

Space Program Operations Contract

Electrical Power System Training Manual

EPS 21002

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Final Version

**This document has been reviewed and updated.
No subsequent updates to this document are anticipated or required due to the
approaching shuttle program closure.**

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Electrical Power System Training Manual EPS 21002

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<u>Page No.</u>	<u>Change No.</u>
Foreword	Rev. A
Preface	Rev. A
i - iv	Rev. A
1-1 – 1-2	Rev. A
2-1 – 2-22	Rev. A
3-1 – 3-44	Rev. A
4-1 – 4-36	Rev. A
A-1 – A-2	Rev. A
B-1 – B-6	Rev. A

FOREWORD

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A Training Materials Evaluation is included at the end of this document. Inputs on this sheet will be used to evaluate the lesson material. You do not need to sign the sheet.

PREFACE

This training manual is designed to furnish you with the operational knowledge needed by a crewmember to successfully interface with the Electrical Power System (EPS). The training manual does not contain the actual Flight Data File (FDF) procedures but explains how the crew interfaces with the EPS to accomplish the procedures.

This training manual is divided into five sections. Section 1 (Introduction) is a brief overview of the EPS and of the subsystems that are associated with the EPS. Section 2 is a detailed description of the Power Reactant Storage and Distribution (PRSD) subsystem. The Fuel Cell (FC) subsystem is described in Section 3 and the Electrical Power Distribution and Control (EPDC) subsystem in Section 4. Section 5 describes the function and panel location of the switches, circuit breakers, and meters associated with the EPS.

Begin each section by reading the objectives and the learning material. If you are already familiar with the subject matter, skip to the section exercises. If the material is new to you, be sure to read all the text carefully before you complete the exercises. The purpose of the exercises is to emphasize the information you should have learned from reading the associated section.

Before progressing to another section, you should understand the correct answers to each of the exercises.

CONTENTS

Section	Page
1.0 INTRODUCTION	1-1
2.0 POWER REACTANT STORAGE AND DISTRIBUTION SUBSYSTEM ...	2-1
2.1 OBJECTIVES.....	2-1
2.2 ABBREVIATIONS	2-1
2.2.1 PRSD Overview	2-1
2.2.2 Cryo Storage.....	2-2
2.2.3 Pressure Maintenance	2-4
2.2.4 Tank Heaters	2-4
2.2.5 Heater Controller Logic	2-5
2.2.6 Fluid Interface	2-7
2.3 CRYO DISTRIBUTION	2-8
2.3.1 Manifold Plumbing.....	2-9
2.4 CREW INTERFACES/CONTROLS.....	2-10
2.4.1 Tank Controls.....	2-11
2.4.2 Tank Instrumentation	2-12
2.5 NOMINAL OPERATIONS	2-18
2.5.1 Prelaunch.....	2-18
2.5.2 Ascent.....	2-19
2.5.3 Orbit	2-19
2.5.4 Entry.....	2-20
3.0 FUEL CELL SUBSYSTEM.....	3-1
3.1 OBJECTIVES.....	3-1
3.2 FUEL CELL SUBSYSTEM OVERVIEW.....	3-1
3.3 FUEL CELL STACK.....	3-2
3.4 FUEL CELL ACCESSORY SECTION.....	3-4
3.4.1 Cyro Supply	3-6
3.4.2 Water Removal Loop	3-8
3.4.3 Purge System	3-12
3.4.4 Coolant Loop.....	3-14
3.4.5 Cell Performance Monitor (CPM)	3-16
3.4.6 Electrical Control Unit.....	3-17
3.5 FUEL CELL CREW INTERFACES/CONTROLS.....	3-17
3.5.1 Fuel Cell Controls.....	3-17
3.5.2 Fuel Cell Instrumentation	3-24
3.5.3 Crew Displays	3-35
3.5.4 Nominal Operations	3-40

Section	Page
4.0 ELECTRICAL POWER DISTRIBUTION AND CONTROL	
SUBSYSTEM	4-1
4.1 OBJECTIVES.....	4-1
4.2 EPDC SUBSYSTEM OVERVIEW.....	4-1
4.3 ELECTRICAL CONTROL ASSEMBLIES.....	4-2
4.4 REMOTE SWITCHING DEVICES.....	4-3
4.5 ELECTRICAL BUSES.....	4-5
4.5.1 Main Buses	4-6
4.5.2 Tie Bus.....	4-8
4.5.3 Essential Buses	4-9
4.5.4 Control Buses	4-11
4.5.5 AC Buses.....	4-12
4.5.6 AC Bus Sensors.....	4-13
4.5.7 Payload Buses	4-14
4.6 CREW INTERFACES/CONTROLS.....	4-15
4.6.1 EPDC Controls.....	4-15
4.6.2 EPDC Instrumentation	4-25
4.6.3 EPDC Displays.....	4-28
4.7 NOMINAL OPERATIONS	4-33
4.7.1 Ascent.....	4-33
4.7.2 Orbit	4-33
4.7.3 Entry.....	4-33
4.7.4 Postlanding	4-33
 Appendix	
A ACRONYMS AND ABBREVIATIONS	A-1
B ANSWERS	B-1

TABLES

Table		Page
2-1	Cryo tank pressure control limits	2-4
2-2	GSE supply pressures	2-10
2-3	Cryo displays	2-15
3-1	Hydrogen pump/water separator status.....	3-26
3-2	Fuel cell displays	3-35
4-1	Electrical control assemblies	4-2
4-2	Electrical buses	4-5
4-3	Alternating current bus sensor annunciation limits	4-14
4-4	Payload buses	4-14
4-5	EPDC displays.....	4-28

FIGURES

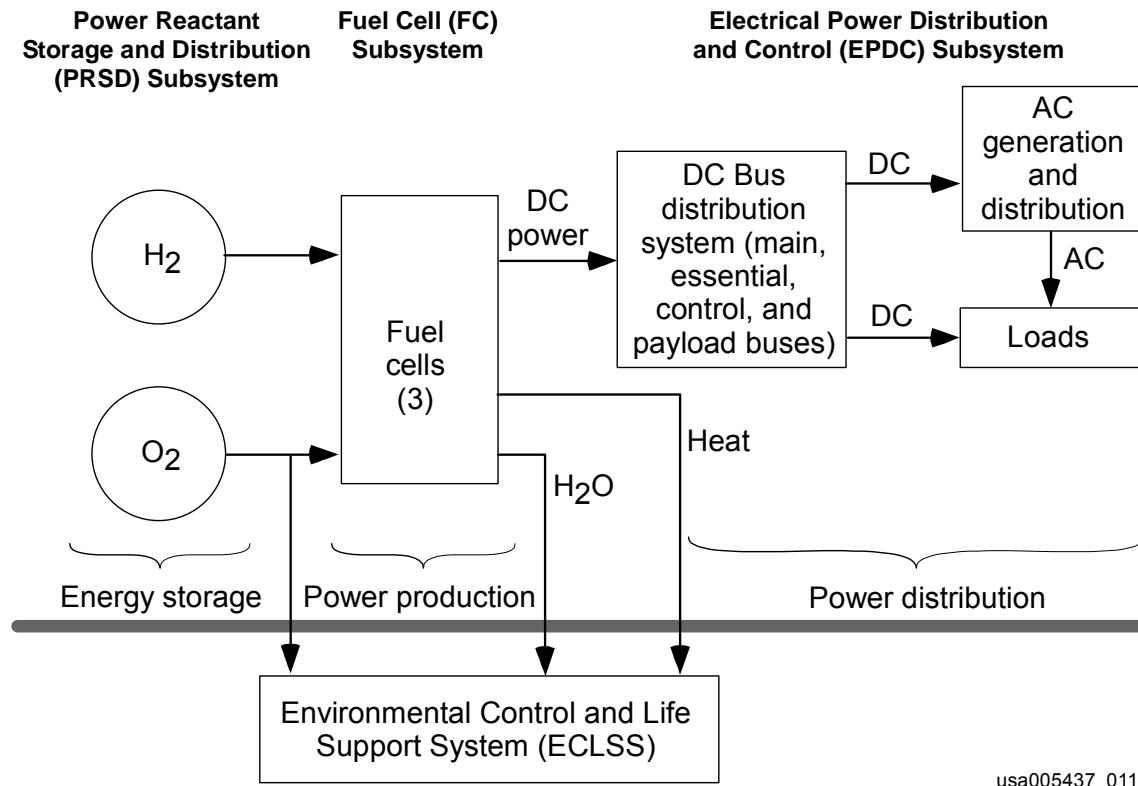
Figure

1-1	Electrical power system functional overview.....	1-1
2-1	Cryo tank locations	2-2
2-2	Cryo tanks cryogenic storage	2-3
2-3	Heater controller logic.....	2-5
2-4	O ₂ heater current sensors.....	2-6
2-5	Cryo tank fluid interface	2-7
2-6	Cryo distribution overview.....	2-8
2-7	O ₂ heater current sensor TEST/RESET switch	2-11
2-8	H ₂ tank instrumentation	2-12
2-9	O ₂ tank instrumentation	2-13
2-10	Cryo manifold controls and instrumentation	2-14
2-11	PASS/BFS SM SYS SUMM 2 display	2-16
2-12	PASS SM SPEC 68.....	2-17
3-1	Fuel cell location	3-1
3-2	Fuel cell stack.....	3-2
3-3	Electrochemical cell	3-3
3-4	Fuel cell accessory section.....	3-5
3-5	Cryo supply.....	3-7
3-6	Water removal loop	3-9
3-7	Fuel cell water removal paths	3-11
3-8	Fuel cell purge system.....	3-13
3-9	Coolant loop	3-15
3-10	Fuel cell performance monitor	3-16

Figure	Page
3-11 Fuel cell reac valve switches	3-18
3-12 Fuel cell ECU.....	3-19
3-13 Fuel cell purge switches	3-21
3-14 Water line heaters	3-23
3-15 Cryo supply instrumentation	3-25
3-16 Water loop instrumentation.....	3-27
3-17 Water removal path temperature and pH instrumentation	3-29
3-18 Purge system instrumentation	3-31
3-19 Coolant loop instrumentation.....	3-33
3-20 Fuel cell ECU instrumentation	3-34
3-21 PASS SM SYS SUMM 1 display	3-36
3-22 BFS SM SYS SUMM 1 display.....	3-37
3-23 SM SPEC 69 FUEL CELLS display.....	3-39
3-24 Fuel cell performance plot	3-42
4-1 Power contactor.....	4-3
4-2 Remote power controller	4-3
4-3 Relays	4-4
4-4 Hybrid drivers	4-4
4-5 Main bus distribution.....	4-6
4-6 Tie bus.....	4-8
4-7 Essential bus power	4-9
4-8 Essential bus distribution	4-10
4-9 Control bus power sources	4-11
4-10 Alternating current voltage sine wave.....	4-12
4-11 Three-phase AC bus	4-12
4-12 Three-phase voltage vs. time	4-13
4-13 Main bus controls	4-16
4-14 Essential bus controls.....	4-17
4-15 Control bus controls.....	4-19
4-16 AC bus controls	4-21
4-17 Primary payload bus controls	4-22
4-18 Auxiliary payload bus controls	4-23
4-19 Aft payload bus controls	4-23
4-20 Cabin payload bus controls	4-24
4-21 Alternating current payload buses	4-24
4-22 Main bus instrumentation	4-25
4-23 Essential bus instrumentation.....	4-26
4-24 Control bus instrumentation.....	4-26
4-25 Alternating current bus instrumentation	4-27
4-26 BFS SM SYS SUMM 1	4-29
4-27 PASS SM SYS SUMM 1	4-30
4-28 PASS SM SPEC 67	4-32

1.0 INTRODUCTION

The Electrical Power System (EPS) consists of the equipment and reactants that produce and distribute electrical power, fulfilling all of the orbiter, External Tank (ET), Solid Rocket Booster (SRB), and payload power requirements when not connected to Ground Support Equipment (GSE). The operation of the EPS can be divided into three functions: (1) energy storage, (2) power production, and (3) power distribution. Each of these functions is supplied by a separate subsystem as shown in Figure 1-1.



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Figure 1-1. Electrical power system functional overview

The Power Reactant Storage and Distribution (PRSD) subsystem provides energy storage. It stores energy in chemical form as cryogenic hydrogen (H_2) and oxygen (O_2) and supplies these reactants for use in power production. The PRSD subsystem also supplies O_2 to the Environmental Control and Life Support System (ECLSS) for crew respiration.

The Fuel Cell (FC) subsystem provides power production. Three fuel cells consume the O_2 and the H_2 provided by the PRSD subsystem and, through chemical reactions, produce Direct Current (DC) electricity. Heat and potable water (H_2O), which are byproducts of the reactions, are sent to the ECLSS.

The Electrical Power Distribution and Control (EPDC) subsystem provides power distribution. This subsystem distributes the DC power generated by the fuel cells to DC loads and generates and distributes Alternating Current (AC) power to AC loads.

Each of these subsystems is described in more detail in the following sections of this workbook.

2.0 POWER REACTANT STORAGE AND DISTRIBUTION SUBSYSTEM

2.1 OBJECTIVES

The student should be prepared to accomplish the following tasks as a result of studying this section of the workbook.

- a. Describe the purpose of the PRSD subsystem.
- b. Recognize where the PRSD tanks are located.
- c. Match PRSD subsystem components to their functions.
- d. Understand nominal operations of the PRSD subsystem.

2.2 ABBREVIATIONS

Abbreviations used in the graphics of this section are listed below. These abbreviations are also used in subsequent training materials and shuttle Flight Data File (FDF).

P, Press - Pressure	SNSR - Sensor
T, Temp - Temperature	CUR - Current
TK - Tank	QTY - Quantity
vlv - Valve	HTR - Heater
MANF - Manifold	PNL - Panel
REAC - Reactant	PSIA - Pounds/Square Inch Absolute
rlf - Relief	PSIG - Pounds/Square Inch Gage
GSE - Ground Support Equipment	ASSY - Assembly
	Sys - System

2.2.1 PRSD Overview

The accepted terminology for the PRSD subsystem and the reactants is "cryo." Crews, instructors, and flight controllers refer to the cryo system, cryo tanks, etc. The cryo subsystem has two major functions. First, it stores the cryo, H₂, and O₂. Second, it distributes H₂ and O₂ to the three fuel cells for power production and distributes O₂ to the ECLSS for crew respiration.

2.2.2 Cryo Storage

The cryo is stored in spherical tanks in the payload bay of the orbiter under the payload bay liner (Figure 2-1). The tanks are installed in sets consisting of one hydrogen tank and one oxygen tank each. Each vehicle has five tank sets installed. Each tank set provides enough cryo for about two mission days so five tank sets can support a normal 9 to 10 day mission.

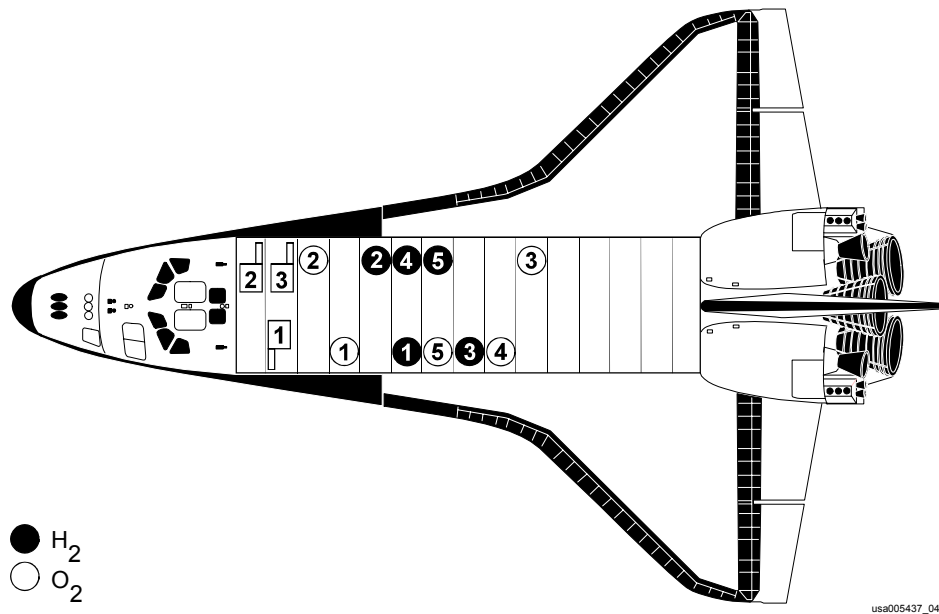
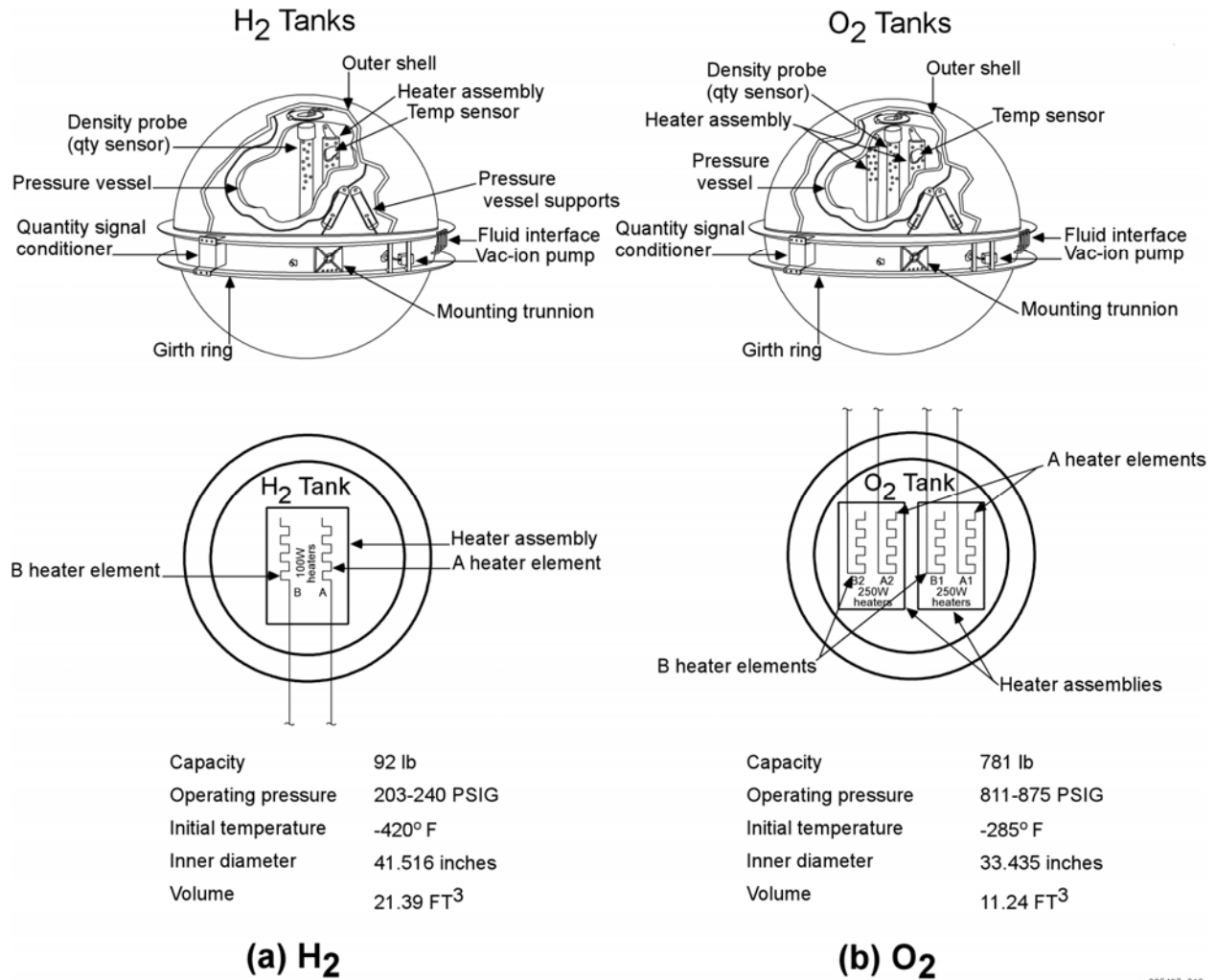


Figure 2-1. Cryo tank locations

The tanks (Figure 2-2) are designed to achieve three major functions: (1) storing cryo at cryogenic temperatures, (2) maintaining cryo at high pressures, and (3) providing a fluid interface for filling the tanks and removal of cryo from the tanks. Each of these major functions is discussed separately in the following sections.



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Figure 2-2. Cryo tanks cryogenic storage

Cryo is stored at cryogenic temperatures of -420° F for H₂ and -285° F for O₂. The tanks are designed to minimize heat leak into the tank to maintain these temperatures for extended periods. As Figure 2-2 shows, the tanks are double walled. They consist of an inner pressure vessel and an outer shell. The volume between these shells is evacuated to minimize convective heat transfer between the shells. A radiation shield is installed between the shells to prevent radiant heat transfer. Without these design features, heat leaking into the tank would cause the cryo pressure to increase.

2.2.3 Pressure Maintenance

Cryo pressure is kept within the ranges shown in Table 2-1. At these pressures, cryo stays in a fluid state (known as the supercritical state) even as cryo temperatures increase and densities decrease. Cryo is forced out of the tanks into the distribution system by the tank pressures. As cryo is removed from a tank, the pressure decreases. To maintain the pressure, heaters in the tank warm the cryo until the pressure is restored. Heater cycling is controlled automatically to maintain tank pressures.

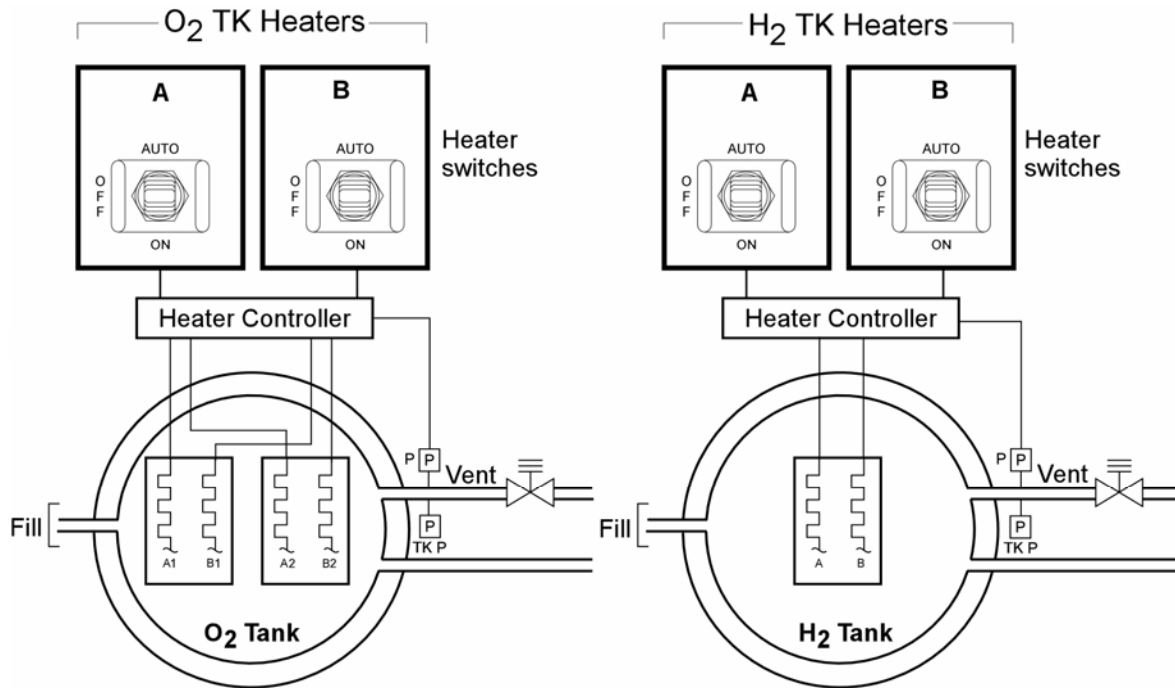
Table 2-1. Cryo tank pressure control limits

Tank	Low pressure control limit, psia	High pressure control limit, psia
O ₂ tanks 1 and 2	811 ± 8	846 ± 8
O ₂ tanks other than 1 and 2	840 ± 8	875 ± 8
H ₂ tanks 1 and 2	203 ± 3	223 ± 3
H ₂ tanks other than 1 and 2	220 ± 3	240 ± 3

2.2.4 Tank Heaters

As shown in Figure 2-3, there are two heater assemblies in each O₂ tank and one heater assembly in each H₂ tank. Each heater assembly contains two heater elements, an A element and a B element. The elements on the H₂ heater assembly supply 100 W of heating each, for a total of 200 W of heating per tank. The elements on the O₂ heater assemblies supply 250 W of heating each, for 500 W of heating per heater assembly and a total of 1000 W of heating per tank. The greater heater power for the O₂ tanks is necessary because of the higher mass of stored O₂ as compared to H₂.

The A and B heaters for each tank can be selected individually with onboard switches. If the A heater for an O₂ tank is activated, the A element on each heater assembly will be powered. If the B heater is activated, the B element on each heater assembly will be powered.



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Figure 2-3. Heater controller logic

2.2.5 Heater Controller Logic

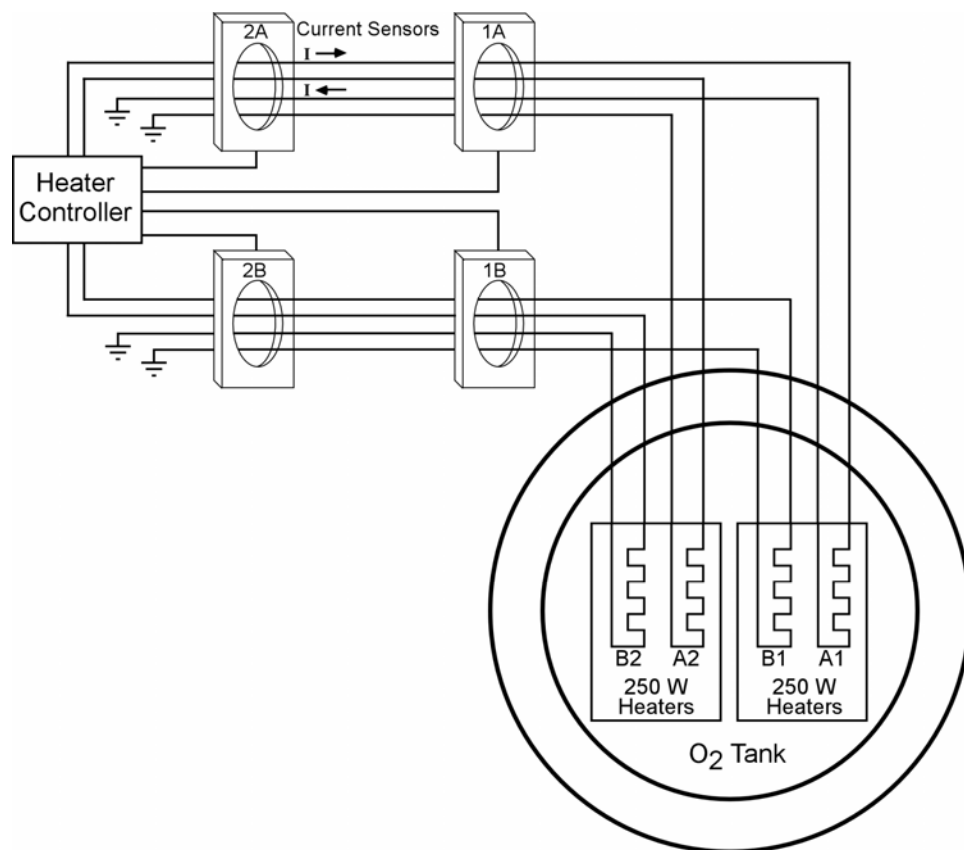
To maintain tank pressures, heater controllers turn the tank heaters on and off, based on switch position. The controllers read the cryo pressure from the "P" pressure transducer on the tank vent line (Figure 2-3). The P pressure transducer is commonly called control P.

The heater controllers have three modes: OFF, ON, and AUTO. These modes are selected individually for the A and B heaters. In the OFF mode, the heaters are turned off and will not come on to maintain tank pressure. In the ON mode, the heaters are turned on continuously and will heat the cryo until the heater switch is taken to OFF or AUTO. The ON mode is not normally used. In the AUTO mode, the heaters turn on when the pressure reaches the low limit shown in Table 2-1 and turn off when the high limit is reached.

The heater control logic has one extra mode of operation, called dual-mode or paired-mode operation, that controls the pressures of pairs of O₂ or H₂ tanks. For paired mode, if at least one heater of each tank in a pair is selected to AUTO, the heaters that are in AUTO will be cycled simultaneously. When the pressure in both tanks falls below the low limit, the heaters that are in AUTO will be turned on. When the pressure in either tank reaches the high limit, the heaters that are in AUTO will be turned off. This prevents over pressurization of the tank that reaches the high limit first. The tanks that can operate in paired mode are 1 with 2 and 3 with 4.

A short circuit in an O₂ tank heater could be disastrous because of the flammable environment. To avoid this problem, the orbiter has fault current sensors for the O₂ tank heaters to detect short circuits and automatically shut off the heater power. There are no current sensors for the H₂ heaters because a short circuit in an H₂ tank heater does not present a flammability hazard.

The wires that go to the heaters and the wires that return from the heaters to ground are routed through current sensors to detect a short circuit (Figure 2-4). Normally, the current going to the heater is the same as the current returning from the heater to ground. In this situation, the currents are equal and there is no net current through the sensors. If a short circuit develops, the current going to the heater will be different from the current returning from the heater, and there will be a net current through the sensors. If a net current of 0.9 amps is detected for greater than 5 milliseconds, the sensors will send a trip signal to the heater logic to turn the heater off. As Figure 2-4 shows, there are two sensors for the A heaters and two sensors for the B heaters. Having separate sensors on the A and B heaters allows one heater to be tripped off while the other heater remains powered so that use of the tank can continue.

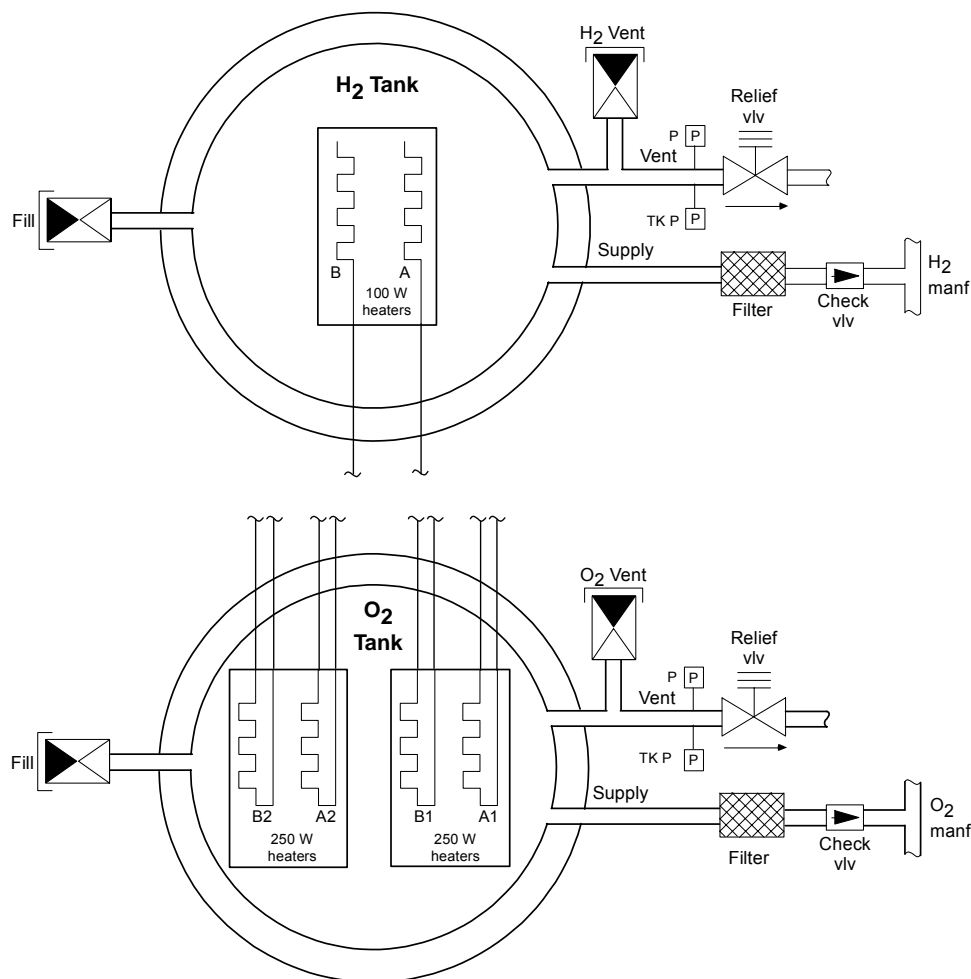


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Figure 2-4. O₂ heater current sensors

2.2.6 Fluid Interface

There are three fluid interfaces to the tanks (Figure 2-5): a fill line, a vent line, and a supply line. Cryo is loaded before flight through the fill line. During the fill procedure, the vent line is open to allow vapors to escape. After filling is complete, the fill and vent connections are closed. The tank vent line is also connected to a relief valve that will open to relieve excess pressure in the tank overboard. The supply line is used to transport the cryo to a common manifold. The O₂ and H₂ manifolds supply cryo to the fuel cells. A filter removes contaminant particles from the cryo. Check valves allow cryo to flow from the tanks into the manifold, but not from the manifold into the tanks, preventing a leak in one tank from draining the other tanks.

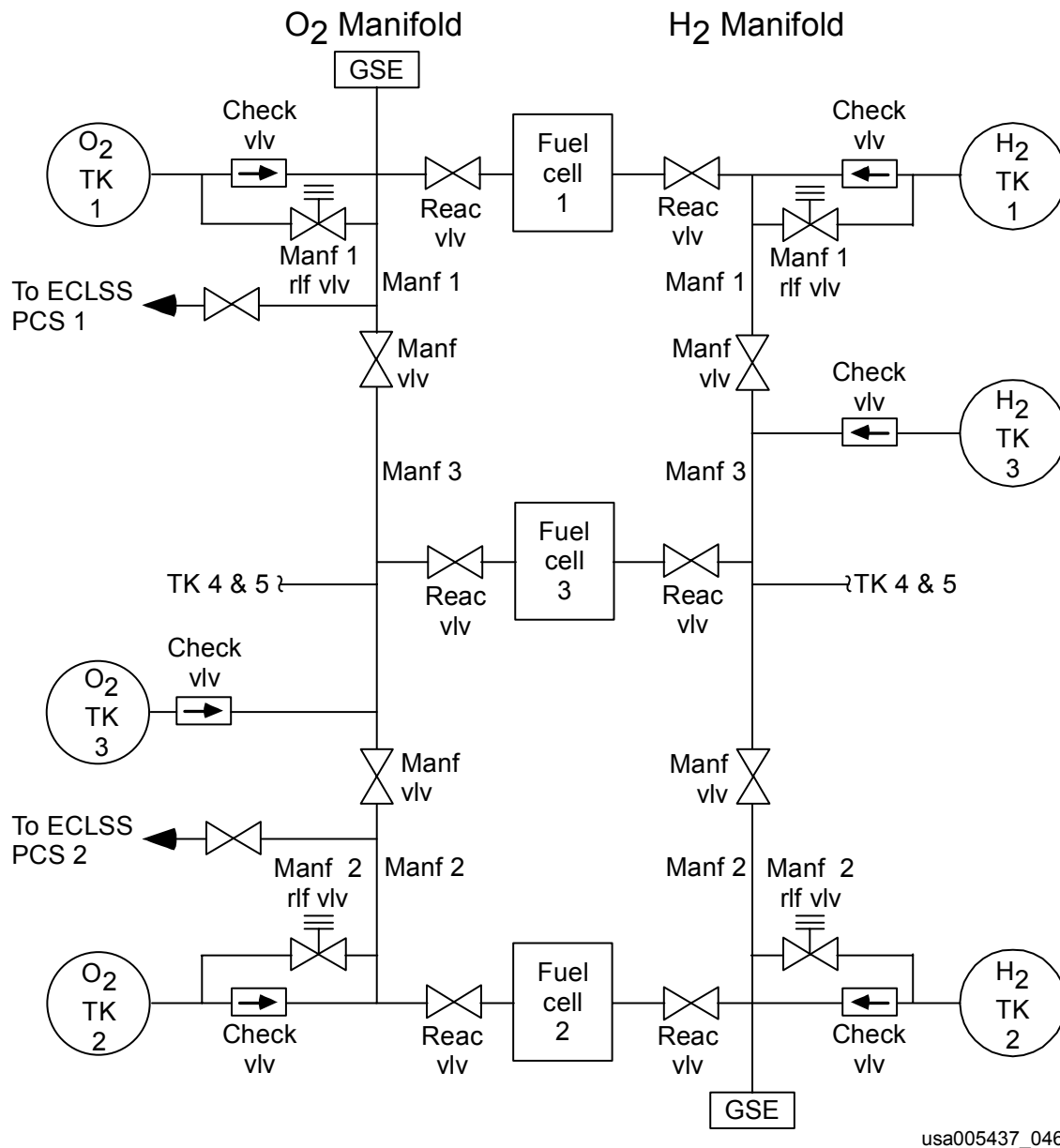


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Figure 2-5. Cryo tank fluid interface

2.3 CRYO DISTRIBUTION

Cryo distribution is responsible for transferring cryo from the tanks to the fuel cells and for supplying O₂ to the ECLSS (Figure 2-6). The H₂ tanks are connected to an H₂ manifold, and the O₂ tanks are connected to an O₂ manifold. Both manifolds are capable of feeding cryo to all three fuel cells. The O₂ manifold also supplies O₂ to the ECLSS Pressure Control System (PCS). The following subsections describe how the tanks are plumbed into the manifolds and how the manifolds are plumbed to the fuel cells and the ECLSS.



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Figure 2-6. Cryo distribution overview

2.3.1 Manifold Plumbing

Each manifold has two manifold valves to isolate parts of the manifold, three reactant (reac) valves connecting the manifolds to the fuel cells, and two relief valves that can relieve excess pressure in the manifolds back into tanks 1 and 2. The manifolds also contain connections to allow cryo to be supplied by GSE while the orbiter is on the launch pad.

2.3.1.1 Manifold Valves

Each manifold contains two manifold valves that can be closed to isolate parts of the manifold. The valve closest to tank 1, known as manifold valve 1, isolates the part of the manifold that is connected to tank 1. This part of the manifold is referred to as manifold 1. Similarly, the valve closest to tank 2 is known as manifold valve 2. When it is closed, it isolates the part of the manifold that is connected to tank 2, which is known as manifold 2. Closing both manifold valves can isolate the section between the two valves, known as manifold 3. One H₂ manifold valve and one O₂ manifold valve is closed during crew sleep to protect against a catastrophic leak. The manifold valves are also closed during leak isolation procedures.

2.3.1.2 Reac Valves

The O₂ and H₂ manifolds are connected to the fuel cell reac valves. These valves can be used to stop the flow of cryo to a malfunctioning fuel cell or to a fuel cell that is shut down. The fuel cell 1 reac valves are connected to O₂ and H₂ manifold 1. The fuel cell 2 reac valves are connected to O₂ and H₂ manifold 2, and the fuel cell 3 reac valves are connected to O₂ and H₂ manifold 3.

2.3.1.3 Manifold Relief Valves

The O₂ and H₂ manifolds have two relief valves that can open to relieve excess pressure in the manifold. There is one valve on manifold 1 that will relieve excess pressure into tank 1 and another valve on manifold 2 that will relieve excess pressure into tank 2. Note that there is no relief valve on manifold 3. If either manifold valve is open, the center manifold will relieve through the relief valve of the manifold to which it is connected. If both manifold valves are closed, there is no relief path for manifold 3. If this should occur and the fuel cell 3 reac valves are closed, the cryo in manifold 3 will be trapped. Because of heat leaking into the line, the pressure of the cryo in this manifold will increase. This configuration will be reached only during leak isolation procedures. These procedures call to open one of the manifold valves as soon as possible when it is determined that the other manifold valve has isolated the leak. If the leak is in manifold 3, both manifold valves will remain closed.

2.3.1.4 GSE Cryo Supply

Cryo is supplied by the GSE until approximately 2.5 minutes before lift-off to ensure that the tanks remain full. As shown in Figure 2-6, the GSE is connected to H₂ manifold 2 and to O₂ manifold 1. The GSE supplies cryo at the pressures shown in Table 2-2. Since these pressures are greater than the tank pressures, the check valves for the tanks will be shut and there will be no flow out of the tanks. Because of slow heat leak into the tanks, the tank pressures will tend to increase up to the GSE pressure. Therefore, the vehicle will be launched with tank pressures at the GSE supply pressure, which is above the normal control range.

Table 2-2. GSE supply pressures

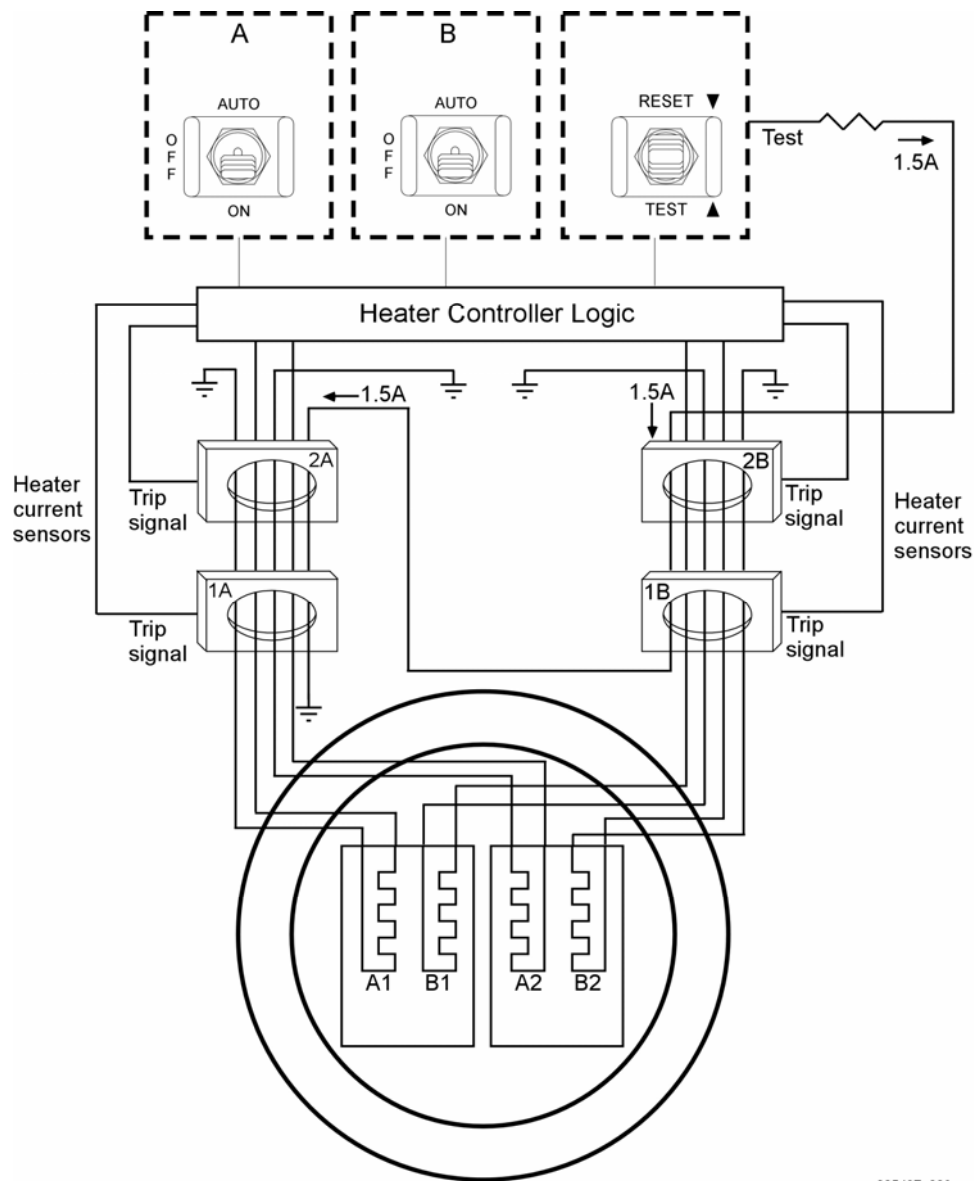
Reactant	Pressure, psia
H ₂	250
O ₂	950

2.4 CREW INTERFACES/CONTROLS

The crew interface to the cryo subsystem consists of switches, talkbacks, circuit breakers, meters, and displays that allow control and monitoring of cryo storage and distribution. The function of controls and sensors for the tanks and manifolds is covered in the following subsections. Next to each sensor are the sensor range and a list of displays, meters, and annunciators that the sensor drives.

2.4.1 Tank Controls

Each tank has an A heater switch and a B heater switch. The O₂ tanks also have a TEST/RESET switch for the heater current sensors (Figure 2-7). If the switch is held in the TEST position, a 1.5 amp test current is fed through all four heater current sensors. This current will cause all four sensors to trip, disabling all the heaters. If the switch is taken to the RESET position, the heater controller logic will clear the trip signals and re-enable the heaters.



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Figure 2-7. O₂ heater current sensor TEST/RESET switch

2.4.2 Tank Instrumentation

The instrumentation available for each tank consists of transducers for cryo temperature, quantity, pressure, and heater assembly temperatures. In addition, each O₂ tank has instrumentation that provides heater current sensor status. The tank sensors are shown in Figure 2-8 and Figure 2-9.

Each tank has a density probe that is used to determine quantity. The probe output is calibrated to give tank quantity in percent.

There are two pressure sensors, labeled P and TK P, for each tank. The P sensor, commonly known as control P, is used by the heater controller logic for maintaining tank pressure. It also drives the F7 Caution and Warning (C&W) annunciation. The value for the TK P sensor can be observed on a Panel O2 meter and on the displays specified next to the sensor in Figure 2-8 and Figure 2-9.

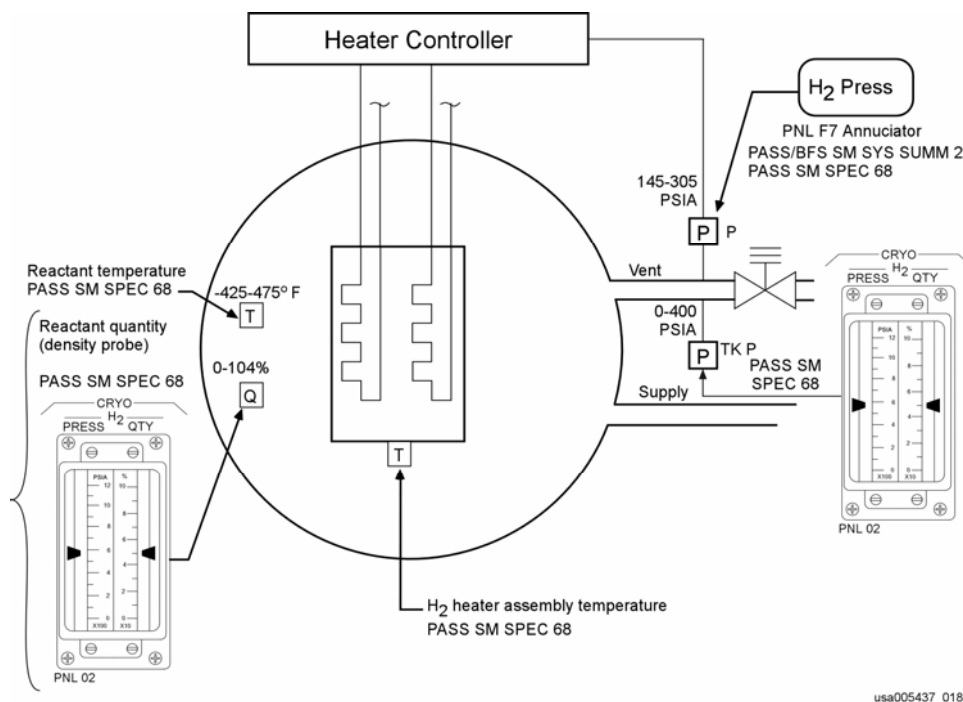


Figure 2-8. H₂ tank instrumentation

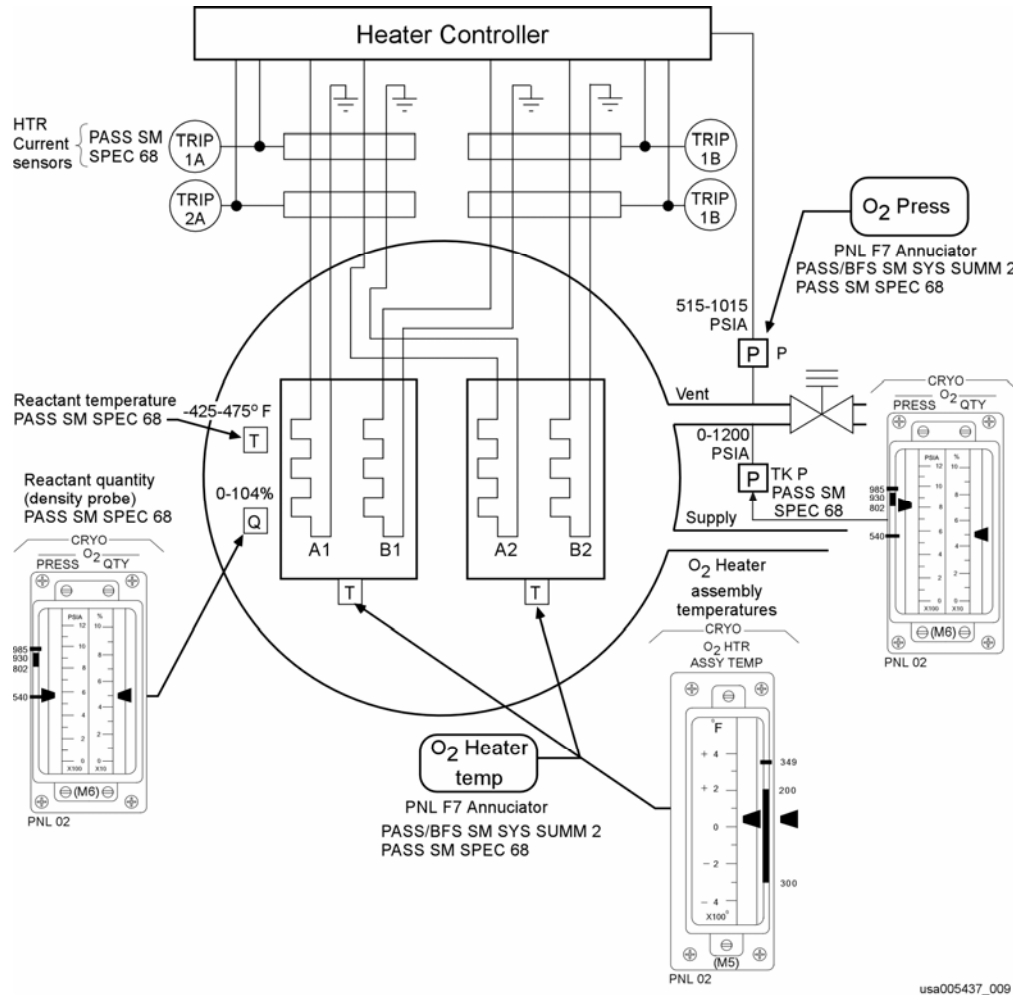


Figure 2-9. O₂ tank instrumentation

2.4.2.1 Manifold Controls

Each manifold has two switches to open and close the manifold valves for cryo management and leak isolation (Figure 2-10).

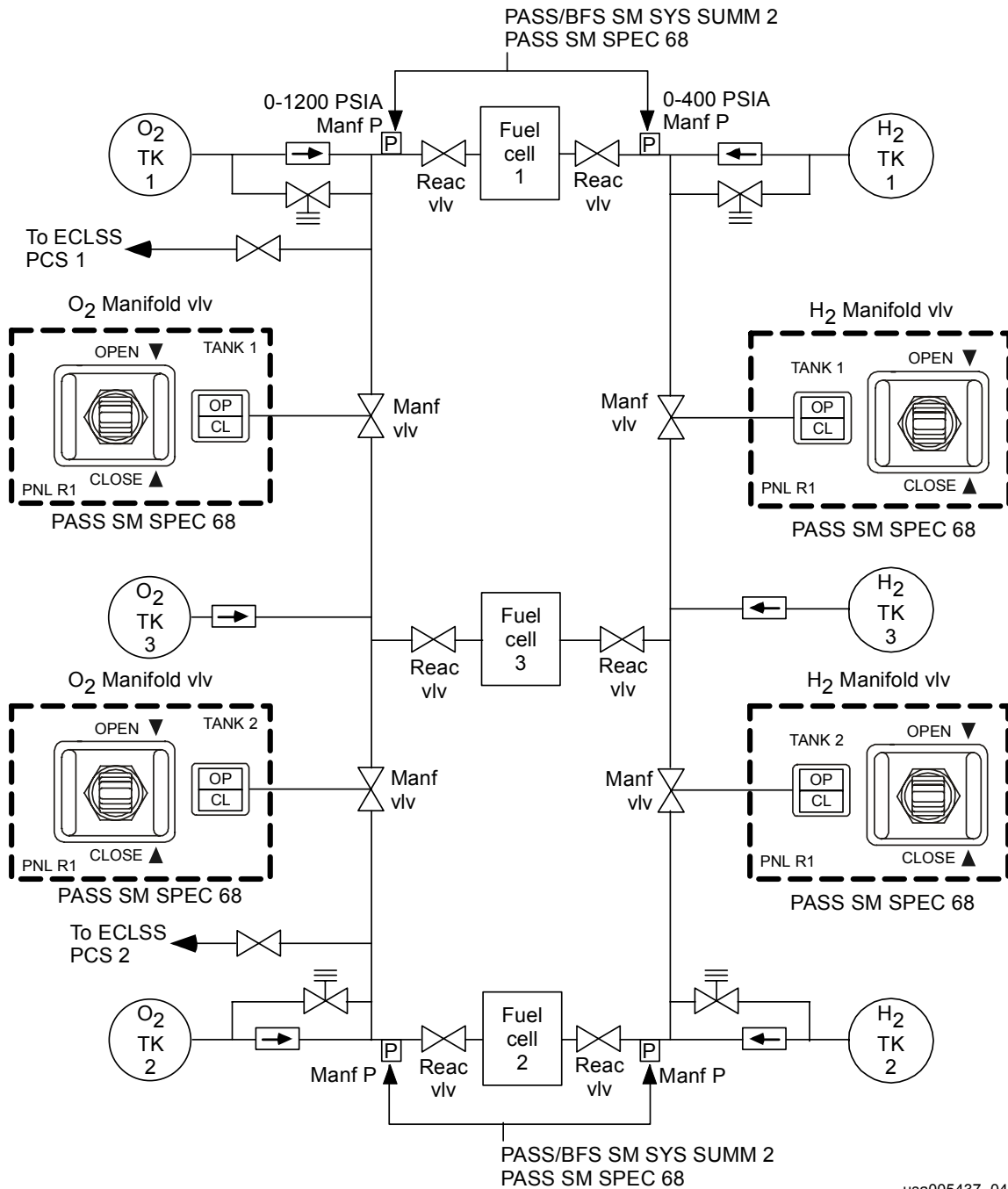


Figure 2-10. Cryo manifold controls and instrumentation

2.4.2.2 Manifold Instrumentation

The instrumentation available for the manifolds consists of two pressure sensors in manifolds 1 and 2 and OPEN/CLOSE status signals for each manifold valve (Figure 2-10). Pressure sensors are placed in manifolds 1 and 2. If the valves of both manifolds are open, the two pressure sensors in a manifold should give approximately equal readings. If the tank 1 manifold valve is closed, the manifold 1 sensor will give the pressure of manifold 1 and the manifold 2 sensor will give the pressure of manifolds 2 and 3. Similarly, if the tank 2 manifold valve is closed, the manifold 2 sensor will provide the pressure of manifold 2 and the manifold 1 sensor will provide the pressure of manifolds 1 and 3. If both manifold valves are closed, the pressure sensors will provide the pressures of manifolds 1 and 2. There will be no direct insight into the pressure of manifold 3, but it can be inferred from the tank pressures.

2.4.2.3 Crew Displays

Table 2-3 summarizes the cryo displays that are available for each mission phase. Each of these displays is described in the following sections.

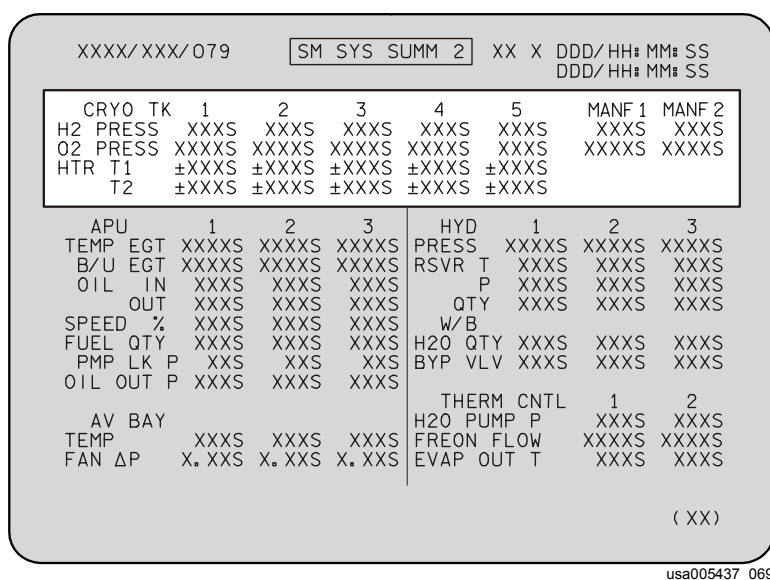
Table 2-3. Cryo displays

Mission phase	Display
Ascent/entry	BFS SM SYS SUMM 2
Orbit	PASS SM SYS SUMM 2 PASS SM SPEC 68

2.4.2.4 BFS SM SYS SUMM 2 and PASS SM SYS SUMM 2

PASS SM SYS SUMM 2 and BFS SM SYS SUMM 2 display cryo tank control pressures, O₂ tank heater assembly 1 and 2 temperatures, and pressures for manifolds 1 and 2 (Figure 2-11). The tank pressure displayed is the same pressure that the heater controller uses for controlling heater cycling (Figure 2-8 and Figure 2-9). The cryo information is identical for both displays.

The control pressures displayed on the SYS SUMMs can be verified by looking at the meters on Panel O2, which are driven by the other tank pressure sensor, TK P (Figure 2-8 and Figure 2-9). The O₂ heater assembly temperatures also can be observed on the Panel O2 meters.



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Sensor name	Units	Displayed range	Status indicators				
Cryo Tank:	H ₂ Press	145 to 305	M	H	L	↑	↓
	O ₂ Press	515 to 1015	M	H	L	↑	↓
	HTR T1	-425 to +475	M	H	L	↑	↓
	T2	-425 to +475	M	H	L	↑	↓
MANF 1,2:	H ₂ Press	0 to 400	M	H	L		↓
	O ₂ Press	0 to 1200	M	H	L		↓

Figure 2-11. PASS/BFS SM SYS SUMM 2 display

2.4.2.5 PASS SM SPEC 68

PASS SM SPEC 68, CRYO SYSTEM, which is available on orbit, provides status information for tank sets 1 through 5 (Figure 2-12). The display is split into O₂ information at the top and H₂ information at the bottom. For each tank, the control pressure and tank pressure measurements (P and TK P), quantity (QTY), fluid temperature (T), and heater assembly temperatures (HTR T) are displayed.

XXXX/XXX/068		CRYO SYSTEM		XX X DDD/HH: MM: SS		DDD/HH: MM: SS	
		TK					
O2	1	2	3	4	5		
P	XXXXS	XXXXS	XXXXS	XXXXS	XXXXS		
TK P	XXXXS	XXXXS	XXXXS	XXXXS	XXXXS		
QTY	XXXXS	XXXXS	XXXXS	XXXXS	XXXXS		
T	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
HTR T 1	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
2	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
HTR 1A	S	S	S	S	S		
CUR 1B	S	S	S	4/5S	S		
SNSR 2A	S	S	S	S	S		
2B	S	S	S	4/5S	S		
MANF P	XXXXS	XXXXS					
VLV	XXS	XXS					
H2							
P	XXXXS	XXXXS	XXXXS	XXXXS	XXXXS		
TK P	XXXXS	XXXXS	XXXXS	XXXXS	XXXXS		
QTY	XXXXS	XXXXS	XXXXS	XXXXS	XXXXS		
T	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
HTR T	±XXXX	±XXXX	±XXXX	±XXXX	±XXXX		
MANF P	XXXXS	XXXXS					
VLV	XXS	XXS					

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Sensor name	Units	Displayed range	Status indicators				
O ₂ TK: P	psia	515 to 1015	M	H	L	↑	↓
TK P	psia	0 to 1200	M	H	L	↑	↓
QTY	percent	0 to 104	M	H	L		
T	deg F	-425 to +475	M	H	L		
HTR T 1, 2	deg F	-425 to +475	M	H	L	↑	
HTR CUR SNSR 1A, 1B, 2A, 2B	on/trip	'blank' or '↓'	M				↓
MANF P	psia	0 to 1200	M	H	L		↓
VLV	text	'CL' or 'OP'	M				↓
H ₂ TK: P	psia	145 to 305	M	H	L	↑	↓
TK P	psia	0 to 400	M	H	L	↑	↓
QTY	percent	0 to 105	M	H	L		
T	deg F	-425 to +475	M	H	L		
HTR T	deg F	-425 to +475	M	H	L	↑	
MANF P	psia	0 to 400	M	H	L		↓
VLV	text	'CL' or 'OP'	M				↓

Figure 2-12. PASS SM SPEC 68

Control pressure, or P, is the pressure that is used by the heater controller logic. It is the same value as seen on PASS SM SYS SUMM 2. The second sensor on the tank vent line measures TK P. This sensor has a broader measurement range and can also be seen on the Panel O2 meters.

The tank quantity measurements and O₂ heater assembly temperatures are the same as those seen on the Panel O2 meters. Since O₂ tanks have two heater assemblies, there are two heater temperature measurements, labeled 1 and 2.

The O₂ tanks also have four heater current sensor status flags (HTR CUR SNSR 1A, 1B, 2A, and 2B). If an O₂ heater current sensor should detect a short circuit, a down arrow will be displayed for the corresponding sensor, and the associated heaters will be tripped off. The 1A and 2A sensors are the first and second sensors for the A heaters, and the 1B and 2B sensors are the first and second sensors for the B heaters. When the heater current sensor TEST/RESET switches are taken to TEST, all four sensors will detect the simulated short circuit, four down arrows will occur on this display under the corresponding tank, and both A and B heaters will be tripped off.

PASS SM SPEC 68 also displays status of the distribution manifolds. The first value on the MANF P line is the pressure read by the sensor in manifold 1, whereas, the second value is the pressure read by the sensor in manifold 2. The status of the manifold valves (VLV) is displayed below the manifold pressures as CL or OP. The first status is for the tank 1 manifold valve, and the second status is for the tank 2 manifold valve.

2.5 NOMINAL OPERATIONS

Operation of the cryo subsystem during a mission includes managing tank quantities by reconfiguring heaters and manifold valves, and verifying operation of the O₂ heater current sensors. Nominal operations for each flight phase are discussed in the following sections.

2.5.1 Prelaunch

Approximately 2 days before lift-off, the cryo tanks are loaded through the tank fill lines (Figure 2-5). Even though the tanks are loaded, GSE still supplies cryo (Figure 2-6) until 2.5 minutes before launch. The GSE cryo is supplied at the pressures shown in Table 2-2. These pressures cause the tank check valves to close because the tanks are controlled to a lower pressure. Heat leaking into the tanks will cause the tank pressures to increase to the pressures of the GSE cryo. As more heat leaks into the tanks, small amounts of cryo will be forced out of the tanks and into the manifold, which is termed "boiling off."

No switch throws are required for the cryo subsystem before launch. At crew ingress, both manifold valves on each manifold are open so that all three fuel cells can be supplied by all of the tanks. The A heaters in H₂ and O₂ tanks 1 and 2 are in AUTO, and all other tank heaters are OFF.

During powered flight, tank pressures normally do not decrease enough to require heater cycles. If tank pressures decrease below the heater control range, the A heaters in H₂ and O₂ tanks 1 and 2 will begin to cycle. The B heaters are not placed in AUTO. If too many cryo tank heaters come on at once to increase the already high power loads of ascent, voltages at the SRB interface could drop too low. This could cause loss of SRB thrust vector control.

2.5.2 Ascent

The only cryo operation during ascent is to take the H₂ and O₂ tank 1 and 2 B heaters to the AUTO position. This is done in the timeframe following the first Orbital Maneuvering System (OMS) burn (post-OMS-1) to prepare for heater cycling. For direct-insertion flights, on which OMS-1 is not required, the post-OMS-1 procedures are performed following main engine cutoff.

2.5.3 Orbit

Orbit cryo operations normally occur before and after sleep periods. During pre-sleep and post-sleep procedures, the tank heater and manifold valve configuration is changed to manage tank quantities. The flight control team on the ground performs analyses to determine these configurations and sends the desired configuration up to the crew each day.

On a single-shift mission, the tank heaters and manifold valves are used to control cryo consumption from the tanks. One manifold valve on both the O₂ and the H₂ manifolds is closed during sleep periods to prevent a massive leak from causing all three fuel cells to fail. The management of the valves and the heaters depends on mission requirements. On a dual-shift mission, the manifold valves are not closed since there are always crewmembers awake to respond to a cryo leak. Therefore, only the tank heaters are used to manage consumption.

As Table 2-1 shows, tanks 1 and 2 are controlled to pressures lower than those of the other tanks. When any of the other tanks are activated, their higher pressures prevent tanks 1 or 2 from supplying cryo. Tank 1 or 2 is usually in AUTO while tanks 3, 4, or 5 are in AUTO. In this case, tank 3, 4, or 5 will supply all the cryo.

On flight day 2, the O₂ heater current sensors are tested to verify their operation. For this procedure, the heater current sensor status flags on PASS SM SPEC 68 are observed while the heater current sensor switches for each tank are taken to the TEST position. When this switch is taken to the test position, a 1.5 amp current is passed through the current sensors. Once the arrows occur, the switch will be taken to the RESET position to reset the sensors and re-enable the heaters. The only other action that might be required on orbit will be to turn off the B heaters in any O₂ tank with a quantity of less than 50 percent. If both heaters in an O₂ tank are enabled below this quantity, the heater assemblies could heat too rapidly and overheat during a heater cycle, with the potential of starting a fire.

2.5.4 Entry

During de-orbit preparations, the cryo manifold valves are open, the O₂ and H₂ heaters in tanks 1 and 2 are in AUTO, and all other tank heaters are OFF. The quantity in the O₂ tanks will usually be less than 50 percent; therefore, the B heaters will be OFF. For the H₂ tanks, the B heaters will be left in AUTO. Overheating of the heater assemblies is not a problem for the H₂ tanks as it is for the O₂ tanks. During entry, no actions are required for the cryo subsystem.

Questions

Answers provided in Appendix B

1. What is the purpose of the cryo subsystem?

2. The cryo tanks are located in

- a. The crew cabin
- b. The external tank
- c. The payload bay
- d. All of the above
- e. None of the above

3. Match the following cryo components to their functions.

- | | | |
|---------------------------|-------|---|
| a. Tank heaters | _____ | 1. Remove contaminants from cryo |
| b. Heater controllers | _____ | 2. Relieve excess pressure in manifolds into tanks 1 and 2 |
| c. Heater current sensors | _____ | 3. Relieve excess tank pressure overboard |
| d. Filters | _____ | 4. Detect shorts in O ₂ tank heaters |
| e. Check valves | _____ | 5. Manage tank heaters to maintain tank pressure |
| f. Tank relief valves | _____ | 6. Isolate parts of H ₂ or O ₂ manifold |
| g. Manifold valves | _____ | 7. Allow cryo to flow out of tanks but not back in |
| h. Manifold relief valves | _____ | 8. Add heat to cryo to maintain tank pressure |

4. All the O₂ and H₂ heaters for tanks 1 and 2 are on during ascent.

True or False

5. The B heaters in an O₂ tank are turned off when the quantity in the tank is less than 50 percent.

True or False

6. For a single-shift mission, the cryo manifold valves are kept open while the crew is asleep.

True or False

7. The O₂ heater current sensors are tested only once during a flight.

True or False

3.0 FUEL CELL SUBSYSTEM

3.1 OBJECTIVES

The student should be prepared to accomplish the following tasks as a result of studying this section of the workbook.

- Describe the purpose of the FC subsystem.
- Recognize where the fuel cells are located.
- Specify the byproducts of the fuel cells when they produce electricity.
- Match fuel cell components to their functions.
- Understand nominal operations of the FC subsystem.

3.2 FUEL CELL SUBSYSTEM OVERVIEW

The FC subsystem produces all the 28 V DC electrical power required by the orbiter, the ET, the SRBs, and most payloads. This subsystem consists of three independent fuel cells that produce electricity through chemical reactions involving O_2 and H_2 . Byproducts of the reactions are water and heat. The water is removed and sent to the ECLSS supply water tanks. The heat is transferred to the orbiter Freon loops to be rejected into space. The three fuel cells are located in the forward end of the payload bay under the payload bay liner (Figure 3-1).

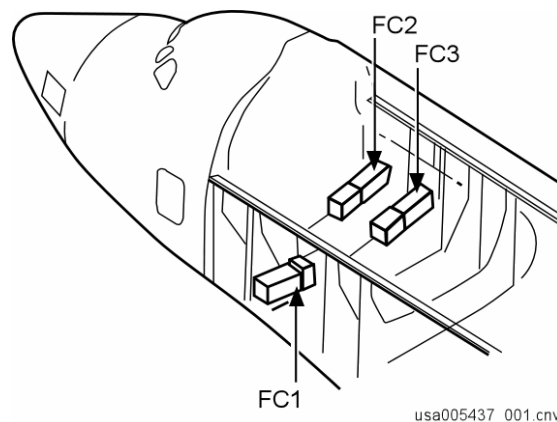


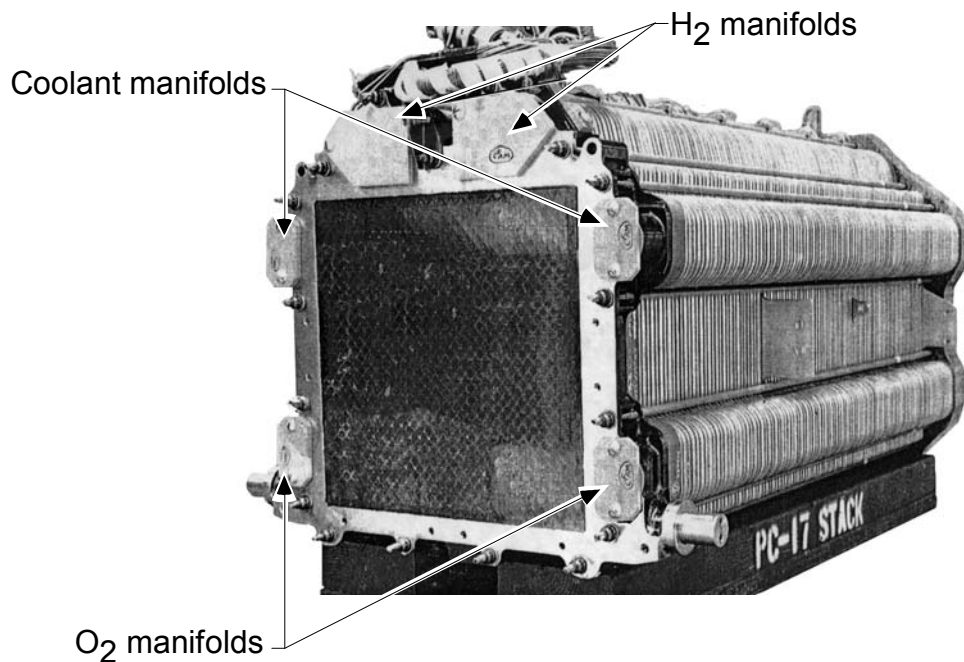
Figure 3-1. Fuel cell location

The fuel cells are made up of two sections: the power section, or stack, and the accessory section. The chemical reactions occur and electrical power is produced in the stack. The accessory section controls and monitors stack performance and removes water and heat.

3.3 FUEL CELL STACK

The fuel cell stack consists of 96 electrochemical cells sandwiched together as shown in Figure 3-2. Manifolds run the length of the stack to provide H_2 and O_2 for the reactions and coolant for heat removal.

Each cell produces approximately 1.15 V with no load. This voltage decreases to 0.9 to 1 V under normal loads. To achieve the required 28 V of potential, 32 cells are connected in series. This configuration provides a voltage of 28 to 32 V, which is the number of cells times the 0.9 to 1 V that each cell provides. Each set of 32 cells is known as a substack. Three substacks are connected in parallel to provide the current capability required for operations.



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Figure 3-2. Fuel cell stack

Figure 3-3 is a diagram of one electrochemical cell in a fuel cell stack. In each cell, O_2 and H_2 enter opposite sides of the cell and begin two reactions with an electrolyte of potassium hydroxide (KOH). On the H_2 side of the cell, the H_2 reacts with hydroxide (OH) ions to produce water and electrons ($2H_2 + 4OH \rightarrow 4H_2O + 4e$). These electrons (e) leave the cell as current to power orbiter loads. As electrons return to the cell from the loads, they react with O_2 and water on the O_2 side of the cell to produce

OH ions that replenish those consumed in the H_2 reaction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$). The quantity of electrons leaving the stack (the current) determines the amount of O_2 and H_2 used by the fuel cell. If no current is being produced, no cryo will be consumed.

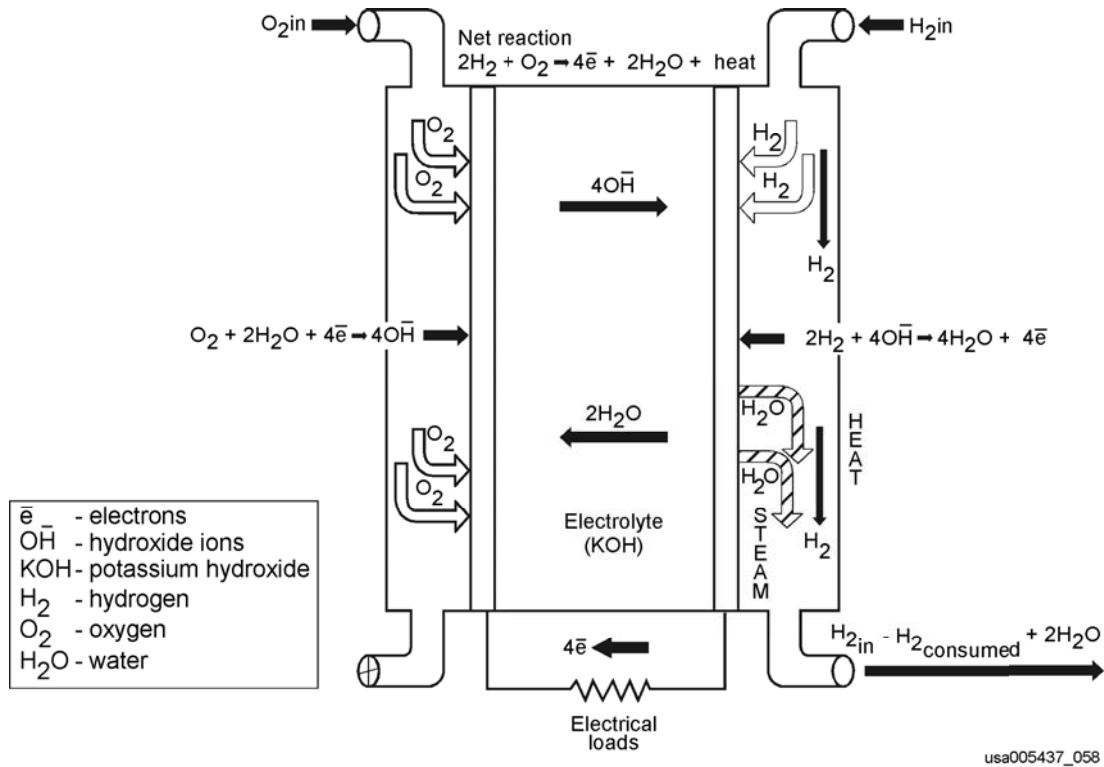
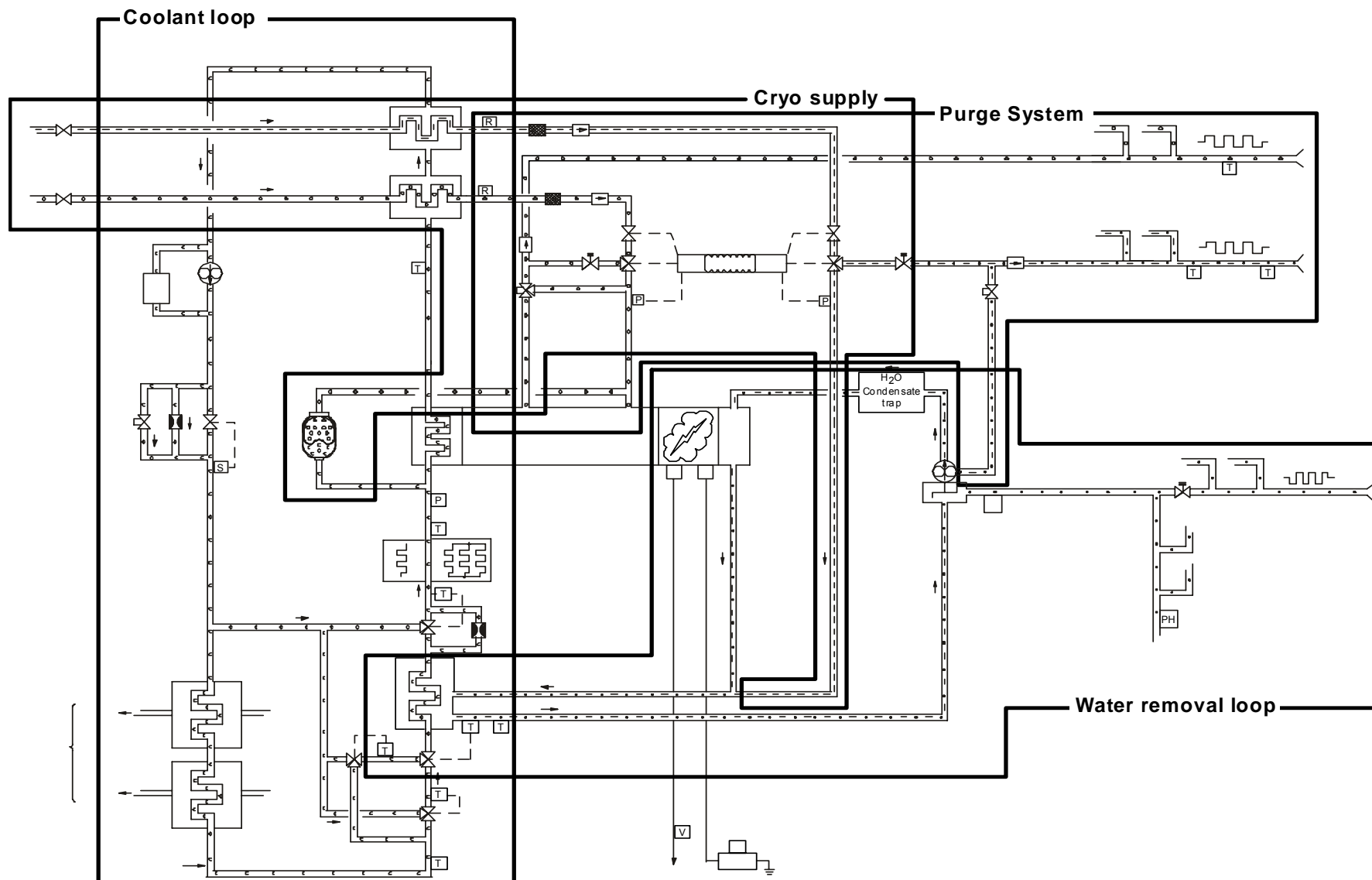


Figure 3-3. Electrochemical cell

The net of the two reactions is that two hydrogen molecules and one oxygen molecule are consumed to produce the flow of four electrons, two water molecules, and heat. Water produced on the H_2 side of the cell is removed from the cell as water vapor by flowing excess H_2 through the cell. Heat is removed by coolant flowing through the stack.

3.4 FUEL CELL ACCESSORY SECTION

The fuel cell accessory section controls and monitors the performance of the stack by supplying the required cryo flow, removing waste heat and water, and monitoring the performance of the cells. Functions of the accessory section can be broken down into cryo supply, the water removal loop, the purge system, and the coolant loop (Figure 3-4). The cell performance monitor and the Electrical Control Unit (ECU) are also located in the accessory section.



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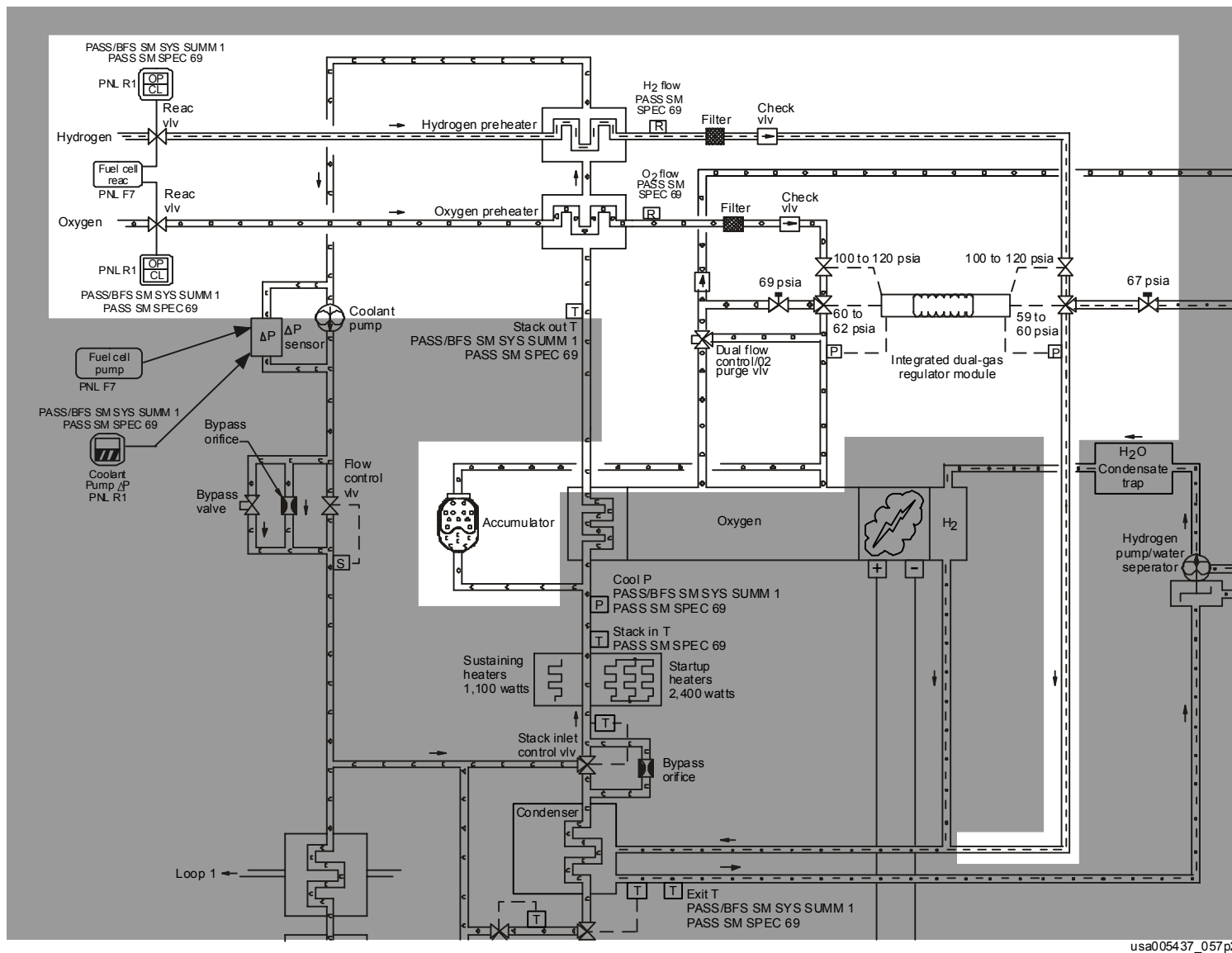
Figure 3-4. Fuel cell accessory section

3.4.1 Cyro Supply

The O₂ and H₂ flowing into the fuel cell are supplied by the cryo subsystem through the reac valves (Figure 3-5). The cryo is supplied at cryogenic temperatures and must be heated before it enters the fuel cell. As the cryo enters the accessory section, it passes through preheaters. The preheaters use hot coolant that has passed through the stack to warm the cryo, preventing freezing of any fuel cell components. After passing through the preheaters, the cryo flows through filters to remove contaminant particles.

Cryo is supplied to the fuel cells at high pressure. The high-pressure cryo enters a dual-gas regulator in which pressures are initially decreased to approximately 100 to 120 psia by the first-stage regulators. The pressure of the O₂ is further decreased to 60 to 62 psia, and the pressure of the H₂ is reduced to 1 to 2 psia less than that of the O₂ by the second-stage regulators. The dual-gas regulator ensures that the O₂ pressure stays greater than the H₂ pressure. If H₂ pressure ever increases above the O₂ pressure, the KOH electrolyte in the cells will be forced out of its storage plates allowing crossover. Crossover means that O₂ and H₂ mix freely, a potentially explosive condition.

After leaving the dual-gas regulator, the O₂ enters the stack through two ports and is completely consumed. The O₂ supply also interfaces with the fuel cell accumulator. The accumulator keeps the pressure of the fuel cell coolant the same as the O₂ pressure to prevent pressure differentials between the coolant and the cryo in the stack. Dry H₂ does not flow directly into the stack. It enters the H₂ loop as it carries steam from the stack. After most of the water has been removed, the "moist" H₂ flows into the stack, conditioning the reaction area.

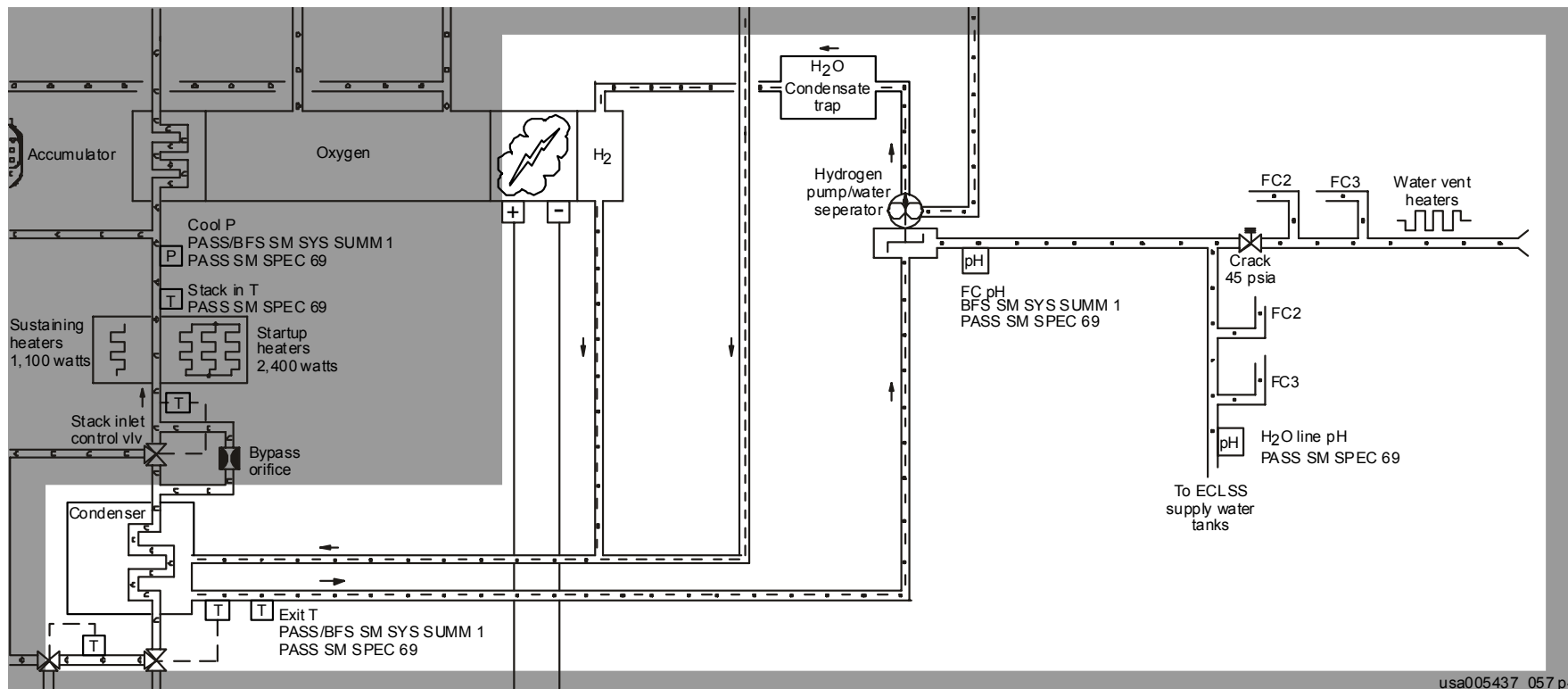


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Figure 3-5. Cryo supply

3.4.2 Water Removal Loop

As shown in Figure 3-3, water produced in the electrochemical cells is removed as steam by flowing extra H_2 through the cell. When this H_2 /steam mixture leaves the stack (Figure 3-6), it mixes with H_2 entering the fuel cell to replenish the H_2 that was consumed in the reaction. The mixture is then passed through a condenser that cools it to approximately 150° F. At this temperature, the water condenses into droplets and the H_2 /water mixture is sent to the hydrogen pump/water separator. The pump removes the water and sends it to the ECLSS supply water tanks. The H_2 is then passed through a water condensate trap to catch any stray water droplets that may have made it through the pump, and is then finally fed into the stack. Part of the H_2 that enters the stack is consumed in the reactions. The H_2 that is not consumed carries the steam out of the stack and the water removal cycle continues.

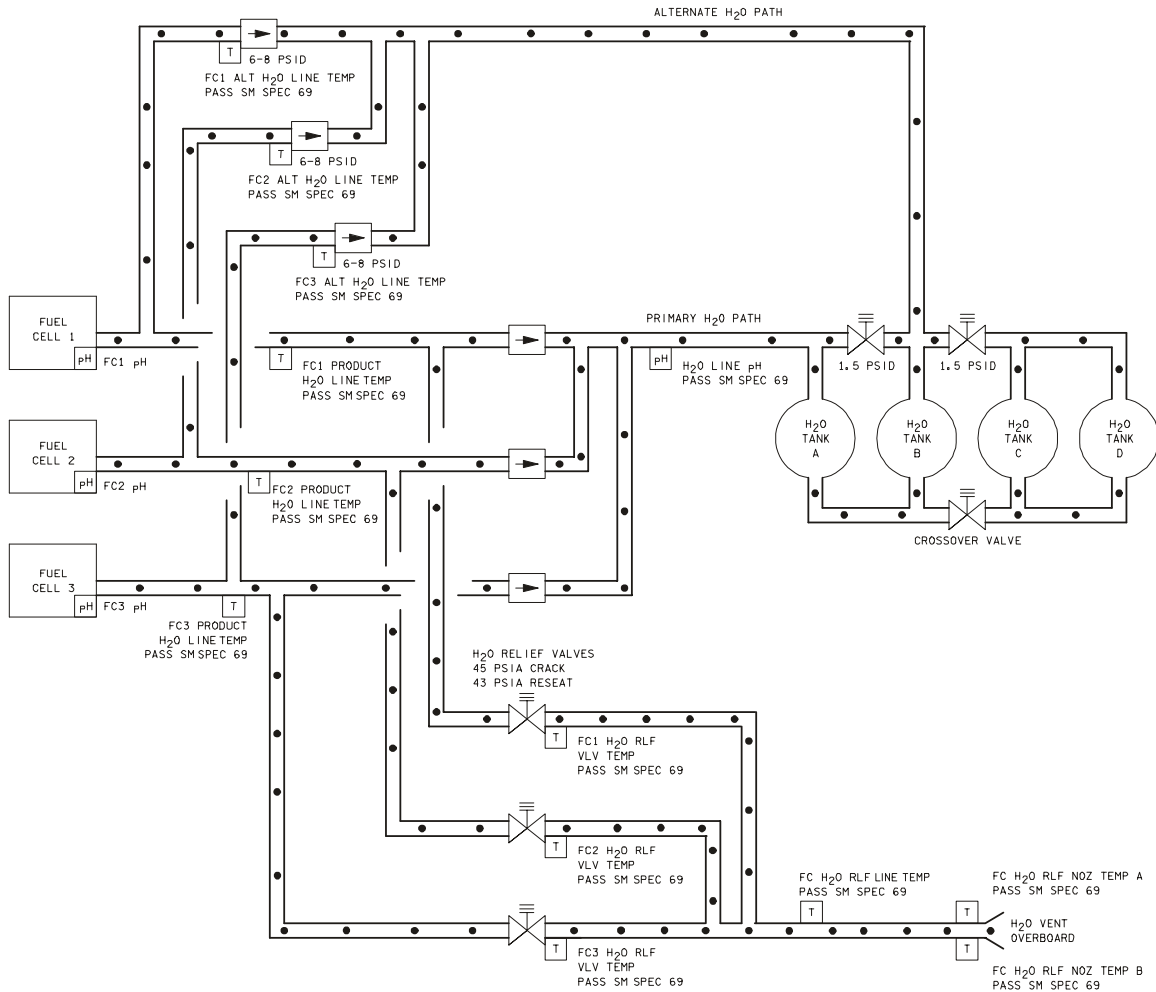


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Figure 3-6. Water removal loop

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The water leaving the fuel cells is fed to supply water tank A through the primary water path (Figure 3-7). If the primary path should fail, an alternate water path would feed the water into supply water tank B. If both paths should fail, the water would be relieved overboard through a nozzle. Since the primary, alternate, and relief paths are exposed to the cold temperatures of the payload bay, the lines are wrapped with thermostatically controlled heaters to prevent the water from freezing in the lines.



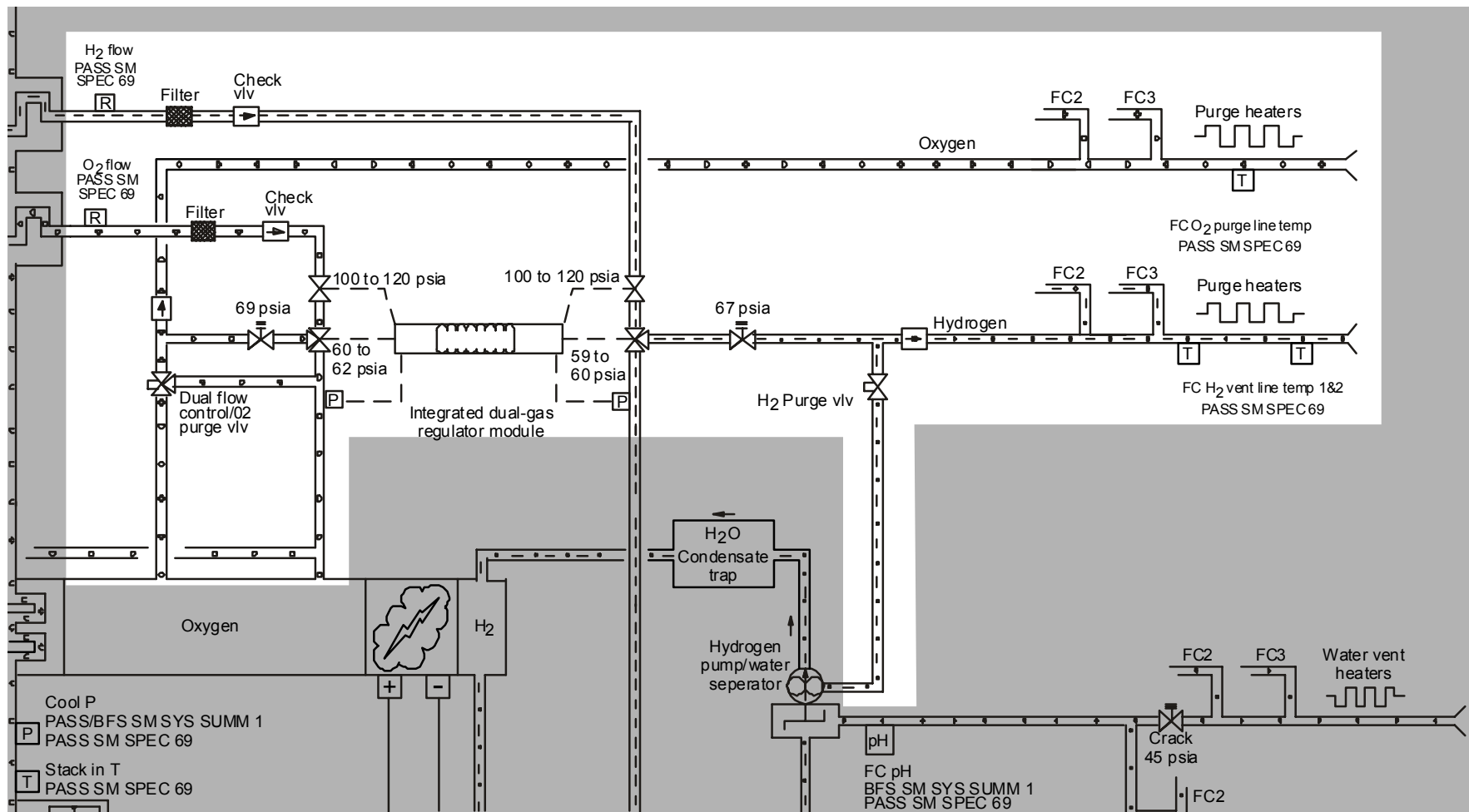
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Figure 3-7. Fuel cell water removal paths

3.4.3 Purge System

Cryo remains in the fuel cell until it is completely consumed by the reactions. Inert gases entering the fuel cell with the cryo have no way to escape; therefore, their concentrations tend to increase inside the stack. This condition results in fuel cell performance degradation. The fuel cells are periodically purged to remove contaminants and to increase performance. During a purge, the O₂ and H₂ systems are opened to purge lines, allowing extra cryo flow through the fuel cells and flushing impurities overboard.

For the O₂ system, the dual flow control/O₂ purge valve in the dual-gas regulator is opened to the purge line (Figure 3-8). This action causes the O₂ to flow into the stack through one of the oxygen ports, flow through the stack, and then flow out the other port carrying impurities overboard through the O₂ purge line. Since the H₂ is already in a circulating loop, some of the impurities are already being carried out of the stack with the H₂/steam mixture, but they are still building up in the water removal loop. Impurities are bled out of the loop by opening the H₂ purge valve. This action allows H₂, along with impurities, to flow out of the loop and overboard through the H₂ purge line. The O₂ and H₂ purge lines are wrapped with heaters to prevent freezing of moisture that may be carried out of the fuel cell with the purge flow. Fuel cell power production continues normally during purge operations; however, flow increases to account for the cryo being purged overboard.



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Figure 3-8. Fuel cell purge system

3.4.4 Coolant Loop

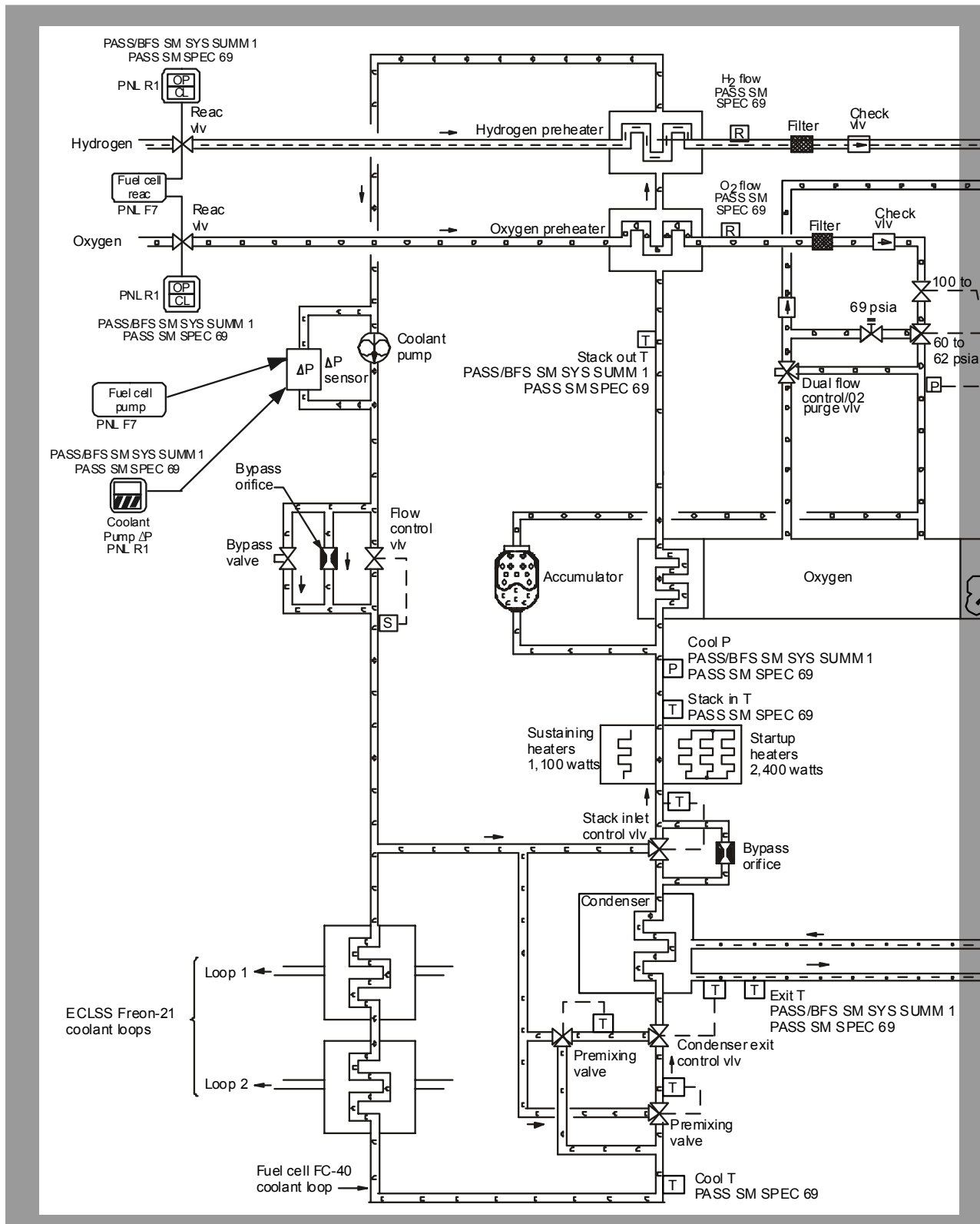
The fuel cell coolant loop circulates fluorocarbon 40 (FC-40) to cool the stack, cool the H₂/steam mixture exiting the stack, and preheat the cryo as it enters the fuel cell (Figure 3-9). The coolant is circulated around the loop by the coolant pump. After the coolant leaves the pump, it flows through the flow control valve. This valve throttles the flow to maintain the temperature of the coolant leaving the valve between 192° F and 209° F. Parallel with the flow control valve is a bypass orifice that prevents the flow control valve from completely shutting off coolant flow. There is also a bypass valve that opens during fuel cell startup to allow full coolant flow while the stack is being brought up to operating temperature. After passing through the flow control valve, part of the coolant leaves the fuel cell and enters the fuel cell heat exchanger, where excess heat is transferred into the orbiter Freon loops. The cooled FC-40 then reenters the fuel cell through two premixing valves and the condenser exit control valve. These valves mix hot coolant, which has bypassed the heat exchanger, with cool coolant returning from the heat exchanger. In turn, a coolant temperature is provided that will cool the H₂/steam mixture in the condenser to approximately 150° F. The two premixing valves prevent large temperature oscillations.

After the coolant leaves the condenser, it enters the stack inlet control valve. This valve mixes hot coolant, which has bypassed the heat exchanger, with the cooler coolant leaving the condenser. This mixture regulates the temperature of the coolant entering the stack to approximately 185° F. There is a bypass orifice across this valve to allow a minimum flow through the condenser and the fuel cell heat exchanger.

Before the coolant enters the stack, it passes through two sets of heaters. The startup heater is used when the fuel cell is first started to add heat to the coolant loop and achieve stack-operating temperature. When this heater is on, the bypass valve around the flow control valve is opened to allow full coolant flow. After the fuel cell start is complete, the heater is disabled and the bypass valve is closed. The sustaining heater is activated if the fuel cell stack temperature drops too low. This condition would result from fuel cell operation at low power levels, because the amount of heat produced by the stack is proportional to the power produced.

Immediately past the heaters is the accumulator, which equalizes the pressure between the coolant and the O₂. The coolant then enters the stack. Normally, the coolant absorbs waste heat from the stack. However, if the fuel cell is starting or running at low power, the coolant actually transfers heat from the startup or sustaining heaters to the stack.

After the coolant leaves the stack, it passes through the preheaters, heating the cryo. Past the preheaters, the coolant enters the coolant pump, beginning the cooling cycle again.



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Figure 3-9. Coolant loop

3.4.5 Cell Performance Monitor (CPM)

Because of the highly reactive nature of the O_2 and H_2 used in the fuel cell, the performance of the stack is monitored to detect potential problems. If direct O_2 and H_2 mixing, called crossover, occurs in a cell, its voltage degrades. The CPM was developed to detect cell voltage degradation.

The CPM splits each substack of 32 cells into two groups of 16 cells (Figure 3-10). It then measures the voltage across each group of 16 cells and calculates the absolute value of the voltage difference between each group. This value is measured and displayed in millivolts, but it is often called substack “delta volts.” If all the cells are working properly, the delta volts value should be small. If one cell starts to degrade in either set of 16 cells, the voltage degradation will show up as an increase or decrease in the substack delta volts. A voltage degradation of 300 mV for a cell is considered significant. Since the absolute value of the delta volts is used, 150 mV is the limit used to determine that a cell problem is occurring.

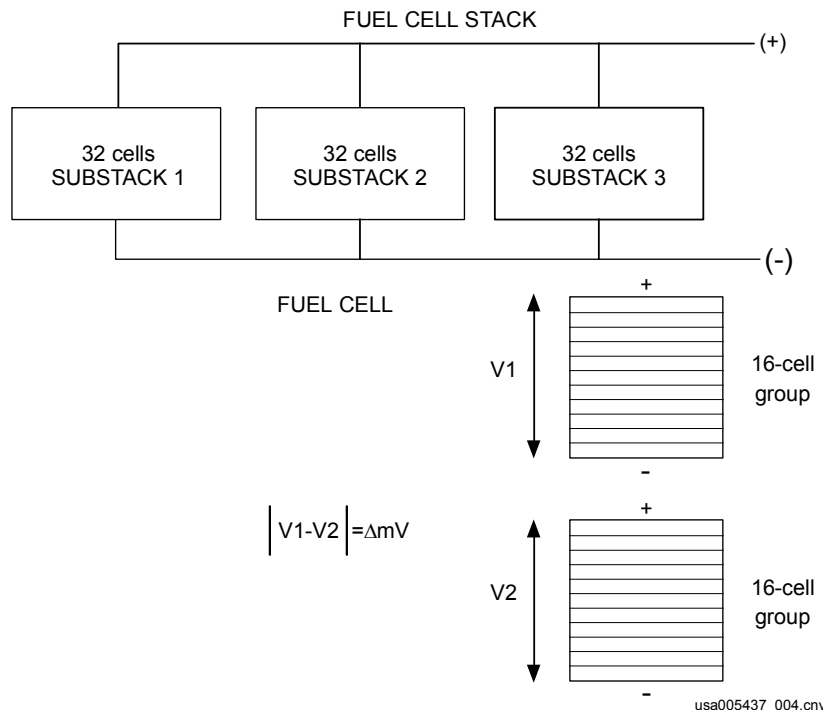


Figure 3-10. Fuel cell performance monitor

Every 7.5 minutes, the CPM performs a self-test. During the self-test, the monitor introduces a test signal of 50 mV for each substack and measures to make sure that it is reading the appropriate delta volts. If the test fails, the delta volts reading for the failed substack is driven to its high value of 500 mV for annunciation by the C&W system. The delta volts stay at this value until the next self-test. If the self-test passes, the substack delta volts monitoring for the affected substack is resumed; otherwise, the substack reading will remain at 500 mV.

The capability of the CPM became an issue during the STS-83 mission. Early in the mission, one of the CPM measurements for fuel cell 2 went out of limits but appeared as if it might eventually stabilize. The available data did not allow for ground personnel to rule out the possibility of a crossover condition in the fuel cell. The decision was made to save the fuel cell and execute a minimum-duration flight timeline. Subsequent testing showed that, instead of one cell having a large degradation, several cells in the same substack had slightly degraded.

To preclude another incident of early mission termination due to lack of insight into fuel cell single cell voltages, the Fuel Cell Monitoring System (FCMS) was developed. The FCMS takes single cell voltage measurements from a test harness on the fuel cell and creates a file on a Payload General Support Computer (PGSC) which is downlinked to the MCC for analysis.

3.4.6 Electrical Control Unit

The ECU is an electrical module located within the accessory section that contains the startup logic, heater thermostats, relays, and timer. The ECU interfaces with the crew controls and displays that pertain to fuel cell startup and shutdown. It controls valve positions, pump operation, and heater operation, so that the fuel cell operates properly. The operation of the ECU is documented in the section on fuel cell controls and instrumentation.

3.5 FUEL CELL CREW INTERFACES/CONTROLS

The interface to the FC system consists of switches, talkbacks, circuit breakers, meters, and displays that allow the control and monitoring of fuel cell operation. The function of controls and sensors for the fuel cells is covered in the following subsections. Following this will be a description of the displays on which the data are displayed.

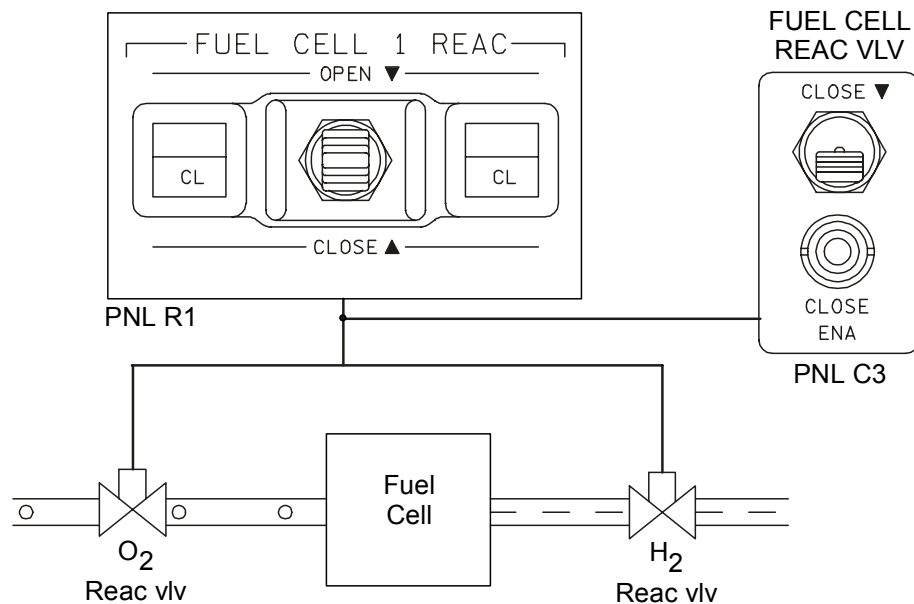
3.5.1 Fuel Cell Controls

Controls for the fuel cells consist of switches to open and close the fuel cell react valves, power the ECU, start and stop the ECU, perform purges, and enable heaters. Each of these controls is discussed separately in the following sections.

3.5.1.1 Fuel Cell Reac Valve Controls

The reac valves for each fuel cell are controlled by a momentary switch known as the FUEL CELL REAC switch (Figure 3-11). Next to each switch are two talkbacks that indicate the open or closed status of the O₂ and H₂ reac valves. To open the reac valves, the FUEL CELL REAC switch is held to the OPEN position until the talkbacks indicate that the valves are open (OP). Since the valves are latching valves, they will remain open when the switch is released. To close the valves, the switch is held to the CLOSE position until the talkbacks indicate that the valves are closed (CL). The valves will then stay latched closed until the switch is taken to the OPEN position.

If any of the FUEL CELL REAC switches should fail, each fuel cell has a redundant switch and a circuit breaker to allow reac valve closure. The circuit breaker enables the FUEL CELL REAC VLV switch, which can be taken to the CLOSE position to close the reac valves. It is critical to note that any time one of the reac valve closure circuit breakers is pushed in, the open capability of the corresponding FUEL CELL REAC switch for that fuel cell will be disabled. The circuit breakers are kept opened and covered at all times except when performing reac valve closure with the redundant switch.

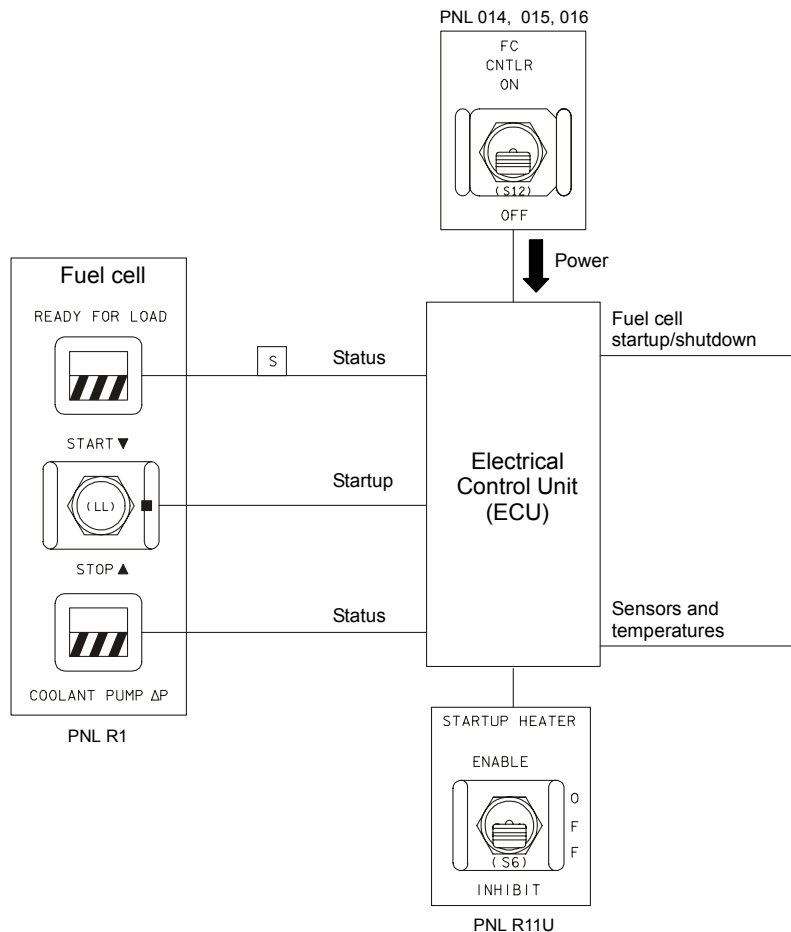


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Figure 3-11. Fuel cell reac valve switches

3.5.1.2 Electrical Control Unit Controls

The ECU for each fuel cell is controlled by three switches (Figure 3-12). The FC CNTLR switch provides power to the ECU. With this switch in the ON position, the associated ECU receives power so that it can control the fuel cell. These switches are normally always left in the ON position and are protected with switch guards.



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Figure 3-12. Fuel cell ECU

The fuel cell START/STOP switch starts and stops the operation of the fuel cell pumps and heaters. When the switch is held to the START position, the ECU performs the fuel cell startup sequence. When the switch is held to the STOP position, the ECU removes power from the coolant pump, the H₂ pump/water separator, and the startup and sustaining heaters.

The FUEL CELL STARTUP HEATER switch enables or inhibits the startup heaters (Figure 3-9) that are commanded on during a fuel cell start. The startup heaters add heat to the fuel cell coolant loop to heat the stack up to its operating temperature. These switches are normally always left in the ENABLE position. ECU startup and shutdown are described in the following paragraphs.

- a. ECU Startup - When the fuel cell START/STOP switch is taken to START, the ECU connects power to the coolant pump and to the hydrogen pump/water separator. Once the coolant pump is running, the COOLANT PUMP ΔP talkback, which is located below the START/STOP switch (Figure 3-12), goes from barberpole to gray. At this point, the start sequence is initiated and the START/STOP switch can be released.

After the coolant pump is running, the ECU enables the startup heaters. These heaters add heat to the coolant loop until the temperature of the coolant leaving the stack is 186° F, or the temperature of the coolant entering the stack is 212° F. During operation of the startup heaters, the bypass valve across the coolant loop flow control valve (Figure 3-9) is opened to allow full coolant flow while the stack is being warmed. The startup heaters and the bypass valve are automatically disabled by the ECU once the stack reaches operating temperature.

When the startup heaters and the bypass valve are disabled, the READY FOR LOAD talkback above the START/STOP switch (Figure 3-12) changes from barberpole to gray to indicate that the stack is ready to be connected to electrical loads. If the fuel cell is restarted soon after it has been stopped, the stack may already be at operating temperature. In this case, a timer in the ECU waits 30 seconds to allow time for temperatures to stabilize before the startup heaters and the bypass valve are disabled. Therefore, the minimum time for taking the fuel cell to START and seeing the READY FOR LOAD talkback turn to gray is 30 seconds.

- b. ECU Shutdown - When the START/STOP switch is held to the STOP position, the ECU removes power from the coolant pump, the H₂ pump/water separator, and the startup and sustaining heaters. **The fuel cell does not stop producing power.** The fuel cell ceases producing power only when it is disconnected from all electrical loads or when cryo is shut off so that the electrochemical reactions can no longer occur. If the pumps are stopped and the stack continues to produce power, the heat and water generated in the stack will not be removed, resulting in thermal runaway and a hazardous condition.

3.5.1.3 Purge Controls

The switches for fuel cell purging allow a purge to be done automatically under General Purpose Computer (GPC) control or manually by a crewmember (Figure 3-13). The PURGE HEATER switch will automatically turn the purge line heaters on during an auto purge if it is placed in the GPC position. In the ON position, this switch turns on a different set of heaters than those used during an auto purge.

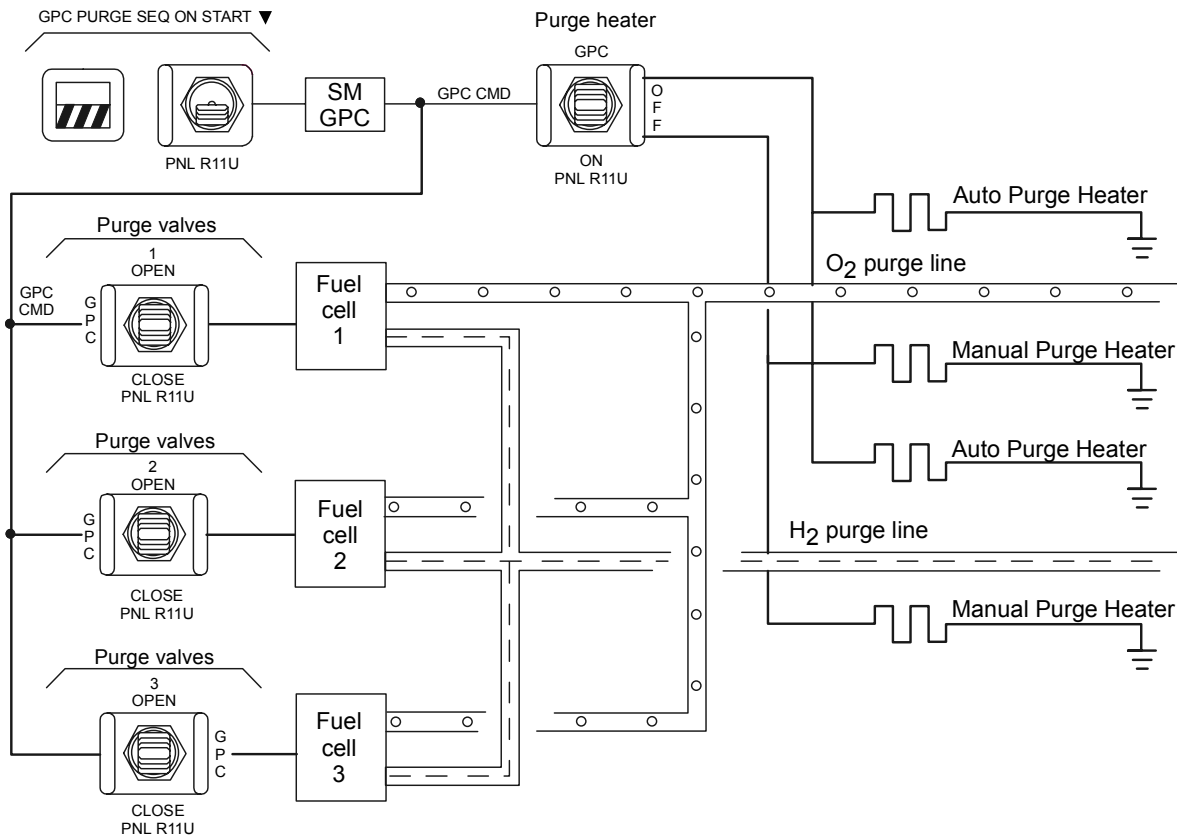


Figure 3-13. Fuel cell purge switches

The PURGE VALVES switch controls the O₂ and H₂ purge valves for each fuel cell. In the OPEN position, the purge valves open to begin a purge. If the switch is taken to the GPC position, the valves will be automatically opened and closed when an auto purge is performed.

The GPC PURGE SEQ switch is used to initiate an auto purge. After the heaters and the purge valves are placed in the GPC position, this switch is held to the START position UNTIL 3 SECONDS AFTER the GPC PURGE SEQ ON talkback goes from barberpole to gray. The switch must be held for an extra 3 seconds for the GPC to properly start the purge; otherwise, the GPC will generate an alarm. Once the purge is started, the GPC will automatically control the heaters and the purge valves. When the entire purge sequence is complete, the GPC PURGE SEQ ON talkback will go barberpole again.

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3.5.1.4 Water Removal Line Heater Controls

The primary and alternate water paths to the supply water tanks are wrapped with two sets of thermostatically controlled heaters to prevent water from freezing in the lines. The fuel cell H₂O LINE HEATER switch (Figure 3-14) enables selection of the first string of heaters by placing the switch in the A AUTO position or selection of the second string of heaters by placing the switch in the B AUTO position.

The water relief line is also wrapped with two sets of thermostatically controlled heaters to keep the relief line warm in case the primary and alternate water relief paths should fail. The H₂O RELIEF HEATER switch (Figure 3-14) can be used to select the A or B heaters.

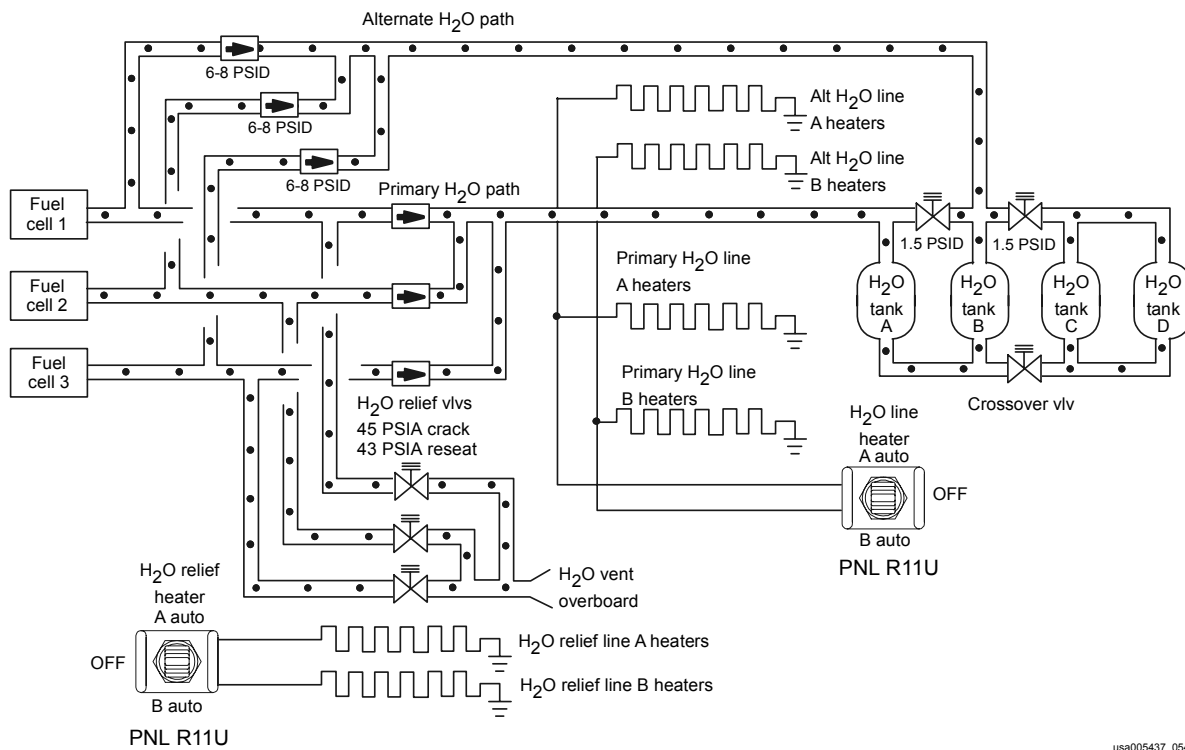


Figure 3-14. Water line heaters

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3.5.2 Fuel Cell Instrumentation

Fuel cell instrumentation can be divided into instrumentation for the stack and instrumentation for the accessory section. Instrumentation for the stack consists of a voltage sensor and a current sensor. Instrumentation for the accessory section can be broken down into cryo supply, water removal, purge, coolant loop, cell performance monitor, and ECU instrumentation. Each of these categories is discussed separately in the following sections. For each category, a figure is supplied showing the location of the sensors and listing all displays and meters on which the data are displayed.

3.5.2.1 Cryo Supply Instrumentation

Instrumentation for the cryo supply consists of O₂ and H₂ flow and reac valve status (Figure 3-15). Because of the importance of maintaining cryo flow to the fuel cells, the reac valve status sensors drive the FUEL CELL REAC C&W light as well as the reac valve talkbacks and the displays shown. With ascent power loads, a fuel cell will fail within approximately 20 seconds if it loses H₂ flow and within 90 seconds if it loses O₂ flow.

The pressure of the cryo supplied to the stack cannot be directly observed. However, there is a pressure sensor on the coolant loop that measures coolant pressure at the accumulator (Figure 3-15). Because of the operation of the accumulator, the pressure of the coolant is the same as the pressure of the O₂ supplied to the stack. The pressure of the H₂ supplied to the stack is 1 to 2 psia below the O₂ pressure because of the operation of the dual-gas regulator.

3-25

3.5.2.2 Water Removal Loop Instrumentation

Instrumentation for the water removal loop consists of sensors for determining the status of the hydrogen pump/water separator; the temperature of the H₂/water mixture leaving the condenser; the temperature of the water removal paths, relief line, and nozzles; and sensors for determining water purity. The status of the H₂ pump (Figure 3-16) is given as a voltage value that indicates whether the pump is running properly and whether it is running on two phases. These voltage values are listed in Table 3-1. (Alternating current phases are discussed in a later section about the EPDC subsystem.)

Table 3-1. Hydrogen pump/water separator status

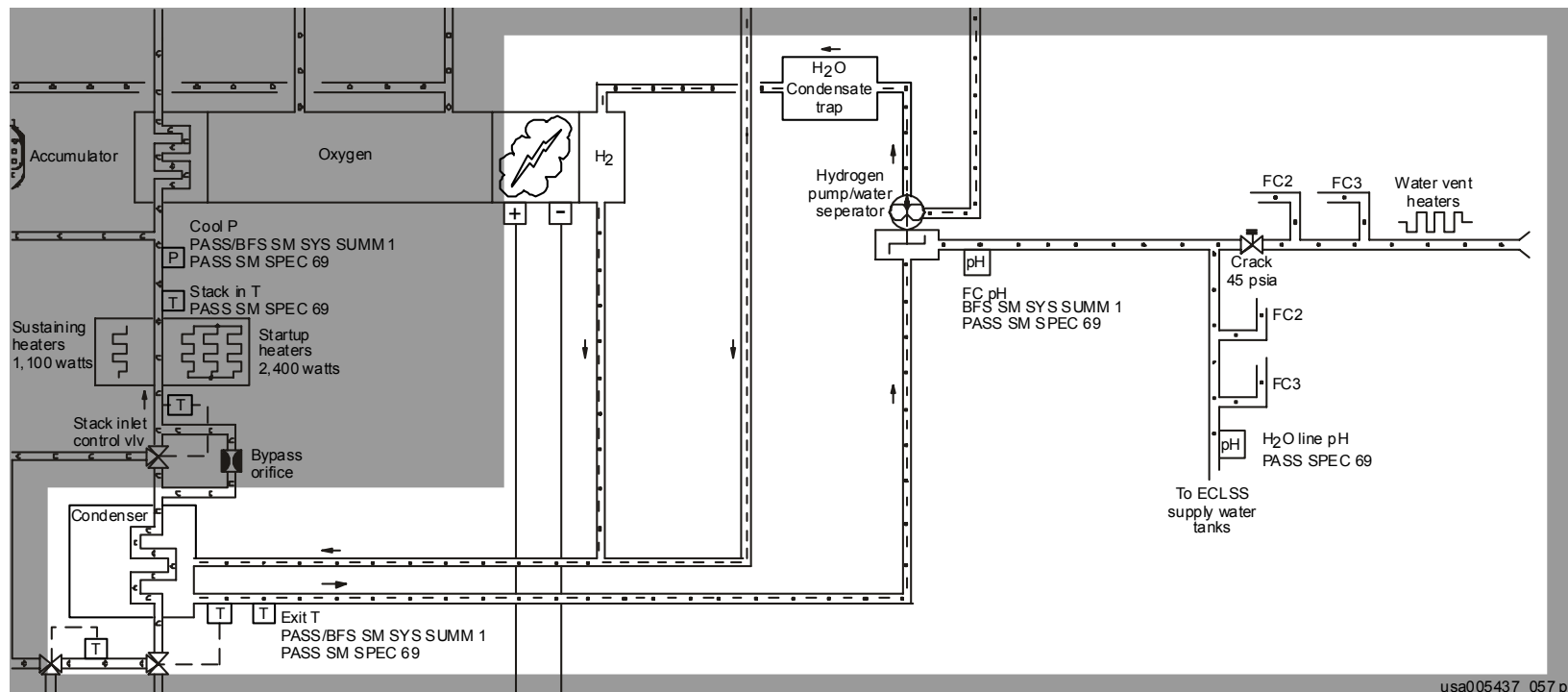
Status	Voltage
Normal three-phase operation	0.28 to 0.65
Overload (three-phase)	> 0.8
Stall (three-phase)	2.2
Two-phase operation due to open motor winding	3.15 to 3.5
Two-phase operation due to open circuit breaker	4.15 to 4.5
Stall (two-phase)	4.8

The condenser exit temperature sensor provides the temperature of the H₂/water mixture as it leaves the condenser. If the condenser and the coolant loops are working correctly, this temperature should be maintained at approximately 150° F.

At the exit of the H₂ pump/water separator, there is a water purity sensor (Figure 3-16) to detect possible KOH contamination, indicating a fuel cell problem. The sensor measures the conductivity of the water. If KOH is present, the water will exhibit increased conductivity. Since KOH also increases the pH of the water, these sensors are referred to as pH sensors.

At the primary water line, there is another pH sensor, known as the common pH sensor, which also checks for the presence of KOH (Figure 3-16). If KOH escapes from a fuel cell, the pH indication for that fuel cell and the common pH indication should both occur. The common pH indication will be delayed from the fuel cell pH indication until the contaminated water flows past the common pH sensor about 10 minutes later.

The pH sensors have a self-test feature. When the sensor is initially powered, the sensor will give a high pH indication for 20 to 30 seconds. The self-test happens whenever a fuel cell is started.

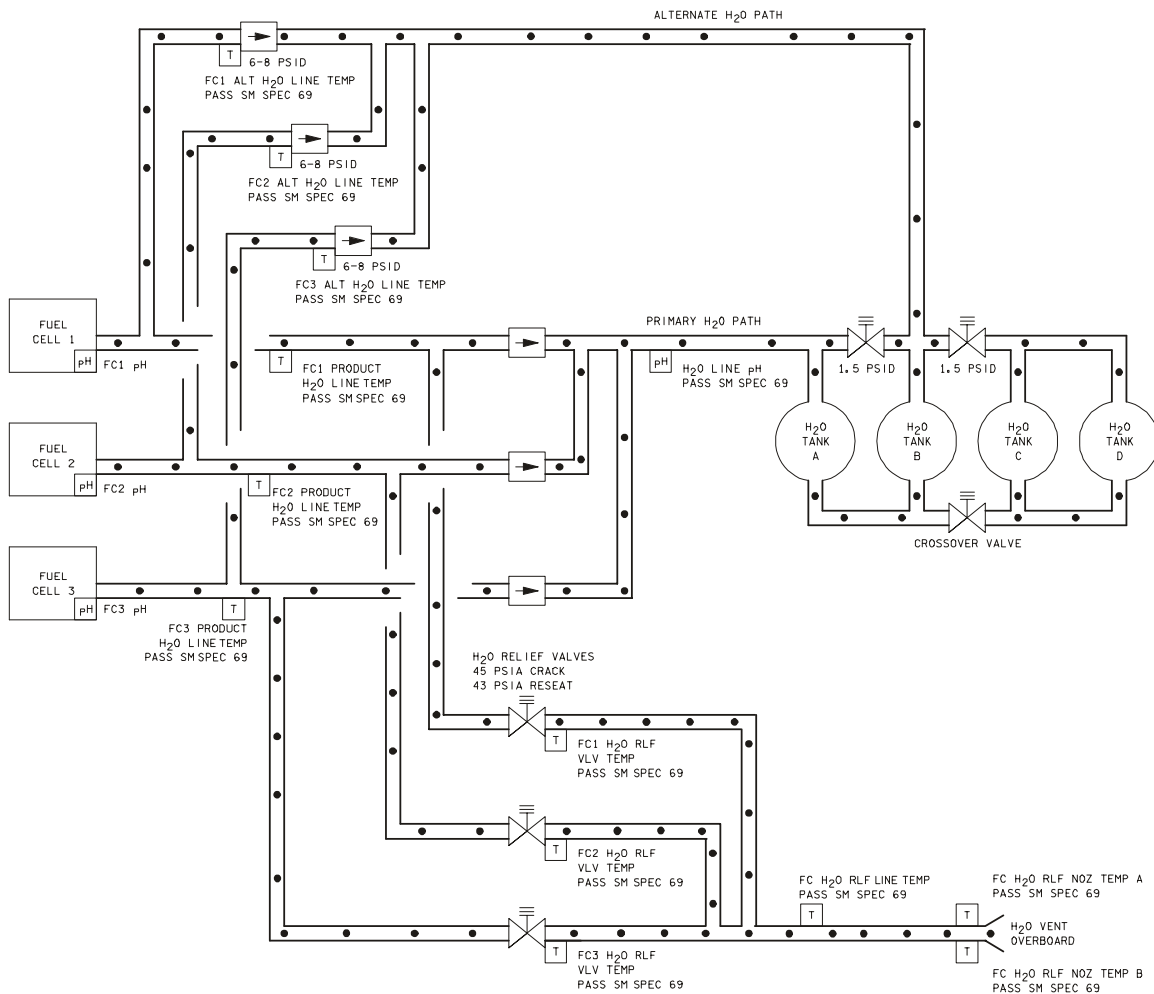


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Figure 3-16. Water loop instrumentation

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The primary and alternate water paths and the water relief line are instrumented with temperature sensors so that they can be monitored to ensure that they are not freezing (Figure 3-17). A temperature sensor is on each of the primary and alternate water paths from each fuel cell. A temperature sensor is also on the water relief valve for each fuel cell. Only one temperature sensor is on the relief line. It is placed after the point at which the fuel cell relief lines merge into the common overboard line. The relief nozzle has two temperature sensors.

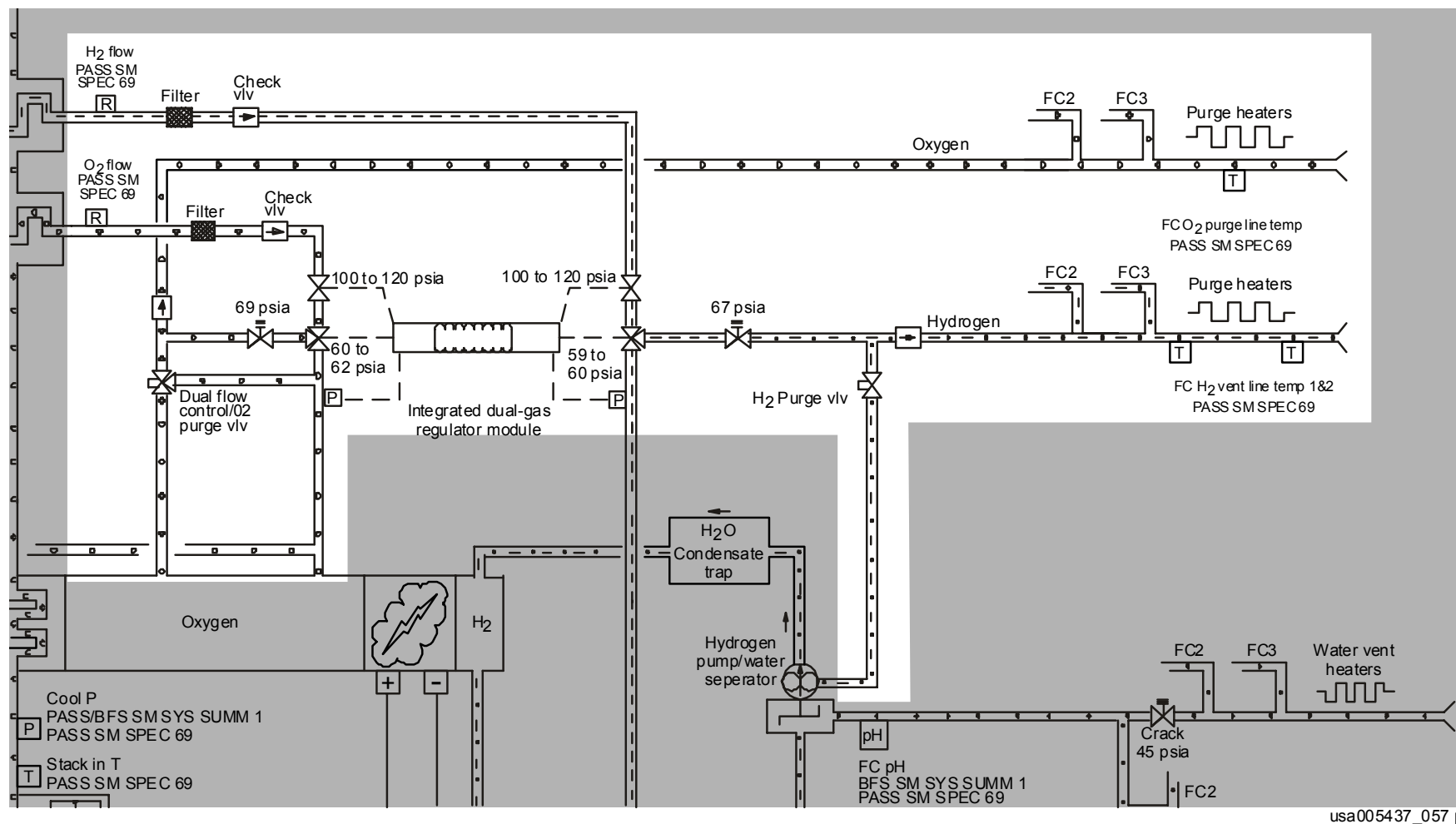


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Figure 3-17. Water removal path temperature and pH instrumentation

3.5.2.3 Purge System Instrumentation

The operation of the purge system is monitored by watching the cryo flows to verify the purge occurs and by watching the purge line temperatures to verify that the purge lines are not freezing (Figure 3-18). Two temperature sensors are on the H₂ purge lines because the H₂ contains water vapor. The temperatures of the lines indicate whether the purge heaters are working. An increase in O₂ and H₂ flows indicates that the purge valves have opened, and a corresponding decrease indicates that the purge valves have closed.



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Figure 3-18. Purge system instrumentation

3.5.2.4 Coolant Loop Instrumentation

Instrumentation for the coolant loop measures the delta pressure across the coolant pump, the temperature of the coolant returning from the fuel cell heat exchangers, the coolant pressure, and the temperature of the coolant leaving the stack (Figure 3-19). The temperature of the H₂/water mixture leaving the condenser is also a good indication of whether the coolant loop is working properly.

The coolant pump delta pressure sensor provides a status indication of whether the pressure across the pump is sufficient for good coolant flow. Because of the importance of maintaining coolant flow, this sensor drives the FUEL CELL PUMP C&W light as well as the COOLANT PUMP ΔP talkback and the displays shown in Figure 3-19. If coolant flow stops and the fuel cell continues to produce power, the stack can overheat within 9 minutes if it is producing the high power levels required during ascent.

The temperature of the coolant returning from the fuel cell heat exchanger is known as the coolant return temperature (Cool T). This temperature is read in the coolest part of the loop.

The coolant pressure sensor (Cool P) provides the pressure of the coolant loop. Because of the operation of the accumulator, this pressure should be the same as the pressure of the O₂ entering the stack. Since the O₂ pressure is controlled to approximately 60 psia, the coolant pressure should also be approximately 60 psia.

The temperature of the coolant leaving the stack, known as stack out T, gives an indication of the operating temperature of the stack. The flow control valve throttles coolant flow which keeps stack out T around 200° F. The stack out T sensor is located outside the stack near the O₂ preheater. With the coolant pump running, stack out T is approximately the temperature of the stack. If the coolant flow stops, cryogenic O₂ flowing through the preheater will cause the stack out T reading to decrease even though the temperature of the stack is increasing. The stack out T sensor drives the FUEL CELL STACK TEMP C&W light, as well as a meter and the displays specified in Figure 3-19.

The condenser exit temperature, known as exit T, mentioned in the section on water removal loop instrumentation, is also a good indication of coolant loop operation. If the coolant loop should fail, the H₂/steam mixture entering the condenser would no longer be cooled and the exit T would rapidly increase to around 200° F.

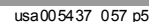


Figure 3-19. Coolant loop instrumentation

3.5.2.5 Electrical Control Unit Instrumentation

The instrumentation for the ECU consists of the COOLANT PUMP ΔP and READY FOR LOAD talkbacks next to the START/STOP switch, and a status flag indicating that the fuel cell is ready for load (Figure 3-20). Other than these talkbacks, correct operation of the ECU must be inferred from correct operation of the pumps, the heaters, and the crew interfaces that it controls.

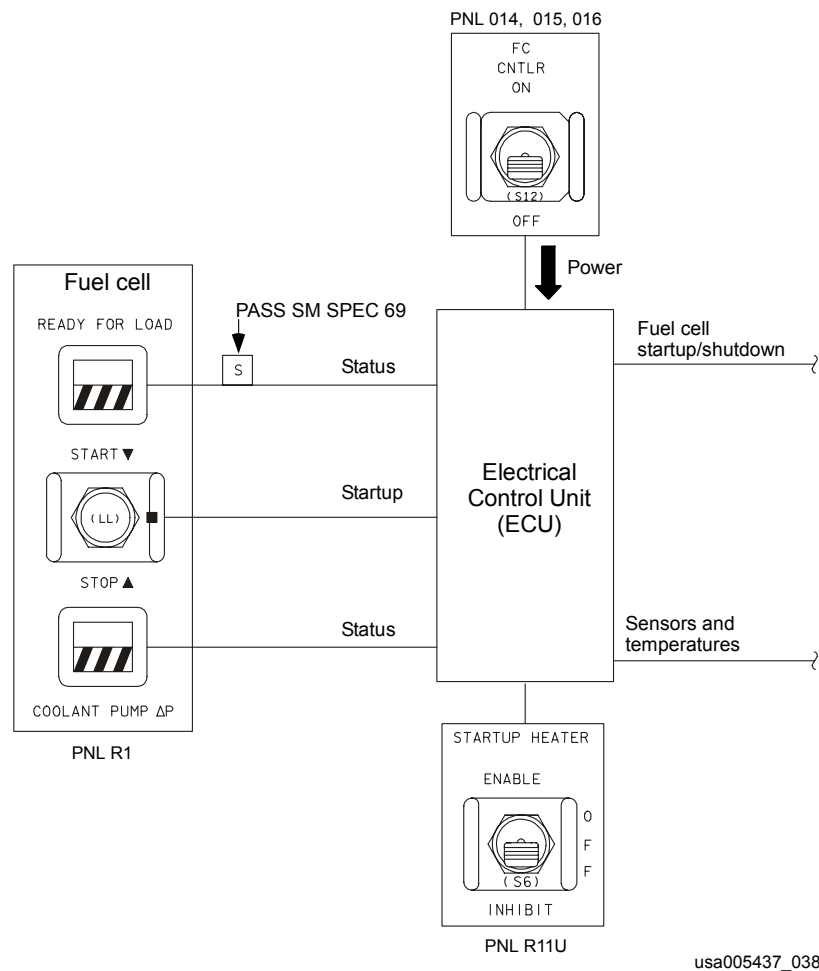


Figure 3-20. Fuel cell ECU instrumentation

3.5.3 Crew Displays

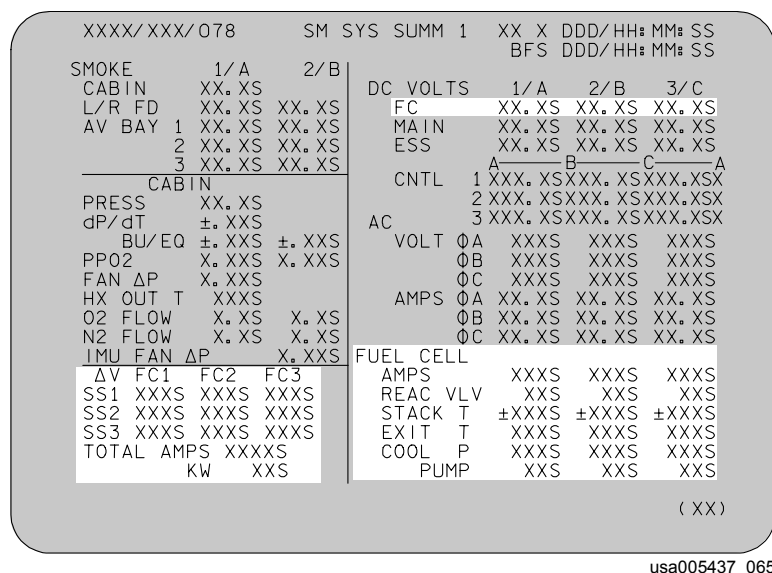
Table 3-2 summarizes the available displays that contain fuel cell information for each mission phase. Each of these displays is described in the following sections.

Table 3-2. Fuel cell displays

Mission phase	Display
Ascent/entry	BFS SM SYS SUMM 1
Orbit	PASS SM SYS SUMM 1
	PASS SM SPEC 69 FUEL CELLS

3.5.3.1 BFS and PASS SM SYS SUMM 1

PASS and BFS SM SYS SUMM 1 display the minimum information necessary to monitor the health of the fuel cells (Figure 3-21 and Figure 3-22). The fuel cell information of the PASS and BFS displays is identical except that the BFS display provides the fuel cell pH indications. The columns on the right side of the display are arranged such that the information for fuel cell 1 is under the column labeled 1/A, for fuel cell 2 under 2/B, and for fuel cell 3 under 3/C. The voltage and current generated by each fuel cell are displayed in these columns. At the bottom left of the display are GPC-calculated values for total fuel cell current and total fuel cell power.

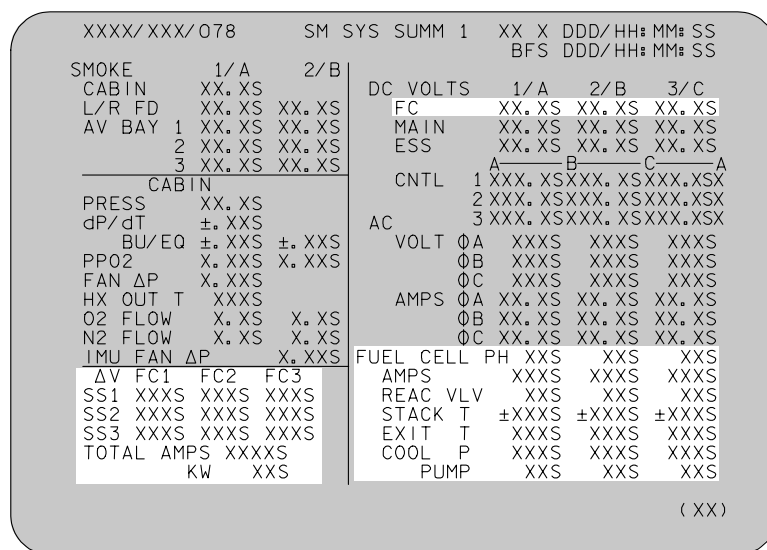


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Sensor name	Units	Displayed range	Status indicators				
ΔV SS 1, 2, 3	mvdc	0 to 500	M	H	L	↑	↓
TOTAL: AMPS	amps	0 to 1500	M				
kW	kW	0 to 60	M				
DC VOLTS: FC	volts	0 to 40	M	H	L	↑	↓
FUEL CELL: AMPS	amps	0 to 500	M	H	L	↑	↓
REAC VLV	text	'CL' or 'OP'	M				↓
STACK T	deg F	-75 to +300	M	H	L	↑	↓
EXIT T	deg F	0 to 250	M	H	L	↑	↓
COOL P	psia	0 to 100	M	H	L	↑	↓
PUMP	text	'ΔP' or 'blank'	M				↓

Figure 3-21. PASS SM SYS SUMM 1 display

The REAC VLV field provides status of the reac valves. If either reac valve for a fuel cell is closed, this field will show CL. If both valves are open, the field will show OP. The STACK T field provides the stack out T reading. The EXIT T field displays the condenser exit temperature. The COOL P field provides the pressure of the coolant loop at the accumulator. Because the accumulator keeps the coolant pressure the same as that of the O₂, it should stay close to 60 psia. The PUMP field is blank if the fuel cell coolant pump is working properly. If the coolant pump fails, this field will contain a ΔP and a down arrow. The cell performance monitor substack delta volt readings are displayed at the bottom left corner of this display. There are three substack readings for each fuel cell.



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Sensor name	Units	Displayed range	Status indicators				
ΔV SS 1, 2, 3	mvdc	0 to 500	M	H	L	↑	↓
TOTAL: AMPS	amps	0 to 1500	M				
kW	kW	0 to 60	M				
DC VOLTS: FC	volts	0 to 40	M	H	L	↑	↓
FUEL CELL: pH	text	'pH' or 'blank'	M				↓
AMPS	amps	0 to 500	M	H	L	↑	↓
REAC VLV	text	'CL' or 'OP'	M				↓
STACK T	deg F	-75 to +300	M	H	L	↑	↓
EXIT T	deg F	0 to 250	M	H	L	↑	↓
COOL P	psia	0 to 100	M	H	L	↑	↓
PUMP	text	'ΔP' or 'blank'	M				↓

Figure 3-22. BFS SM SYS SUMM 1 display

3.5.3.2 PASS SM SPEC 69 FUEL CELLS

On orbit, the SM SPEC 69 FUEL CELLS display (Figure 3-23) contains all fuel cell information available onboard. Fuel cell voltage, current, STACK T, EXIT T, COOL P, and COOL PUMP are the same as on SM SYS SUMM 1. Cryo flow rates are given, followed by the individual status of the reac valves (Figure 3-15).

COOL T is the coolant return temperature (Figure 3-19) as it returns from the fuel cell heat exchangers. The H₂ PUMP status displays a voltage that indicates the health of the hydrogen pump/water separator (Table 3-1). The READY field displays RDY when the fuel cell is up and ready for load. If the ECU is stopped, this field will show OFF.

The bottom left of SPEC 69 provides the temperature of the primary and alternate water lines going to the supply water tanks (Figure 3-17). Between these values is the temperature of the overboard relief valves. To the top right of the display are the temperature of the relief line and two measurements of the relief nozzle temperature (Figure 3-17). The HTR SW field repeats the position of the H₂O RELIEF HEATER switch on Panel R12.

The O₂ and H₂ purge line temperatures (Figure 3-18) are displayed below the water relief line information. Below the purge line temperatures is the status of the common pH sensor (Figure 3-17). If a pH problem occurs, this field will contain pH and a down arrow. The individual fuel cell pH sensor readings (Figure 3-17) are provided just above the fuel cell substack delta volts at the bottom right of the display.

The substack delta volts are the same as on SM SYS SUMM 1. Below these readings are GPC-calculated values for the differences between the fuel cell currents. The value in the first column is fuel cell 1 current minus fuel cell 2 current. The second column contains fuel cell 2 current minus fuel cell 3 current, and the third column contains fuel cell 3 current minus fuel cell 1 current.

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			XXXS	
AMPS				XXXX	XXXX	XXXX	NOZ T A			XXXS	
							B			XXXS	
FLOW O2				XX.XS	XX.XS	XX.XS	HTR SW			XXXS	
H2				X.XS	X.XS	X.XS	PURGE LN O2 T			XXXS	
REAC O2				XXS	XXS	XXS	H2 T1			XXXS	
H2				XXS	XXS	XXS	T2			XXXS	
							H2O LINE PH			XXS	
STACK T				±XXXX	±XXXX	±XXXX					
EXIT T				XXXX	XXXX	XXXX					
COOL T				XXXX	XXXX	XXXX					
P				XXXX	XXXX	XXXX					
PUMP				XXS	XXS	XXS					
H2 PUMP				X.XS	X.XS	X.XS	PH				
READY				XXXX	XXXX	XXXX	ΔV SS1			XXXS	
							SS2			XXXS	
							SS3			XXXS	
							ΔAMPS			±XXXX	
H2O											
PRI LN T				XXXX	XXXX	XXXX					
VLV T											
ALT LN T				XXXX	XXXX	XXXX					

(XX)

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Sensor name	Units	Displayed range	Status indicators				
FC: VOLTS	volts	0 to 40	M	H	L	↑	↓
AMPS	amps	0 to 500	M	H	L	↑	↓
FLOW O ₂	lbm/hr	0 to 15	M	H	L	↑	
H ₂	lbm/hr	0 to 2.5	M	H	L	↑	
REAC O ₂	text	'CL' or 'OP'	M				↓
H ₂	text	'CL' or 'OP'	M				↓
STACK T	deg F	-75 to +300	M	H	L	↑	↓
EXIT T	deg F	0 to 250	M	H	L	↑	↓
COOL T	deg F	0 to 250	M	H	L		
P	psia	0 to 100	M	H	L	↑	↓
PUMP	text	'ΔP' or 'blank'	M				↓
H ₂ PUMP	volts	0 to 5	M	H	L	↑	↓
READY	text	'OFF' or 'RDY'	M				↓
H ₂ O PRI LN T	deg F	0 to 250	M	H	L	↑	↓
VLV T	deg F	0 to 250	M	H	L	↑	↓
ALT LN T	deg F	0 to 250	M	H	L	↑	↓
RLF LINE T	deg F	0 to 250	M	H	L	↑	↓
NOZ T A,B	deg F	0 to 450	M	H	L	↑	↓
HTR SW	text	'A', 'B', 'A/B', 'OFF'	M				
PURGE LN O ₂ T	deg F	0 to 400	M	H	L	↑	
H ₂ T1, T2	deg F	0 to 400	M	H	L	↑	
H ₂ O LINE pH [1]	text	'blank' or 'pH'	M				↓
pH [1]	text	'blank' or 'pH'	M				↓
ΔV SS 1,2,3	mvdc	0 to 500	M	H	L	↑	
ΔAMPS [2]	amps	-500 to 500	M			↑	↓

Figure 3-23. SM SPEC 69 FUEL CELLS display

REMARKS

- [1] "pH" and "↓" appear when fuel cell pH is outside of normal range.
- [2] Fuel Cell Delta Amps are calculated by subtracting the current of FC2 from FC1, FC3 from FC2, and FC1 from FC3. The difference, positive or negative, is displayed as ΔAMPS 1, 2, and 3, respectively.

3.5.4 Nominal Operations

When the crew enters the vehicle, the fuel cells are already activated and producing power; however, the vehicle is being powered by both the fuel cells and the GSE until 5 minutes before launch. As the GSE stops supplying power to the vehicle, the fuel cells automatically pick up the extra load.

For ascent and entry, no crew actions are required for the fuel cells. Orbit operations consist of an FCMS data take, switching heaters, and performing fuel cell purges. Usually on flight day two, a crewman will perform an FCMS data take to provide a history of fuel cell performance in case of a subsequent problem. At approximately midmission, the water line heaters and the water relief line heaters are switched from the A heaters to the B heaters. This action is done to check the redundant heaters on orbit to reduce vehicle turnaround time on the ground. Auto fuel cell purges are normally commanded from the ground so that the crew does not have to do any purges. However, at midmission, they will do one manual purge. The manual purge is done to verify manual purge capabilities. Checking manual purge capabilities is important since the purge line heaters used during a manual purge are different from those used during an auto purge. The procedures for an auto and a manual purge are discussed in the following sections.

3.5.4.1 Manual Purge

A manual purge is accomplished using the PURGE HEATER and PURGE VALVE switches on Panel R12 (Figure 3-18). To start the purge, the PURGE HEATER is taken to the ON position. This action will begin heating the O₂ and H₂ purge lines. The temperatures of these lines are monitored on PASS SM SPEC 69 FUEL CELLS (Figure 3-23).

Once the lines are heated sufficiently, the PURGE VALVE switch for fuel cell 1 is taken to the OPEN position. When this is done, the O₂ and H₂ flows on SPEC 69 are checked to verify that they have increased, indicating a good purge flow. This valve is left open for 2 minutes; the switch is then taken to the GPC position, which causes the valve to close. Once the valve closes, the O₂ and H₂ flows on SPEC 69 are again checked to verify that they have decreased, indicating closure of the purge valves. This procedure is then repeated for the fuel cell 2 and 3 purge valves. After fuel cell 3 is purged, the purge line heaters are left on for 30 minutes to bake out any moisture that may be left in the line. After the 30-minute interval, the PURGE HEATER switch is taken to the GPC position, turning off the heaters.

Several constraints must be followed during a fuel cell purge. First, and absolutely most important, is that only one fuel cell should be purged at a time. If all three fuel cells are purged simultaneously, the sizing of the H₂ purge line could cause a backpressure, resulting in an H₂ pressure greater than O₂ pressure. As mentioned previously, the dual-gas regulator should take care of this problem and keep the O₂ pressure greater than the H₂ pressure in the fuel cell. However, if a design flaw in these regulators allowed the H₂ pressure to increase above the O₂ pressure, the KOH electrolyte in the fuel cells would be forced out of the storage plates and all three fuel cells could fail at the same time.

The second constraint is that a fuel cell should not be purged if it is producing a current greater than 350 amps. At such a high power level, any additional flow would overcome the preheaters ability to warm the cryo, which could result in the dual gas regulator freezing up.

Third, a fuel cell that is shut down should not be purged. When a fuel cell is shut down, the reac valves are closed. If the fuel cell is purged with closed reac valves, the cryo left in the stack will be vented overboard, exposing the stack to a vacuum. This condition will dry out the KOH electrolyte and ruin the fuel cell.

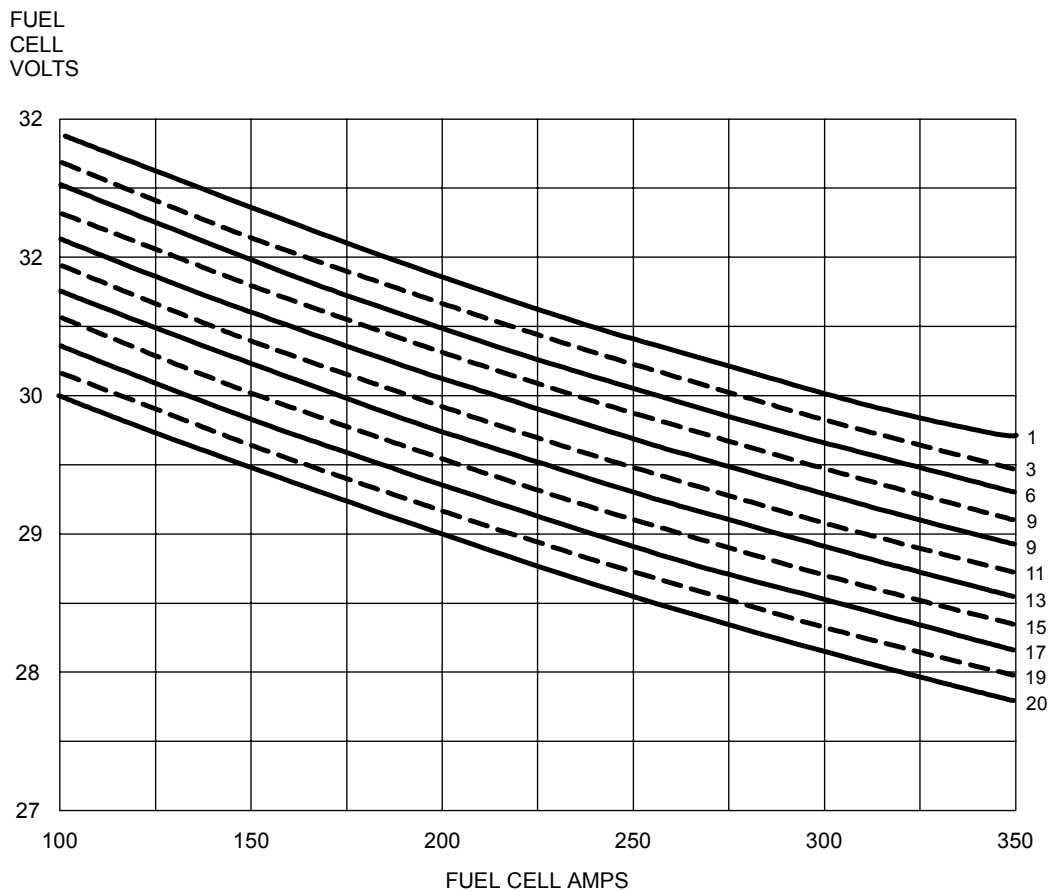
The final constraint is that a fuel cell should not be purged within 3 hours of deorbit burn. The purge line nozzles are heated to relatively high temperatures in the 30-minute bakeout period at the end of the purge. If these nozzles do not have time to cool, the extra heating of entry can cause damage to the structure around the nozzles.

3.5.4.2 Auto Purge

For an AUTO purge, the PURGE HEATER and PURGE VALVE switches on Panel R11U (Figure 3-21) are placed in the GPC position. To initiate the purge, the GPC PURGE SEQ switch is held in the START position UNTIL 3 SECONDS AFTER the GPC PURGE SEQ ON talkback goes from barberpole to gray. The switch must be held the extra 3 seconds for the GPC to properly initiate the purge. Once the purge is initiated, the GPC turns on the purge heaters, waits for the purge line temperatures to increase, purges the fuel cells for 2 minutes each, and then bakes out the lines for 30 minutes. When the purge heaters are turned off at the end of the sequence, the GPC PURGE SEQ ON talkback will go back to barberpole, indicating that the purge sequence is complete.

In addition to the limitations on manual purges, an extra limitation is placed on auto purges. An auto purge should not be initiated within 1 hour of a transition out of the operational software that is controlling the purge (OPS 2). If a transition should occur while a purge is in progress, the purge would be terminated prematurely. If purging had already occurred and the purge lines did not receive sufficient bakeout, moisture in the line could freeze and cause a blockage in the O₂ or H₂ vent line.

Early in the mission, the fuel cell voltages and currents are plotted on the fuel cell performance chart (Figure 3-24). This chart contains several curves that represent the typical relationship between fuel cell voltage and fuel cell current. Because of differences in age and tolerances, different fuel cells will probably follow different curves. The voltage of each fuel cell will be plotted against its current. Each point should be on or near one of the curves drawn. If the fuel cell is operating properly and purges are being done properly, the voltage and current relationship for that fuel cell should stay on or near the same curve that it started on. However, if a fuel cell starts degrading, a later plot of fuel cell voltage versus current may be on a lower curve. If the performance of the fuel cell should drop by 0.5 V, a significant degradation is occurring. This measurement provides the crew with insight into fuel cell health and would be especially important for fuel cell problems that occur during periods of no communication with ground controllers.



Notes: Record FC performance after first on-orbit purge. Select a curve for each FC. A drop of 0.5 volts below a selected curve during a subsequent check indicates a degraded FC.

0 = FC1

X = FC2

Δ = FC3

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Figure 3-24. Fuel cell performance plot

Questions

Answers provided in Appendix B

1. What is the purpose of the fuel cell subsystem?

2. The fuel cells are located in

- a. The crew cabin
- b. The external tank
- c. The payload bay
- d. All of the above
- e. None of the above

3. The byproducts of the reaction in the fuel cell are

- a. Hydrogen and oxygen
- b. Nitrogen
- c. Potassium hydroxide (KOH)
- d. Water and heat
- e. None of the above

4. During a manual purge of the fuel cells, all three fuel cells should be purged at the same time.

True or False

5. During a fuel cell purge, the fuel cell should not be purged if the current is greater than 350 ampsA.

True or False

6. One manual purge is done during a mission since the heaters used for a manual purge are separate from the heaters used for an auto purge and they need to be checked out.

True or False

7. Match the following fuel cell components to their functions.

- | | | |
|--|-------|--|
| a. Fuel cell stack | _____ | 1. Allow extra cryo flow to remove contaminants from stack |
| b. Cryo preheaters | _____ | 2. Contains startup logic, thermostats, relays, and timers for control of fuel cell |
| c. Dual-gas regulator | _____ | 3. Uses hot coolant from stack to heat cryo as it enters the fuel cell |
| d. Condenser | _____ | 4. Heats coolant during initial fuel cell startup to bring stack up to operating temperature |
| e. H ₂ pump/water separator | _____ | 5. Uses coolant to cool H ₂ /steam mixture coming out of the stack so that water can be removed |
| f. Purge valves | _____ | 6. Decreases cryo pressures to approximately 60 psia with O ₂ pressure maintained a few psia greater than H ₂ pressure |
| g. Coolant pump | _____ | 7. Monitors substacks to detect cell degradation |
| h. Startup heater | _____ | 8. Keeps pressure of coolant equal to pressure of O ₂ |
| i. Sustaining heater | _____ | 9. Contains electrochemical cells which produce electricity |
| j. Accumulator | _____ | 10. Adds heat to coolant when stack is cooling off due to fuel cell operating at low power levels |
| k. Cell performance monitor | _____ | 11. Separates water from H ₂ /water mixture and sends water to ECLSS supply water tanks |
| l. Electrical control unit | _____ | 12. Causes coolant to flow through coolant loop |

4.0 ELECTRICAL POWER DISTRIBUTION AND CONTROL SUBSYSTEM

4.1 OBJECTIVES

The student should be prepared to accomplish the following tasks as a result of studying this section of the workbook.

- a. Describe the purpose of the EPDC subsystem.
- b. Match the electrical control assemblies to their purpose.
- c. Identify the power sources of the electrical buses.
- d. Understand nominal operations of the EPDC subsystem.

4.2 EPDC SUBSYSTEM OVERVIEW

The architecture of the wires and distribution assemblies on the orbiter is similar to the electrical system in your home. Power from your electricity provider goes to the circuit breaker box on the back of your house. The circuit breaker box is basically a distribution assembly. One set of wires feeds power into the box and many sets of wires feed out of the box, protected by circuit breakers. In the circuit breaker box, power goes through circuit breakers and feeds to various parts of the house. If there is a short circuit in the toaster, the circuit breaker feeding the toaster will trip, isolating the short from the rest of the electrical system. Circuit breakers are fault protection devices. They prevent a problem in one part of the electrical system from affecting the rest of the system.

The purpose of the EPDC subsystem is to distribute power generated by the fuel cells to the electrical loads. Power is routed to the forward, mid, and aft sections of the orbiter by sets of wires and distribution assemblies known as buses. Referring to the house analogy, a bus on the orbiter is similar to the wires and circuit breaker box that feed power throughout the house.

4.3 ELECTRICAL CONTROL ASSEMBLIES

A network of electrical control assemblies is placed in the forward, mid, and aft areas of the orbiter. Each assembly receives power from one or more buses and feeds power to the electrical loads in its area of the orbiter. There are four types of assemblies with different purposes as shown in Table 4-1.

Table 4-1. Electrical control assemblies

Electrical assembly	Purpose
Distribution Assembly (DA)	Distribute power from the fuel cells to the forward, mid and aft sections of the orbiter
Power Control Assembly (PCA)	Power sub assemblies and larger DC loads
Load Control Assembly (LCA)	Power smaller DC loads
Motor Control Assembly (MCA)	Power noncontinuous AC loads

4.4 REMOTE SWITCHING DEVICES

In general, loads requiring constant power are fed by a fuse or circuit breaker, and loads requiring intermittent power are fed by some sort of remote switching device. The type of remote switching device used is determined by the power requirement of its associated load.

a. Power contactors

A power contactor (Figure 4-1) is a heavy-duty switch that is driven open and closed by a motor. Power contactors are used to connect the fuel cells to the main buses, to connect a fuel cell or main bus to the primary payload bus, or to tie one main bus to another main bus.

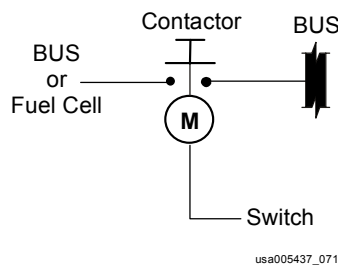


Figure 4-1. Power contactor

b. Remote Power Controllers

A Remote Power Controller (RPC) (Figure 4-2) is a remotely controlled electronic switch with overcurrent protection. Applying a control signal (C) to the RPC allows power (P) to flow through it, turning on the load. Removing the control signal interrupts the power, turning the load off. If too much current is drawn from an RPC, it will limit its current output to 150 percent of its rated current capacity. If this high current continues for approximately 3 seconds, the RPC will automatically trip off as if a circuit breaker opened. If an RPC trips off, it can be reset by removing and then reapplying the control signal.

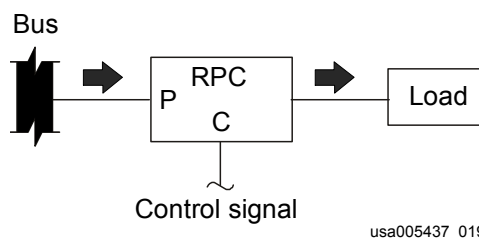


Figure 4-2. Remote power controller

c. Relays

Relays (Figure 4-3) are used as a switch to connect a power source to a load. The relay is closed and opened by applying or removing a control signal to a solenoid as illustrated in Figure 4-3.

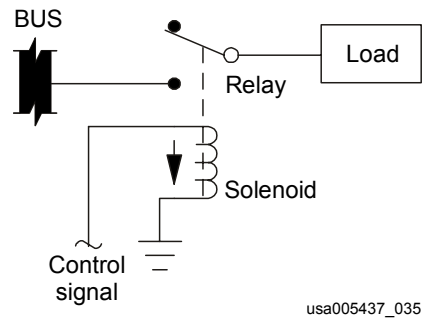


Figure 4-3. Relays

d. Hybrid circuit drivers

Hybrid circuit drivers (Figure 4-4) are used to connect power to smaller DC loads. Hybrid circuit drivers are electronic switches with one or more inputs. Their use can allow a load to be controlled by multiple sources such as a crew switch, GPC, or GSE.

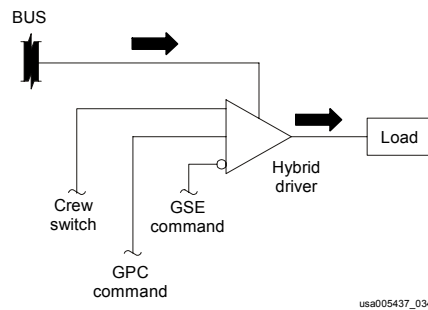


Figure 4-4. Hybrid drivers

4.5 ELECTRICAL BUSES

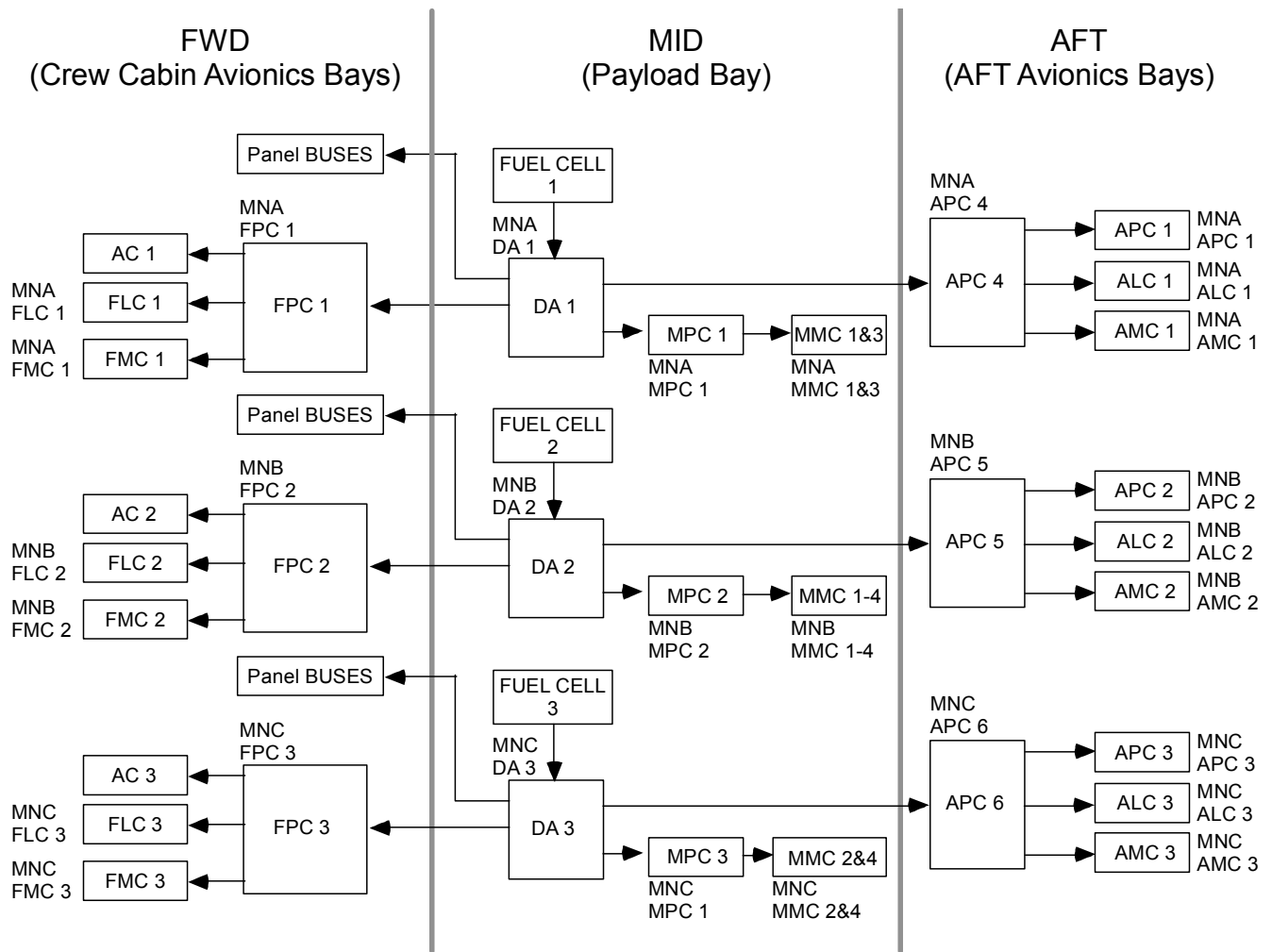
Various buses are used to distribute power to the electrical assemblies and loads (Table 4-2). The primary sources of DC power are three main buses labeled main (MN) A, MN B, and MN C. Crew controls and electrical loads deemed essential to crew and vehicle safety are powered by three essential (ESS) buses labeled ESS 1BC, ESS 2CA, and ESS 3AB. Nine control (CNTL) buses labeled CNTL AB1, AB2, AB3; CNTL BC1, BC2, BC3; and CNTL CA1, CA2, CA3 supply power for switches and DC logic. Power for AC loads is provided by three AC buses: AC1, AC2, and AC3. Various payload buses provide power to payloads in the crew cabin and payload bay. Each of these bus systems is discussed separately in the following sections.

Table 4-2. Electrical buses

Bus type	Bus names		
Main bus	MN A	MN B	MN C
Essential bus	ESS 1BC	ESS 2CA	ESS 3AB
Control bus	CNTL AB1 CNTL BC1 CNTL CA1	CNTL AB2 CNTL BC2 CNTL CA2	CNTL AB3 CNTL BC3 CNTL CA3
AC bus	AC1	AC2	AC3
Primary payload bus		PL PRI	
Aft payload bus	-	PL AFT MN B	PL AFT MN C
Auxiliary payload bus	PL AUX		-
Cabin payload bus	PL CAB MN A	PL CAB MN B	-
AC payload bus	-	AC2 PL 3 ϕ	AC3 PL 3 ϕ

4.5.1 Main Buses

MN A, MN B, and MN C are the primary sources of DC power for the electrical loads and assemblies. Each main bus originates in a distribution assembly and receives power from a dedicated fuel cell (Figure 4-5). MN A receives power from fuel cell 1 through a power contactor in DA 1, MN B from fuel cell 2 in DA 2, and MN C from fuel cell 3 in DA 3.



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Figure 4-5. Main bus distribution

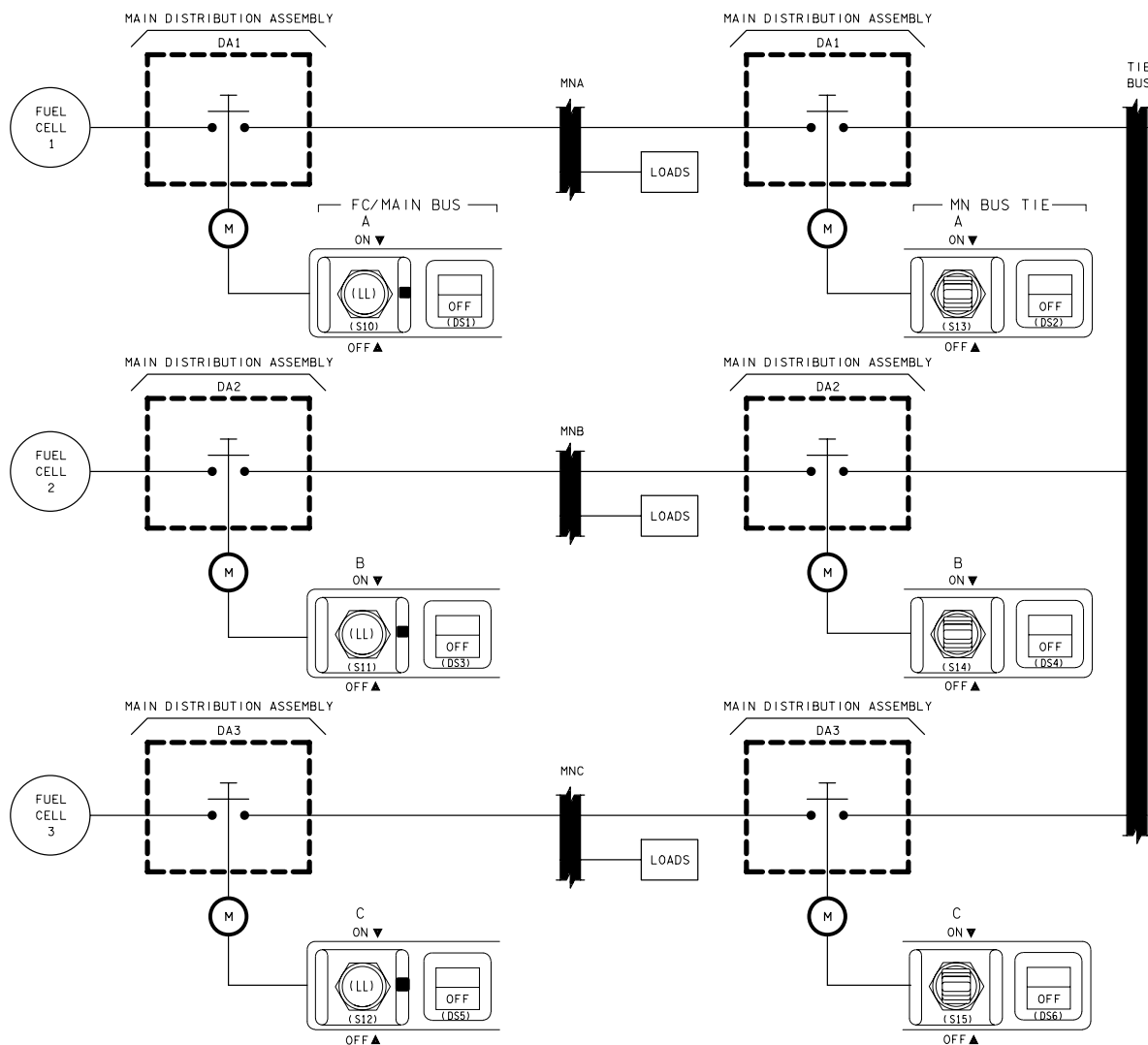
Each DA distributes power from the fuel cells to the Forward Power Controllers (FPCs), the Mid Power Controllers (MPCs), and the Aft Power Controllers (APCs). The PCAs supply power to large DC loads and other subassemblies in their area of the orbiter. Each FPC powers a Forward Motor Controller (FMC), a Forward Load Controller (FLC), and three AC inverters that power the AC buses. Each MPC powers Mid Motor Controllers (MMCs), and each APC powers an Aft Motor Controller (AMC), an Aft Load Controller (ALC), and another APC. The extra PCAs in the aft area of the vehicle are there because of the high number of large DC loads in that part of the vehicle. Power from the DAs is also distributed to panels in the crew cabin.

LCAs supply main bus power to small DC loads in their area of the orbiter. Because of the low number of DC loads in the mid section of the orbiter, there are no mid LCAs so the MPCs power all the mid DC loads.

There is a numbering convention for the electrical assemblies. All number 1 assemblies contain MN A as a power source, number 2 assemblies contain MN B as a power source, and number 3 assemblies contain MN C as a power source. The exception to this rule is the MMCs. MMC 1 and 3 receive power from MN A and MN B, and MMC 2 and 4 receive power from MN B and MN C. Also, APC 4, 5, and 6 receive power from MN A, B, and C, respectively.

4.5.2 Tie Bus

If the fuel cell powering a main bus fails, the bus can still remain powered by performing a "bus tie". Tying main buses is achieved by connecting the buses to the tie bus circuit (Figure 4-6). Power is then transferred between the buses across the tie bus. To perform a bus tie, the "bad bus" (the one with a fuel cell problem) is tied to a good bus. The tying convention is A to B, B to C and C to A. If fuel cell 2 has a problem, MN B is the "bad bus," so MN B is tied to MN C by taking the MN B bus tie switch to ON followed by the MN C bus tie switch.



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Figure 4-6. Tie bus

4.5.3 Essential Buses

Essential buses (ESS 1BC, ESS 2CA, and ESS 3AB) supply power to selected crew controls and electrical loads that are deemed essential to crew and vehicle safety. Examples of such essential loads are the fuel cell ECUs, the power supplies for the C&W system, and switches necessary to recover a failed fuel cell or bus. Each essential bus is powered by three redundant power sources (Figure 4-7). One power source is directly from a fuel cell through a fuse and a switch, and the other two power sources are from main buses through RPCs. An essential bus will receive sufficient power as long as one of the three power sources is connected and supplying power.

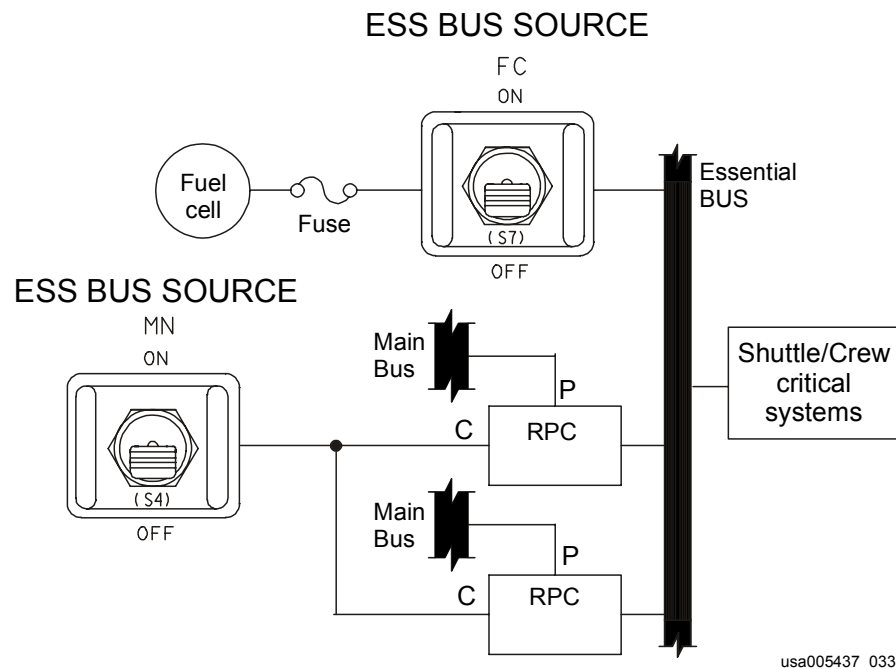
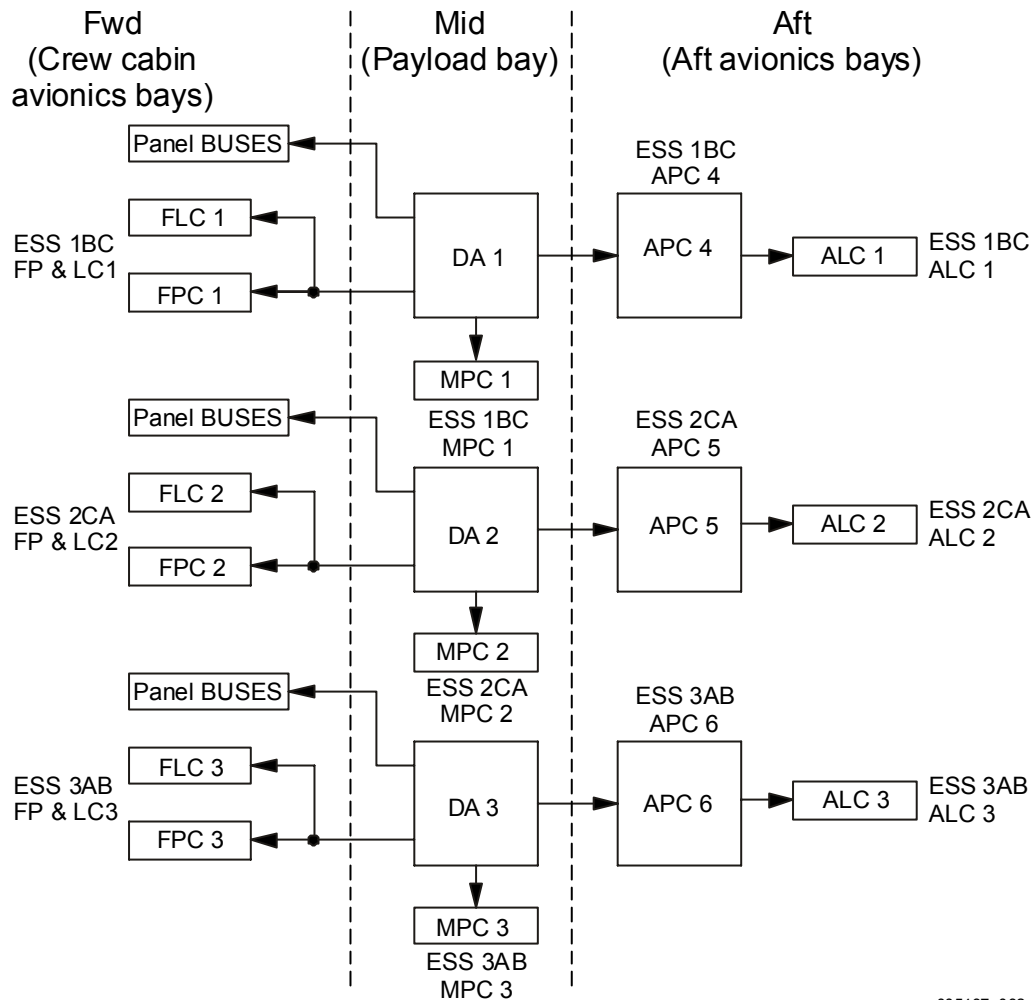


Figure 4-7. Essential bus power

The power sources for each essential bus are implied by the three characters of its name. The number (1, 2, 3) indicates the fuel cell that is powering the bus. The two letters indicate the two main buses that are powering the bus. For example, ESS 2CA is powered by fuel cell 2, MN C and MN A.

Essential bus distribution through the electrical assemblies is similar to main bus distribution. ESS 1BC is routed to number 1 assemblies, ESS 2CA to number 2 assemblies, and ESS 3AB to number 3 assemblies (Figure 4-8). The major differences are that the essential buses are not routed to the MCAs, and the FLC is powered from the DA rather than the FPC. Essential bus power is also routed to selected panels in the crew cabin.



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Figure 4-8. Essential bus distribution

4.5.4 Control Buses

Nine control buses (CNTL AB1, AB2, AB3; CNTL BC1, BC2, BC3; and CNTL CA1, CA2, CA3) supply power for switches. They do not supply the power for any electrical loads. They supply the control signal allowing other buses to power loads. Each control bus is powered by all three main buses (Figure 4-9). One power source is directly from a main bus through a circuit breaker and a fuse, and the other two power sources are from main buses through RPCs. A control bus will be sufficiently powered as long as at least one of the three sources is supplying power.

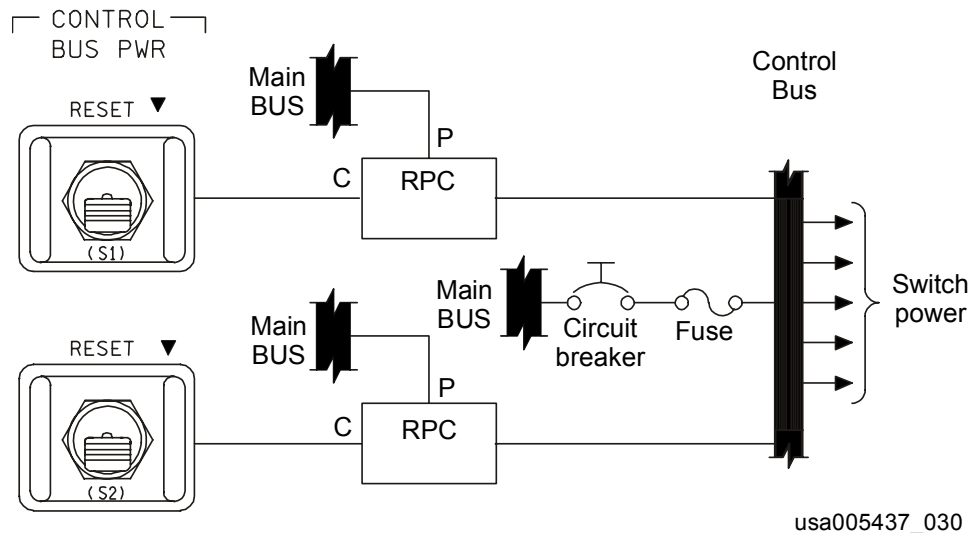


Figure 4-9. Control bus power sources

Control buses are routed differently than the main and essential buses. Since these buses are used only for switch and logic power, they are not routed through the electrical assemblies. Instead, they are just routed behind the panels in the crew cabin.

The naming conventions for the control buses are slightly different from those for the other buses. The two letters in the name indicate the two main buses that power the control bus through RPCs. The number does not indicate a power source; it distinguishes between the three control buses that receive power from the same sources. The third power source for a control bus comes through a circuit breaker and then a fuse from the main bus that is not specified in the name. For example, CNTL BC2 is powered by MN B and MN C through RPCs. Since A is not part of the name, CNTL BC2 is powered by MN A through a circuit breaker and a fuse. The "2" at the end of the name distinguishes CNTL BC 2 from the other buses powered in the same fashion, CNTL BC1 and CNTL BC3.

4.5.5 AC Buses

Three AC buses (AC1, AC2, and AC3) provide AC power to AC loads such as pumps and fans. Direct current power is converted to AC power using electronic inverters. Each inverter generates one AC output, known as a phase, that has a voltage waveform as shown in Figure 4-10. This voltage waveform is a sine wave that repeats at a frequency of 400 Hz and has a magnitude of 117 V rms. Each AC bus is a three-phase bus, so it has three single-phase AC buses powered by three separate inverters (Figure 4-11). The three phases for each AC bus are labeled phase A, phase B, and phase C.

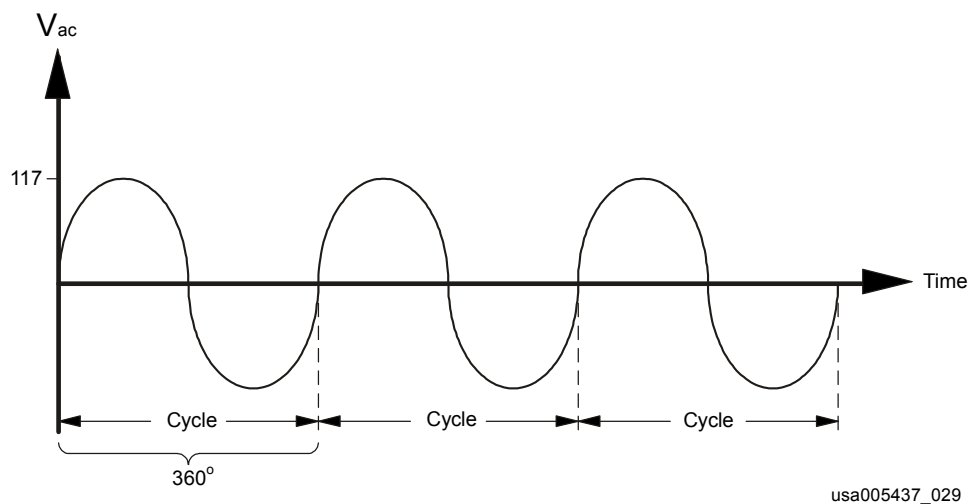


Figure 4-10. Alternating current voltage sine wave

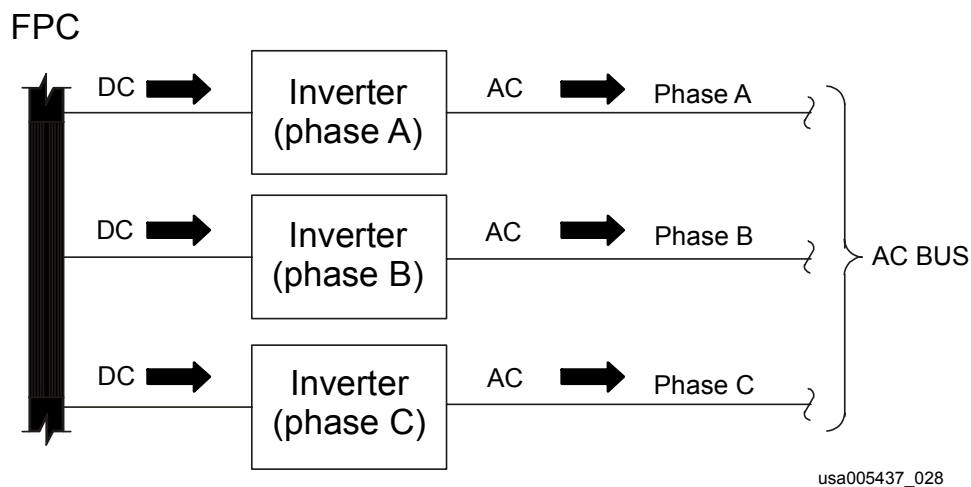


Figure 4-11. Three-phase AC bus

The three phases of a bus are not completely independent. The inverters are synchronized so that phase B lags one-third of the sine wave cycle after phase A and phase C lags one-third of a cycle after phase B, as shown in Figure 4-10. Since each

sine wave cycle is interpreted geometrically as consisting of 360° (Figure 4-12), each one-third of a cycle is 120° . Therefore, the three AC phases are described as being 120° out of phase.

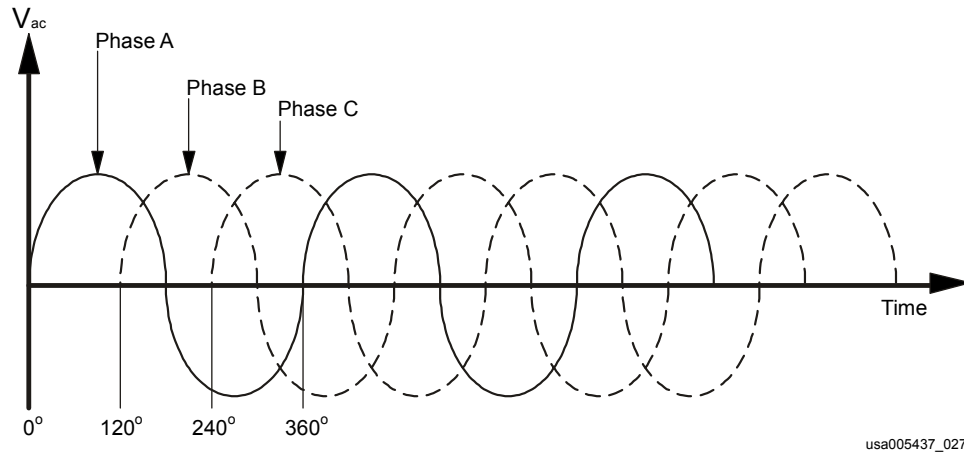


Figure 4-12. Three-phase voltage vs. time

A three-phase system has advantages over a single-phase system. These advantages are most apparent in the operation of motors. The power output of a motor varies with the input voltage. Since single-phase AC voltage is sinusoidal, the power output of a single-phase motor varies sinusoidally. A three-phase motor effectively combines three single-phase motors so that the power of one phase is peaking while the power of another phase is declining. This has the effect of averaging the available power and results in uniform motor output. The result is a three-phase motor that can do the same work as a single-phase motor and with lower peak current requirements.

Another advantage is that three-phase motors can be reversed electronically. If any two of the phases being fed to the motor are interchanged, the motor rotates in the opposite direction. Since many of the motors on the orbiter open and close valves, doors, and latches, this reversing scheme is essential. Three-phase motors also offer greater reliability since all the orbiter motors will continue to run on two of the three phases if one phase fails. All the motors, except those for the cabin fans, are also certified to start on two of three phases.

4.5.6 AC Bus Sensors

Each AC bus has an AC bus sensor that can provide annunciation of a high or low voltage or a high current and can disconnect a problem phase from the inverter. The sensor has two modes of operation: MONITOR and AUTO TRIP. In the MONITOR mode, the sensor will monitor the voltages and currents of the three phases of the AC bus. If the sensor detects a high or low voltage for any of the phases, the AC VOLTAGE light on the F7 annunciator panel will be lit, and if it detects excessive current, known as an overload, the AC OVERLOAD light on the F7 Panel will be lit. In the AUTO TRIP mode, the sensor will light the F7 lights and will also disconnect the affected phase from its inverter. The AC bus sensor does not disconnect a phase that

has a low voltage. The bus sensor can also be turned off so that it will not light the F7 lights and will not disconnect a problem phase from the inverter. The limits detected by the AC bus sensors are listed in Table 4-3.

Table 4-3. Alternating current bus sensor annunciation limits

F7 light	Annunciation limits
AC VOLTAGE	Volts < 102 to 108 V AC (for 6.5 to 8.5 sec) - or - Volts > 123 to 127 V AC (for 50 to 90 msec)
AC OVERLOAD	Amperes > 14.5 A (for 10 to 20 sec) - or - Amperes > 17.3 to 21.1 A (for 4 to 6 sec)

If the AC bus sensor is taken to OFF for 1 second and then to AUTO TRIP or MONITOR, the sensor will reset. This action will cause the F7 AC VOLTAGE and AC OVERLOAD lights to extinguish. If it is taken to AUTO TRIP and there is a preexisting overvoltage, the sensor will again light the F7 lights and trip the phase off automatically. However, if there is a preexisting overload, the sensor will not trip the phase off since it must see a transition from normal current to overload current while it is in AUTO TRIP.

4.5.7 Payload Buses

Various payload buses provide power to payloads in the crew cabin and payload bay (Table 4-4). The primary source of power for payloads in the payload bay is the primary payload bus. This bus can be powered from MN B, from MN C, or directly from fuel cell 3, but is normally powered by MN C.

Table 4-4. Payload buses

Payload bus	Maximum power
Primary Payload Bus (PL PRI)	7 kW (powered by MNC or fuel cell 3)/ 5 kW (powered by MNB)
Aft Payload B (AFT PLB)	2 kW
Aft Payload C (AFT PLC)	2 kW
Aux Payload A (AUX PLA)	0.4 kW
Aux Payload B (AUX PLB)	0.4 kW
Cabin Payload 1 (CABPL1)	15 A
Cabin Payload 2 (CABPL2)	15 A
Cabin Payload 3 (CABPL3)	15 A
AC2 Payload (AC2 PL 3 ϕ)	3 A/phase
AC3 Payload (AC3 PL 3 ϕ)	3 A/phase

Payloads in the back of the payload bay can also receive power from AFT PL buses, which are powered by MN B and MN C. There are also two auxiliary payload buses, AUX PLA and AUX PLB, which can be used to power emergency equipment or controls associated with payloads. These buses are powered by MN A and MN B, respectively.

There are three DC cabin payload buses, CABPL1, CABPL2, and CABPL3, which can be powered by MN A or MN B. These payload buses power payload-related equipment in the crew compartment or payload bay. There are also two AC payload buses, the AC2 payload bus and the AC3 payload bus, which can power AC payload-related equipment in the cabin.

4.6 CREW INTERFACES/CONTROLS

The crew interface to the EPDC subsystem consists of switches, talkbacks, circuit breakers, meters, and displays that allow the control and monitoring of electrical distribution. The function of controls and instrumentation for the electrical buses is covered in the following sections. Following this information is a description of the displays on which the EPDC data can be monitored.

4.6.1 EPDC Controls

The controls for the EPDC subsystem consist of switches that control the connection of power sources to buses and buses to loads as well as circuit breakers that provide circuit protection and connection of buses to loads. The bus-powering switches are discussed in the following subsections. Because of the large number of circuit breakers, they are not covered individually.

The controls for the main buses consist of switches and talkbacks for connecting the main buses to their dedicated fuel cells or for connecting the main buses to the tie bus (Figure 4-13). The FC/MAIN BUS switches are momentary switches used for connecting the fuel cells to the main buses. To power a main bus, the FC/MAIN BUS switch must be held to the ON position until the talkback next to it indicates ON. This action causes a power contactor to connect the fuel cell to the bus.

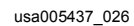


Figure 4-13. Main bus controls

The MN BUS TIE switches and talkbacks operate similarly to the FC/MAIN BUS switches and talkbacks. However, they cause the main buses to be connected to the tie bus. To tie two main buses, the MN BUS TIE switches are used to connect both buses to the tie bus.

4.6.1.2 Essential Buses

The controls for the essential buses consist of switches for connecting them to their dedicated fuel cells and to the main buses that power them (Figure 4-17). The ESS BUS SOURCE FC switches connect the essential buses to a dedicated fuel cell through a fuse. The ESS BUS SOURCE MN switches control two RPCs that connect the essential bus to two main buses.

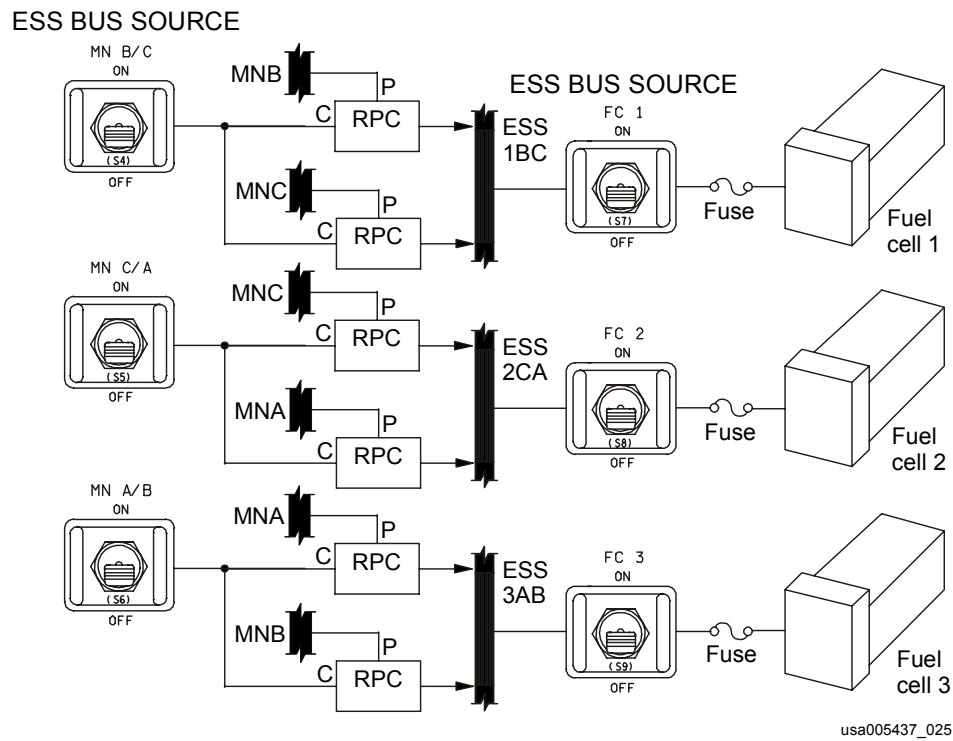
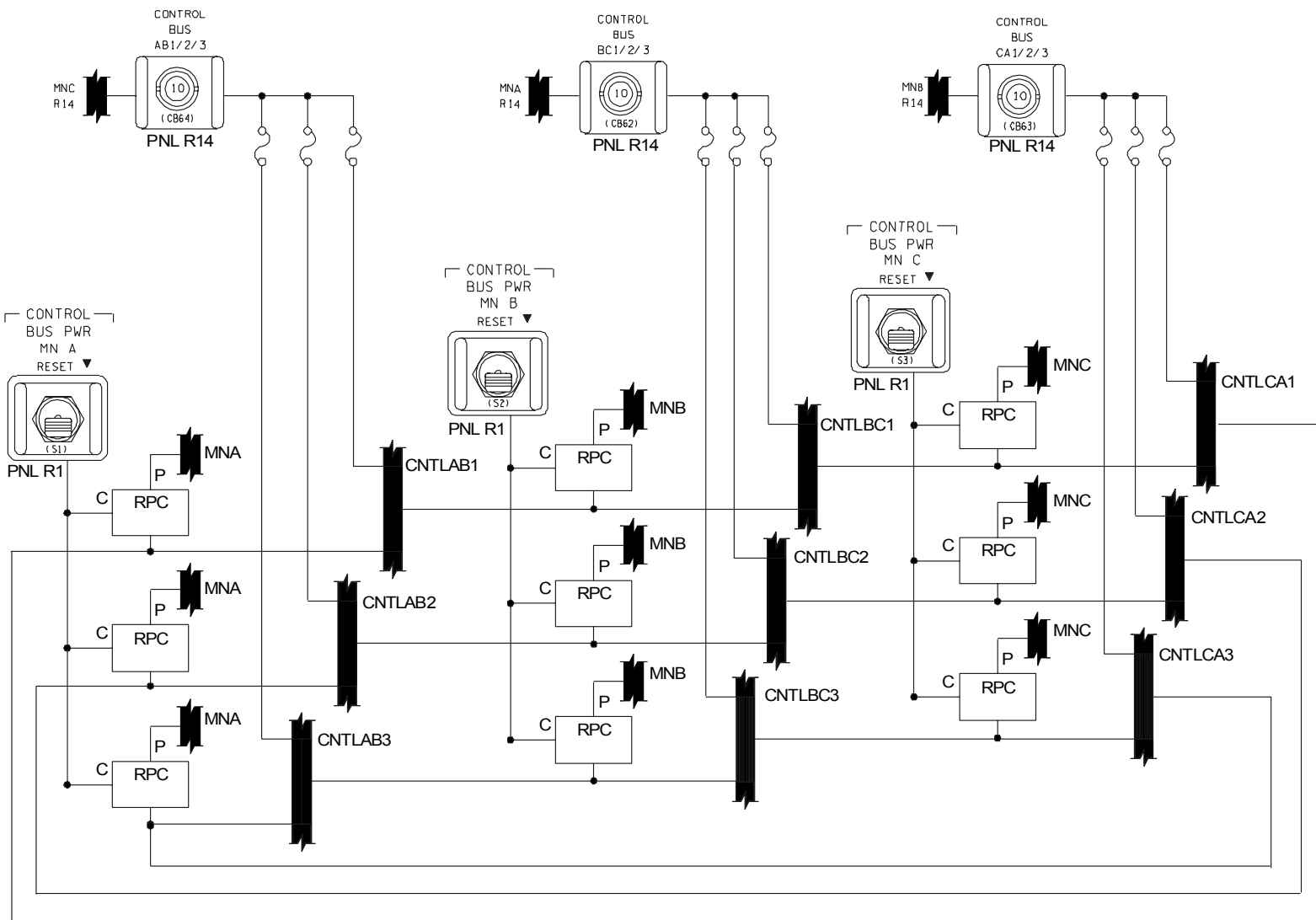


Figure 4-14. Essential bus controls

4.6.1.3 Control Buses

Three switches and three circuit breakers control power to the control buses (Figure 4-18). The CONTROL BUS POWER MN switches are momentary switches that can be used to reset the RPCs that power the control buses, and the CONTROL BUS circuit breakers provide a direct power path from the main buses through fuses to the control buses. When a CONTROL BUS POWER MN switch is held to the RESET position, the control signal for all the RPCs connected to the associated main bus will be taken off, disabling all control bus RPCs on that main bus. For example, if CONTROL BUS POWER MN B is held to the RESET position, the three control bus RPCs connected to MN B are disabled. This action will remove MN B power from CNTL AB1, AB2, and AB3, and CNTL BC1, BC2, and BC3. However, these buses will still be powered through their other two power sources. When the CONTROL BUS POWER MN switch is released, it will return to its normal position and the control signal for the RPCs will be reapplied, causing them to be reenabled. The RPCs are reset (repowered) when the CONTROL BUS POWER MN switch is released from the RESET position, not while the switch is in the RESET position.

The CONTROL BUS circuit breakers provide direct connection of the control buses to their associated main buses. Each circuit breaker provides a power source to three control buses. If a circuit breaker is opened, the three affected control buses still receive power from their other two sources if the RPCs have not been disabled.



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Figure 4-15. Control bus controls

4.6.1.4 AC Buses

The controls for powering the AC buses consist of switches and circuit breakers for connecting the DC input power to the inverters and for connecting the output AC power to the AC buses (Figure 4-16). The INV PWR switch is used to connect the DC input power to the inverters, and the INV/AC BUS switch is used to connect the inverters to the AC bus. Since there are three sets of inverters and only one set of switches for each AC bus, the AC CONTR circuit breakers are used to select which inverter or inverters are affected by the INV PWR and INV/AC BUS switches. The phase A inverter is selected by closing the ϕA circuit breaker, phase B by closing the ϕB circuit breaker, and phase C by closing the ϕC circuit breaker. Multiple phases can be manipulated at the same time by closing multiple circuit breakers. If no circuit breakers are closed, moving the INV PWR and INV/AC BUS switches has no effect.

The INV PWR and INV/AC BUS switches are momentary switches. To connect a phase, the INV PWR switch must be held to the ON position momentarily; to disconnect the phase, it must be held to the OFF position momentarily. When the switch is released, it will spring back to its center position. When the switches are operated, the circuit breaker for the desired phase or phases must be closed. The talkbacks above the INV PWR and INV/AC BUS switches only indicate ON when all three phases are connected to their DC power source. If any one of the phases is not connected, the talkback will indicate OFF, even though the other two phases are still connected.

4.6.1.5 AC Bus Sensor Control

Each AC bus has a switch that controls its AC bus sensor (Figure 4-16). When this switch is in the OFF position, the AC bus sensor is completely disabled. When the switch is in the MONITOR position, the bus sensor will monitor for overvoltage, undervoltage, and overload. If it detects one of these conditions, it will cause the F7 AC VOLTAGE or AC OVERLOAD light to annunciate. When the switch is in the AUTO TRIP position, the bus sensor will light the F7 lights, and it will also automatically disconnect the affected bus from its inverter. The bus sensor does not trip off a phase with an undervoltage problem since this is not likely to damage equipment.

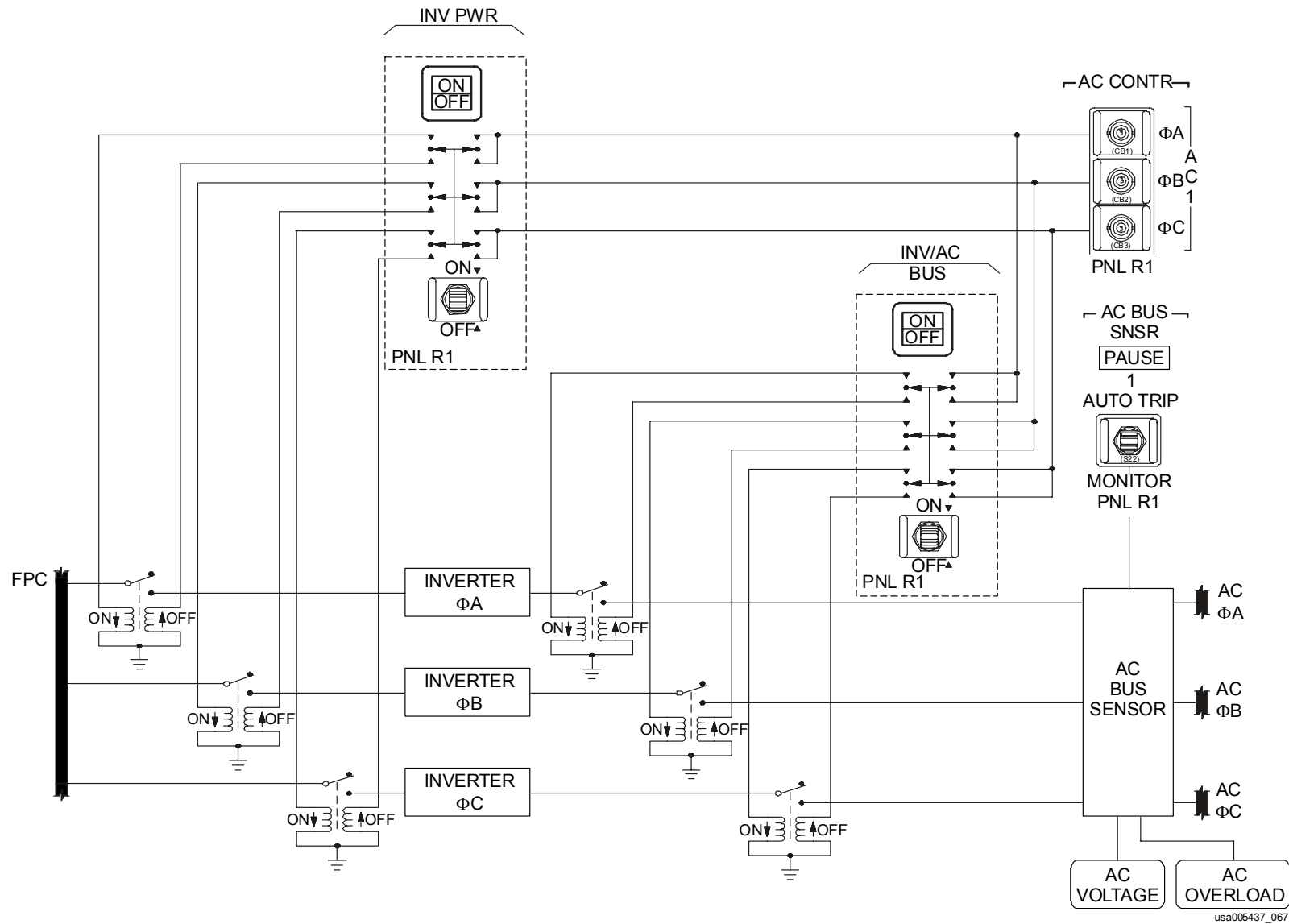


Figure 4-16. AC bus controls

4.6.1.6 Payload Buses

The controls for the payload buses consist of switches for controlling the primary payload, auxiliary payload, aft payload, and cabin payload buses, and circuit breakers for powering the AC payload buses. Each of these will be discussed in the following paragraphs.

1. Primary Payload Bus - The controls for the primary payload bus consist of three switches and talkbacks that can connect the bus to MN B, MN C, or fuel cell 3 (Figure 4-17). These switches are momentary switches that control power contactors. When one of these switches is held to the ON position until the associated talkback shows ON, a power contractor connects the primary payload bus to the power source selected. To disconnect a power source, the switch must be held to the OFF position until the associated talkback shows OFF. More than one power source can be connected to the primary payload bus. This capability can even result in MN B and MN C being tied together through the payload bus, which is known as the "back door" bus tie.

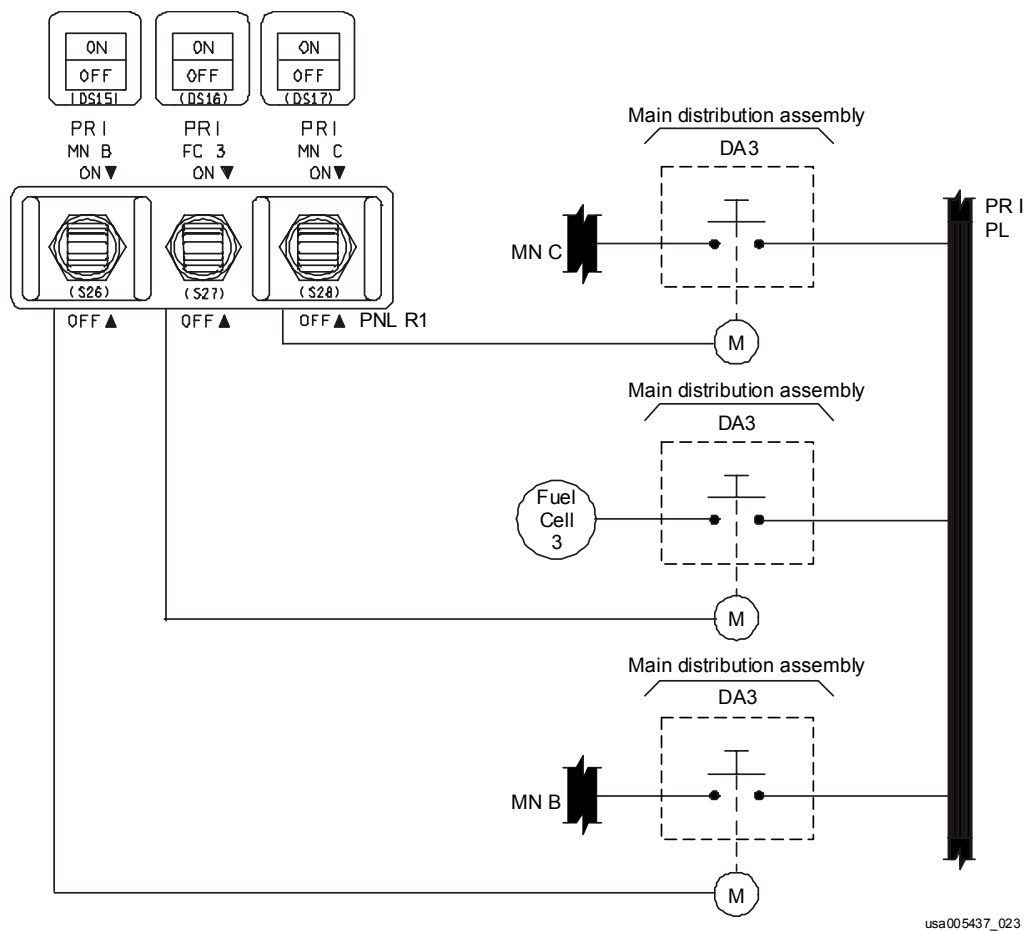


Figure 4-17. Primary payload bus controls

2. Auxiliary Payload Buses - The two auxiliary payload buses are controlled by one switch (Figure 4-18). When the AUX switch is on, one RPC connects AUX PLA to MN A, and another RPC connects AUX PLB to MN B.

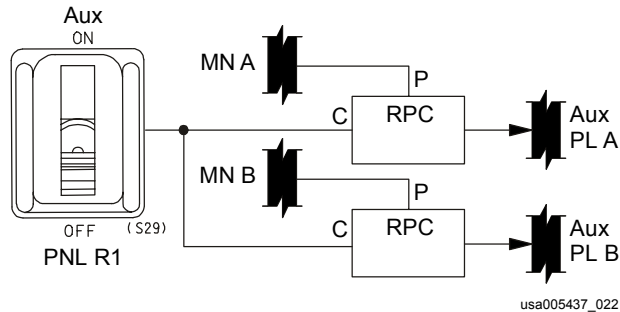


Figure 4-18. Auxiliary payload bus controls

3. Aft Payload Buses - The aft payload buses are controlled by two switches (Figure 4-19). These switches control relays that connect AFT PLB to MN B, and AFT PLC to MN C. When the switches are in the ON position, solenoids close the contacts and power the buses.

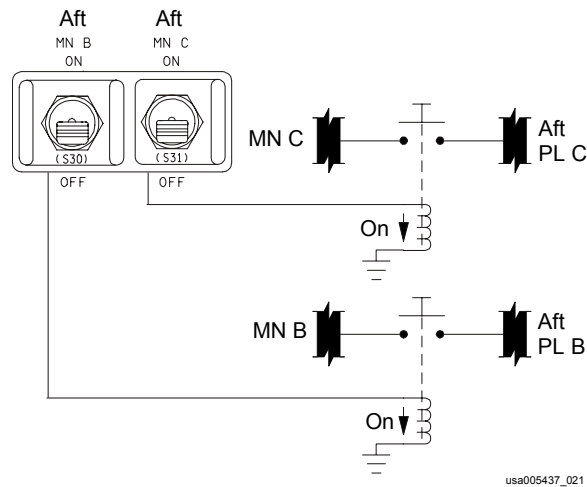


Figure 4-19. Aft payload bus controls

4. Cabin Payload Buses - The three cabin payload buses are controlled by one switch (Figure 4-20). This switch enables MN A or MN B to be connected to the cabin payload buses.

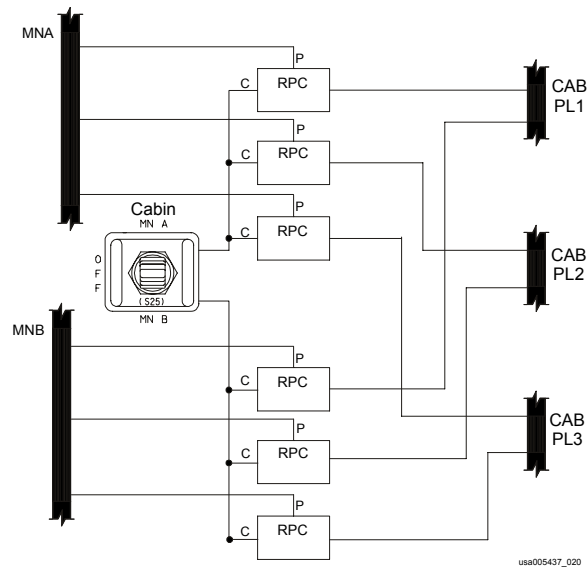


Figure 4-20. Cabin payload bus controls

5. Alternating Current Payload Buses - The AC payload buses are connected to AC2 and AC3 through circuit breakers (Figure 4-21). AC2 PL 3 ϕ is connected to AC2 through the AC2 PAYLOAD 3 ϕ circuit breaker, and AC3 PL 3 ϕ is connected to AC3 through the AC3 PAYLOAD 3 ϕ circuit breaker.

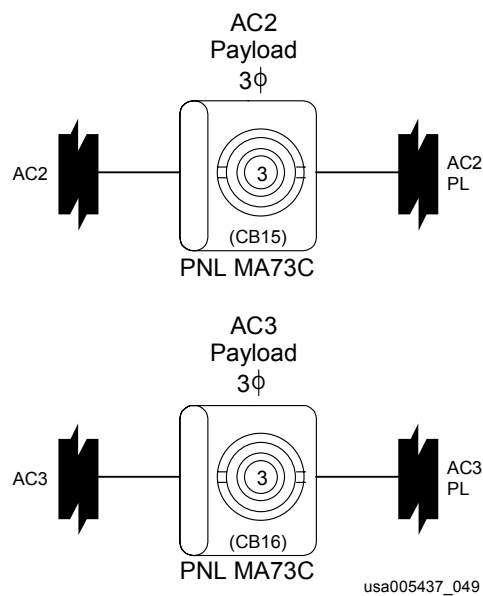


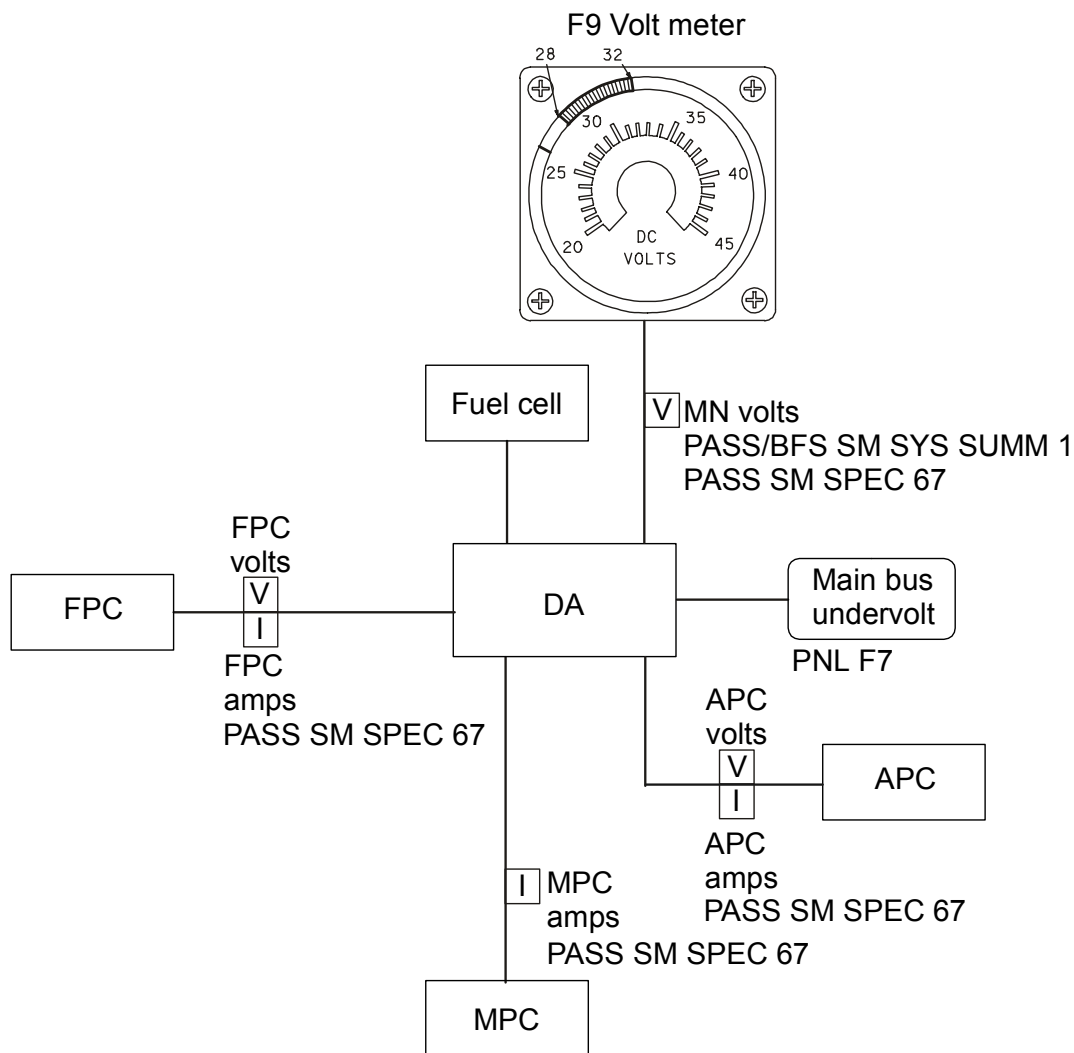
Figure 4-21. Alternating current payload buses

4.6.2 EPDC Instrumentation

Instrumentation for the EPDC subsystem is broken down by bus in the sections that follow. For each category, a figure is supplied showing the location of the sensors and listing all displays and meters on which the data are displayed.

4.6.2.1 Main Bus Instrumentation

Instrumentation for the main buses consists of voltage and current readings placed as shown in Figure 4-22. Main bus voltage is measured in the DA and can be viewed on the Panel F9 meter or a CRT display. A separate pickup feeds the MAIN BUS UNDERVOLT C&W light on Panel F7. Voltage readings are also available for the FPC and APC, but not the MPC. Current sensors provide readings for the current flowing to the FPC, MPC and APC.



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Figure 4-22. Main bus instrumentation

4.6.2.2 Essential Bus Instrumentation

The essential buses are instrumented as shown in Figure 4-23. A sensor reads the voltage of the essential bus at the distribution assembly. The DC voltmeter, on the other hand, is connected to the essential bus on the panel bus circuit.

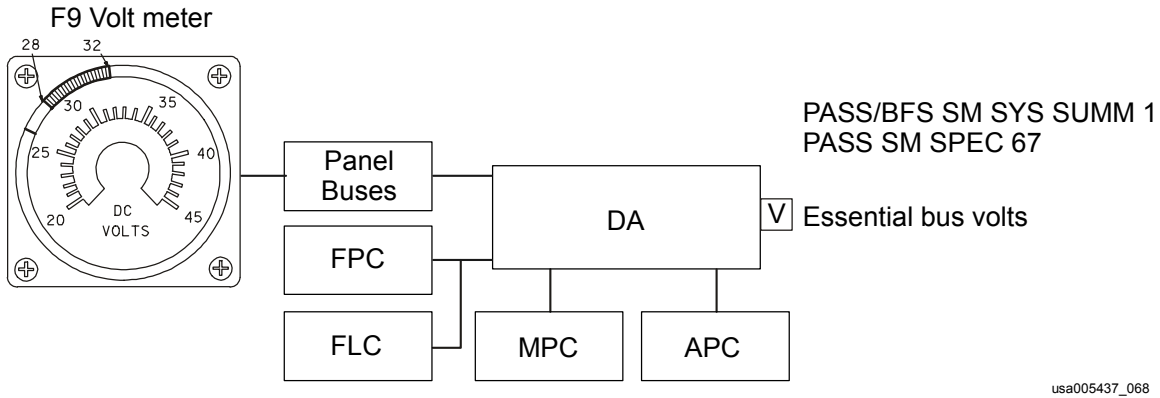


Figure 4-23. Essential bus instrumentation

4.6.2.3 Control Bus Instrumentation

Instrumentation for the control buses consists of a voltage reading for each control bus and status signals that indicate whether the RPCs are tripped (Figure 4-24). Control bus voltage cannot be read on the F9 meter.

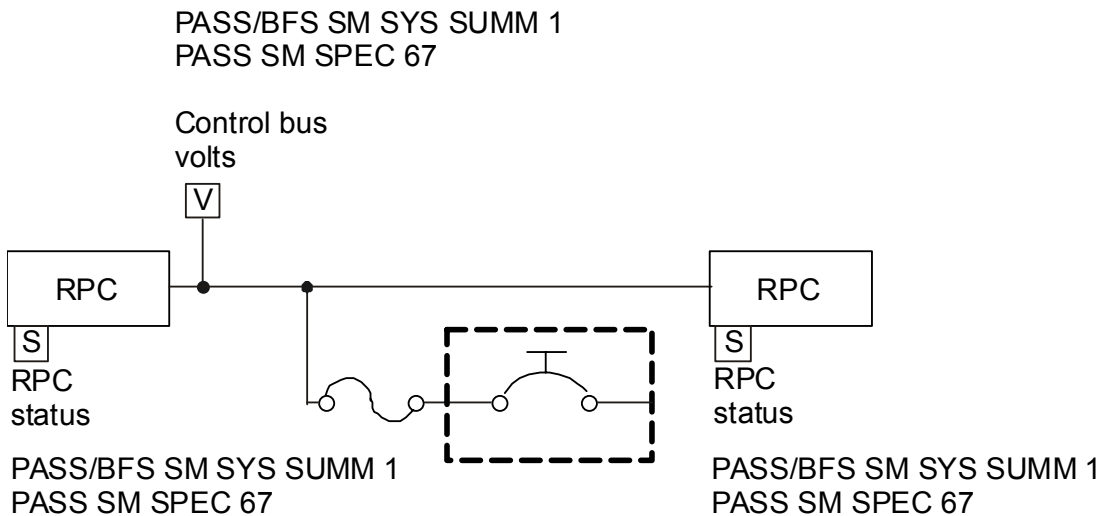


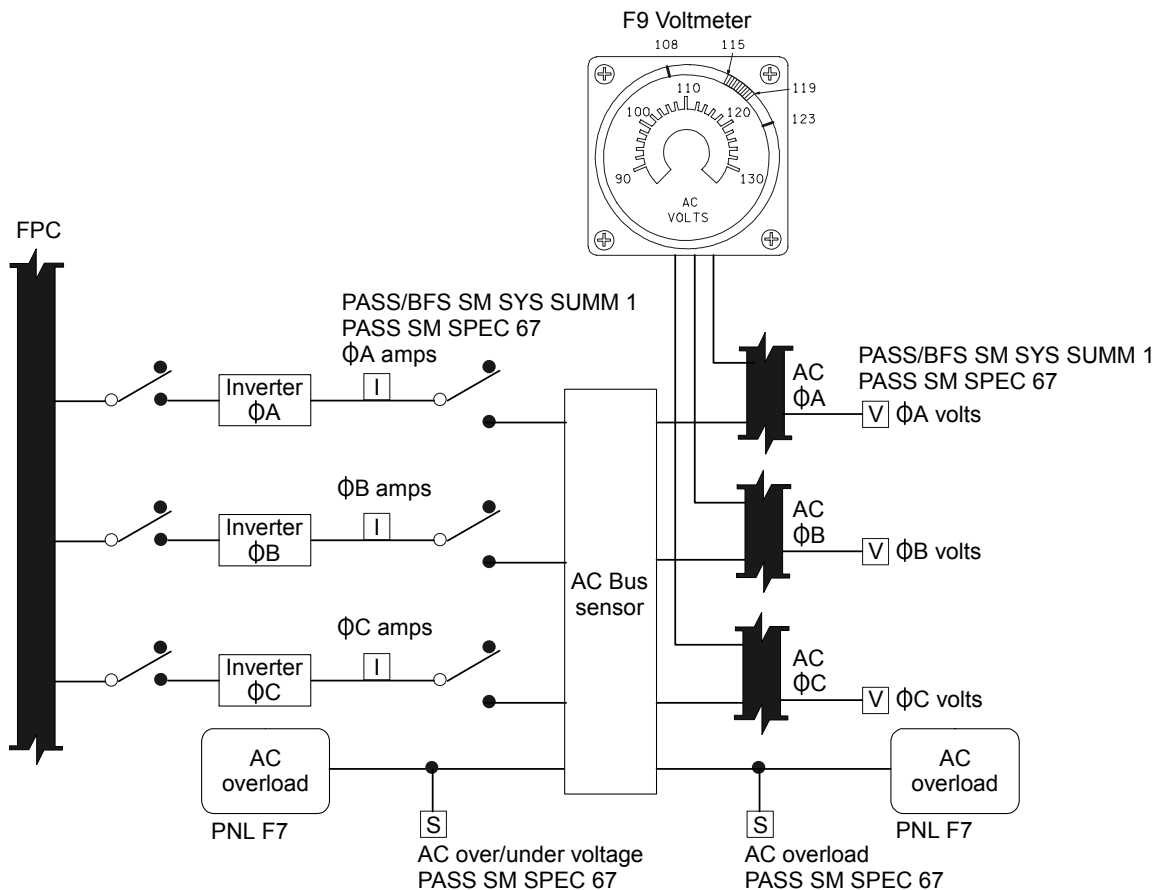
Figure 4-24. Control bus instrumentation

4.6.2.4 Payload Bus Instrumentation

The only payload buses that have instrumentation are the aft payload buses. The current to AFT PLB and to AFT PLC is displayed on PASS SM SPEC 67.

4.6.2.5 AC Bus Instrumentation

Instrumentation for the AC buses consists of voltage and current readings for each phase, as well as signals from the AC bus sensors that indicate an overvoltage/undervoltage or an overload (Figure 4-25). The current is read at the output of each inverter. The voltage is measured at the AC bus. The AC voltmeter on Panel F9 reads the AC voltage at the same point as the volt sensor. The overvoltage/undervoltage and overload signals drive the F7 lights and the Spec 67 status.



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Figure 4-25. Alternating current bus instrumentation

4.6.3 EPDC Displays

Table 4-5 summarizes the displays that contain EPDC information and are available for each mission phase. Each of these displays is described separately in the following sections.

Table 4-5. EPDC displays

Mission phase	Display
Ascent/Entry	BFS SM SYS SUMM 1
Orbit	PASS SM SYS SUMM 1 PASS SM SPEC 67

4.6.3.1 BFS SM SYS SUMM 1

BFS SM SYS SUMM 1 displays the voltages of the main, essential, control, and AC buses (Figure 4-26). It also displays the currents of the AC buses. The columns are arranged such that MN A volts are listed under the column labeled 1/A, MN B volts under the column labeled 2/B, and MN C volts under the column labeled 3/C. The control bus volts for CNTL AB1, AB2, and AB3 are under column 1/A, CNTL BC1, BC2, and BC3 are under column 2/B and CNTL CA1, CA2, and CA3 are under column 3/C. Underneath the control bus column labels are status fields that indicate the status of the control bus RPCs. If all the RPCs are powered, all the status fields are blank, but for any RPCs that are not powered, an asterisk will be displayed. For example, if the main B RPC for control buses CNTL AB2 and CNTL BC2 trips off, an asterisk will appear between the voltage values for CNTL AB2 and CNTL BC2. If an A RPC trips off, an asterisk will appear under the A column on the left side, and another asterisk will appear under the A column on the right side. The voltage for ESS 1BC is listed under 1/A; ESS 2CA under 2/A; and ESS 3AB under 3/C. Finally, the AC buses are arranged such that AC1 is listed under 1/A; AC2 is under 2/B; and AC3 is under 3/C.

XXXX/XXX/078			SM SYS SUMM 1			XX X DDD/HH: MM: SS		
						DDD/HH: MM: SS		
SMOKE	1/A	2/B	DC VOLTS	1/A	2/B	3/C		
CABIN	XX.XS		FC	XX.XS	XX.XS	XX.XS		
L/R FD	XX.XS	XX.XS	MAIN	XX.XS	XX.XS	XX.XS		
AV BAY 1	XX.XS	XX.XS	ESS	XX.XS	XX.XS	XX.XS		
2	XX.XS	XX.XS	A-----B-----C-----A					
3	XX.XS	XX.XS	CNTL 1	XXX.XSXXX.XSXXX.XSX				
CABIN			2	XXX.XSXXX.XSXXX.XSX				
PRESS	XX.XS		3	XXX.XSXXX.XSXXX.XSX				
dP/dT-EQ	±.XXX±X.XXXS		AC					
O2 CONC	XXX.XS		VOLT ΦA	XXXS	XXXS	XXXS		
PPO2			ΦB	XXXS	XXXS	XXXS		
FAN ΔP			ΦC	XXXS	XXXS	XXXS		
HX OUT T	XXXS		AMPS ΦA	XX.XS	XX.XS	XX.XS		
O2 FLOW	XX.XS	XX.XS	ΦB	XX.XS	XX.XS	XX.XS		
N2 FLOW	XX.XS	XX.XS	ΦC	XX.XS	XX.XS	XX.XS		
IMU FAN	AXS	BXS	FUEL CELL PH	XXS	XXS	XXS		
ΔV FC1	FC2	FC3	AMPS	XXXS	XXXS	XXXS		
SS1	XXXS	XXXS	REAC VLV	XX	XX	XX		
SS2	XXXS	XXXS	STACK T	±XXXS	±XXXS	±XXXS		
SS3	XXXS	XXXS	EXIT T	XXXS	XXXS	XXXS		
TOTAL AMPS	XXXS		COOL P	XXXS	XXXS	XXXS		
KW	XXS		PUMP	XXS	XXS	XXS		
						(XX)		

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Sensor name	Units	Displayed range	Status indicators				
MAIN	volts	0 to 40	M	H	L	↑	↓
ESS	volts	0 to 40	M	H	L	↑	↓
CNTL 1,2,3	volts	0 to 40	M	H	L	↑	↓
AC: VOLT ΦA, ΦB, ΦC	volts	0 to 140	M	H	L	↑	↓
AMPS ΦA, ΦB, ΦC	amps	0 to 20	M	H	L	↑	↓

Figure 4-26. BFS SM SYS SUMM 1

4.6.3.2 PASS SM SYS SUMM 1

PASS SM SYS SUMM 1 (Figure 4-27) displays the same EPDC information as BFS SM SYS SUMM 1. There is one addition to C&W monitoring for AC amps. A reading above 10 amps will drive an AC amps message and a status indicator.

XXXX/XXX/078			SM SYS SUMM 1			XX X DDD/HH: MM: SS		
						DDD/HH: MM: SS		
SMOKE	1/A	2/B	DC VOLTS	1/A	2/B	3/C		
CABIN	XX.XS		FC	XX.XS	XX.XS	XX.XS		
L/R FD	XX.XS	XX.XS	MAIN	XX.XS	XX.XS	XX.XS		
AV BAY 1	XX.XS	XX.XS	ESS	XX.XS	XX.XS	XX.XS		
	2	XX.XS	A-----B-----C-----A					
	3	XX.XS	CNTL 1	XXX.XSXXX.XSXXX.XSX				
CABIN			2	XXX.XSXXX.XSXXX.XSX				
PRESS	XX.XS		3	XXX.XSXXX.XSXXX.XSX				
dP/dT-EQ	±.XXS±X.XXS	AC						
O2 CONC	XXX.XS		VOLT ΦA	XXXS	XXXS	XXXS		
PP02			ΦB	XXXS	XXXS	XXXS		
FAN ΔP			ΦC	XXXS	XXXS	XXXS		
HX OUT T	XXXS		AMPS ΦA	XX.XS	XX.XS	XX.XS		
O2 FLOW	XX.XS	XX.XS	ΦB	XX.XS	XX.XS	XX.XS		
N2 FLOW	XX.XS	XX.XS	ΦC	XX.XS	XX.XS	XX.XS		
IMU FAN	AXS	BXS	FUEL CELL					
ΔV FC1	FC2	FC3	AMPS	XXXS	XXXS	XXXS		
SS1	XXXS	XXXS	REAC VLV	XX	XX	XX		
SS2	XXXS	XXXS	STACK T	±XXXS	±XXXS	±XXXS		
SS3	XXXS	XXXS	EXIT T	XXXS	XXXS	XXXS		
TOTAL AMPS	XXXS		COOL P	XXXS	XXXS	XXXS		
KW	XXS		PUMP	XXS	XXS	XXS		
						(XX)		

TD3600439. CRT; 2

Sensor name	Units	Displayed range	Status indicators				
MAIN	volts	0 to 40	M	H	L	↑	↓
ESS	volts	0 to 40	M	H	L	↑	↓
CNTL 1,2,3	volts	0 to 40	M	H	L	↑	↓
AC: VOLT ΦA, ΦB, ΦC	volts	0 to 140	M	H	L	↑	↓
AMPS ΦA, ΦB, ΦC	amps	0 to 20	M	H	L	↑	↓

Figure 4-27. PASS SM SYS SUMM 1

4.6.3.3 PASS SM SPEC 67

PASS SM SPEC 67 (Figure 4-28), available on orbit, displays much of the same information as the SM SYS SUMM 1 displays, but it adds the rest of the EPDC data. At the top left of the display, the main bus, essential bus, and control bus voltages are displayed similar to SM SYS SUMM 1. Under these columns, the voltages of the FPCs and APCs have been added. At the bottom left of the display, the FPC, MPC, and APC currents are displayed.

At the upper right of the display, the AC bus voltages and currents are displayed similar to SM SYS SUMM 1. Under this are fields that indicate the status of the overload and overvoltage/undervoltage flags from the AC bus sensors. If an overload occurs on an AC bus, the overload field will indicate OL; otherwise, the overload field will be blank. Similarly, if an overvoltage or an undervoltage occurs, the overvoltage/undervoltage field will indicate OU and will be blank otherwise. At the bottom right of the display, the currents flowing to the aft payload buses, AFT PLB and AFT PLC, are displayed.

XXXX/XXX/067									
ELECTRIC XX X									
DDD/HH:MM:SS									
DDD/HH:MM:SS									
DC	1/A	2/B	3/C	AC	1	2	3		
VOLT FC	XX.XS	XX.XS	XX.XS	V	ΦA	XX.XS	XX.XS	XX.XS	
MN	XX.XS	XX.XS	XX.XS		ΦB	XX.XS	XX.XS	XX.XS	
PCA FWD	XX.XS	XX.XS	XX.XS		ΦC	XX.XS	XX.XS	XX.XS	
AFT	XX.XS	XX.XS	XX.XS	AMP	ΦA	XX.XS	XX.XS	XX.XS	
ESS	XX.XS	XX.XS	XX.XS		ΦB	XX.XS	XX.XS	XX.XS	
					ΦC	XX.XS	XX.XS	XX.XS	
CNTL 1	XX.XS	XX.XS	XX.XS	OVLD	XX.XS	XX.XS	XX.XS	XX.XS	
2	XX.XS	XX.XS	XX.XS	O/U V	XX.XS	XX.XS	XX.XS	XX.XS	
3	XX.XS	XX.XS	XX.XS						
AMPS FC	XX.XS	XX.XS	XX.XS	PAYLOAD DC AMPS					
FWD	XX.XS	XX.XS	XX.XS	AFT B				XX.XS	
MID	XX.XS	XX.XS	XX.XS	C				XX.XS	
AFT	XX.XS	XX.XS	XX.XS						
TOTAL AMPS		XXXXXS							
KW		XXX.XS							

(XX)

Sensor name	Units	Displayed range	Status indicators				
DC: VOLT: FC	volts	0 to 40	M	H	L	↑	↓
MN	volts	0 to 40	M	H	L	↑	↓
PCA FWD	volts	0 to 40	M	H	L		↓
AFT	volts	0 to 40	M	H	L		↓
ESS	volts	0 to 40	M	H	L		↓
CNTL 1 [1]	volts	0 to 40	M	H	L		↓
2	volts	0 to 40	M	H	L		↓
3	volts	0 to 40	M	H	L		↓
VOLT: FC	amps	0 to 500	M	H	L	↑	↓
FWD	amps	0 to 250	M	H	L		
MID	amps	0 to 100	M	H	L		
AFT [2]	amps	0 to 175	M	H	L		
TOTAL AMPS	amps	0 to 1500	M	H	L		
kW	kW	0 to 60	M	H	L		
AC: V: ΦA, ΦB, ΦC	volts	0 to 140	M	H	L	↑	↓
AMP: ΦA, ΦB, ΦC	amps	0 to 20	M	H	L	↑	
OVLD	text	'blank' or 'OL'	M				↓
O/UV [3]	text	'blank' or 'OU'	M				
PAYLOAD DC AMPS: AFT B	amps	0 to 75	M	H	L		
C	amps	0 to 75	M	H	L		

Figure 4-28. PASS SM SPEC 67

REMARKS

- [1] Each parameter is preceded/followed by an RPC trip status indicator. These indicators are located under the alpha column headers (A-B-C-A); they read '*' if the associated RPC is OFF (blank otherwise). Examples: MNA AB1/CA1 = OFF produces an '*' for CNTL 1 under both the left and right A; MNB AB2/BC2 = OFF produces an '*' for CNTL 2 under the B; MNC BC3/CA3 = OFF produces an '*' for CNTL 3 under the C.
- [2] Transducer range is -325 to +175 to accommodate GSE power; only positive values will be seen in flight.
- [3] Parameter reflects status of over/under-voltage sensing of AC Bus Voltage Sensor. If sensor and backup C/W operate properly, C/W alert "AC VOLTAGE" would also have a CRT message (S67 AC VOLTS), an "↑" or "↓" by one or more "AC V" parameters, and "OU" would be displayed.

4.7 NOMINAL OPERATIONS

When the crew enters the vehicle, all the main, essential, control, and AC buses are powered. However, the ESS BUS SOURCE FC switches are off. With these switches off, the ground can completely power down the vehicle without any crew interaction. Once these switches are taken to ON, the crew must take action to turn them OFF for an emergency powerdown. Even though these switches are off, the essential buses are still getting power from their other two power sources. At 8 minutes before launch, the ESS BUS SOURCE FC switches are taken to the ON position so that the essential buses are powered by all their power sources. The AC BUS SENSOR switches are in the MONITOR position. The bus sensors stay in this position through ascent since AC buses power the main engine controllers. Two AC buses power each controller, and if the two AC buses should have problems, at least one main engine controller would fail and one engine would shut down. With the bus sensors in MONITOR, a phase that has a voltage or an overload problem will not be tripped off. As long as the voltage or overload problem has not caused the main engine controller to fail and there is no indication of fire or smoke, the problem will be allowed to continue until after main engine cutoff. After main engine cutoff, the AC bus sensors will be taken to AUTO TRIP, and the sensors will automatically trip off any phase that has excessive voltage. For an overload condition, the INV/AC BUS switch would be used to disconnect the affected phase. Taking the AC BUS SENSOR switch to AUTO TRIP does not have any effect for a pre-existing short. The sensor must be in AUTO TRIP when the short first occurs to trip the phase off line.

4.7.1 Ascent

The only EPDC operation during ascent is to take the AC bus sensors from MONITOR to AUTO TRIP. This is done during the post-OMS-1 procedures. At this point, the main engines have been shut down, and it is no longer necessary to protect against loss of the main engine controllers. Therefore, it is prudent to take the bus sensors to AUTO TRIP so that a phase with a problem can be disconnected to protect the rest of the AC equipment. When the bus sensors are taken from MONITOR to AUTO TRIP, they must be left in the OFF position for at least 1 second to give the sensor time to reset.

4.7.2 Orbit

The only nominal EPDC operations while on orbit are to power and unpower payload buses during payload activation and deactivation.

4.7.3 Entry

There are no EPDC operations during entry.

4.7.4 Postlanding

There are no EPDC operations during postlanding.

Questions

Answers provided in Appendix B

1. What is the purpose of the EPDC subsystem?

2. Match the following electrical assemblies with their purpose.

- | | | |
|-------------------------------|-------|---|
| a. Main distribution assembly | _____ | 1. Powers noncontinuous alternating current loads |
| b. Power control assembly | _____ | 2. Connects fuel cells to buses |
| c. Load control assembly | _____ | 3. Powers large direct current loads |
| d. Motor control assembly | _____ | 4. Powers smaller direct current loads |

3. Identify the power sources of the following buses by checking in the columns for each power source.

	Fuel Cell 1	Fuel Cell 2	Fuel Cell 3	Main A	Main B	Main C
Main A						
Main B						
Main C						
ESS 1BC						
ESS 2CA						
ESS 3AB						
CNTLAB1						
CNTLAB2						
CNTLAB3						
CNTLBC2						
CNTLCA3						
AC1						
AC2						
AC3						

4. The AC bus sensors are launched in AUTO TRIP so that an AC problem will trip off an AC phase to protect the main engine controllers.

True or False

5. When the essential bus source/FC switches are on, the ground can completely power down the vehicle while it is on the launch pad.

True or False

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APPENDIX A ACRONYMS AND ABBREVIATIONS

AC	alternating current
ALC	Aft Load Controller
AMC	Aft Motor Controller
APC	Aft Power Controller
ASSY	Assembly
C&W	Caution and Warning
CRT	Cathode-Ray Tube
CUR	Current
DA	Distribution Assembly
DC	direct current
ECLSS	Environmental Control and Life Support System
ECU	Electrical Control Unit
EPDC	Electrical Power Distribution and Control
EPS	Electrical Power System
ET	External Tank
FC	Fuel Cell
FC-40	Fluorocarbon 40
FDF	Flight Data File
FLC	Forward Load Controller
FMC	Forward Motor Controller
FPC	Forward Power Controller
GPC	General Purpose Computer
GSE	Ground Support Equipment
H ₂	Hydrogen
HTR	Heater
IMU	Inertial Measurement Unit
JSC	Johnson Space Center
KOH	Potassium Hydroxide
LCA	Load Control Assembly
MANF	Manifold
MCA	Motor Control Assembly
MMC	Mid Motor Control
MOD	Mission Operations Directorate
MPC	Mid Power Control

NASA	National Aeronautics and Space Administration
O ₂	Oxygen
OH	Hydroxide
OMS	Orbital Maneuvering System
P	Pressure
PCA	Power Control Assembly
PCS	Pressure Control System
PNL	Panel
Press	Pressure
PRSD	Power Reactant Storage and Distribution
PSIA	Pounds/Square Inch Absolute
PSIG	Pounds/Square Inch Gauge
QTY	Quantity
REAC	Reactant
Rlf	Relief
RPC	Remote Power Controller
SNSR	Sensor
SRB	Solid Rocket Booster
SYS	System
TAMS	Training Administration and Management System
Tk	Tank
Vlv	Valve

APPENDIX B ANSWERS

Section 2 Answers

1. What is the purpose of the PRSD subsystem?

The cryo subsystem provides cryo storage and distribution. It distributes the cryo to the fuel cells, and also supplies O₂ to the ECLSS.

2. The cryo tanks are located in

c. The payload bay

3. Match the following cryo components to their functions.

- | | | |
|---------------------------|--------------|---|
| a. Tank heaters | <u> d </u> | 1. Remove contaminants from cryo |
| b. Heater controllers | <u> h </u> | 2. Relieve excess pressure in manifolds into tanks 1 and 2 |
| c. Heater current sensors | <u> f </u> | 3. Relieve excess tank pressure overboard |
| d. Filters | <u> c </u> | 4. Detect shorts in O ₂ tank heaters |
| e. Check valves | <u> b </u> | 5. Manage tank heaters to maintain tank pressure |
| f. Tank relief valves | <u> g </u> | 6. Isolate parts of H ₂ or O ₂ manifold |
| g. Manifold valves | <u> e </u> | 7. Allow cryo to flow out of tanks but not back in |
| h. Manifold relief valves | <u> a </u> | 8. Add heat to cryo to maintain tank pressure |

4. All the O₂ and H₂ heaters for tanks 1 and 2 are on during ascent.

False. Only the A heaters in these tanks are on. The B heaters are left off so that if the tank heaters should need to come on, the vehicle power loading will not be so great that the SRB voltages drop too low.

5. The B heaters in an O₂ tank are turned off when the quantity in the tank is less than 50 percent.

True. The B heaters must be turned off because if two sets of heaters operate in an O₂ tank below 50 percent quantity, the heater assemblies can overheat.

6. For a single-shift mission, the cryo manifold valves are kept open while the crew is asleep.

False. One manifold valve on each manifold will be closed to prevent a large leak from causing all three fuel cells to fail.

7. The O₂ heater current sensors are tested only once during a flight.

False. The O₂ heater current sensors are tested during post-sleep operations each day of flight.

Section 3 Answers

1. What is the purpose of the fuel cell subsystem?

The fuel cell subsystem produces all the 28 V direct current electrical power required by the orbiter, the external tank, and the solid rocket boosters.

2. The fuel cells are located in

- c. The payload bay. The fuel cells are located in the forward end of the payload bay under the payload bay liner.

3. The byproducts of the reaction in the fuel cell are

- d. Water and heat. Hydrogen and oxygen react in the fuel cell stack to produce electricity, water, and heat.

4. During a manual purge of the fuel cells, all three fuel cells should be purged at the same time.

False. The fuel cells should be purged one at a time. Purging all three at the same time allows the possibility of all three fuel cells failing at the same time.

5. During a fuel cell purge, the fuel cell should not be purged if the current is greater than 350 amps.

True. Cryo flow is proportional to the current being produced. When the flow required for a purge is added to the flow required for 350 amps, it is at the maximum at which the preheaters can adequately heat the cryo.

6. One manual purge is done during a mission since the heaters used for a manual purge are separate from the heaters used for an auto purge and they need to be checked out.

True. The heaters for auto and manual purges are separate heaters. To decrease turnaround work on the ground, the manual purge heaters are checked out on orbit by doing one manual purge.

7. Match the following fuel cell components to their functions.

- | | | |
|--|--------------|--|
| a. Fuel cell stack | <u> f </u> | 1. Allow extra cryo flow to remove contaminants from stack |
| b. Cryo preheaters | <u> l </u> | 2. Contains startup logic, thermostats, relays, and timers for control of fuel cell |
| c. Dual-gas regulator | <u> b </u> | 3. Uses hot coolant from stack to heat cryo as it enters the fuel cell |
| d. Condenser | <u> h </u> | 4. Heats coolant during initial fuel cell startup to bring stack up to operating temperature |
| e. H ₂ pump/water separator | <u> d </u> | 5. Uses coolant to cool H ₂ /steam mixture coming out of the stack so that water can be removed |
| f. Purge valves | <u> c </u> | 6. Decreases cryo pressures to approximately 60 psia with O ₂ pressure maintained a few psia greater than H ₂ pressure |
| g. Coolant pump | <u> k </u> | 7. Monitors substacks to detect cell degradation |
| h. Startup heater | <u> j </u> | 8. Keeps pressure of coolant equal to pressure of O ₂ |
| i. Sustaining heater | <u> a </u> | 9. Contains electrochemical cells which produce electricity |
| j. Accumulator | <u> i </u> | 10. Adds heat to coolant when stack is cooling off due to fuel cell operating at low power levels |
| k. Cell performance monitor | <u> e </u> | 11. Separates water from H ₂ /water mixture and sends water to ECLSS supply water tanks |
| l. Electrical control unit | <u> g </u> | 12. Causes coolant to flow through coolant loop |

Section 4 Answers

1. What is the purpose of the EPDC subsystem?

The purpose of the EPDC subsystem is to distribute power generated by the fuel cells to the electrical loads.

2. Match the following electrical assemblies with their purpose.

- | | | |
|-------------------------------|--------------|---|
| a. Main distribution assembly | <u> d </u> | 1. Powers noncontinuous alternating current loads |
| b. Power control assembly | <u> a </u> | 2. Connects fuel cells to buses |
| c. Load control assembly | <u> b </u> | 3. Powers large direct current loads |
| d. Motor control assembly | <u> c </u> | 4. Powers smaller direct current loads |

3. Identify the power sources of the following buses by checking in the columns for each power source.

	Fuel Cell 1	Fuel Cell 2	Fuel Cell 3	Main A	Main B	Main C
Main A	X					
Main B		X				
Main C			X			
ESS 1BC	X				X	X
ESS 2CA		X		X		X
ESS 3AB			X	X	X	
CNTLAB1				X	X	X
CNTLAB2				X	X	X
CNTLAB3				X	X	X
CNTLBC2				X	X	X
CNTLCA3				X	X	X
AC1				X		
AC2					X	
AC3						X

4. The AC bus sensors are launched in AUTO TRIP so that an AC problem will trip off an AC phase to protect the main engine controllers.

False. The bus sensors are launched in MONITOR. An attempt is made to keep AC buses with problems powered until after main engine cutoff so that the main engine controllers do not lose any of their power sources. If two AC buses have a problem, one main engine controller will definitely fail and cause an engine to shut down.

5. When the essential bus source/FC switches are on, the ground can completely power down the vehicle while it is on the launch pad.

False. When the essential bus source/FC switches are on, the essential buses are directly connected to the fuel cells without the ground being able to disconnect them. Therefore, if the ground tries to power down the vehicle, the essential buses will still be powered through these switches.

Training Materials Evaluation

Please answer the following questions regarding the lesson you just completed. Your feedback will allow us to produce more effective training materials. When complete, mail to: MOD Training Resource Center, DT49.

TITLE/CODE OF LESSON: EPS 21002

SIZE OF AUDIENCE/CLASS: _____

1. How well did this lesson meet its purpose?

For each statement below, mark one box on the scale

	Strongly Disagree				Strongly Agree
a. The lesson objectives are clearly stated.	1	2	3	4	5
b. The lesson objectives are clearly defined.	1	2	3	4	5
c. The lesson effectively teaches skills and information.	1	2	3	4	5
d. The lesson meets its purpose and objectives.	1	2	3	4	5

2. How satisfying is the content of this lesson?

For each statement below, mark one box on the scale

	Strongly Disagree				Strongly Agree
a. The information is structured in a logical flow.	1	2	3	4	5
b. The content is clear.	1	2	3	4	5
c. The content is complete.	1	2	3	4	5
d. The level of detail is correct for this information.	1	2	3	4	5
e. The amount of information is effective.	1	2	3	4	5
f. The graphics contribute to my understanding.	1	2	3	4	5

3. How appealing was the presentation of this lesson?

For each statement below, mark one box on the scale:

	Strongly Disagree				Strongly Agree
a. The overall presentation is appealing.	1	2	3	4	5
b. The visuals chosen are appropriate for the lesson.	1	2	3	4	5
c. The visuals make the information more interesting.	1	2	3	4	5
d. The graphics are legibly reproduced.	1	2	3	4	5
e. The audio/visual or print quality is good.	1	2	3	4	5

4. How valuable is this information?

For each statement below, mark one box on the scale:

	Strongly Disagree				Strongly Agree
a. The lesson teaches skills and information I need.	1	2	3	4	5
b. The lesson meets my expectations.	1	2	3	4	5
c. This information is useful for later reference.	1	2	3	4	5
d. I would recommend this lesson to others.	1	2	3	4	5

PLEASE WRITE YOUR COMMENTS/QUESTIONS ON THE BACK OF THIS FORM.

EXPLAIN ANY NEGATIVE ANSWERS IN SPECIFIC TERMS

THANK YOU IN ADVANCE FOR YOUR ASSISTANCE!

TITLE: Electrical Power System Training Manual

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