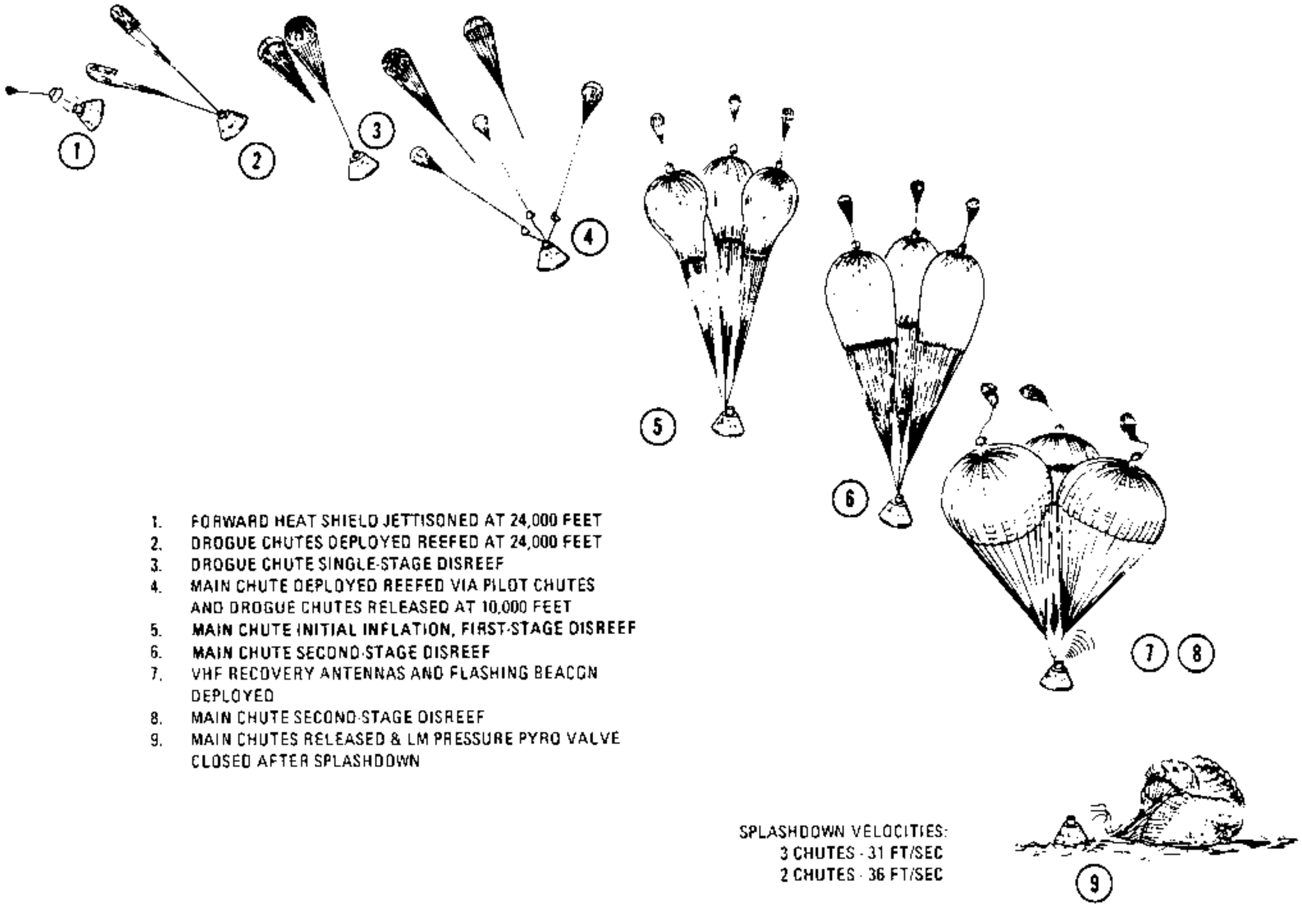


1. FORWARD HEAT SHIELD JETTISONED AT 24,000 FEET
2. DROGUE CHUTES DEPLOYED REEFED AT 24,000 FEET
3. DROGUE CHUTE SINGLE-STAGE DISREEF
4. MAIN CHUTE DEPLOYED REEFED VIA PILOT CHUTES AND DROGUE CHUTES RELEASED AT 10,000 FEET
5. MAIN CHUTE INITIAL INFLATION, FIRST-STAGE DISREEF
6. MAIN CHUTE SECOND-STAGE DISREEF
7. VHF RECOVERY ANTENNAS AND FLASHING BEACON DEPLOYED
8. MAIN CHUTE SECOND-STAGE DISREEF
9. MAIN CHUTES RELEASED & LM PRESSURE PYRO VALVE CLOSED AFTER SPLASHDOWN

SPLASHDOWN VELOCITIES:
3 CHUTES - 31 FT/SEC
2 CHUTES - 36 FT/SEC

P-132

Normal sequence of operation for earth landing subsystem

parachutes are automatically deployed 12 seconds later, or between zero and 12 seconds by the astronauts. For high-altitude aborts, the main parachutes are deployed in the same manner as normal entry.

After splashdown, the main parachutes are released and the recovery aid subsystem is set in operation by the crew. The subsystem consists of an uprighting system, swimmer's umbilical cable, a sea dye marker, a flashing beacon, and a VHF beacon transmitter. A sea recovery sling of steel cable also is provided to lift the CM aboard a recovery ship.

The two VHF recovery antennas are located in the forward compartment with the parachutes. They are deployed automatically 8 seconds after the main parachutes. One of them is connected to the beacon transmitter, which emits a 2-second signal every 5 seconds to aid recovery forces in locating the CM. The other is connected to the VHF/AM transmitter and receiver to provide voice communications between the crew and recovery forces.

Automatic operation of the earth landing subsystem is provided by the event sequencing system located in the right-hand equipment bay of the command module. The system contains the barometric pressure switches, time delays, and relays necessary to control automatically the jettisoning of the heat shield and the deployment of the parachutes.

The parachute subsystem is produced by the Northrop Corporation, Ventura Division, Newbury Park, Calif.

EQUIPMENT

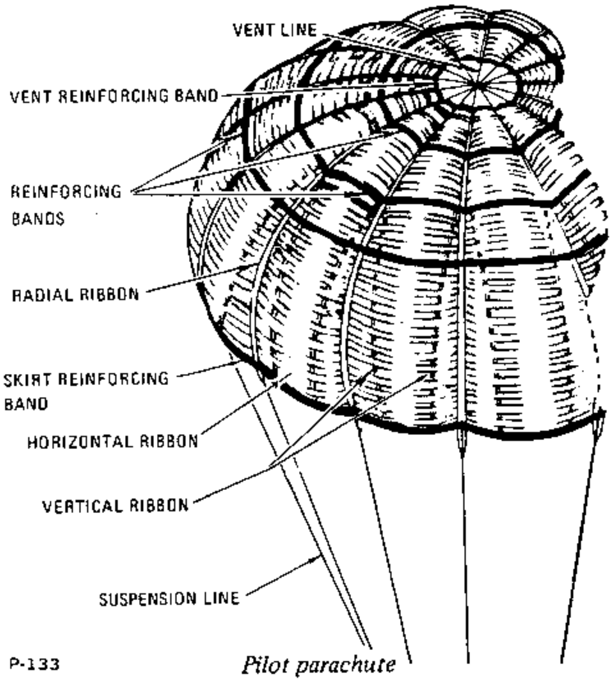
Drogue Parachutes (Northrop-Ventura, Newbury Park, Calif.) – Two white nylon conical-ribbon parachutes with canopy diameters of 16.5 feet. They are deployed at 23,000 feet to orient and slow the spacecraft from 300 miles an hour to 175 miles an hour so that the main parachutes can be safely deployed. They are 65 feet above the command module.

Pilot Parachutes (Northrop-Ventura) – Three white nylon ring-slot parachutes with canopy diameters of 7.2 feet. They deploy the main parachutes and are 58 feet above the main parachutes.

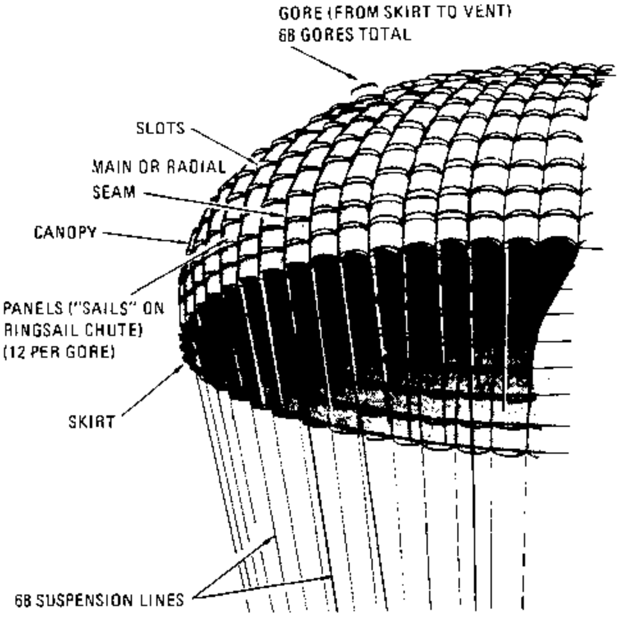
Main Parachutes (Northrop-Ventura) – Three orange-and-white-striped ringsail parachutes with canopy diameters of 83.5 feet. Each weighs 127 pounds counting canopy, risers, and deployment bag. They are deployed at 10,000 feet to reduce the speed of the spacecraft from 175 miles an hour to 22 miles an hour when it enters the water. The parachutes are 120 feet above the command module.

Reefing Line Cutters (Northrop-Ventura) – Each assembly is about the size of a fountain pen and consists of slow-burning powder, small explosive charge, blade, and hole through which the reefing line passes. Burning powder sets off a charge, which drives the blade into the reefing line, severing it and allowing full inflation of the parachutes.

Sequence Controller – Two 3 by 3 by 6-inch boxes each containing four barometric pressure switches, four time delays, and four relays to sequence and control the deployment and release of parachutes automatically. Each box weighs less than four pounds. They are in the forward compartment of the command module.



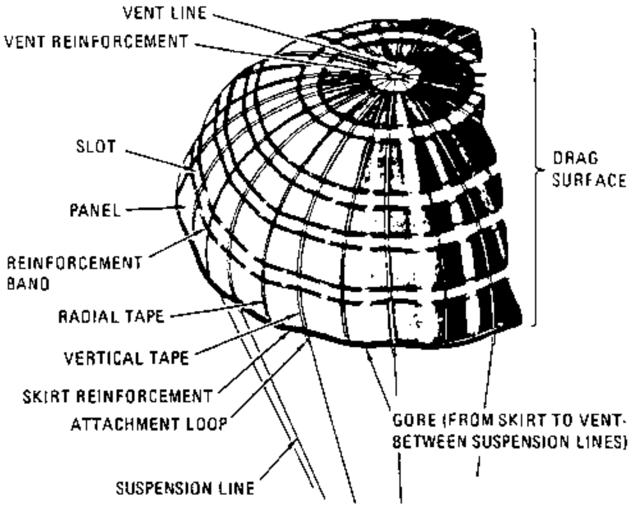
P-133 *Pilot parachute*



P-134 *Main parachute*

Pyro Continuity Verification Box – A 2-1/2 by 8 by 10-inch box containing relays and fusistors located in the forward compartment of the command module. It provides an accessible point within the command module to verify the continuity of the pyrotechnic device firing circuits.

Uprighting System – Three inflatable bags in the forward compartment of the command module



P-135 *Drogue parachute*

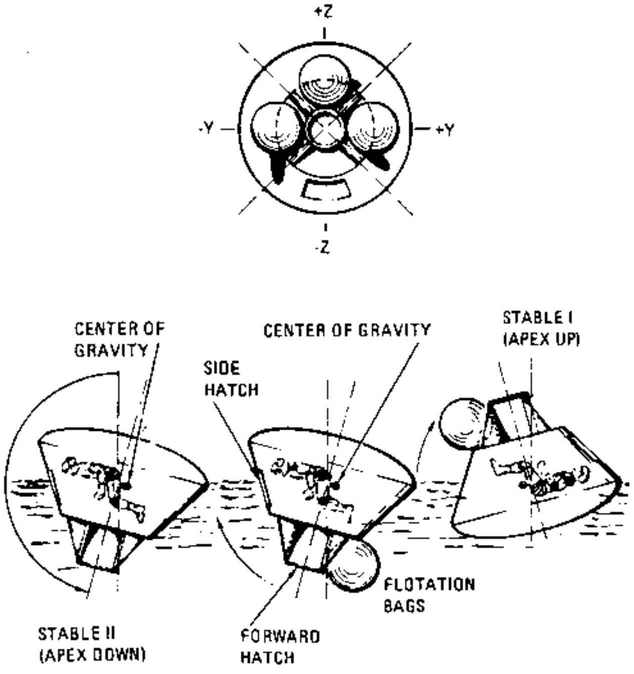
and two air compressors in the aft compartment. The compressors are manually initiated to provide air to the bags through tubes. Each bag has a volume of 22 cubic feet. If the command module turns apex down after landing, the air bags are inflated to right the spacecraft.

Sea Dye Marker – Powdered fluorescein dye packed in a 3 by 3 by 6-inch metal container. When the marker is deployed, dye colors the sea yellow-green around the command module. The marker is in the forward compartment of the command module. It is released manually and is connected to the command module by a 12-foot tether. The dye lasts approximately 12 hours.

Flashing Beacon – Flashing self-powered strobe light to aid in recovery of crew and command module. Eight seconds after main parachutes are deployed, the beacon is automatically extended from the forward compartment of the command module. The light is turned on manually. The arm is one-foot long.

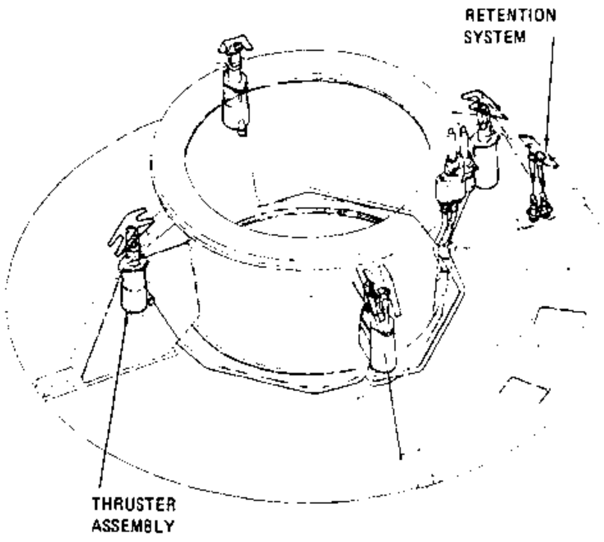
Swimmer's Umbilical – This is the 12-foot dye marker tether. •A recovery frogman can connect his communications equipment to the end of the tether to talk to the command module crew.

Automatic and manual control circuits for jettisoning the forward heat shield are included in the integrated master events sequence controllers, the earth landing sequence controllers, and the lunar docking events controllers.



P-136

CM uprighting system



P-137

Forward heat shield retention and thruster system

The shield is jettisoned by the use of a thruster mechanism and a drag parachute. When gas pressure is generated by the pressure cartridges, two pistons are forced apart, breaking a tension tie which connects the shield to the forward compartment structure. The lower piston is forced against a stop and the upper piston is forced out of its cylinder. The piston rod ends are fastened to fittings on the shield, which is thrusted away from the CM. Two of the thruster assemblies have breeches and pressure cartridges; plumbing connects the breeches to thrusters mounted on diametrically opposite CM structural members.

The mortar-deployed parachute drags the heat shield out of the area of negative air pressure following the CM and prevents recontact with the CM. Lanyard-actuated switches are used to fire mortar pressure cartridges.

The forward heat shield must be jettisoned before earth landing equipment may be used. Drogue and pilot parachutes are mortar-deployed to assure that they are ejected beyond the turbulent air around and following the CM. An engine protector bar prevents damage to CM reaction control engines by the drogue cables. The drogue cables (risers) are protected from damage by spring-loaded covers over the launch escape tower attachment studs.

The sea recovery cable loop will spring into position after the parachutes have been deployed. Three uprighting bags are installed under the main parachutes. A switch is provided for the crew to deploy the sea dye marker and swimmer umbilical any time after landing.

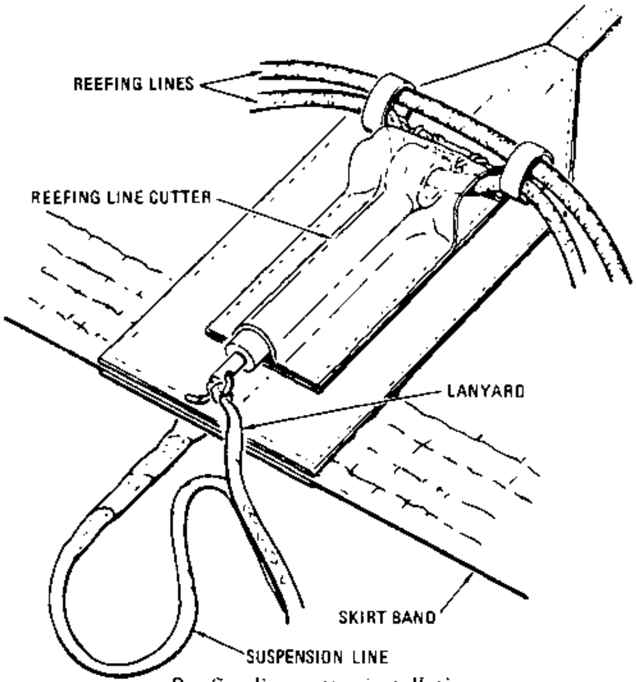
Eight parachutes are used in the earth landing subsystem: two drogue, three pilot, and three main. The drogue parachutes are the conical ribbon type and are 16.5 feet in diameter. The pilot parachutes are the ring slot type and are 7.2 feet in diameter. The main parachutes are the ring sail type and are 83.5 feet in diameter.

The drogue and main parachutes are deployed reefed for 10 seconds. The reefing lines run through rings which are sewn to the inside of the parachute skirts and reefing line cutters. When the suspension lines pull taut, a lanyard pulls the sear release from the reefing line cutter and a pyrotechnic time-delay is started. When the delay train has burned through, a propellant is ignited, driving a cutter through the reefing line.

Each of the drogue parachutes has two reefing lines with two cutters per line to prevent disreefing in case one reefing line cutter fires prematurely. Each of the three main parachutes has three reefing lines with two cutters per line. Two of the three reefing lines are severed after 6 seconds, allowing the main parachutes to open slightly wider than when deployed. The remaining reefing line is cut 4 seconds later, or 10 seconds after deployment. At this time the parachutes inflate fully.

Reefing line cutters also are used in the deployment of the two VHF antennas and the flashing beacon light during descent. These recovery devices are retained by spring-loaded devices which are secured with parachute rigging cord. The cord is passed through reefing line cutters which are activated by action of the main parachute risers.

Redundant channels in the sequential events system command the sequence of operations of the subsystem.



P-138

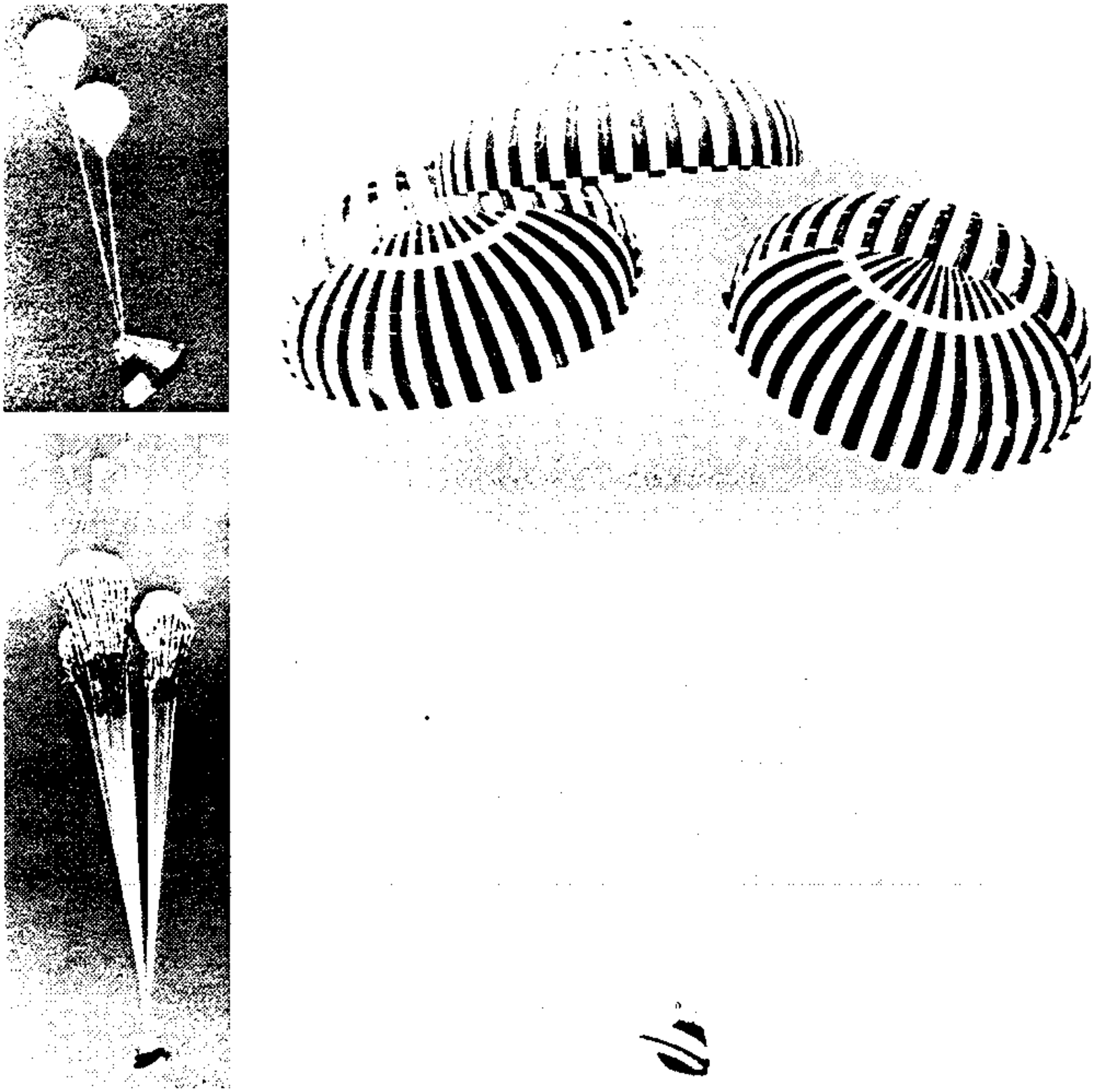
Reefing line cutter installation

Activation of the earth landing subsystem switch ("ELS Logic") on the main display console closes logic power circuits to redundant transistorized switches in the master events sequence controllers. Each of these solid-state switches requires two conditions to close; one is closure of the logic power circuits, the other is closure of the 24,000-foot barometric switches. Assuming that the subsystem is set for automatic operation, closure of the barometric switches activates the earth landing subsystem controller and begins the landing sequence.

The barometric switches are devices which use air pressure to trigger a switch at a set altitude. The dorgue baroswitches are set to close at the normal pressure for 24,000 feet; because air pressure varies with meteorological conditions, however, the switches may close a little above or a little below that altitude.

In addition to activating the earth landing subsystem controllers, closure of the 24,000-foot baroswitches energizes the 24,000-foot lockup relay in the controllers. This establishes logic power holding circuits which bypass the baroswitches. When the controllers are activated a signal is relayed to the unlatching coils of the reaction jet engine control to disable the automatic firing of the reaction control engines.

The first function of the earth landing subsystem controllers is to jettison the forward heat shield. After a delay of 0.4 second, the shield thrusters are fired and the lanyard-actuated switches used to deploy the drag parachute are armed. The lanyard, which is attached to the forward heat shield, pulls



P-139

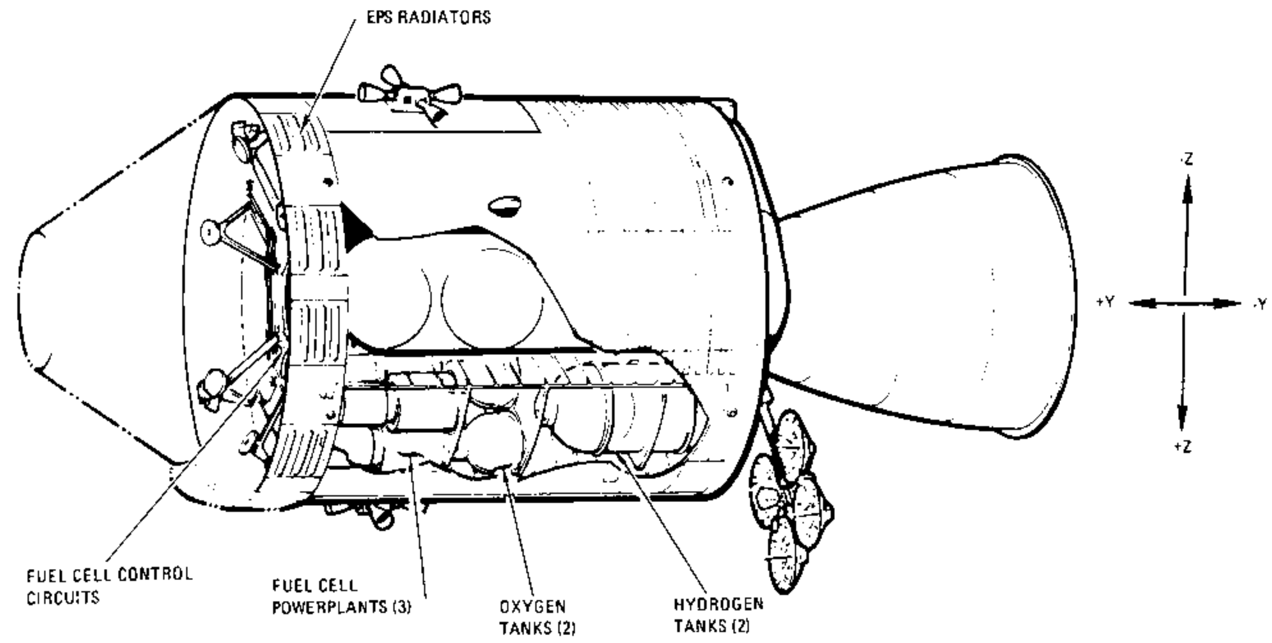
Parachute sequence: drogues (top left) open at 24,000 feet, pilots pull out main chutes (bottom left), and main chutes open fully

holding pins from the switches which, because of spring loading, close circuits to energize relays to fire the drag parachute mortar.

Two seconds after the forward heat shield is jettisoned, relays close to send signals that fire the drogue mortars and deploy the drogue parachutes. When the CM has descended to 10,000 feet, another set of baroswitches closes to energize relays which fire the mortars to deploy the pilot parachutes. The main parachutes are deployed by the pilot chutes.

After splashdown, a crewman activates a switch on the main display console which fires ordnance devices to drive a chisel-type cutter through the main parachute risers, releasing the chutes.

ELECTRICAL POWER



Location of major electrical power subsystem equipment

The electrical power subsystem provides electrical energy sources, power generation and control, power conversion and conditioning, and power distribution to the spacecraft throughout the mission. For checkout before launch, dc electrical power is supplied by ground support equipment. The electrical power subsystem furnishes drinking water to the astronauts as a byproduct of its fuel cell powerplants, and includes the cryogenic gas storage system.

Each of the three fuel cell powerplants (produced by United Aircraft Corp.'s Pratt & Whitney Aircraft Division, Hartford, Conn.) consists of 31 cells connected in series. Each cell consists of a hydrogen compartment, an oxygen compartment, and two electrodes (conductors) — one hydrogen and one oxygen. The electrolyte (substance through which ions are conducted) is a mixture of approximately 72 percent potassium hydroxide and approximately 28 percent water and provides a constant conduction path between electrodes. The hydrogen electrode is nickel and the oxygen electrode is nickel and nickel oxide.

The reactants (hydrogen and oxygen) are supplied to the cell under regulated pressure (referenced to a nitrogen gas supply which also is used to pressurize the powerplants). Chemical reaction produces electricity, water, and heat, with the reactants being consumed in proportion to the electrical load. The byproducts—water and heat—are used to maintain the drinking water supply and to keep the electrolyte at the proper operating temperature. Excess heat is rejected to space through the space radiators. The fuel cell powerplants are located in Sector 4 of the service module.

Three silver oxide-zinc storage batteries supply power to the CM during entry and after landing, provide power for sequence controllers, and supplement the fuel cells during periods of peak power demand. These batteries are located in the lower equipment bay of the CM. A battery charger located in the same bay re-charges the batteries after each use and assures that they will be fully charged before entry. These batteries are produced by Eagle Picher Co., Joplin, Mo.

Two other silver oxide-zinc batteries, independent of and completely isolated from the rest of the dc power system, are used to supply power for explosive devices. These batteries are not recharged. They are produced by the Electric Storage Battery Co., Raleigh, N.C.

The cryogenic (ultra low temperature) gas storage system (produced by Beech Aircraft Corp., Boulder, Colo.) supplies the hydrogen and oxygen used in the fuel cell powerplants, as well as the oxygen used in the environmental control subsystem. The system consists of storage tanks and associated valves, switches, lines, and other plumbing. The hydrogen and oxygen are stored in a semi-gas, semi-liquid state; by the time they reach the fuel cells, however, they have warmed considerably and are in a gaseous state. The system is located in Sector 4 of the service module beneath the fuel cell powerplants.

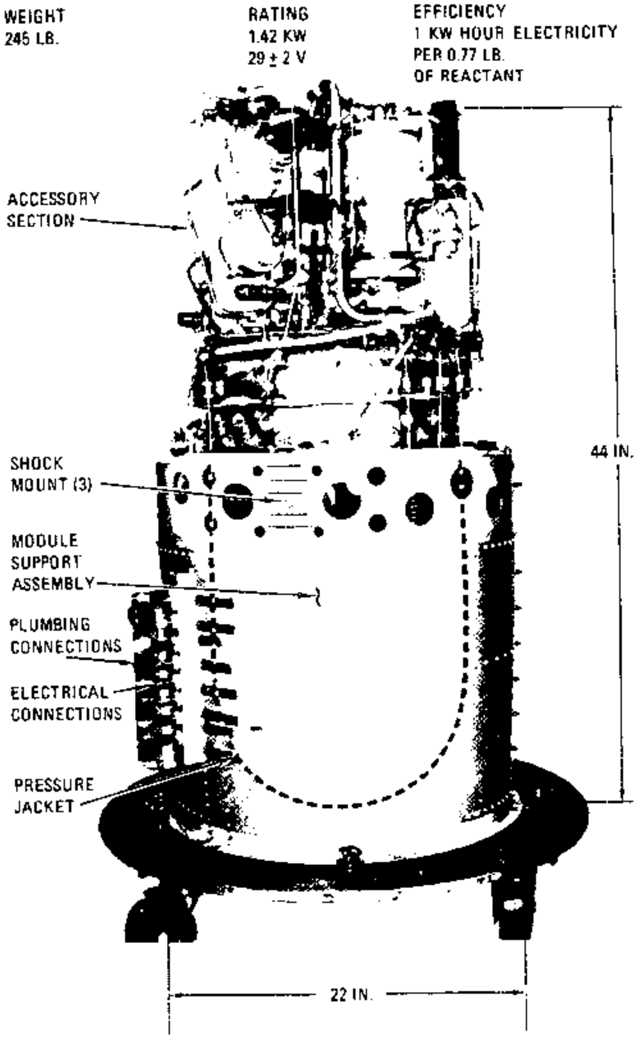
Three solid-state inverters, located in the lower equipment bay of the CM, supply the ac power for the spacecraft. These inverters are devices which convert dc electrical power into ac. Both the fuel cell powerplants and batteries, the two electrical power sources in the spacecraft, produce dc power.

The inverters operate from the two 28-volt dc main buses (connecting circuits) to supply 115/120-volt, 400-cycle, 3-phase ac power to two ac buses. Normally two inverters are used; however, one inverter can supply all primary ac electrical power needed by the spacecraft. If one inverter fails, a crewman can switch in the standby. Two inverters cannot be paralleled (hooked up together).

The inverters are produced by Westinghouse Electric's Aerospace Electrical Division, Lima, Ohio.

EQUIPMENT

Oxygen Tanks (Beech Aircraft Corp., Boulder, Colo.) — Two spherical dewar-type tanks made of Inconel (nickel-steel alloy) in Sector 4 of the service module store oxygen for production of power by fuel cells, for command module pressurization, and for metabolic consumption. Outer diameter of each is 26.55 inches and wall thickness is 0.020 inch. Tanks with accessories are 36.39 inches tall. Each tank has an inner vessel with a diameter of 25.06 inches and wall thickness of 0.061 inch. Rupture pressure of the tanks is 1530 pounds per square inch. Insulation between the inner and outer shells is fiberglass, paper mating, and aluminum foil. In addition, a pump maintains a vacuum between the inner and outer vessels. Each tank weighs 79-1/2 pounds, has a volume of 4.73 cubic feet, and a capacity of 320 pounds — 210 pounds for fuel cells and 110 pounds for environmental control. Each tank has a repressurization probe with two heaters and two fans to keep the tank pressurized and a capacitive probe which measures the amount of oxygen. A resistance element measures temperature.



P-141 *Fuel cell powerplant*

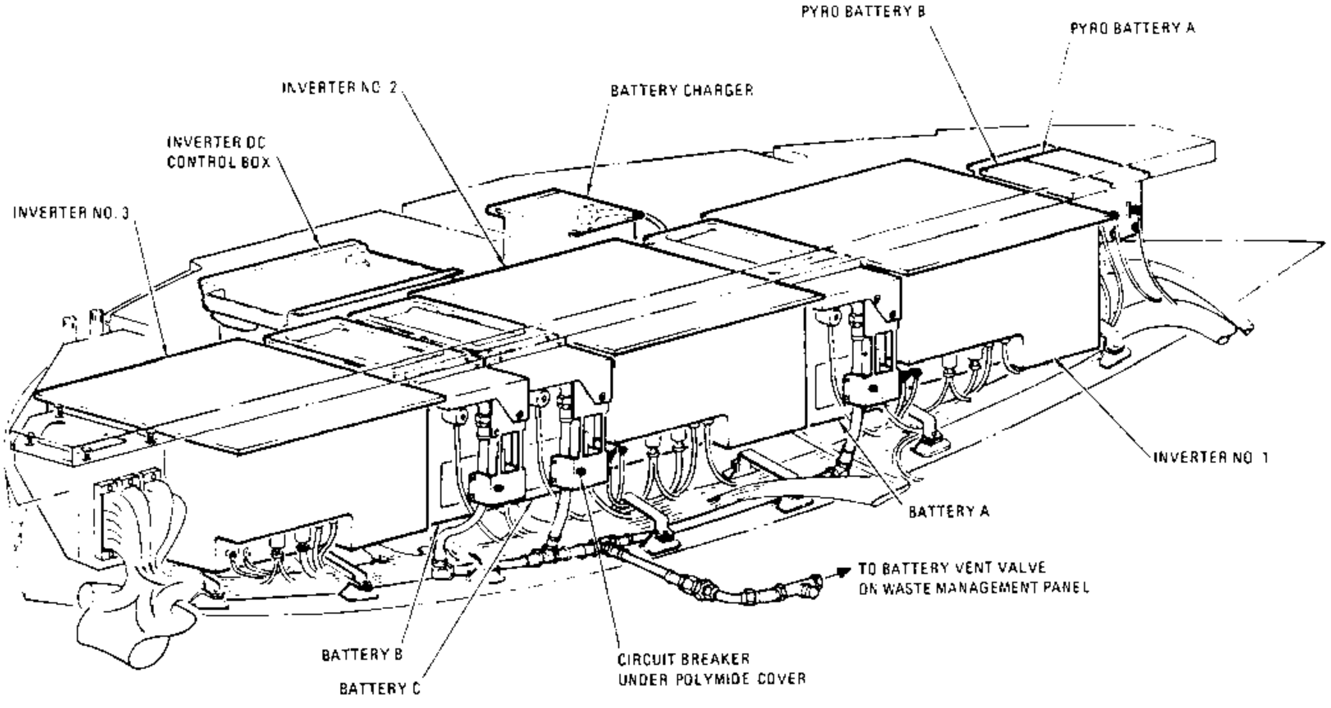
Hydrogen Tanks (Beech) — Two spherical dewar-type titanium tanks located in Sector 4 of the service module contain the hydrogen that powers the fuel cell. Outer diameter of each is 31.80 inches and wall thickness is 0.033 inch. Each tank is 31.9 inches tall and has an inner vessel 28.24 inches in diameter with a wall thickness of 0.046 inch. Rupture pressure is 450 pounds per square inch. Unlike the oxygen tank, which has insulation between the inner and outer shells, the hydrogen tanks have a vapor-cooled shield suspended in a vacuum as a heat barrier. Each tank weighs 69 pounds, has a volume of 6.75 cubic feet, and a capacity of 28 pounds of usable fluid. Similar to the oxygen tanks, they contain repressurization and capacitive probes, a pump to maintain the vacuum, and temperature transducers.

Batteries (Eagle Picher Co., Joplin, Mo.) – Three silver oxide-zinc storage batteries are in the command module lower equipment bay. Each has 20 cells with potassium hydroxide and water as an electrolyte. Battery cases are plastic, coated with fiberglass epoxy, and are vented overboard for outgassing. Each is 6-7/8 by 5-3/4 inches and weighs 28 pounds. The batteries are rated at 40 ampere hours, providing a high power-to-weight ratio. Open circuit voltage is 37.2 volts. The battery characteristics are such that a minimum of 27 volts can be maintained until the battery is depleted. The batteries have been shock-tested to 80-g impact. The batteries provide all CM power during entry and after landing. They also supplement fuel cells during major thrusting maneuvers and provide power for the sequence system and fuel cell and inverter control circuits.

Battery Charger – The constant-voltage, current-limited charger is 4 by 6 by 6 inches and weighs 4.3 pounds. The current is limited to 2.8 amperes so as not to overheat the batteries. It has an operating life of more than 1,000 hours. The charger is located near the entry and postlanding batteries.

Pyrotechnic Batteries (Electric Storage Battery Co., Raleigh, N.C.) – Each of the two silver oxide-zinc batteries in the lower equipment bay has 20 cells with potassium hydroxide and water as an electrolyte. The cases are plastic. There is a relief valve venting arrangement for outgassing. Each is 2-3/4 by 3 by 6-3/4 inches and is rated at 0.75 ampere hours with an open-circuit voltage of 37.2 volts and a 20-volt minimum underrated load. They power mild explosive devices for CM-SM separation, parachute deployment and separation, Saturn third stage separation, launch escape tower separation, and other functions.

Fuel Cell Powerplants (United Aircraft Corporation's Pratt & Whitney Aircraft Division, Hartford, Conn.) – Three fuel cell powerplants, each 44 inches high, 22 inches in diameter, and weighing 245 pounds, are located in Sector 4 of the SM. They are mainly constructed of titanium, stainless steel, and nickel. They are rated at 27 to 31 volts under normal loads. There are 31 separate cells in a stack, each producing 1 volt, with potassium hydroxide and water as electrolyte. Each cell consists of a hydrogen and an oxygen



P-142

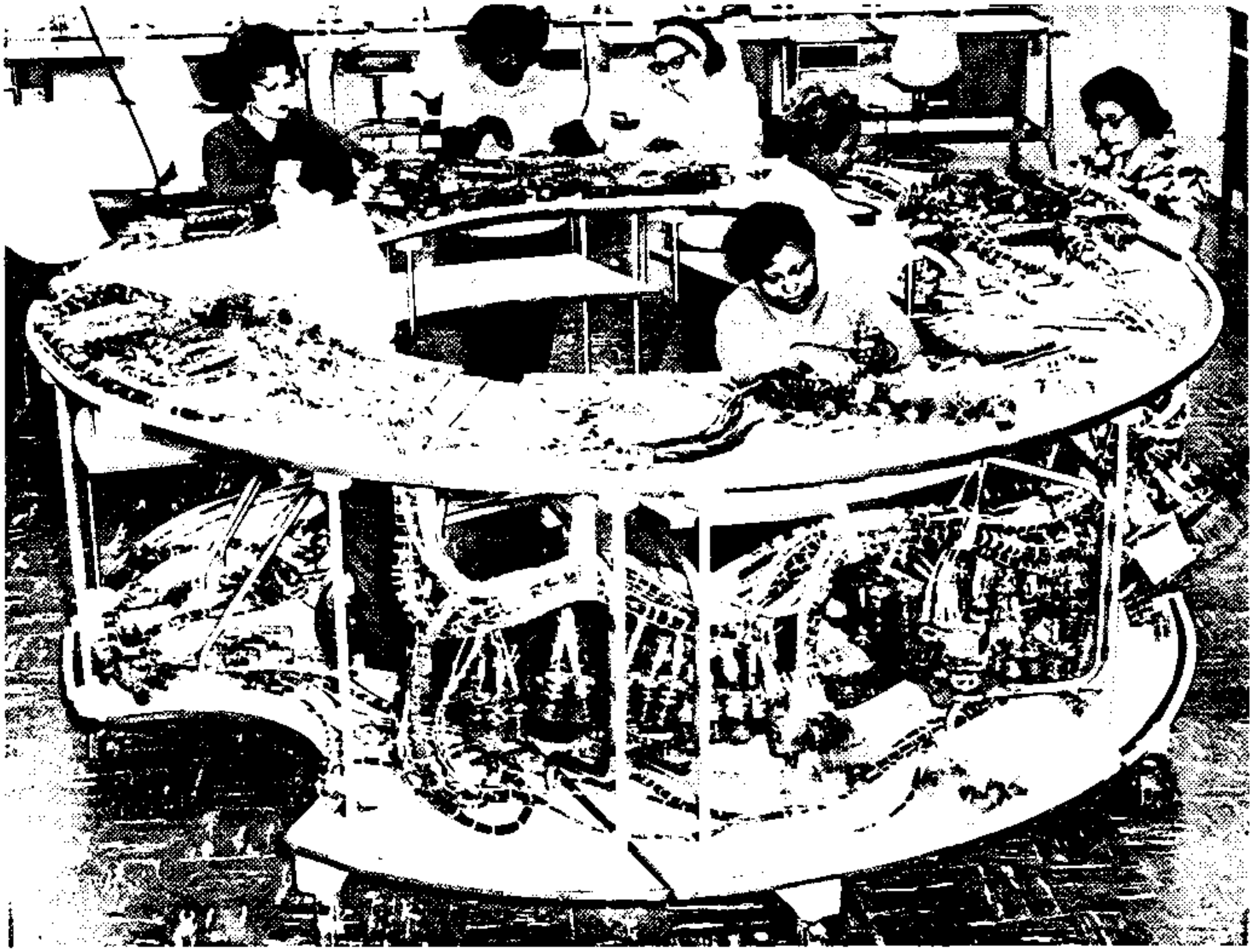
Electrical power subsystem components in CM lower equipment bay electrode, a hydrogen and an oxygen gas compartment, and the electrolyte. Each gas reacts independently to produce a flow of electrons. The fuel cells are nonregenerative. They are normally operated at 400 degrees F with limits of 385 and 500 degrees. Water-glycol is used for temperature control. The fuel cells use hydrogen, oxygen, and nitrogen under regulated pressure to produce power and, as a by-product, water.

Inverters (Westinghouse Electric's Aerospace Electrical Division, Lima, Ohio) — Three solid-state inverters are in the lower equipment bay. Each is contained in an aluminum enclosure and coldplated with a water-glycol loop. The inverters weigh 53 pounds each and are 14-3/4 by 15 by 5 inches. They produce 1250 volt-amperes each. They convert 28-volt dc to 115-volt ac, 3 phase, 400 Hertz. They are designed to compensate for input and output voltage variations. Two of the three inverters are in constant use. They provide alternating current for fuel cell pumps, environmental control system glycol pumps, space suit compressors, and other circuitry.

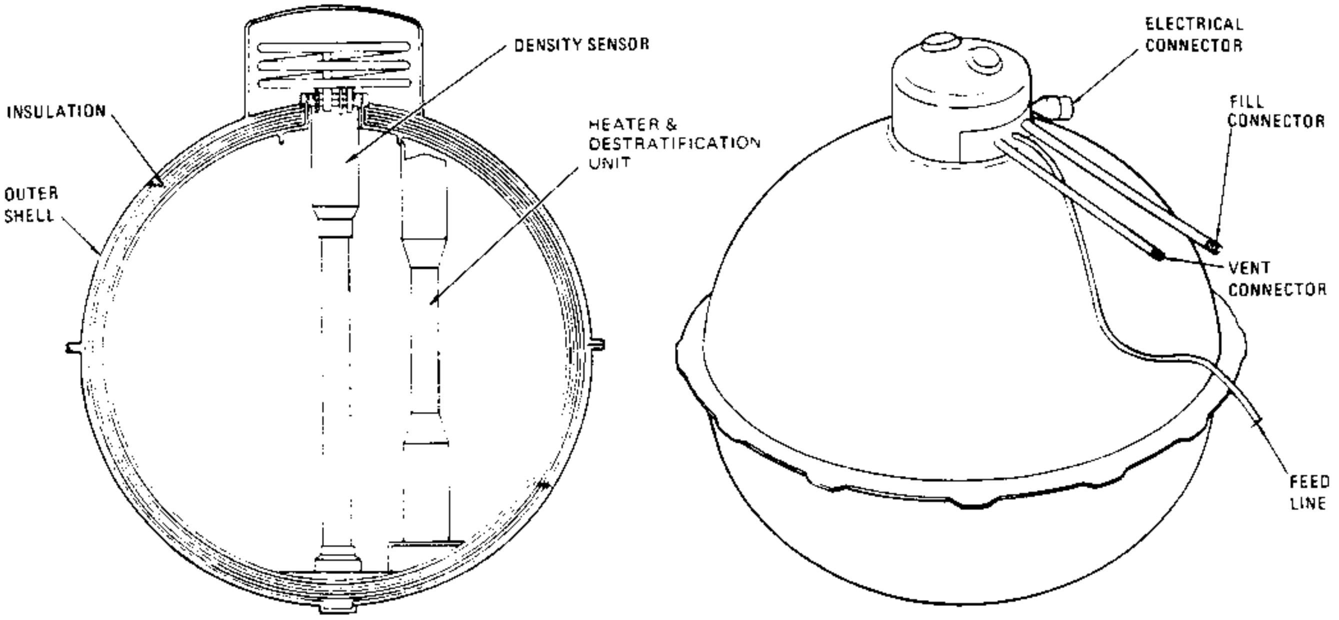
DETAILED DESCRIPTION

CRYOGENIC STORAGE

The cryogenic storage subsystem supplies oxygen and hydrogen to the fuel cell powerplants and oxygen to the environmental control subsystem and for initial pressurization of the lunar module. Each of the two tanks of hydrogen and oxygen holds enough fluid to assure a safe return from the furthest point of the mission. The cryogenic tanks



Command module wire harness is first assembled on this mockup stand



P-144

Cryogenic tank (hydrogen)

are pressurized by internal heaters after filling is complete.

Two parallel dc heaters in each tank supply heat necessary to maintain pressure. Two parallel 3-phase ac circulating fans circulate the fluid over the heating elements to maintain a uniform density and decrease the probability of thermal stratification. Relief valves provide overpressure relief and check valves provide tank isolation. A malfunctioning fuel cell powerplant can be isolated by a shutoff valve. Filters extract particles from the flowing fluid to protect components. Pressure transducers and temperature probes indicate the thermodynamic state of the fluid and capacitive quantity probes indicate the amount of fluid in the tanks.

The systems can be repressurized automatically or manually. The automatic mode is designed to give a single-phase reactant flow into the fuel cell and feed lines at design pressures. The heaters and fans are automatically controlled through pressure and motor switches. As pressure decreases, the pressure switch in each tank closes to energize the motor switch, closing contacts in the heater and fan circuits. Both tanks have to decrease in pressure before heater and fan circuits are energized. When either tank reaches the upper operating pressure limit, its pressure switch opens, again energizing the motor switch and opening the heater and fan circuits to both tanks. The oxygen tank circuits are energized at 865 psia minimum and de-energized at 935 psia maximum. The hydrogen circuits energize at 225 psia minimum and de-energize at 260 psia maximum.

When the systems reach the point where heater and fan cycling is at a minimum (due to a reduced heat requirement), the heat leak of the tank is sufficient to maintain proper pressures provided flow is within proper values. The minimum heat requirement region for oxygen starts at approximately 40-percent quantity in the tanks and ends at approximately 25-percent quantity. Between these tank quantities, minimum heater and fan cycling will occur under normal usage. The heat needed for pressurization at quantities below 25 percent starts to increase until at the 5-percent level practically continuous heater and fan operation is required. In the hydrogen system, the quantity levels for minimum heater and fan cycling are between approximately 53 and 33 percent, with continuous operation occurring at approximately 1 percent.

The oxygen system heaters and fans can sustain proper pressures for 30 minutes at a total flow of 10.4 pounds per hour (5.2 pounds per hour per tank). The hydrogen system heaters and fans can sustain proper pressures at a total flow of 1.02 pounds per hour (0.51 pound per hour per tank).

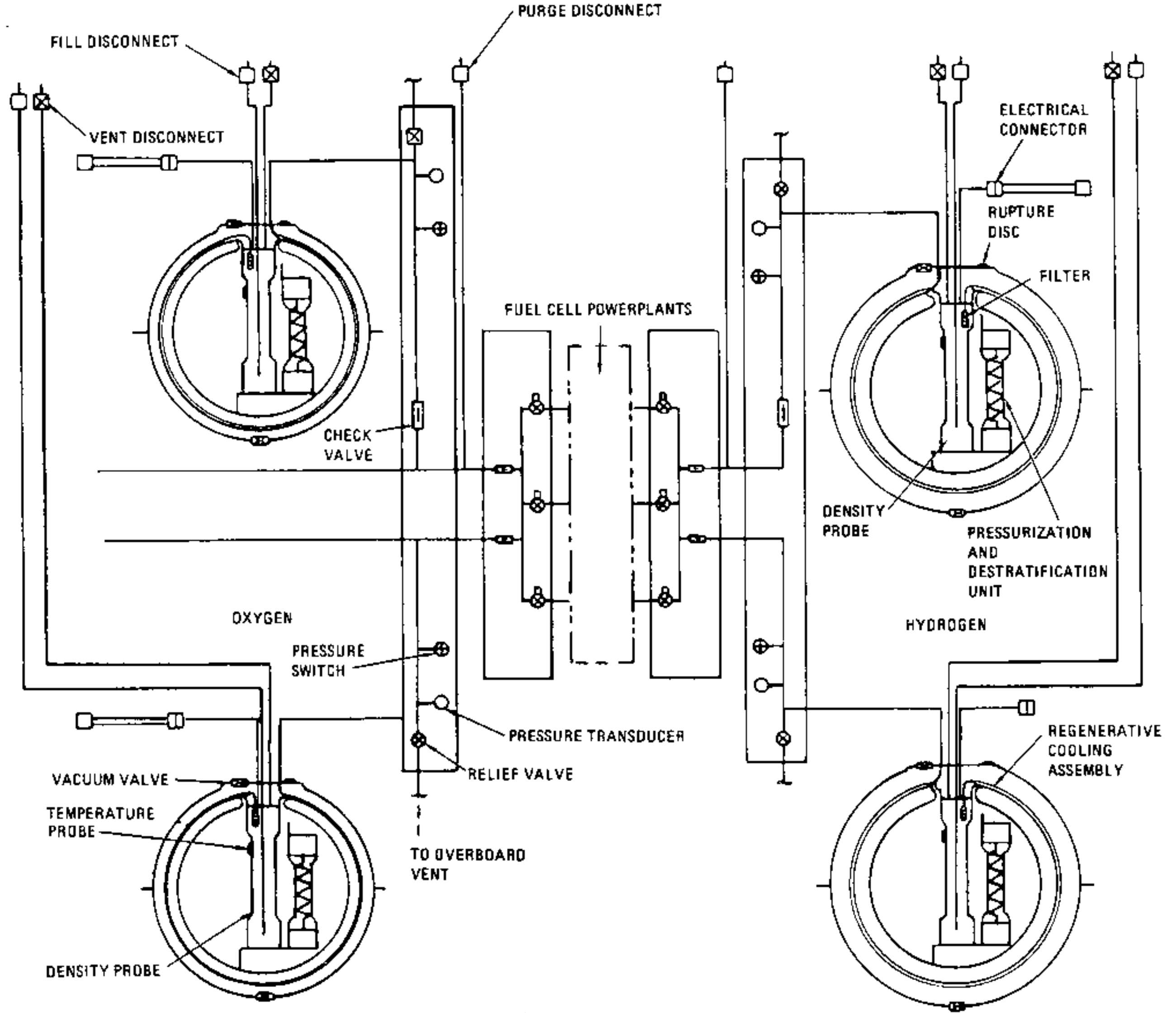
Manual repressurization supplies power directly to the heaters and fans through the control switches.

It can be used in case of automatic control failure, heater failure, or fan failure.

Tank pressure and quantity are monitored on meters located on the main display console. The caution and warning system will activate on alarm when oxygen pressure in either tank exceeds 950 psia or falls below 800 psia or when the hydrogen system pressure exceeds 270 psia or drops below 220 psia. Pressure, quantity, and reactant temperature of each tank are telemetered to MSFN.

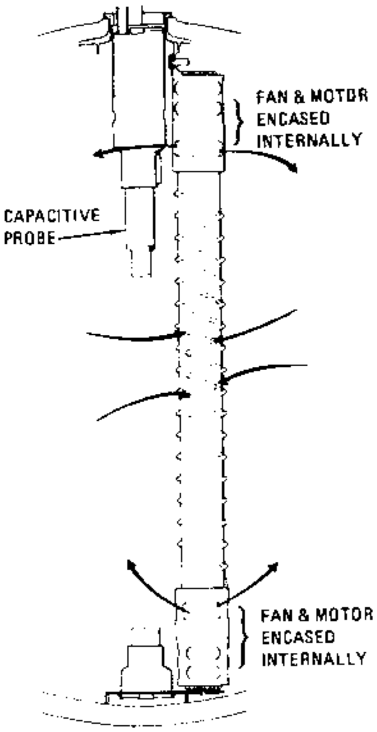
Oxygen relief valves vent at a pressure between 983 and 1010 psig and reseat at 965 psig. Hydrogen relief valves vent at a pressure between 273 and 285 psig and reseat at 268 psig. Relief opening of the relief valves will be prevented if possible to minimize the probability of improper reseating, resulting in eventual depletion of one tank.

Overpressurization may be prevented in two ways. The first is to disable the heater and fan circuits when tank quantities reach approximately 55 percent, allowing pressure in the tanks to decrease. This provides wider range for eventual pressure increase during minimum-value operation. This method retains the maximum amount of fluid for spacecraft use. The second method is to perform an unscheduled fuel cell purge to deplete tank pressure.



P-145

Schematic of cryogenic storage system



P-146

Cryogenic tank pressure and quantity measurement devices

The reactant tanks have vacuum-ion pumps which function as ion traps to maintain the vacuum between the inner and outer shells.

BATTERIES

The five silver oxide-zinc storage batteries of the electrical power subsystem are located in the lower equipment bay of the CM.

Three rechargeable entry and post-landing batteries (A, B, and C) power the CM systems after CM-SM separation. Before separation, the batteries provide a secondary source of power while the fuel cells are the primary source. They supplement fuel cell power during peak load periods (velocity change maneuvers), provide power during emergency operations (failure of two fuel cells), and provide power for power subsystem control circuitry (relays, indicators, etc.) and sequencer logic. They can also be used to power pyro circuits.

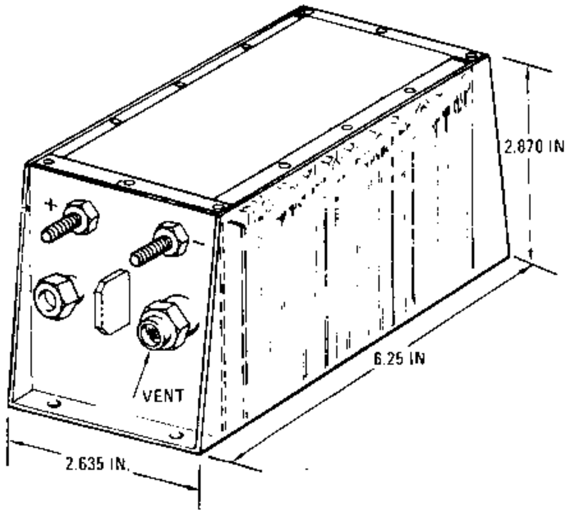
Each entry and post-landing battery consists of 20 silver oxide-zinc cells connected in series. The cells are individually encased in plastic containers which contain relief valves that open at 35 ± 5 psig, venting during an overpressure into the battery case. Each battery case is vented overboard through a common manifold and the urine/water dump line. The vent line prevents battery-generated gas from entering the crew compartment.

In the event a battery case fractures, the vent is closed. The battery manifold pressure is monitored on the meter and when it approaches CM pressure the vent valve is opened to prevent the gas going into the cabin. Battery manifold pressure can be used as an indication of urine/waste water dump line plugging.

Each battery delivers a minimum of 40 ampere-hours at a current output of 35 amps for 15 minutes and a subsequent output of 2 amps, or at a current output of 25 amps for 30 minutes and a subsequent output of 2 amps. At Apollo mission loads, each battery can provide 50 ampere-hours.

Open circuit voltage is 37.2 volts. Since sustained battery loads are extremely light (2 to 3 watts), voltages very close to open circuit voltage will be indicated on the spacecraft voltmeter, except when the main bus tie switches have been activated to tie the battery output to the main dc buses. Normally only batteries A and B will be connected to the main dc buses. Battery C is isolated during the pre-launch period and provides a backup for main dc bus power. The two-battery configuration provides more efficient use of fuel cell power during peak power loads and decreases overall battery recharge time.

The two pyrotechnic batteries supply power to activate ordnance devices in the spacecraft. The



P-147

Pyrotechnic battery

pyrotechnic batteries are isolated from the rest of the electrical power system to prevent the high-power surges in the pyrotechnic system from affecting it and to assure source power when required. These batteries are not recharged in flight. The entry and post-landing batteries can be used as a redundant source of power for initiating pyro circuits if either pyro battery fails.

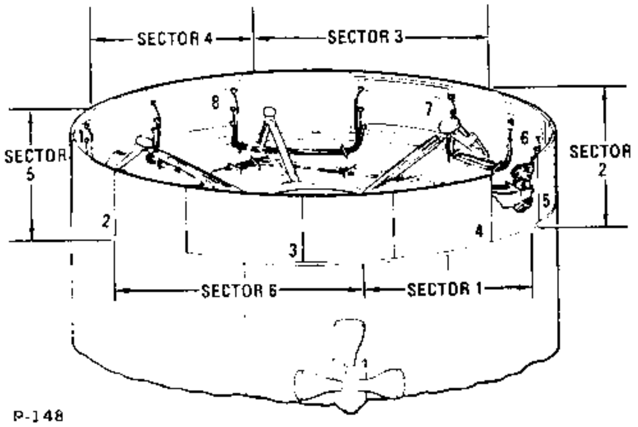
FUEL CELL POWERPLANTS

Each of the three Bacon-type fuel cell powerplants is individually coupled to a heat rejection (radiator) system, the hydrogen and oxygen cryogenic storage systems, a water storage system, and a power distribution system.

The powerplants generate dc power on demand through an exothermic chemical reaction. A byproduct of this chemical reaction is water, which is fed to a potable water storage tank in the CM where it is used for astronaut consumption and for cooling purposes in the environmental control subsystem. The amount of water produced is proportional to the ampere-hours.

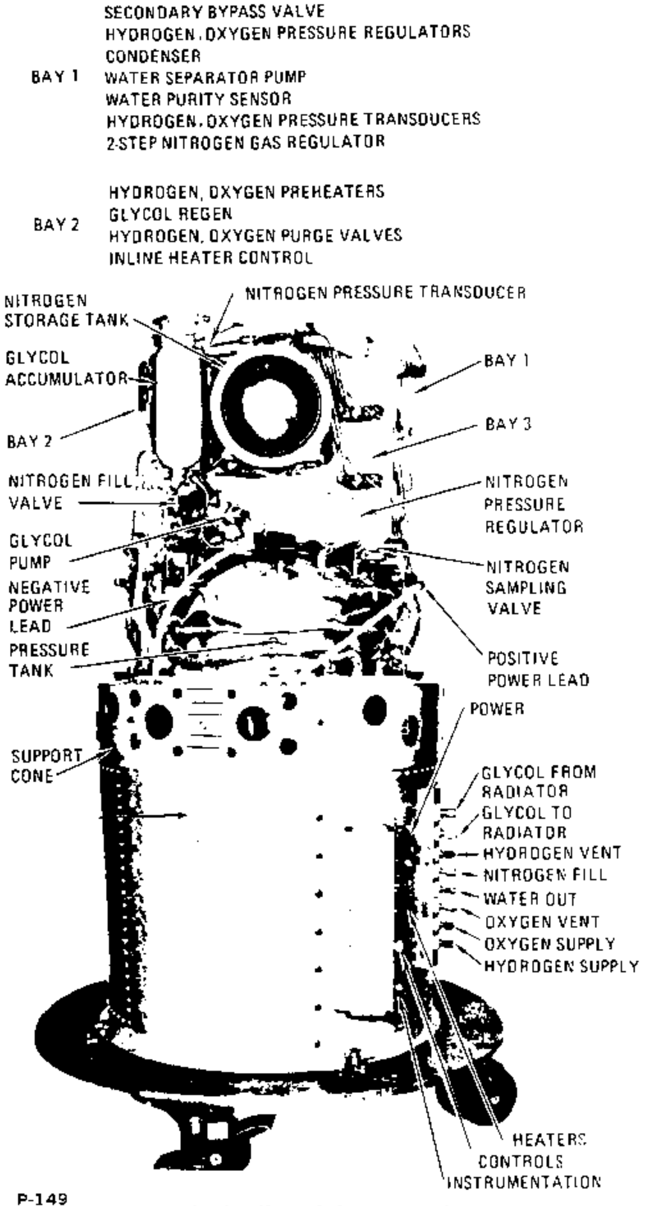
Each powerplant consists of 31 single cells connected in series and enclosed in a metal pressure jacket. The water separation, reactant control, and heat transfer components are mounted in a compact accessory section attached directly above the pressure jacket.

Powerplant temperature is controlled by the primary (hydrogen) and secondary (glycol) loops. The hydrogen pump, providing continuous circulation of hydrogen in the primary loop, withdraws water vapor and heat from the stack of cells. The primary bypass valve regulates flow through the hydrogen regenerator to impart exhaust heat to the incoming hydrogen gas as required to maintain the proper cell temperature. The exhaust gas flows to the condenser where waste heat is transferred to the glycol, the resultant temperature decrease liquifying some of the water vapor. The motor-driven centrifugal water separator extracts the liquid and feeds it to the potable water tank in the CM. The temperature of the hydrogen-water vapor exiting from the condenser is controlled by a bypass valve which regulates flow through a secondary regenerator to a control condenser exhaust within desired limits. The cool gas is then pumped back to the fuel cell through the primary regenerator by a motor-driven



P-148

Location of electrical power subsystem radiators



P-149

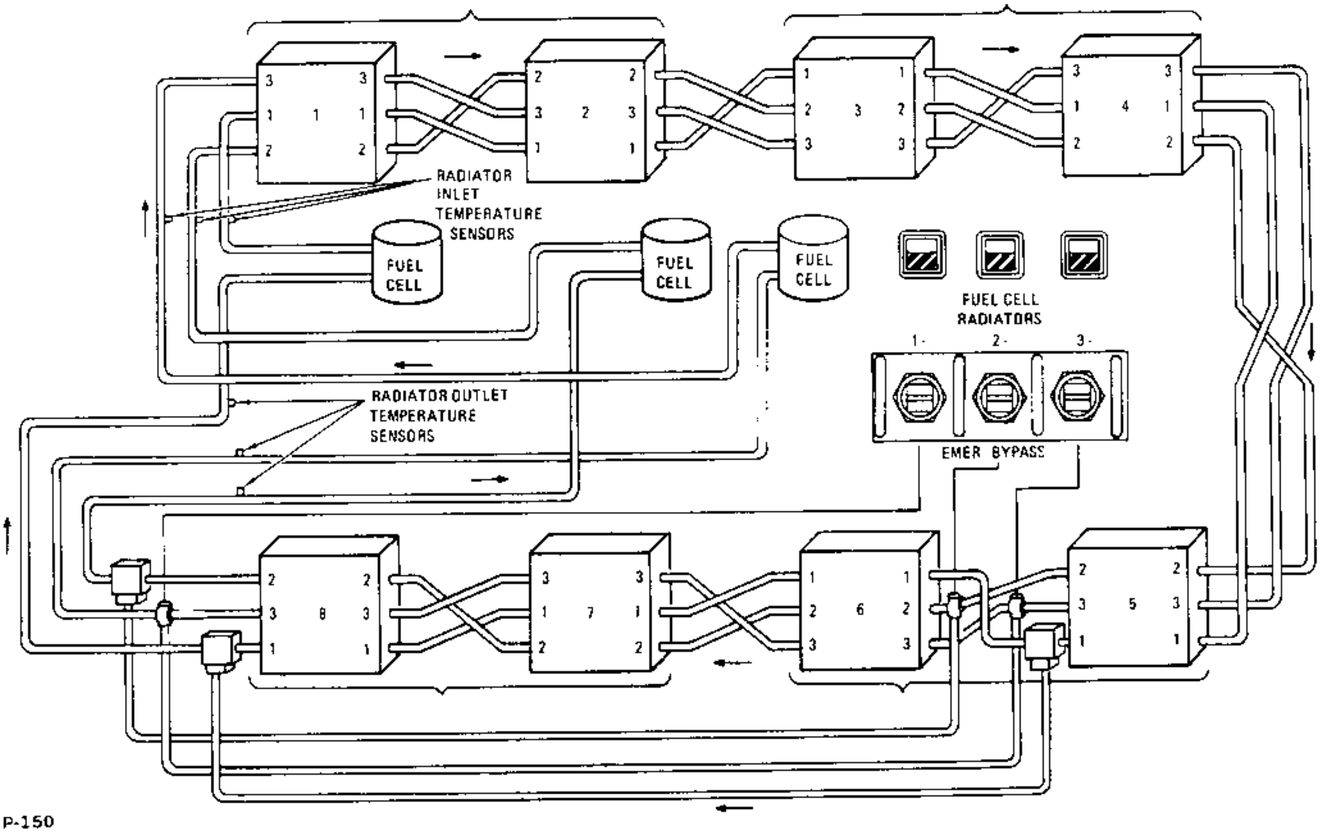
Fuel cell module accessories

vane pump, which also compensates for pressure losses due to water extraction and cooling. Waste heat, transferred to the glycol in the condenser, is transported to the radiators located on the fairing between the CM and SM, where it is radiated into space. Radiator area is sized to reject the waste heat resulting from operation in the normal power range. If an emergency arises in which an extremely low power level is required, individual controls can bypass three of the eight radiator panels for each powerplant. This area reduction improves the margin for radiator freezing which could result from the lack of sufficient waste heat to maintain adequate glycol temperature. This is not a normal procedure and is considered irreversible due to freezing of the bypassed panels.

Reactant valves provide the connection between the powerplants and the cryogenic system. They are opened during pre-launch fuel cell startup and closed only after a powerplant malfunction necessitating its isolation from the cryogenic system. Before launch, a valve switch is operated to apply a holding voltage to the open solenoid of the hydrogen and oxygen reactant valves of the three powerplants. This voltage is required only during boost to prevent inadvertent closure due to the effects of high vibration. The reactant valves cannot be closed with this holding voltage applied. After earth orbit insertion, the holding voltage is removed and three circuit breakers are opened to prevent valve closure through inadvertent activation of the reactant valve switches.

Nitrogen is stored in each powerplant at 1500 psia and regulated to a pressure of 53 psia. Output of the regulator pressurizes the electrolyte in each cell through a diaphragm arrangement, the coolant loop through an accumulator, and is coupled to the oxygen and hydrogen regulators as a reference pressure.

Cryogenic oxygen, supplied to the powerplants at 900±35 psia, absorbs heat in the lines, absorbs additional heat in the fuel cell powerplant reactant preheater, and reaches the oxygen regulator in a gaseous form at temperatures above 0°F. The differential oxygen regulator reduces pressure to 9.5 psia above the nitrogen reference, thus supplying it to the fuel cell stack at 62.5 psia. Within the porous oxygen electrodes, the oxygen reacts with the water in the electrolyte and the electrons



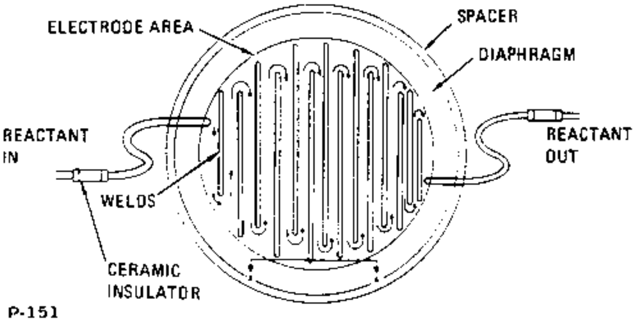
P-150

Flow and control of electrical power subsystem radiators provided by the external circuit to produce hydroxyl ions.

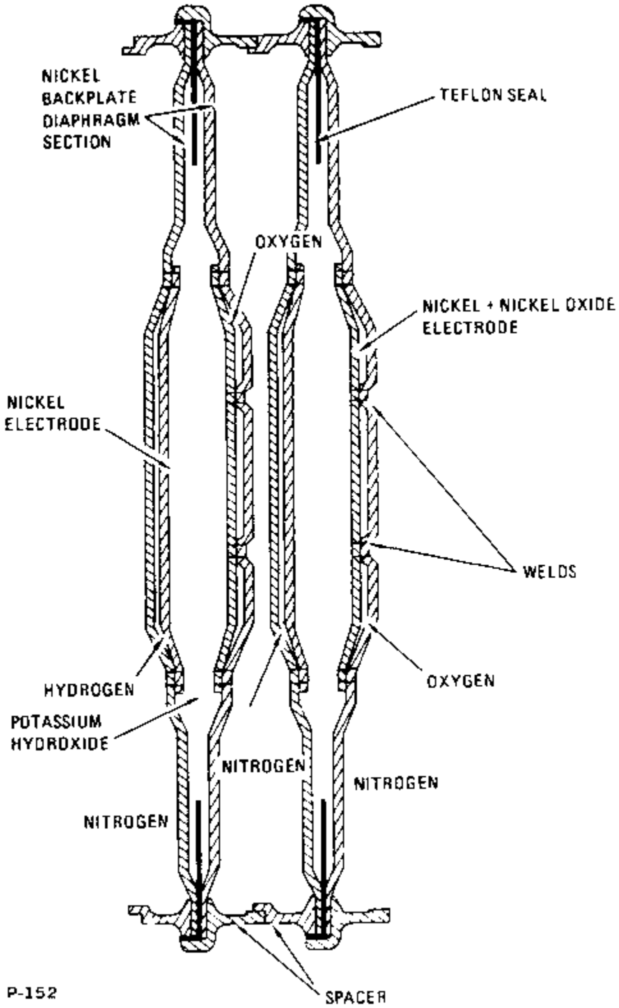
Cryogenic hydrogen, supplied to the powerplants at 245 (+15, -20) psia, is heated in the same manner as the oxygen. The differential hydrogen regulator reduces the pressure to 8.5 psia above the reference nitrogen, thus supplying it in a gaseous form to the fuel cells at 61.5 psia. The hydrogen reacts in the porous hydrogen electrodes with the hydroxyl ions in the electrolyte to produce electrons, water vapor, and heat. The nickel electrodes act as a catalyst in the reaction. The water vapor and heat are withdrawn by the circulation of hydrogen gas in the primary loop and the electrons are supplied to the load.

Each of the 31 cells comprising a powerplant contains electrolyte which on initial fill consists of approximately 83 percent potassium hydroxide (KOH) and 17 percent water by weight. The powerplant is initially conditioned to increase the water ratio, and during normal operation, water content will vary between 23 and 28 percent. At this ratio, the electrolyte has a critical temperature of 360°F. Powerplant electrochemical reaction becomes effective at the critical temperature. The powerplants are heated above the critical temperature by ground support equipment. A load on the powerplant of approximately 563 watts is required to maintain it above the normal minimum operating temperature of 385°F. The automatic in-line heater circuit will maintain powerplant temperature in this range with smaller loads applied.

Purging is a function of power demand and gas purity. Oxygen purging requires 2 minutes and hydrogen purging 80 seconds. The purge frequency is determined by the mission power profile and gas purity as sampled after spacecraft tank fill. A degradation purge can be performed if powerplant current output decreases approximately 3 to 5 amps during sustained operation. The oxygen purge has more effect during this type of purge, although it would be followed by a hydrogen purge if recovery to normal were not realized. If the performance degradation were due to powerplant electrolyte flooding, which would be indicated by activation of the pH high indicator, purging would not be performed due to the possibility of increasing the flooding.



Construction of cell

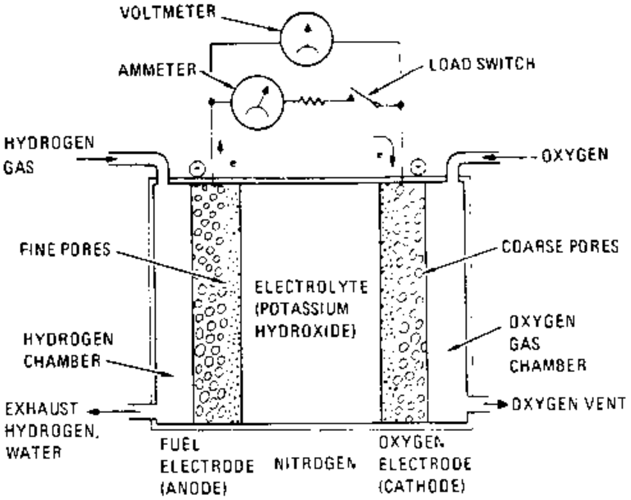


Cutaway view of cell

The application and removal of fuel cell loads causes the terminal voltage to decrease and increase, respectively. A decrease in terminal voltage, resulting from an increased load, is followed by a gradual increase in fuel cell skin temperature which causes an increase in terminal voltage. Conversely, an increase in terminal voltage, resulting from a decreased load, is followed by a gradual decrease in fuel cell skin temperature which causes a decrease in terminal voltage. This performance change with temperature is regulated by the primary regenerator bypass valve and provides the capability of operating over an increased power range within voltage regulation limits.

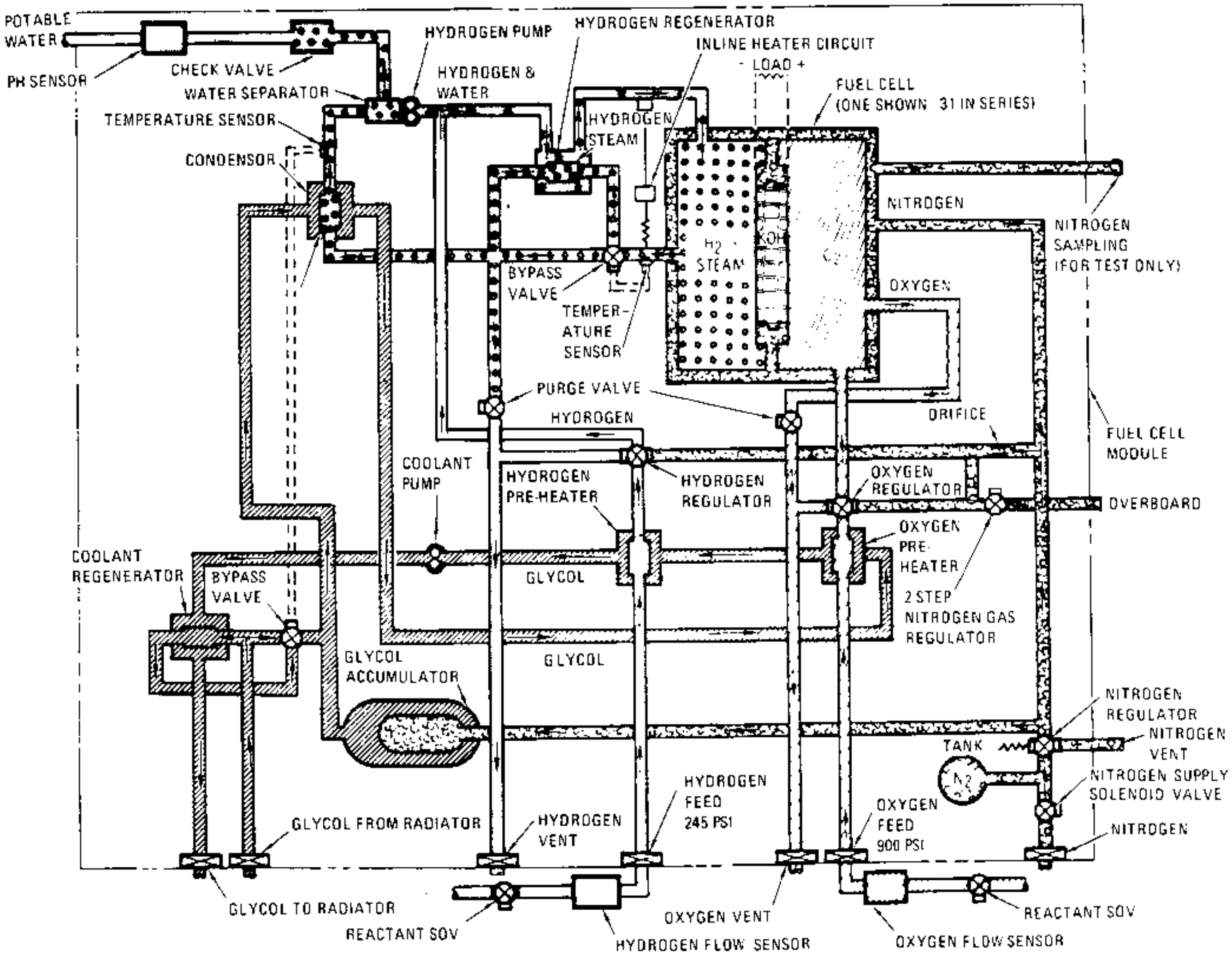
The range in which the terminal voltage is permitted to vary is determined by the high and low voltage input design limits of the components being powered. For most components the limits are 30 volts dc and 25 volts dc. To remain within these design limits, the dc bus voltage must be maintained between 31.0 and 26.2 volts dc. Bus voltage is maintained within prescribed limits during high power requirements by the use of entry and post-landing batteries.

Spacecraft systems are powered up in one continuous sequence providing the main bus voltage does not decrease below 26.2 volts. If bus voltage



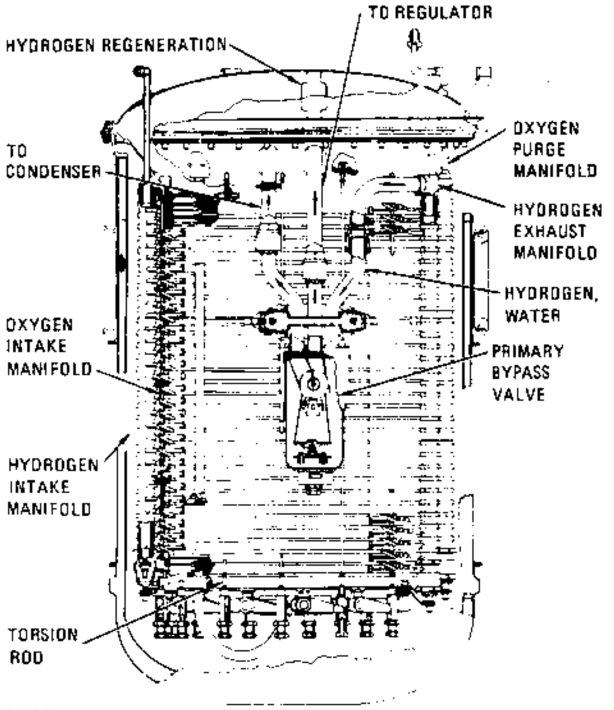
P-154

Electrochemical flow in fuel cell



P-153

Schematic of fuel cell module



Fuel cell module

decreases to this value the power-up sequence can be interrupted for the time required for fuel cell temperatures to increase with the resultant voltage increase, or the batteries can be connected to the main buses reducing the fuel cell load. In most cases, powering up can be performed in one continuous sequence; however, when starting from an extremely low spacecraft load, it is probable that a power-up interruption or batteries will be required. The greatest load increase occurs while powering up for a velocity change maneuver.

Spacecraft systems are powered down in one continuous sequence providing the main bus voltage does not increase above 31.0 volts. In powering down from relatively high spacecraft load levels, the sequence may have to be interrupted for the time required for fuel cell temperature, and thus bus voltage, to decrease.

If a powerplant fails it is disconnected from the main dc buses and the in-line heater circuit is deactivated. Before disconnecting a fuel cell, if a single inverter is being used, the two remaining powerplants are connected to each main dc bus to enhance load sharing since bus loads are unbalanced. If two inverters are being used, each of the remaining powerplants is connected to a separate main dc bus for bus isolation, since bus loads are relatively equal.

INVERTERS

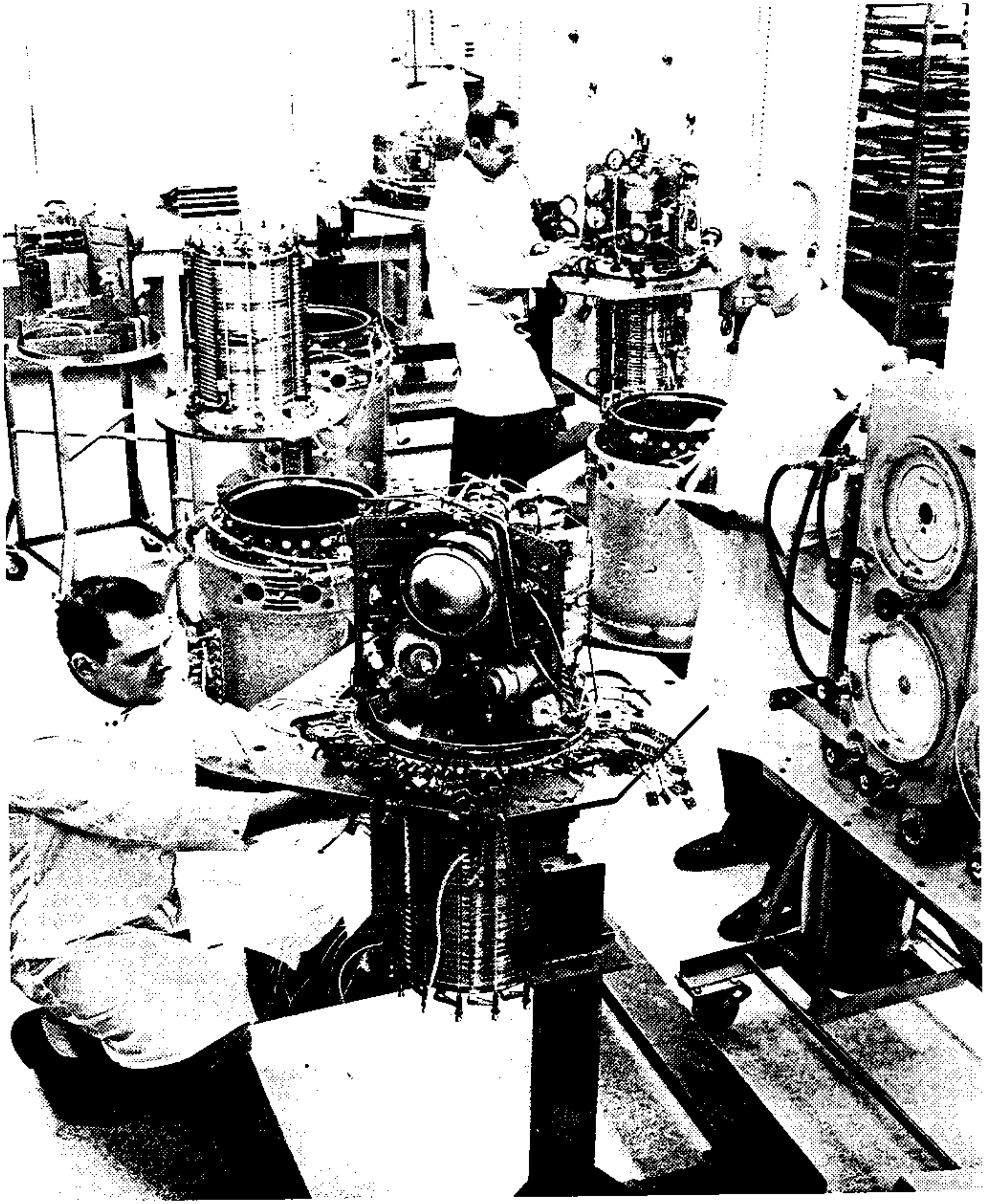
Each inverter is composed of an oscillator, an eight-stage digital countdown section, a dc line filter, two silicon-controlled rectifiers, a magnetic amplifier, a buck-boost amplifier, a demodulator, two dc filters, an eight-stage power inversion section, a harmonic neutralization transformer, an ac output filter, current sensing transformers, a Zener diode reference bridge, a low-voltage control, and an overcurrent trip circuit. The inverter normally uses a 6.4 kiloHertz square wave synchronizing signal from the central timing equipment which maintains inverter output at 400 Hertz. If this external signal is completely lost, the free running oscillator within the inverter will provide pulses that will maintain inverter output within ±7 Hertz. The internal oscillator is normally synchronized by the external pulse.

The 6.4 kiloHertz square wave provided by central timing equipment is applied through the internal oscillator to the eight-stage digital countdown section. The oscillator has two divider circuits which provide a 1600-pulse per second to the magnetic amplifier.

The eight-stage digital countdown section produces eight 400-cycle square waves, each mutually displaced one pulse-time from the preceding and following wave. One pulse-time is 156 microseconds and represents 22.5 electrical degrees. The eight square waves are applied to the eight-stage power inversion section.

The eight-stage power inversion section, fed by a controlled voltage from the buck-boost amplifier, amplifies the eight 400-Hertz, square waves produced by the eight-stage digital countdown section. The amplified square waves, still mutually displaced 22.5 electrical degrees, are next applied to the harmonic neutralization transformer.

The harmonic neutralization section consists of 31 transformer windings on one core. This section accepts the 400-Hertz square-wave output of the eight-stage power inversion section and transforms it into a 3-phase, 400-Hertz 115-volt signal. The manner in which these transformers are wound on a single core produces flux cancellation which eliminates all harmonics up to and including the fifteenth of the fundamental frequency. The 22.5-degree displacement of the square waves provides a means of electrically rotating the square wave excited primary windings around the 3-phase,



P-156 *Pratt & Whitney technicians assemble fuel cell powerplants at plant in Hartford, Conn.*

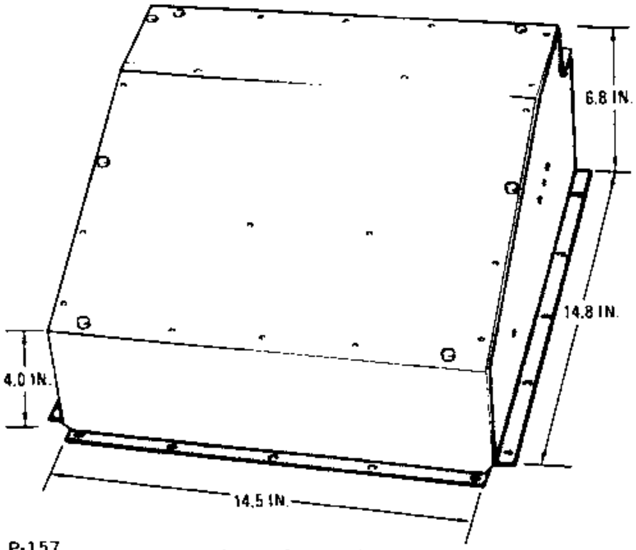
wye-connected secondary windings, thus producing the 3-phase 400 cycle sine wave output. This 115-volt signal is then applied to the ac output filter.

The ac output filter eliminates the remaining higher harmonics. Since the lower harmonics were eliminated by the harmonic neutralization transformer, the size and weight of this output filter is reduced. Circuitry in this filter also produces a rectified signal which is applied to the Zener diode reference bridge for voltage regulation. The amplitude of this signal is a function of the amplitude of ac output voltage. After filtering, the 3-phase, 115-volt ac 400-hertz sine wave is applied to the ac buses through individual phase current-sensing transformers.

The current-sensing transformers produce a rectified signal, the amplitude of which is a direct function of inverter output current magnitude. This dc signal is applied to the Zener diode reference bridge to regulate inverter current output; it is also paralleled to an overcurrent trip circuit.

The Zener diode reference bridge receives a rectified dc signal, representing voltage output, from the circuitry in the ac output filter. A variance in voltage output unbalances the bridge, providing an error signal of proper polarity and magnitude to the buck-boost amplifier via the magnetic amplifier. The buck-boost amplifier, through its bias voltage output, compensates for voltage variations. When inverter current output reaches 200 to 250 percent of rated current, the rectified signal applied to the bridge from the current sensing transformers is of sufficient magnitude to provide an error signal, causing the buck-boost amplifier to operate in the same manner as during an overvoltage condition. The bias output of the buck-boost amplifier, controlled by the error signal, will be varied to correct for any variation in inverter voltage or a beyond-tolerance increase in current output. When inverter current output reaches 250 percent of rated current, the overcurrent trip circuit is activated.

The overcurrent trip circuit monitors a rectified dc signal representing current output. When total inverter current output exceeds 250 percent of rated current, this circuit will disconnect an inverter in 15 ± 5 seconds. If current output of any single phase exceeds 300 percent of rated current, this circuit will disconnect an inverter in 5 ± 1 seconds.



P-157

Size of static inverter

The disconnect is provided through relays located in the motor switch circuits that connect the inverters to the ac buses.

Dc power to the inverter is supplied from the main dc buses through the dc line filter. The filter reduces the high-frequency ripple in the input, and the 25 to 30 volts dc is applied to the silicon-controlled rectifiers.

The silicon-controlled rectifiers are alternately set by the 1600 pulses-per-second signal from the magnetic amplifier to produce a dc square wave with an on-time of greater than 90 degrees from each rectifier. This is filtered and supplied to the buck-boost amplifier where it is transformer-coupled with the amplified 1600 pulses-per-second output of the magnetic amplifier to develop a filtered 35 volts dc which is used for amplification in the power inversion stages.

The buck-boost amplifier also provides a variable bias voltage to the eight-stage power inversion section. The amplitude of this bias voltage is controlled by the amplitude and polarity of the feedback signal from the Zener diode reference bridge which is referenced to output voltage and current. This bias signal is varied by the error signal to regulate inverter voltage and maintain current output within tolerance.

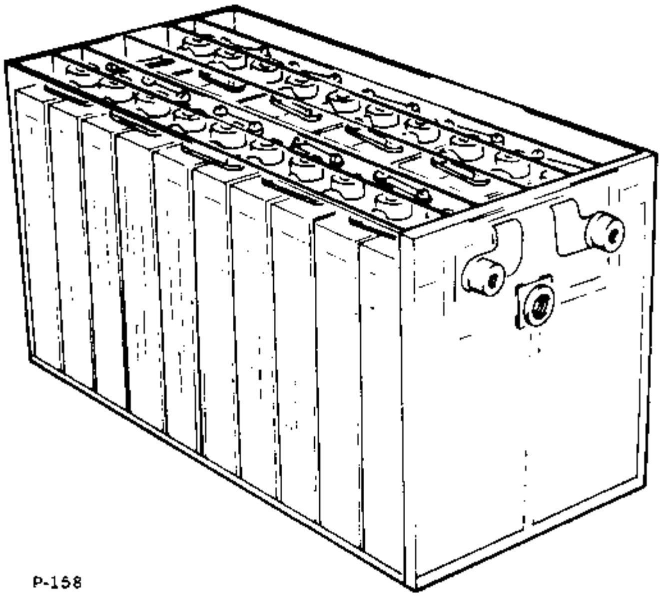
The demodulator circuit compensates for any low-frequency ripple in the dc input to the inverter. The high-frequency ripple is attenuated by the input filters. The demodulator senses the 35-volt dc output of the buck-boost amplifier and the current input to the buck-boost amplifier. An input dc voltage drop or increase will be reflected in a drop or increase in the 35-volt dc output of the buck-boost amplifier, as well as a drop or increase in current input to the buck-boost amplifier. A sensed decrease in the buck-boost amplifier voltage output is compensated for by a demodulator output, coupled through the magnetic amplifier to the silicon-controlled rectifiers. The demodulator output causes the silicon-controlled rectifiers to conduct for a longer time, thus increasing their filtered dc output. An increase in buck-boost amplifier voltage output caused by an increase in dc input to the inverter is compensated for by a demodulator output coupled through the magnetic amplifier to the silicon-controlled rectifiers causing them to conduct for shorter periods, thus producing a lower filtered dc output to the buck-boost amplifier. In this manner, the 35-volt dc input to the power inversion section is maintained at a relatively constant level irrespective of the fluctuations in dc input voltage.

The low-voltage control circuit samples the input voltage to the inverter and can terminate inverter operation. Since the buck-boost amplifier provides a boost action during a decrease in input voltage to the inverter, in an attempt to maintain a constant 35 volts dc to the power inversion section and a regulated 115-volt inverter output, the high boost required during a low-voltage input would tend to overheat the solid-state buck-boost amplifier. As a precautionary measure, the low-voltage control will terminate inverter operation by disconnecting operating voltage to the magnetic amplifier and the first power inversion stage when input voltage decreases to between 16 and 19 volts dc.

A temperature sensor with a range of 32° to 248°F is installed in each inverter and will illuminate a light in the caution and warning system at an inverter overtemperature of 190°F. Inverter temperature is telemetered to the ground.

BATTERY CHARGER

A constant-voltage, solid-state battery charger is located in the CM lower equipment bay. It is provided 25 to 30 volts from both main dc buses and 115 volts 400-cps 3-phase from either of the ac buses. All three phases of ac are used to boost the 25 to 30-volt dc input and produce 40 volts dc for charging. In addition, Phase A of the ac is used to supply power for the charger circuitry. The logic network in the charger, which consists of a two-stage differential amplifier (comparator), Schmitt trigger, current-sensing resistor, and a voltage amplifier, sets up the initial condition for operation. The first stage of the comparator is on, with the second stage off, thus setting the Schmitt trigger first stage to on with the second stage off. Maximum base drive is provided to the current amplifier which turns on the switching transistor. With the switching transistor on, current flows from the transformer rectifier through the switching transistor, current sensing resistor, and switch choke to the battery being charged. Current lags voltage due to switching choke action. As current flow increases, the voltage drop across the sensing resistor increases, and at a specific level sets the first stage of the comparator off and the second stage on. The voltage amplifier is set off to reverse the Schmitt trigger to first stage off and second stage on. This sets the current amplifier off, which in turn sets the switching transistor off. This terminates power from the source, causing the field in the choke to continue collapsing, discharging into the battery, then through the switching diode and the current sensing resistor to the opposite side of the choke. As the electromagnetic field in the choke decreases, current through the sensing resistor decreases, reducing the voltage drop across the resistor. At some point, the decrease in voltage drop across the sensing resistor reverses the comparator circuit, setting up the initial condition and completing one cycle of operation. The output load current, due to the choke action, remains relatively



Entry and post-landing battery