Fuel Cell Power Plants

Each of the three fuel cell power plants is reusable and restartable. The fuel cells are located under the payload bay area in the forward portion of the orbiter's midfuselage.

The three fuel cells operate as independent electrical power sources, each supplying its own isolated, simultaneously operating 28-volt dc bus. The fuel cell consists of a power section, where the chemical reaction occurs, and an accessory section that controls and monitors the power section's performance. The power section, where hydrogen and oxygen are transformed into electrical power, water and heat, consists of 96 cells contained in three substacks. Manifolds run the length of these substacks and distribute hydrogen, oxygen and coolant to the cells. The cells contain electrolyte consisting of potassium hydroxide and water, an oxygen electrode (cathode) and a hydrogen electrode (anode).

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

Oxygen is routed to the fuel cell's oxygen electrode, where it reacts with the water and returning electrons to produce hydroxyl ions. The hydroxyl ions then migrate to the hydrogen electrode, where they enter into the hydrogen reaction. Hydrogen is routed to the fuel cell's hydrogen electrode, where it reacts with the hydroxyl ions from the electrolyte. This electrochemical reaction produces electrons (electrical power), water and heat. The electrons are routed through the orbiter's EPDC subsystem to perform electrical work. The oxygen and hydrogen are reacted (consumed) in proportion to the orbiter's electrical power demand.

Excess water vapor is removed by an internal circulating hydrogen system. Hydrogen and water vapor from the reaction exits the cell stack, is mixed with replenishing hydrogen from the storage and distribution system, and enters a condenser, where waste heat from the hydrogen and water vapor is transferred to the fuel cell coolant system. The resultant temperature decrease condenses some of the water vapor to water droplets. A centrifugal water separator extracts the liquid water and pressure-feeds it to potable tanks in the lower deck of the pressurized crew cabin. Water from the potable water storage tanks can be used for crew consumption and cooling the Freon-21 coolant loops. The remaining circulating hydrogen is directed back to the fuel cell stack.

The fuel cell coolant system circulates a liquid fluorinated hydrocarbon and transfers the waste heat from the cell stack through the fuel cell heat exchanger of the fuel cell power plant to the Freon-21 coolant loop system in the midfuselage. Internal control of the circulating fluid maintains the cell stack at a normal operating temperature of approximately 200 F.

When the reactants enter the fuel cells, they flow through a preheater (where they are warmed from a cryogenic temperature to 40 F or greater); a 6-micron filter; and a two-stage, integrated dual gas regulator module. The first stage of the regulator reduces the pressure of the hydrogen and oxygen to 135 to 150 psia. The second stage reduces the oxygen pressure to a range of 62 to 65 psia and maintains the hydrogen pressure at 4.5 to 6 psia differential below the oxygen pressure. The regulated oxygen lines are connected to the accumulator, which maintains an equalized pressure between the oxygen and the fuel cell coolant. If the oxygen's and hydrogen's pressure decreases, the coolant's pressure is also decreased to prevent a large differential pressure inside the stack that could deform the cell stack structural elements.

Upon leaving the dual gas regulator module, the incoming hydrogen mixes with the hydrogen-water vapor exhaust from the fuel cell stack. This saturated gas mixture is routed through a condenser, where the temperature of the mixture is reduced, condensing a portion of the water vapor to form liquid water droplets. The liquid water is then separated from the hydrogen-water mixture by the hydrogen pump/water separator.

The hydrogen pump circulates the hydrogen gas back to the fuel cell stack, where some of the hydrogen is consumed in the reaction. The remainder flows through the fuel cell stack, removing the product water vapor formed at the hydrogen electrode. The hydrogen-water vapor mixture then combines with the regulated hydrogen from the dual gas generator module, and the loop begins again.

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

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

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

If the water tanks are full or there is line blockage, the water relief valves open at 45 psia to allow the water to vent overboard through the water relief line and nozzle. Check valves prevent water tanks from discharging through an open relief valve. An alternate water delivery path is also available to deliver water to the ECLSS tanks if the primary path is lost.

For redundancy, there are two thermostatically activated heaters wrapped around the discharge and relief lines to prevent blockage caused by the formation of ice in the lines. Two switches on panel R12, fuel cell H 2 O line htr and H2O relief htr , provide the flight crew with the capability to select either auto A or auto B for the fuel cell water discharge line heaters and the water relief line and vent heaters, respectively.

Thermostatically controlled heaters will maintain the water line temperature above 53 F, when required. The normal temperature of product water is approximately 140 to 150 F. The thermostatically controlled heaters maintain the water relief valve's temperature when in use between 70 to 100 F. Temperature sensors located on the fuel cell water discharge line, relief valve, relief line and vent nozzle are displayed on the CRT.

If the potassium hydroxide electrolyte in the fuel cell migrates into the product water, a pH sensor located downstream of the hydrogen pump/water separator will sense the presence of the electrolyte, and the crew will be alerted by an SM alert and display on the CRT.

During normal fuel cell operation, the reactants are present in a closed-loop system and are 100 percent consumed in the production of electricity. Any inert gases or other contaminants will accumulate in and around the porous electrodes in the cells and reduce the reaction efficiency and electrical load support capability. Purging, therefore, is required at least twice daily to cleanse the cells. When a purge is initiated by opening the purge valves, the oxygen and hydrogen systems become open-loop systems; and increased flows allow the reactants to circulate through the stack, pick up the contaminants and blow them out overboard through the purge lines and vents. Electrical power is produced throughout the purge sequence, although no more than 10 kilowatts should be required from a fuel cell being purged because of the increased reactant flow and preheater limitations.

Fuel cell purge can be activated automatically or manually by the use of fuel cell switches on panel R12. In the automatic mode, the fuel cell purge heater switch is positioned to GPC . The purge line heaters are turned on to heat the purge lines to ensure that the reactants will not freeze in the lines. The hydrogen reactant is the more likely to freeze because it is saturated with water vapor. Depending on the orbit trajectory and vehicle orientation, the heaters may require 27 minutes to heat the lines to the required temperatures. The fuel cell current is checked to ensure a load of less than 350 amps, due to limitations on the hydrogen and oxygen preheaters in the fuel cells. As the current output of the fuel cell increases, the reactant flow rates increase, and the preheaters raise the temperature of the reactants to a minimum of minus 40 F in order to prevent the seals in the dual gas regulator from freezing.

The purge lines from all three fuel cells are manifolded together downstream of their purge valves and associated check valves. The line leading to the purge outlet is sized to permit unrestricted flow from only one fuel cell at a time. If purging of more than one cell at a time is attempted, pressure could build in the purge outlet line and cause a decrease in the flow rate through the individual cells, which would result in an inefficient purge.

When the fuel cell purge valves 1, 2 and 3 switches are positioned to GPC, the fuel cell GPC purge seq switch is positioned to start and must be held until the GPC purge seq talkback indicator indicates gray (in approximately three seconds). The automatic purge sequence will not begin if the indicator indicates barberpole. The GPC turns the purge line heaters on and monitors the temperature. The one oxygen line temperature sensor must register at least 69 F and the two hydrogen line temperature sensors 79 and 40 F, respectively, and be verified by the GPC before the purge sequence begins. If the temperatures are not up to minimum after 27 minutes, the GPC will issue an SM alert and display the data on the CRT. When the proper temperatures have been attained, the GPC will open for two minutes and then close the hydrogen and oxygen purge valves for fuel cells 1, 2 and 3 in that order. Thirty minutes after the fuel cell 3 purge valves have been closed (to ensure that the purge lines have been totally evacuated), the GPC will turn off the purge line heaters. This provides sufficient time and heat to bake out any remaining water vapor. If the heaters are turned off before 30 minutes have elapsed, water vapor left in the lines may freeze.

The manual fuel cell purge would be initiated by the flight crew using the switches on panel R12. In the manual mode, the three fuel cells must be purged separately. The fuel cell purge heater switch is positioned to on for the same purpose as in the automatic mode, and the flight crew verifies that the temperatures of the oxygen line and two hydrogen lines are at the same minimum temperatures as in the automatic mode before the purge sequence is initiated. The fuel cell purge valves 1 switch is positioned to open for two minutes, and the flight crew observes that the oxygen and hydrogen flow rates increase on the CRT. The fuel cell purge valves 1 switch is then positioned to close , and a decrease in the oxygen and hydrogen flow rates is observed on the CRT, indicating the purge valves are closed. Fuel cell 2 is purged in the same manner using the fuel cell purge valves 2 switch. Fuel cell 3 is then purged in the same manner using the fuel cell purge valves 3 switch. After the 30-minute line bakeout period, the fuel cell purge heater switch is positioned to off.

In order to cool the fuel cell stack during its operations, distribute heat during fuel cell starting, and warm the cryogenic reactants entering the stack, the fuel cell circulates a coolant-fluorinated hydrocarbon-throughout the fuel cell. The fuel cell coolant loop and its interface with the ECLSS Freon-21 coolant loops are identical in fuel cells 1, 2 and 3.

Where the coolant enters the fuel cell, the temperature of the F-40 coolant returning from the ECLSS Freon-21 coolant loops is sensed before it passes through a 75-micron filter. After the filter, two temperature-controlled mixing valves allow some of the hot coolant to mix with the cool returning coolant to prevent the condenser exit control valve from oscillating. The condenser exit control valve adjusts the flow of the coolant through the condenser to maintain the hydrogen-water vapor exiting the condenser at a temperature between 148 and 153 F.

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

The coolant is circulated through the fuel cell stack to absorb the waste heat from the hydrogen/oxygen reaction occurring in the individual cells. After the coolant leaves the stack, its temperature is sensed and the data transmitted to the GPC, to the fuel cell stack temp meter through the fuel cell 1, 2, 3 switch located below the meter on panel O2, and to the CRT display. The yellow fuel stack temp C/W and the backup C/W alarm lights on panel F7 and the SM alert light will be illuminated if fuel cell and stack temperatures exceed certain limits: below 172.5 F or above 243.7 F. The hot coolant from the stack flows through the oxygen and hydrogen preheaters, where it warms the cryogenic reactants before they enter the stack.

The coolant pump utilizes three-phase ac power to circulate the coolant through the loop. The differential pressure sensor senses a pressure differential across the pump to determine the status of the pump. The fuel cell pump C/W light on panel F7 will be illuminated if fuel cell 1, 2 or 3 coolant pump delta pressure is lost. The SM alert light also will be illuminated, and a fault message will be sent to the CRT. If the coolant pump for fuel cell 1, 2 or 3 is off , the backup C/W alarm light will be illuminated, and a fault message will be sent to the CRT. The temperature-actuated flow control valve downstream from the pump adjusts the coolant flow to maintain the fuel cell coolant exit temperature between 190 and 210 F. The stack inlet control valve and flow control valve have bypass orifices to allow coolant flow through the coolant pump and to maintain some coolant flow through the condenser for water condensation, even when the valves are fully closed due to the requirements of thermal conditioning.

The coolant (that which is not made to bypass) exits the fuel cells to the fuel cell heat exchanger, where it transfers its excess heat to be dissipated through the ECLSS Freon-21 coolant loop systems in the midfuselage.

In addition to thermal conditioning by means of the coolant loop, the fuel cell has internal startup and sustaining heaters. The 2,400-watt startup heater is used only during startup to warm the fuel cell to its operational level. The 1,100-watt sustaining heaters normally are used during low power periods to maintain the fuel cells at their operational temperature.

Two 160-watt end-cell electrical heaters on each fuel cell power plant were used to maintain a uniform temperature throughout the fuel cell power section. As an operational improvement, the end-cell electrical heaters on each fuel cell power plant were deleted due to potential electrical failures and were replaced by fuel cell power plant coolant (F-40) passages. This permits waste heat from each fuel cell power plant to be used to maintain a uniform temperature profile for each fuel cell power plant.

The hydrogen pump and water separator of each fuel cell power plant were also improved. To minimize excessive hydrogen gas entrained in each fuel cell power plant's product water, modifications were made to the water pickup (pitot) system. The centrifugal force of high-velocity water flowing around the pitot tube's bends separates the hydrogen gas and water. Pitot pressure then expels the hydrogen gas into the hydrogen pump's inlet housing though a bleed orifice.

A current measurement detection system was added to monitor the hydrogen pump load for each fuel cell power plant. Excessive load could indicate improper water removal, which could lead to flooding of the fuel cell power plant and eventually render that power plant inoperative.

The start/sustaining heater system for each fuel cell power plant was also modified. The modification was required specifically for fuel cell power plant No. 1, mounted on the port, or left, side. The No. 1 fuel cell power plant start/sustaining heater system added heat to that fuel cell power plant's F-40 coolant loop system during the startup of the power plant. Because of its orientation, any entrained gas in the coolant could enter the heater and become trapped at the heater elements. This would result in overheating of the heater elements, which could vaporize the F-40 coolant, causing heater failure and extensive damage to the fuel cell power plant. The F-40 coolant loop flow system within the start/sustaining heater of each fuel cell power plant was modified to prevent a gas bubble from developing or being trapped at the heater elements, preventing the loss of the start/sustaining heater.

A stack inlet temperature measurement was added to each fuel cell power plant. The temperature measurement was added to the in-flight system to provide full visibility of the thermal conditions of each fuel cell power plant (similar to the existing stack exit and condenser exit temperatures of each fuel cell power plant).

The product water from all three fuel cell power plants flows to a single water relief control panel. The water can be directed from the single panel to the ECLSS potable water tank A or to the fuel cell power plant water relief nozzle. Normally, the water is directed to water tank A. In the event of a line rupture in the vicinity of the single water relief panel, water could spray on all three water relief panel lines, causing them to freeze and prevent fuel cell power plant water discharge.

The product water lines from all three fuel cell power plants were modified to incorporate a parallel (redundant) path of product water to ECLSS potable water tank B in the event of a freeze-up of the single water relief panel. In the event of the single water relief panel freeze-up, pressure would build up and relieve through the redundant paths to water tank B. Temperature sensors and a pressure sensor installed on each of the redundant water line paths transmit data via telemetry for ground monitoring.

A water purity sensor (pH) was added at the common product water outlet of the water relief panel to provide a redundant measurement of water purity. A single measurement of water purity in each fuel cell power plant was provided previously. If the fuel cell power plant pH sensor failed, the flight crew was required to sample the potable water.

The electrical control unit located in each fuel cell power plant is the brain of the power plants. The ECU contains the start up logic, heater thermostats, and 30-second timer and interfaces with the controls and displays for fuel cell startup, operation and shutdown. The ECU controls the supply of ac power to the coolant pump, hydrogen pump/water separator, the pH sensor, and the dc power supplied to the flow control bypass valve (open only during startup) and the internal startup and sustaining heaters. The ECU also controls the status of the fuel cell 1, 2, 3 ready for load and coolant pump P talkback indicators on panel R1.

The nine fuel cell circuit breakers that connect the three-phase ac power to the three fuel cells are located on panel L4, and the fuel cell ECU receives its power from an essential bus through the FC cntlr switch on panel O14.

The fuel cell start/stop switch on panel R1 for each fuel cell is used to initiate the start sequence or stop the fuel cell operation. When this switch is held in its momentary start position, the ECU connects the three-phase ac power to the coolant pump and hydrogen pump/water separator (allowing the coolant and the hydrogen-water vapor to circulate through these loops) and connects the dc power to the internal startup and sustaining heaters and the flow control bypass valve. The switch must be held in the start position until the coolant pump P talkback shows gray in approximately three to four seconds, which indicates that the coolant pump is functioning properly by creating a differential pressure across the pump. When the coolant pump P talkback indicates barberpole, it indicates the coolant pump is not running.

The ready for load talkback for each fuel cell will show gray after the 30-second timer times out and the stack-out temperature is above 187 F (which can be monitored on panel O2 in conjunction with the 1, 2, 3 switch located beneath the fuel cell stack out temp meter). This indicates that the fuel cell is up to the proper operating temperature and is ready for loads to be attached to it. It should not take longer than 25 minutes for the fuel cell to warm up and become fully operational, the actual time depending on the fuel cell's initial temperature. The ready for load indicator remains gray until the fuel cell start/stop switch for each fuel cell is placed to stop, the FC cntlr switch is placed to off , or the essential bus power is lost to the ECU.

The startup heater enable/inhibit switch on panel R12 for each fuel cell provides the crew control of the off/on status of the startup heaters during fuel cell startup. The inhibit position allows the startup heaters to remain off and would be used only when immediate power is required from a shutdown fuel cell.

Fuel cell 1, 2 or 3 dc voltage and current (amps) can be monitored on the dc volts and dc amps meters on panel F9, using the fuel cell volts/amp rotary switch to select a specific fuel cell.

The fuel cells will be on when the crew boards the vehicle, and the vehicle is powered by the fuel cells and load sharing with the ground support equipment power supplies. Just before lift-off (T minus three minutes and 30 seconds), the GSE is powered off and the fuel cells take over all of the vehicle's electrical loads. Indication of the switchover can be noted on the CRT display and the dc amps meter. The fuel cell current will increase to approximately 220 amps; the oxygen and hydrogen flow will increase to approximately 4 and 0.6 pound per hour, respectively; and the fuel cell stack temperature will increase slightly.

Fuel cell standby consists of removing the electrical loads but continuing operation of the fuel cell pumps, controls, instrumentation and valves, with the electrical power being supplied by the remaining fuel cells. A small amount of reactants is used to generate power for the fuel cell internal heaters.

Fuel cell shutdown, after standby, consists of stopping the coolant pump and hydrogen pump/water separator by positioning that fuel cell start/stop switch on panel R1 to the stop position. If the temperature in the fuel cell compartment beneath the payload bay is lower than 40 F, the fuel cell should be left in standby instead of being shut down to prevent it from freezing.

Each fuel cell power plant is 14 inches high, 15 inches wide and 40 inches long and weighs 255 pounds.

The voltage and current range of each is 2 kilowatts at 32.5 volts dc, 61.5 amps, to 12 kilowatts at 27.5 volts dc, 436 amps. Each fuel cell is capable of supplying 12 kilowatts peak and 7 kilowatts maximum continuous power. The three fuel cells are capable of a maximum continuous output of 21,000 watts with 15-minute peaks of 36,000 watts. The average power consumption of the orbiter is expected to be approximately 14,000 watts, or 14 kilowatts, leaving 7 kilowatts average available for payloads. Each fuel cell will be serviced between flights and reused until each accumulates 2,000 hours of on-line service.
