	54 – 350 A
Control bus current	5 A
Essential bus current	15 A
AC bus 1,2,3 phase A,B,C voltage	116 – 120 V ac
AC bus 1,2,3 phase A,B,C current	
continuously	6.4A
for 30 min	9.6 A
for 2 min	12.8 A

3.5.2 Design Features That Enhance EPDC System Reliability

- Fail operational/fail safe
 - One fuel cell failure does not degrade reliability of any other subsystem
- Three independent distribution systems
- Any main bus can be connected to any fuel cell through bus ties
- Three independent essential buses
 - Each powered by three sources
 - Each hardwired to a fuel cell (through a manual switch)
 - Computers powered by essential buses
 - Essential buses power emergency functions and critical systems
- Nine control buses for operating switching devices
 - Each control bus powered by two main buses (for OV102)
 - Each control bus powered by three main buses

3.5.3 Remote Switching Devices

The types of remote switching devices used on the Orbiter are hybrid circuit drivers, remote power controllers (RPC), relays, power contactors, and hybrid relays. The type of remote switching device used by a load is dependent mainly upon the power requirements of a load.

Hybrid circuit drivers are solid state switching devices (no mechanical parts) used as logic switches and for low power electrical loads (less than 5 A). When used as a logic switch, several control inputs are required to turn on a load. Hybrid circuit drivers are located in the

forward and aft load control assemblies, mid power control assemblies, and in the motor control assemblies. They are used only as logic switches in the motor control assemblies. They are current-protected by internal fuses.

RPCs are solid state switching devices used for loads requiring current in a range of 3 to 20 A. They are located in the forward, mid, and aft power control assemblies. They are current-protected by fuses and also have a current limiting capability whereby they 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, which removes the output current. To restore power to the load, the RPC must be reset, which is done by cycling the control switch. If multiple control inputs are required before an RPC is turned on, hybrid circuit drivers usually will be used as the logic switch, which then drives the control input of the RPC.

For loads larger than 20 A, relays are used. They range from 12 to 135 A, and are located in the power control assemblies and motor control assemblies.

For loads larger than 135 A, power contactors are used and are rated at 500 A. They are motor-operated switches and are located in the main distribution assemblies and aft power control assemblies. They are used only to connect one bus to another and are not used by any subsystem loads.

Hybrid relays are four-pole, nonlatching relays with a solid state logic circuit for opening/closing the contacts and are used in the forward, mid, and aft motor control assemblies. They are used to switch three-phase ac power to motors and are rated at 4 A inductive.