SECTION 2

SUBSECTION 2.6

ELECTRICAL POWER SYSTEM
(CSM 106 and Subs)

2.6.1 INTRODUCTION.

The electrical power subsystem (EPS) consists of the equipment and reactants required to supply the electrical energy sources, power generation and controls, power conversion and conditioning, and power distribution to the electrical buses (figure 2.6-1). Electrical power distribution and conditioning equipment beyond the buses is not considered a part of this subsystem. Power is supplied to fulfill all command and service module (CSM) requirements, as well as to the lunar module (LM) for operation of heater circuits after transposition and docking.

The EPS can be functionally divided into four major categories:

- Energy storage: Cryogenics storage, entry and postlanding batteries, pyrotechnic batteries.
- Power generation: Fuel cell power plants.
- Power conversion: Solid state inverters, battery charger.
- Power distribution: D-C and a-c power buses, d-c and a-c sensing circuits, controls and displays.

In general, the system operates in three modes: peak, average, and minimum mission loads. Peak loads occur during performance of major delta V maneuvers, including boost. These are of relatively short duration with d-c power being supplied by three fuel cell power plants supplemented by two of three entry batteries. A-C power is supplied by two of three inverters.

The second mode is that part of the mission when power demands vary about the average. During these periods d-c power is supplied by three fuel cell power plants and a-c power by one or two inverters.

During drifting flight when power requirements are at a minimum level, d-c power is supplied by three fuel cell powerplants. A-C power is supplied by one or two inverters. In all cases, operation of one or two inverters is dependent on the total cryogen available. Two-inverter operation results in a slight increase of cryogenic usage because of a small reduction in inverter efficiency due to the lesser loads on each inverter. However, two inverter operation precludes complete loss of ac in the event of an inverter failure.

2.6.2 FUNCTIONAL DESCRIPTION.

2.6.2.1 Energy Storage.

The primary source of energy is provided by the cryogenic gas storage system that provides fuel (H_2) and oxidizer (O_2) to the power generating system. Two hydrogen and two oxygen tanks, with the associated controls and plumbing, are located in the service module. Storage of reactants is accomplished under controlled cryogenic temperatures and pressures; automatic and manual pressure control is provided. Automatic heating of the reactants for repressurization is dependent on energy demand by the power generating and/or environmental control subsystems. Manual control can be used when required.

A secondary source of energy storage is provided by five silver oxide-zinc batteries located in the CM. Three rechargeable entry and postlanding batteries supply sequencer logic power at all times, supplemental d-c power for peak loads, all operating power required for entry and postlanding, and can be connected to power either or both pyro circuits. Two pyro batteries provide energy for activation of pyro devices throughout all phases of a mission.

2.6.2.2 Power Generation.

Three Bacon-type fuel cell power plants, generating power through electrochemical reaction of H_2 and O_2, supply primary d-c power to spacecraft systems until CSM separation. Each power plant is capable of normally supplying from 400 to 1420 watts at 31 to 27 vdc (at fuel cell terminals) to the power distribution system. During normal operation all three power plants generate power, but two are adequate to complete the mission. Should two of the three malfunction, one power plant will insure successful mission termination; however, spacecraft loads must be reduced to operate within the limits of a single powerplant.

Normal fuel cell connection to the distribution system is: Fuel cell 1 to main d-c bus A; fuel cell 2 to main d-c bus A and B; and fuel cell 3 to main d-c bus B. Manual switch control is provided for power plant connection to the distribution system, and manual and/or automatic control for power plant isolation in case of a malfunction.

During the CSM separation maneuver the power plants supply power through the SM buses to two SM jettison control sequencers. The sequencers sustain SM RCS retrofire during CSM separation and fire the SM positive roll RCS engines two seconds after separation to stabilize the SM during entry. Roll engine firing is terminated 7.5 seconds after separation. The power plants and SM buses are isolated from the umbilical through a SM deadface. The sequencers are connected to the SM buses when the CM/SM SEP switch (MDC-2) is activated; separation occurs 100 milliseconds after switch activation.

NOTES:
1. Motor switches S1 and S2 close when main bus tie switches S4 and S5 are set to Bat A/C and Bat B/C.
2. FC1 can be connected to SM bus B & FC 3 to SM bus A
3. DC bus control circuit breakers are illustrated in battery charger and CM DC bus control circuits schematic

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Figure 2.6-1. Electrical Power Subsystem Block Diagram

2.6.2.3 Power Conversion.

Primary d-c power is converted into a-c by solid state static inverters that provide 115/200-volt 400-cps 3-phase a-c power up to 1250 volt-amperes each. A-C power is connected by motor switch controls to two a-c buses for distribution to the a-c loads. One inverter has the capability of supplying all spacecraft primary a-c power. One inverter can power both buses while the two remaining inverters act as redundant sources. However, throughout the flight, each bus is powered by a separate inverter. Provisions are made for inverter isolation in the event of malfunctions. Inverter outputs cannot be phase synchronized, therefore interlocked motorized switching circuits are incorporated to prevent the connection of two inverters to the same bus.

A second conversion unit, the battery charger, assures keeping the three entry and postlanding batteries in a fully charged state. It is a solid state device utilizing d-c from the fuel cells and ac from the inverter to develop charging voltage.

2.6.2.4 Power Distribution.

Distribution of d-c power is accomplished via two redundant d-c buses in the service module which are connected to two redundant buses in the command module through a SM deadface, the CSM umbilical, and a CM deadface. Additional buses provided are: two d-c buses for servicing non-essential loads; a flight bus for servicing inflight telecommunications equipment; two battery buses for distributing power to sequencers, gimbal motor controls, and servicing the battery relay bus for power distribution switching; and a flight and postlanding bus for servicing some communications equipment and the postlanding loads.

Three phase ac is distributed via two redundant a-c buses, providing bus selection through switches in the a-c operated component circuits.

Power to the lunar module is provided through two umbilicals which are manually connected after completion of transposition and docking. An average of 81 watts dc is provided to continuous heaters in the abort sensor assembly (ASA), and cycling heaters in the landing radar, rendezvous radar, S-band antenna and inertial measurement unit (IMU). Power consumption with all heaters operating simultaneously is approximately 309 watts. LM floodlighting is also powered through the umbilical for use during manned lunar module operation while docked with the CSM.

A d-c sensing circuit monitors voltage on each main d-c bus and an a-c sensing circuit monitors voltage on each a-c bus. The d-c sensors provide an indication of an undervoltage by illuminating a warning light. The a-c sensors illuminate a warning light when high- or low-voltage limits are exceeded. In addition, the a-c sensors activate an automatic disconnect of the inverter from the a-c bus during an overvoltage condition. A-C overload conditions are displayed by illumination of an overload warning light and are accompanied by a low voltage light. Additional sensors monitor fuel cell overload and reverse current conditions, providing an automatic disconnect, together with visual indications of the disconnect whenever either condition is exceeded.

Switches, meters, lights, and talk-back indicators are provided for controlling and monitoring all functions of the EPS.

2.6.3 MAJOR COMPONENT/SUBSYSTEM DESCRIPTION.

The subsequent paragraphs describe the cryogenic storage subsystem, and each of the various EPS components.

2.6.3.1 Cryogenic Storage.

The cryogenic storage subsystem (figures 2.6-2 and 2.6-3) supplies hydrogen to the EPS, and oxygen to the EPS, ECS, and for initial LM pressurization. The two tanks in the hydrogen and oxygen systems are of sufficient size to provide a safe return from the furthest point of the mission on the fluid remaining in any one tank. The physical data of the cryogenic storage subsystem are as follows:

	Weight of Usable Cryogenics (lb/tank)	Design Storage Pressure (psia)	Minimum Allowable Operating Pressure (psia)	Approximate Flow Rate at Min dq/dm (+145°F environment) (lb/hr-2 tanks)	Approximate Quantities at Minimum Heater & Fan Cycling (per tank) (min dq/dm)
O_2	320 (min)	900±35	150	1.71	45 to 25%
H_2	28 (min)	245 (+15, -20)	100	0.140	53 to 33%

Initial pressurization from fill to operating pressures is accomplished by GSE. After attaining operating pressures, the cryogenic fluids are in a single-phase condition, therefore completely homogeneous. This avoids sloshing which could cause sudden pressure fluctuations, possible damage to internal components, and prevents positive mass quantity gauging. The single-phase expulsion process continues at nearly constant pressure and increasing temperature above the 2-phase region.

Figure 2.6-2. Cryogenic Storage Subsystem (Oxygen)

Figure 2.6-3. Cryogenic Storage Subsystem (Hyrogen)

Two parallel d-c heaters in each tank supply the heat necessary to maintain design pressures. Two parallel 3-phase a-c circulating fans circulate the fluid over the heating elements to maintain a uniform density and decrease the probability of stratification. A typical heater and fan installation is shown in figure 2.6-4. Relief valves provide overpressure relief, check valves provide tank isolation, and individual fuel cell shutoff valves provide isolation of malfunctioning power plants. Filters extract particles from the flowing fluid to protect the ECS and EPS components. The pressure transducers and temperature probes indicate the thermodynamic state of the fluid. A capacitive quantity probe indicates quantity of fluid remaining in the tanks.

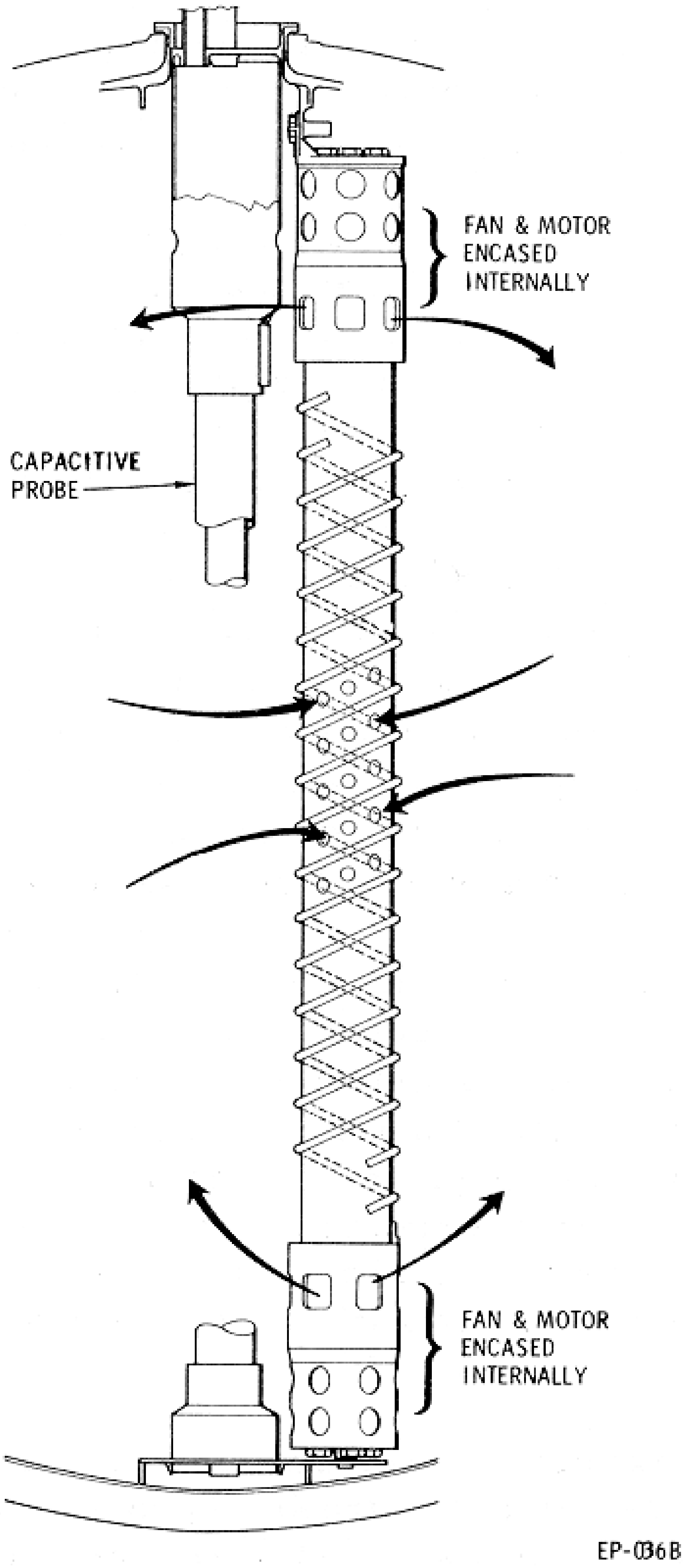


Figure 2.6-4. Cryogenic Pressurization and Quantity Measurement Devices

Repressurization of the systems can be automatically or manually controlled by switch selection. The automatic mode is designed to give a single-phase reactant flow into the fuel cell and ECS feed lines at design pressures. The heaters and fans are automatically controlled through a pressure switch-motor switch arrangement. As pressure in the tanks 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, that respective pressure switch opens to again energize the motor switch, thus opening the heater and fan circuits to both tanks. The O_2 tank circuits are energized at 865 psia minimum and de-energized at 935 psia maximum. The H_2 circuits energize at 225 psia minimum and de-energize at 260 psia maximum. The most accurate quantity readout will be acquired shortly after the fans have stopped. During all other periods partial stratification may degrade quantity readout accuracy.

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 design pressures provided flow is within the min dq/dm values shown in the preceding tabulation. This realm of operation is referred to as the min dq/dm region. The minimum heat requirement region for oxygen starts at approximately 45 percent quantity in the tanks and terminate at approximately 25 percent quantity. Between these tank quantities, minimum heater and fan cycling will occur under normal usage. The amount of heat required for repressurization at quantities below 25 percent starts to increase until below the 3 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 5 percent level.

Assuming a constant level flow from each tank (O_2 - 1 lb/hr, H_2 - 0.09 lb/hr) each successive repressurization period is of longer duration. The periods between repressurizations lengthen as quantity decreases from full to the minimum dq/dm level, and become shorter as quantity decreases from the minimum dq/dm level to the residual level. Approximate repressurization periods are shown in the following chart, which also shows the maximum flow rate in pounds per hour from a single tank with the repressurization circuits maintaining minimum design pressure.

The maximum continuous flow that each cyrogenic tank can provide at minimum design pressure is dependent on the quantity level and the heat required to maintain that pressure. The heat required to maintain a constant pressure decreases as quantity decreases from full to the minimum dq/dm point. As quantity decreases beyond the minimum dq/dm region, the heat required to maintain a constant pressure increases.

As fluid is withdrawn, a specific amount of heat is withdrawn. When the withdrawal rate exceeds the heat that can be supplied by the heaters, fan motors, and heat leak, there is a resultant pressure decrease below the minimum design operating level.

The ability to sustain pressure and flow is a factor of the amount of heat required versus the heat provided by heaters, fan motors, and heat leak. Since heat leak characteristics of each tank vary slightly, the flow each tank can provide will also vary to a small degree. Heat input from heaters, fan motors, and heat leak into an O_2 tank is 595.87 Btu/hour (113.88 watt heaters supply 389.67 Btu, 52.8 watt fan motors supply 180.2 Btu, and heat leak supplies 26 Btu). Heat input from similar sources into a H_2 tank is 94.6 Btu/hr (18.6 watt heaters supply 63.48 Btu, 7 watt fan motors supply 23.89 Btu, and heat leak supplies 7.24 Btu). These figures take into consideration the line loss between the power source and the operating component.

	Oxygen		Hydrogen	
Quantity (percent)	Repressurization Time (Minutes) (865 to 935 psia)	Flow at 865 psia	Repressurization Time (Minutes) (225 to 260 psia)	Flow at 225 psia
100	4.0	3.56	20.0	0.38
95	4.3	3.97	21.0	0.42
90	4.6	4.55	22.0	0.46
85	5.0	5.27	23.0	0.49
80	5.4	6.02	24.5	0.52
75	5.7	7.01	26.5	0.65
70	6.5	7.94	28.5	0.76
65	7.4	9.01	31.0	0.80
60	8.7	10.80	33.5	0.87
55	9.6	12.54	36.0	0.93
50	10.8	14.19	39.0	0.97
45	11.5	15.69	41.0	0.98
40	12.4	17.01	41.0	0.97
35	12.6	17.56	41.0	0.94
30	13.0	17.56	40.5	0.91
25	13.1	16.55	40.5	0.83
20	13.2	15.48	42.0	0.71
15	14.5	12.28	47.0	0.54
10	17.8	8.76	58.0	0.37
7.5	21.4	7.09	71.0	0.23
5	24.0	5.37	Continuous	0.16

To avoid excessive temperatures, which could be realized during continuous heater and fan operation at extremely low quantity levels, a thermal sensitive interlock device is in series with each heater element. The device automatically opens the heater circuits when internal tank shell temperatures reach +90°F, and closes the circuits at +70°F. Assuming normal consumption, oxygen temperature will be approximately -157°F at mission termination, while hydrogen temperature will be approximately -385°F.

The manual mode of operation bypasses the pressure switches, and supplies power directly to the heaters and/or fans through the individual control switches. It can be used in case of automatic control failure, heater failure, or fan failure.

Tank pressures and quantities are monitored on meters located on MDC-2. The caution and warning system (CRYO PRESS) will alarm when oxygen pressure in either tank exceeds 950 psia or falls below 800 psia. The hydrogen system alarms above 270 psia and below 220 psia. Since a common lamp is provided, reference must be made to the individual pressure and quantity meters (MDC-2) to determine the malfunctioning tank. Tank pressures, quantities, and reactant temperatures of each tank are telemetered to MSFN.

Oxygen relief valves vent at a pressure between 983 and 1010 psig and reseat at 965 psig minimum. Hydrogen relief valves vent at a pressure between 273 and 285 psig, and reseat at 268 psig minimum. Full flow venting occurs approximately 2 pounds above relief valve opening pressure.

All the reactant tanks have vac-ion pumps to maintain the integrity of the vacuum between the inner and outer shell, thus maintaining heat leak at or below the design level. SM main d-c bus A distributes power to the H_2 tank 1 pump and bus B to the H_2 tank 2 pump. Fuses provide power source protection. These fuses are removed during prelaunch to disable the circuit for flight. Circuit breakers, O_2 VAC ION PUMPS - MNA - MNB (RHEB-229), provide power source protection for the CM main buses, which distribute power to the O_2 vac-ion pumps. The circuit breakers allow use of the O_2 vac-ion pump circuits throughout flight, and provide a means of disabling circuit if necessary.

The most likely period of overpressurization in the cryogenic system will occur during operation in the minimum dq/dm region. The possibility of overpressurization is predicated on the assumption of a vacuum breakdown, resulting in an increase in heat leak. Also, under certain conditions, i.e., extremely low power levels and/or a depressurized cabin, demand may be lower than the minimum dq/dm flow necessary. Any of the preceding conditions would result in an increase of pressure within a tank.

In the case of hydrogen tank overpressurization, prior to reaching relief valve cracking pressure, tank pressure can be decreased by performing an unscheduled fuel cell hydrogen purge. A second method for relieving overpressure is to increase electrical loads, thus increasing fuel cell demand. However, in using this method, consideration must be given to the fact that there will be an increase in oxygen consumption, which may not be desirable.

Several procedures can be used to correct an overpressure condition in the oxygen system. One is to perform an unscheduled fuel cell purge. A second is to increase oxygen flow into the command module by opening the ECS DIRECT O_2 valve. The third is to increase electrical loads, which may not be desirable because this method will also increase hydrogen consumption.

Increase of electrical loads is probably the least desirable method because of the increase in demand on both reactant systems, although an overpressure correction is required in only one reactant system.

A requirement for an overpressure correction in both reactant systems simultaneously is remote, since both reactant systems do not reach the minimum dq/dm region in parallel.

During all missions, to retain a single tank return capability, there is a requirement to maintain a balance between the two tanks in each of the reactant systems. When a 2 to 4 percent difference is indicated on the oxygen quantity meters (MDC-2), the O_2 HEATERS switch (MDC-2) of the lesser tank is positioned to OFF until tank quantities equalize. A 3 percent difference in the hydrogen quantity meters (MDC-2) will require positioning the H_2 HEATERS switch (MDC-2) of the lesser tank to OFF until tank quantities equalize. This procedure retains the automatic operation of the repressurization circuits, and provides for operation of the fan motors during repressurization to retain an accurate quantity readout in all tanks. The necessity for balancing should be determined shortly after a repressurization cycle, since quantity readouts will be most accurate at this time.

2.6.3.2 Batteries.

Five silver oxide-zinc storage batteries are incorporated in the EPS. These batteries are located in the CM lower equipment bay.

Three rechargeable entry and postlanding batteries (A, B, and C) power the CM systems after CSM separation and during postlanding. Prior to CSM separation, the batteries provide a secondary source of power while the fuel cells are the primary source. The entry batteries are used for the following purposes:

- Provide CM power after CSM separation
- Supplement fuel cell power during peak load periods (Delta V maneuvers)
- Provide power during emergency operations (failure of two fuel cells)
- Provide power for EPS control circuitry (relays, indicators, etc.)
- Provide sequencer logic power
- Provide power for recovery aids during postlanding
- Batteries A, B, or C can power pyro circuits by selection.

Each entry and postlanding battery is mounted in a vented plastic case and 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. The three cases can be vented overboard through a common manifold, the BATTERY VENT valve (RHEB-252), and the ECS waste water dump line.

Since the BATTERY VENT is closed prior to lift-off, the interior of the battery cases is at a pressure of one atmosphere. The pressure is relieved after earth orbit insertion and completion of cabin purge by positioning the control to VENT for 5 seconds. After completion the control is closed, and pressure as read out on position 4A of the System Test Meter (LEB-101) should remain at zero unless there is battery outgassing. This outgassing can be caused by an internal battery failure, an abnormal high-rate discharge, or by overcharging. If a pressure increase is noted on the system test meter, the BATTERY VENT is positioned to VENT for 5 seconds, and reclosed. Normal battery charging procedures require a check of the battery manifold after completion of recharge.

Since the battery vent line is connected to the waste water dump line, it provides a means of monitoring waste water dump line plugging, which would be indicated by a pressure rise in the battery manifold line when the BATTERY VENT control is positioned to VENT. Corrective procedures for dump line plugging are found in section 2. 12.

Each battery is rated at 40-ampere hours (AH) minimum and will deliver this at a current output of 35 amps for 30 minutes and a subsequent output of 2 amps for the remainder of the rating.

At Apollo mission loads each battery is capable of providing 45 AH and will provide this amount after each complete recharge cycle. However, 40 AH is used in mission planning for inflight capability, and 45 AH for postlanding capability of a fully charged battery.

Open circuit voltage is 37.2 volts. Sustained battery loads are extremely light (2 to 3 watts); therefore a battery bus voltage of approximately 34 vdc will be indicated on the spacecraft voltmeter, except when the main bus tie switches have been activated to tie the battery outputs to the main d-c buses. Normally only batteries A and B will be connected to the main d-c buses. Battery C is isolated during prelaunch by opening the MAIN A-BAT C and MAIN B-BAT C circuit breakers (RHEB-275). Battery C will therefore provide a backup for main d-c bus power in case of failure of battery A or B or during the time battery A or B is being recharged. The two-battery configuration provides more efficient use of fuel cell power during peak power loads and decreases overall battery recharge time. The MAIN A- and MAIN B-BAT C circuit breakers are closed prior to CSM separation or as required during recharge of battery A or B.

Battery C, through circuit breakers BAT C to BAT BUS A and BAT C to BAT BUS B (RHEB-250), provides backup power to the respective battery bus in the event of failure of entry battery A or B. These circuit breakers are normally open until a failure of battery A or B occurs. This circuit can also be used to recharge battery A or B in the event of a failure in the normal charging circuit.

The two pyrotechnic batteries supply power to initiate ordnance devices in the SC. The pyrotechnic batteries are isolated from the rest of the EPS to prevent the high-power surges in the pyrotechnic system from affecting the EPS, and to ensure source power when required. These batteries are not to be recharged in flight. Entry and postlanding battery A, B, or C can be used as a redundant source of power for initiating pyro circuits in the respective A or B pyro system, if either pyro battery fails. This can be performed by proper manipulation of the circuit breakers on RHEB-250. Caution must be exercised to isolate the failed battery prior to connecting the replacement battery.

Performance characteristics of each SC battery are as follows:

Battery	Rated Capacity per Battery	Open Circuit Voltage (max.)	Nominal Voltage	Minimum Voltage	Ambient Battery Temperature
Entry and Postlanding, A, B, and C (3)	40 amp-hrs (25 ampere rate)	37.8 vdc max. (37.2 vdc in flight)	29 vdc (35 amps load)	27 vdc (35 amps load)	50° to 110°F
Pyro A and B (2)	0.75 amp-hrs (75 amps for 36 seconds)	37.8 vdc max. (37.2 vdc in flight)	23 vdc (75 amps load)	20 vdc (75 amps load) (32 vdc open circuit)	60° to 110°F

NOTE Pyro battery load voltage is not measurable in the SC due to the extremely short time they power pyro loads.

2.6.3.3 Fuel Cell Power Plants.

Each of the three Bacon-type fuel cell power plants is individually coupled to a heat rejection (radiator) system, the hydrogen and oxygen cyrogenic storage systems, a water storage system, and a power distribution system. A typical power plant schematic is shown in figure 2.6-5.

The power plants generate d-c power on demand through an exothermic chemical reaction. The by-product water is fed to a potable water storage tank in the CM where it is used for astronaut consumption and for cooling purposes in the ECS. The amount of water produced is equivalent to the power produced which is relative to the reactant consumed.

REACTANT CONSUMPTION AND WATER PRODUCTION

Load (amps)	O_2 lb/hr	H_2 lb/hr	H_2O lb/hr	cc/hr
0.5	0.0102	0.001285	0.01149	5.21
1	0.0204	0.002570	0.02297	10.42
2	0.0408	0.005140	0.04594	20.84
3	0.0612	0.007710	0.06891	31.26
4	0.0816	0.010280	0.09188	41.68

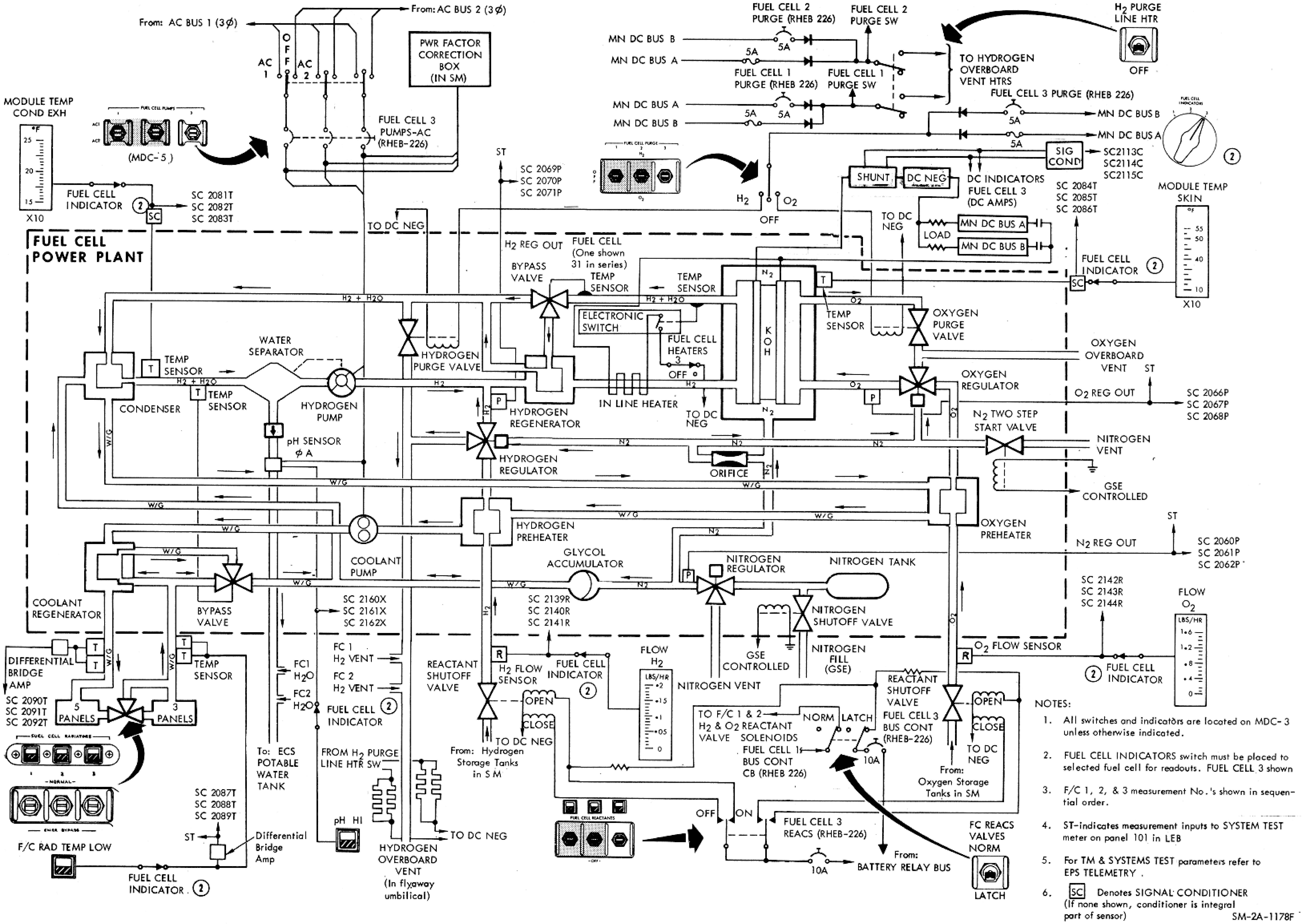
REACTANT CONSUMPTION AND WATER PRODUCTION (Cont)

Load (amps)	O_2 lb/hr	H_2 lb/hr	H_2O lb/hr	cc/hr
5	0.1020	0.012850	0.11485	52.10
6	0.1224	0.015420	0.13782	62.52
7	0.1428	0.017990	0.16079	72.94
8	0.1632	0.020560	0.18376	83.36
9	0.1836	0.023130	0.20673	93.78
10	0.2040	0.025700	0.2297	104.20
15	0.3060	0.038550	0.34455	156.30
20	0.4080	0.051400	0.45940	208.40
25	0.5100	0.064250	0.57425	260.50
30	0.6120	0.077100	0.68910	312.60
35	0.7140	0.089950	0.80395	364.70
40	0.8160	0.10280	0.91880	416.80
45	0.9180	0.11565	1.03365	468.90
50	1.0200	0.12850	1.1485	521.00
55	1.1220	0.14135	1.26335	573.10
60	1.2240	0.15420	1.3782	625.20
65	1.3260	0.16705	1.49305	677.30
70	1.4280	0.17990	1.6079	729.40
75	1.5300	0.19275	1.72275	781.50
80	1.6320	0.20560	1.83760	833.60
85	1.7340	0.21845	1.95245	885.70
90	1.8360	0.23130	2.06730	937.90
95	1.9380	0.24415	2.18215	989.00
100	2.0400	0.25700	2.2970	1042.00

FORMULAS:

$O_2 = 2.04 \times 10^{-2}\ I$ $H_2O = 10.42$ cc/amp/hr

$H_2 = 2.57 \times 10^{-3}\ I$ $H_2O = 2.297 \times 10^{-2}$ lb/amp/hr



NOTES:

1. All switches and indicators are located on MDC-3 unless otherwise indicated.
2. FUEL CELL INDICATORS switch must be placed to selected fuel cell for readouts. FUEL CELL 3 shown
3. F/C 1, 2, & 3 measurement No.'s shown in sequential order.
4. ST-indicates measurement inputs to SYSTEM TEST meter on panel 101 in LEB
5. For TM & SYSTEMS TEST parameters refer to EPS TELEMETRY.
6. SC Denotes SIGNAL CONDITIONER (If none shown, conditioner is integral part of sensor)

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Figure 2.6-5. Fuel Cell Schematic

2.6.3.3.1 Component Description.

Each power plant 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.

Power plant 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. Flow is regulated in accordance with skin 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 cool gas is then pumped back to the fuel cell through the primary regenerator by a motor-driven 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. Individual controls (FUEL CELL RADIATORS, MDC-3), can bypass 3/8 of the total radiator area for each power plant. Radiator area is varied dependent on power plant condenser exhaust and radiator exit temperatures which are relevant to loads and space environment. Internal fuel cell coolant temperature is controlled by a condenser exhaust sensor, which regulates flow through a secondary regenerator to maintain condenser exhaust within desired limits. When either condenser exhaust or radiator exit temperature falls below tolerance limits (150° and -30°F respectively), the respective FUEL CELL RADIATORS switch is positioned to EMERG BYPASS to decrease the radiator area in use, thus decreasing the amount of heat being radiated. Since the three power plants are relatively close in load sharing and temperature operating regimes, the effect on the other power plants must be monitored. Generally simultaneous control over all three power plants will be required. Use of the bypass should be minimal because of powerplant design to retain heat at low loads and expel more heat at higher loads. The bypass is primarily intended for use after failure of two powerplants. Heat radiation effects on the single powerplant require continuous use of the bypass for the one remaining powerplant.

Reactant valves provide the interface between the power plants and cryogenic system. They are opened during pre-launch and closed only after a power plant malfunction necessitating its permanent isolation from the d-c system. Prior to launch, the FC REACS VALVES switch (MDC-3) is placed to the LATCH position. This applies a holding voltage to the open solenoids of the H_2 and O_2 reactant valves of the three power plants.

This voltage is required only during boost to prevent inadvertent closure due to the effects of high vibration. The reactant valves cannot be closed by use of the REACTANTS switches (MDC-3) with the holding voltage applied. The FC REACS VALVES switch is positioned to NORMAL after earth orbit insertion. During prelaunch, after power plant activation, the the three FC REACS circuit breakers (RHEB-226) are opened to prevent valve closure through inadvertent REACTANTS switch activation.

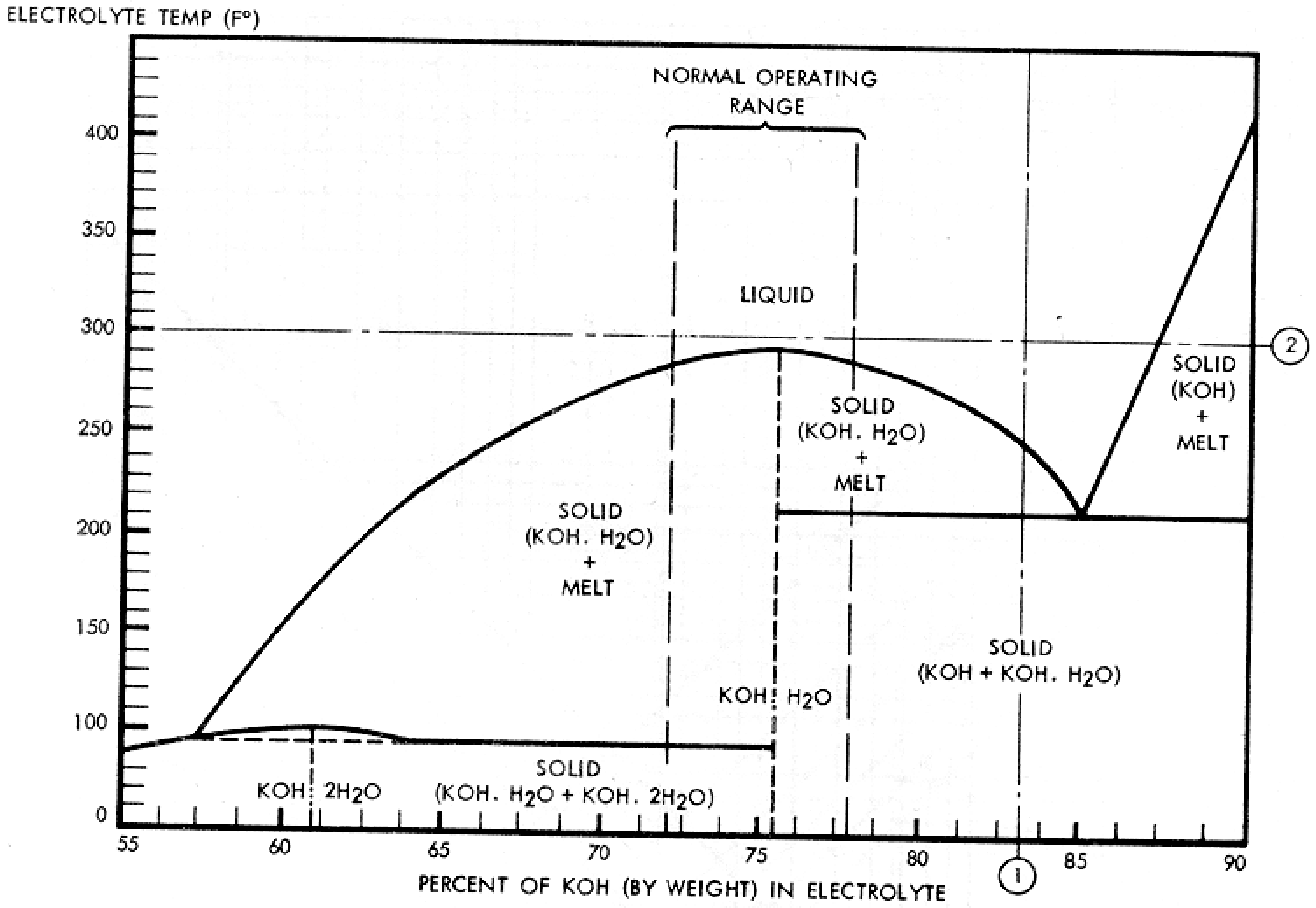
N_2 gas is individually stored in each power plant at 1500 psia and regulated to a pressure of 53±3 psia. Output of the regulator pressurizes the electrolyte in each cell, the coolant loop through an accumulator, and is coupled to the O_2 and H_2 regulators as a reference pressure.

Cryogenic oxygen, supplied to the power plants at 900±35 psia, absorbs heat in the lines, absorbs additional heat in the preheater, and reaches the oxygen regulator in a gaseous form at temperatures above 100°F. The differential regulator reduces oxygen pressure to 9.5 psia above the N_2 reference, thus supplying it to the fuel cell stack at 62.5±2 psia. Within the porous oxygen electrodes, the O_2 reacts with the H_2O in the electrolyte and the electrons provided by the external circuit to produce hydroxyl ions ($O_2 + 2H_2O + 4e = 4OH^-$).

Cryogenic hydrogen, supplied to the power plants 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 N_2, thus supplying it in a gaseous form to the fuel cells at 61.5±2 psia. The hydrogen reacts in the porous hydrogen electrodes with the hydroxyl ions in the electrolyte to produce electrons, water vapor, and heat ($2\,H_2 + 4OH^- = 4H_2O + 4e + \text{heat}$). The nickel electrodes act as a catalyst in the reaction. The water vapor and heat is 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 power plant contains electrolyte which on initial fill consists of 83 percent potassium hydroxide (KOH) and 17 percent water by weight. The power plant 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 300°F (figure 2.6-6). It solidifies at an approximate temperature of 220°F. Power plant electrochemical reaction becomes effective at the critical temperature. Bringing power plants to critical temperature is performed by GSE and cannot be performed from SC power sources. Placing a load on the power plant will maintain it above the critical temperature. The automatic in-line heater circuit will maintain power plant temperature at 385°F with no additional loads applied.

Purging is a function of power demand and gas purity. O_2 purging requires 2 minutes and H_2 purging 80 seconds. A hydrogen



NOTES: 1. Percent (83) of KOH in electrolyte at initial fill.
2. Critical temperature (300°F) of electrolyte at which electrochemical reaction begins, on initial start-up of fuel cell.

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Figure 2.6-6. KOH H_2O Phase Diagram

purge is preceded by activation of the H_2 PURGE LINE HTR switch (MDC-3) 20 minutes prior to the purge. The purge cycle is determined by the mission power profile and gas purity as sampled after spacecraft tank fill. Figures 2.6-7 and 2.6-8 can be used to calculate the purge cycles, dependent on gas purity and load. A degradation purge can be performed if power plant current output decreases approximately 3 to 5 amps during sustained operation. The O_2 purge has more effect during this type of purge, although it would be followed by an H_2 purge if recovery to normal was not realized after performing an O_2 purge. If the pH talk back indicator (MDC-3) is activated, a hydrogen purge will not be performed on the fuel cell with the high pH. This prevents the possibility of clogging the hydrogen vent line.

2.6.3.3.2 Fuel Cell Loading.

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

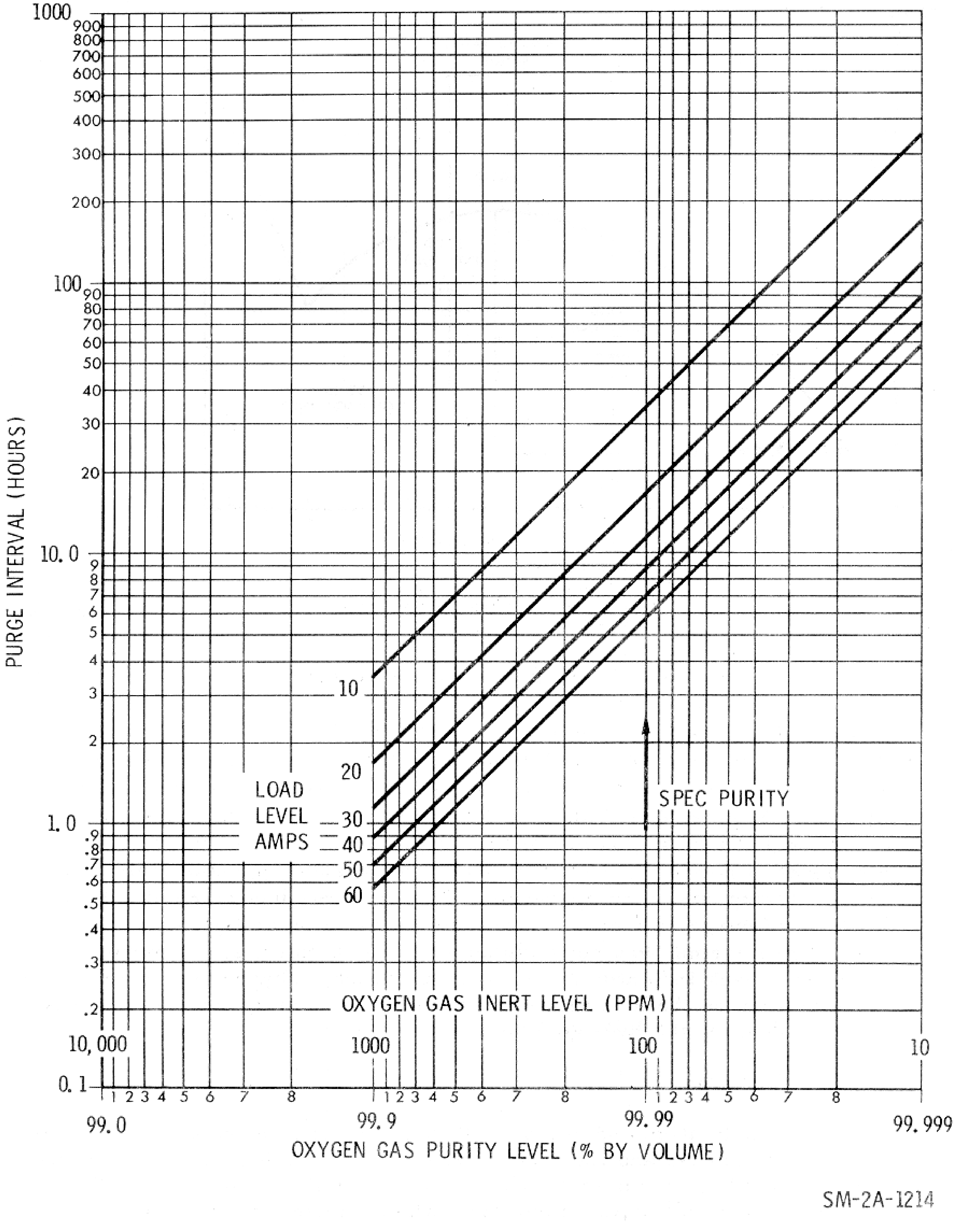


Figure 2.6-7. O_2 Gas Purity Effect on Purge Interval

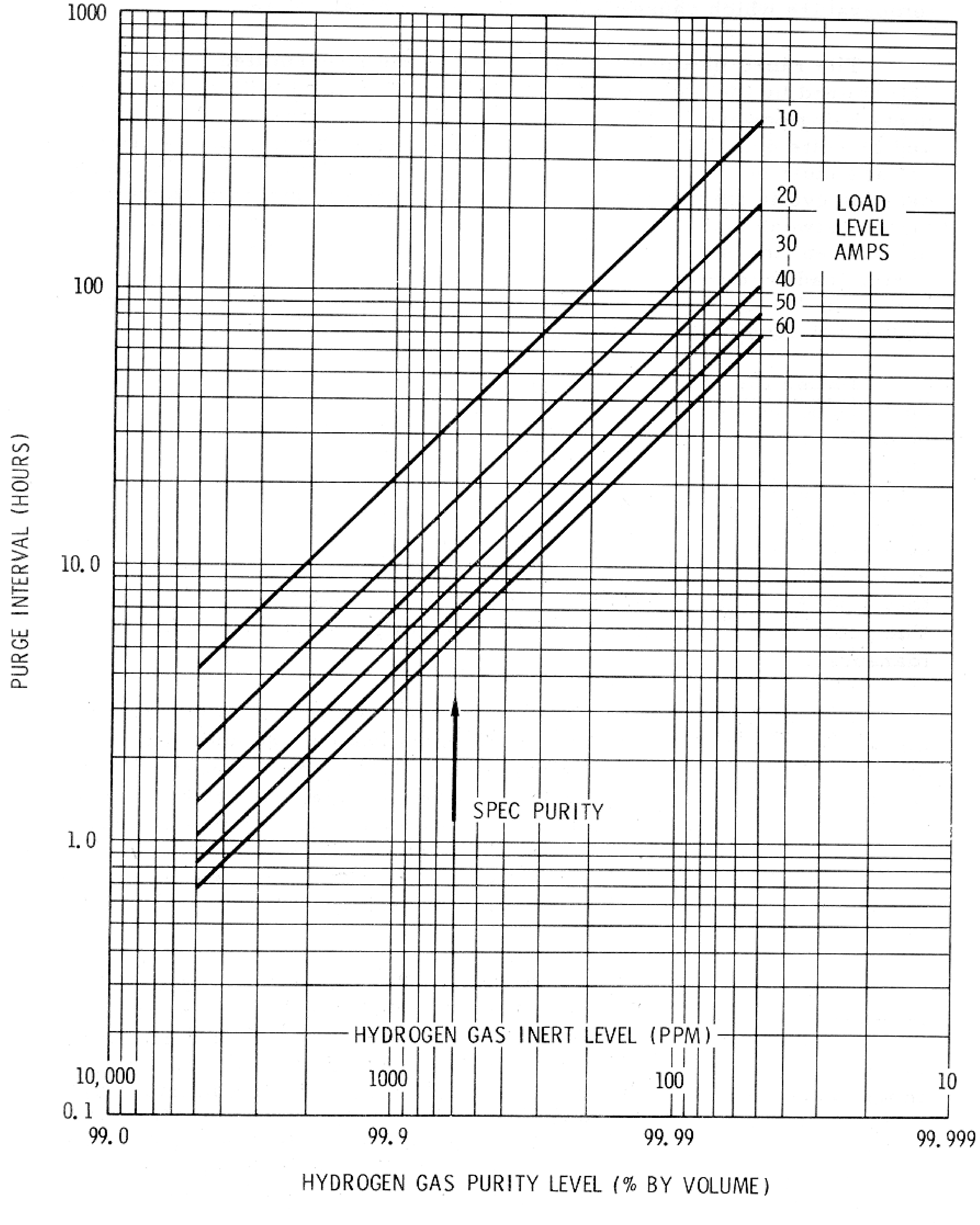


Figure 2.6-8. H_2 Gas Purity Effect on Purge Interval

from a decreased load, is followed by a gradual decrease in fuel cell skin temperature which causes a decrease in terminal voltage.

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 d-c bus voltage must be maintained between 31.0 and 26.2 volts dc. To compensate for cyclic loads, it is recommended sustained bus voltage be maintained between 26.5 and 30.0 vdc. Bus voltage is maintained within prescribed limits by the application of entry and postlanding batteries during load increases (power up). Load increase or decrease falls well within the limits of power supply capability and, under normal conditions, should not require other than normal checklist procedures.

Power Up. Powering up spacecraft systems is performed in one continuous sequence providing the main bus voltage does not decrease below 26.5 volts. If bus voltage decreases to this level, 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 thus 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 earlier battery coupling may be required. The greatest load increase occurs while powering up for a delta V maneuver.

Power Down. Powering down spacecraft systems is performed in one continuous sequence providing the main bus voltage does not increase above 31.0 volts. Powering down from relatively high spacecraft load levels, i.e., following a delta V, the sequence may have to be interrupted for the time required for fuel cell temperature, and as a result, bus voltage to decrease. To expedite power down, one fuel cell can be disconnected from the buses increasing the loads on the remaining fuel cells and decreasing bus voltage, thus allowing continuation of the power down sequence.

Fuel Cell Disconnect. If the requirement arises to maintain a powerplant on open circuit, temperature decay would occur at an average rate of approximately 6°/hr., with the automatic in-line heater circuit activating at a skin temperature of 385°F and maintaining powerplant temperature at 385°F. In-line heater activation can be confirmed by a 4.5 to 6 amp indication as observed on the d-c amps meter (MDC-3) with the d-c indicator switch positioned to the open circuited fuel cell position. Reactant valves remain open. Fuel cell pumps can be turned off until the in-line heater circuit activates, at which time they must be on.

Closing of reactant valves during a power plant disconnect is dependent on the failure experienced. If power plant failure is such as to allow future use, i. e., shutdown due to partially degraded output, it is recommended the reactant valves remain open to provide a positive reactant pressure. The valves should be closed after power-plant skin temperature decays below 300°F. The reactant valves are closed during initial shutdown, if the failure is a reactant leak, an abnormally high regulator output pressure, or complete power-plant failure.

Prior to disconnecting a fuel cell, if a single inverter is being used, each of the remaining power plants is connected to both main d-c buses to enhance load sharing since bus loads are unbalanced. If two inverters are being used, main d-c bus loads are relatively equal; therefore, each of the remaining power plants is connected to a separate main d-c bus for bus isolation. If one power plant had been placed on open circuit for an extended period of time, prior to powering up to a configuration requiring three power plants, reconnecting is accomplished prior to the time of heavy load demands. This permits proper conditioning of the power plant which has been on open circuit. The time required for proper conditioning is a function of skin temperature increase and the load applied to the power plant.

2. 6. 3. 4 Inverters.

Each inverter (figure 2. 6-9) is composed of an oscillator, an eight-stage digital countdown section, a d-c line filter, two silicon-controlled rectifiers, a magnetic amplifier, a buck-boost amplifier, a demodulator, two d-c filters, an eight-stage power inversion section, a harmonic neutralization transformer, an a-c 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-kHz square wave synchronizing signal from the central timing equipment (CTE) which maintains inverter output at 400 Hz. If this external signal is completely lost, the free running oscillator within the inverter will provide pulses that will maintain inverter output within ±7 Hz. The internal oscillator is normally synchronized by the external pulse. The subsequent paragraphs describe the function of the various stages of the inverter.

The 6. 4-kHz square wave provided by the CTE is applied through the internal oscillator to the eight-stage digital countdown section. The oscillator has two divider circuits which provide a 1600-Hz signal to the magnetic amplifier.

The eight-stage digital countdown section, triggered by the 6. 4-kHz signal, produces eight 400-Hz 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.

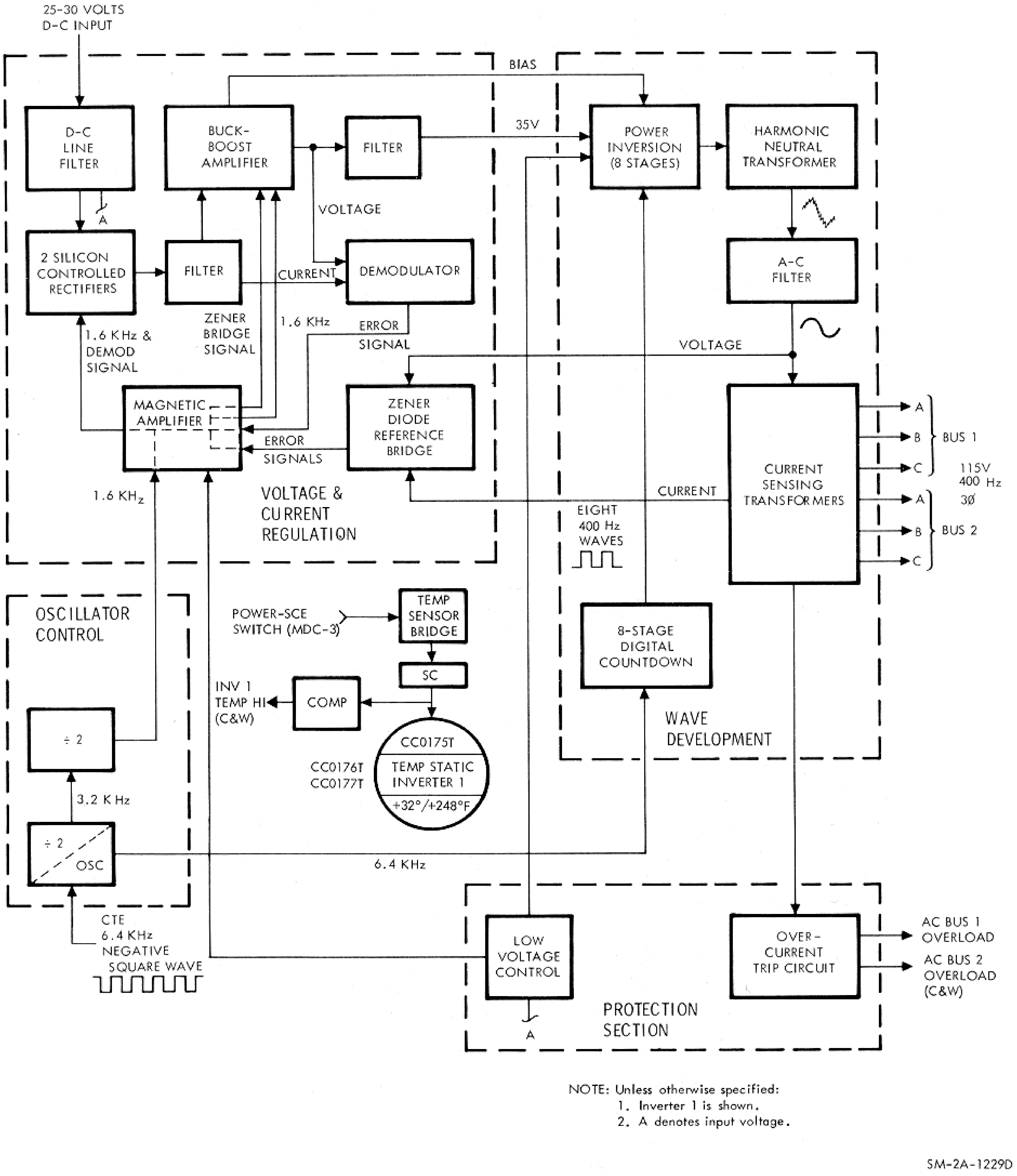


Figure 2.6-9. Inverter Block Diagram

The eight-stage power inversion section, fed a controlled voltage from the buck-boost amplifier, amplifies the eight 400-Hz 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-Hz square-wave output of the eight-stage power inversion section and transforms it into a 3-phase 400-Hz 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, wye-connected secondary windings, thus producing the 3-phase 400-Hz sine wave output. This 115-volt signal is then applied to the a-c output filter.

The a-c output filter eliminates the remaining higher harmonics. Since the lower harmonics were eliminated by the harmonic neutral transformer, the size and weight of this output filter was 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 a-c output voltage. After filtering, the 3-phase 115-volt a-c 400-Hz sine wave is applied to the a-c 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 d-c signal is applied to the Zener diode reference bridge to regulate inverter current output; it is also paralleled to an overcurrent sensing circuit.

The Zener diode reference bridge receives a rectified d-c signal, representing voltage output, from the circuitry in the a-c 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 exceeds 250 percent of rated current, the overcurrent sensing circuit is activated.

The overcurrent sensing circuit monitors a rectified d-c signal representing current output. When total inverter current output exceeds 250 percent of rated current, this circuit will illuminate an overload lamp in 15±5 seconds. If current output of any single phase exceeds 300 percent of rated current, this circuit will illuminate the overload lamp in 5±1 seconds. The AC BUS 1 OVERLOAD and AC BUS 2 OVERLOAD lamps are in the caution/warning matrix on MDC-2.

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

The silicon-controlled rectifiers are alternately set by the 1600-Hz signal from the magnetic amplifier to produce a d-c 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-Hz 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 (10 to 1000 Hz) in the d-c input to the inverter. The high-frequency ripple is attenuated by the input filters. The demodulator senses the 35-volt d-c output of the buck-boost amplifier and the current input to the buck-boost amplifier. An input d-c voltage drop or increase will be reflected in a drop or increase in the 35-volt d-c 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 SCRs to conduct for a longer time, thus increasing their filtered d-c output. A sensed increase in buck-boost amplifier voltage output, caused by an increase in d-c 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 d-c output to the buck-boost amplifier. In this manner, the 35-volt d-c input to the power inversion section is maintained at a relatively constant level irrespective of the fluctuations in d-c input voltage to the inverter.

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 provides an input to the C&WS which will illuminate a light at an inverter overtemperature of 190°F. Inverter temperature is telemetered to MSFN.

2.6.3.5 Battery Charger.

A constant voltage, solid-state battery charger (figure 2.6-10), located in the CM lower equipment bay, is incorporated into the EPS. The BATTERY CHARGER selector switch (MDC-3) controls power input to the charger, as well as connecting the charger output to the selected battery (figure 2.6-14). When the BATTERY CHARGER selector switch is positioned to entry battery A, B, or C, a relay (K1) is activated completing circuits from a-c and d-c power sources to the battery charger. Battery charger output is also connected to the selected battery to be charged through contacts of the MAIN BUS TIE motor switch. Positioning the MAIN BUS TIE switch (A/C or B/C) to OFF for battery A or B, and both switches to OFF for battery C will disconnect main bus loads from the respective batteries and also complete the circuit from the charger to the battery.

The battery charger is provided 25 to 30 volts from both main d-c buses and 115 volts 400-Hz 3-phase from either of the a-c buses. All three phases of ac are used to boost the 25 to 30-volt d-c 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 in the on mode, 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 the switching transistor to the on mode. 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

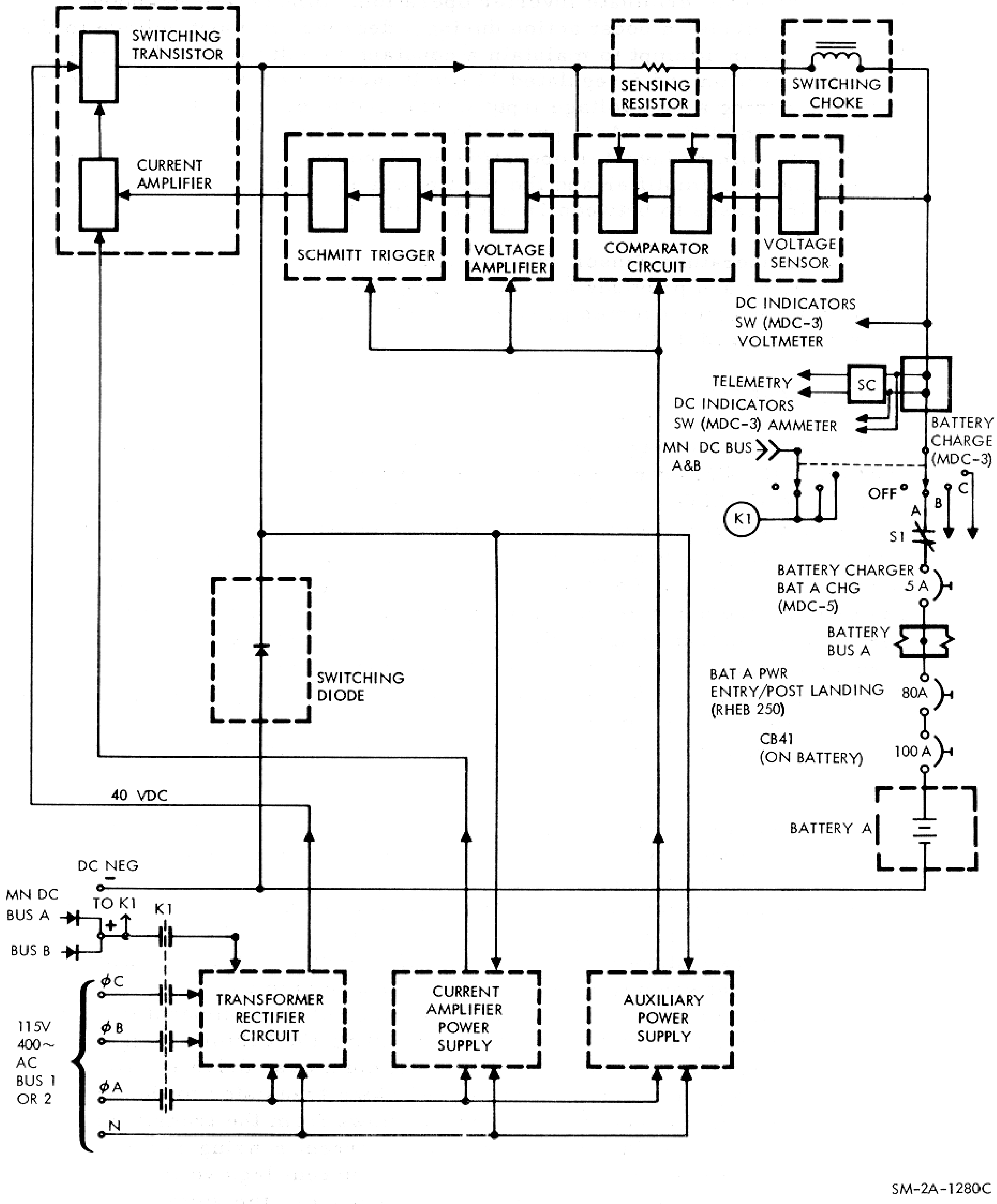


Figure 2.6-10. Battery Charger Block Diagram

of the comparator to off and the second stage to 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. The switching transistor in the off mode 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 EMF 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 constant except for the small variation through the sensing resistor. This variation is required to set and reset the switching transistor and Schmitt trigger through the action of the comparator.

Battery charger output is regulated by the sensing resistor until battery voltage reaches approximately 37 volts. At this point, the biased voltage sensor circuit is unbiased, and in conjunction with the sensing resistor provides a signal for cycling the battery charger. As battery voltage increases, the internal impedance of the battery increases, decreasing current flow from the charger. At 39.8 volts, the battery is fully charged and current flow becomes negligible. (See figure 2.6-11.) Recharging the batteries until battery amp hour input equates amp hours previously discharged from the battery assures sufficient battery capacity for mission completion. The MSFN will monitor this function. If there is no contact with the MSFN, battery charging is terminated when the voltmeter indicates 39.5 vdc with the DC INDICATORS switch set to the BAT CHARGER position.

Charger voltage is monitored on the DC VOLTS METER (MDC-3). Current output is monitored on the inner scale of the DC AMPS meter (MDC-3) by placing the DC INDICATORS switch (MDC-3) to the BAT CHARGER position. Battery charger current output is telemetered to the MSFN.

When charging battery A or B, the respective BAT RLY BUS-BAT A or B circuit breaker (MDC-5) is opened to expedite recharge. During this period, only one battery will be powering the battery relay bus. Relay bus voltage can be monitored by selecting positions 4 and B on the Systems Test Meter (LEB-101) and from the couches by the Fuel Cell-Main Bus B-1 and Fuel Cell - Main Bus A-3 talk back indicators (MDC-3) which will be barber-poled. If power is lost to the relay bus, these indicators will revert to the gray condition indicating loss of power to the relay bus and requiring remedial action.

Recharge of a battery immediately after it is exposed to any appreciable loads requires less time than recharge of a battery commencing

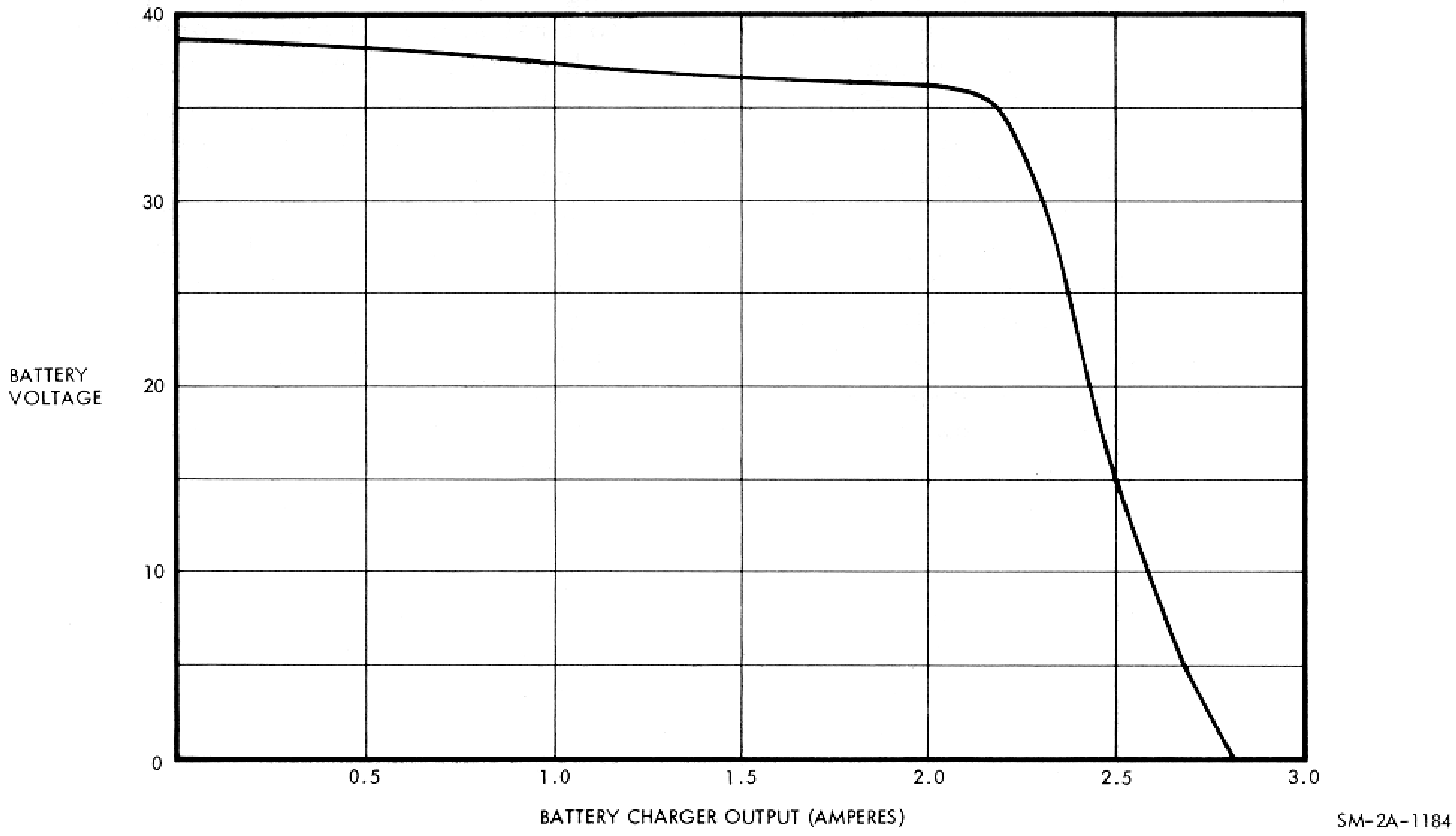


Figure 2.6-11. Battery Charger Output (Amperes)

30 minutes or more after it is disconnected from these loads. Therefore, it is advantageous to connect batteries to the charger as soon as possible after they are disconnected from the main buses since this decreases overall recharge time.

2.6.3.6 Power Distribution.

D-C and a-c power distribution to components of the EPS is provided by two redundant buses in each system. A single-point ground on the spacecraft structure is used to eliminate ground loop effects. Sensing and control circuits are provided for monitoring and protection of each system.

Distribution of d-c power (figure 2.6-12) is accomplished with a two-wire system and a series of interconnected buses, switches, circuit breakers, and isolation diodes. The d-c negative buses are connected to the vehicle ground point (VGP). The buses consist of the following:

- Two main d-c buses (A and B), powered by the three fuel cells and/or entry and postlanding batteries A, B, and C.
- Two battery buses (A and B), each powered by its respective entry and postlanding battery A and B. Battery C can power either or both buses if batteries A and/or B fail.

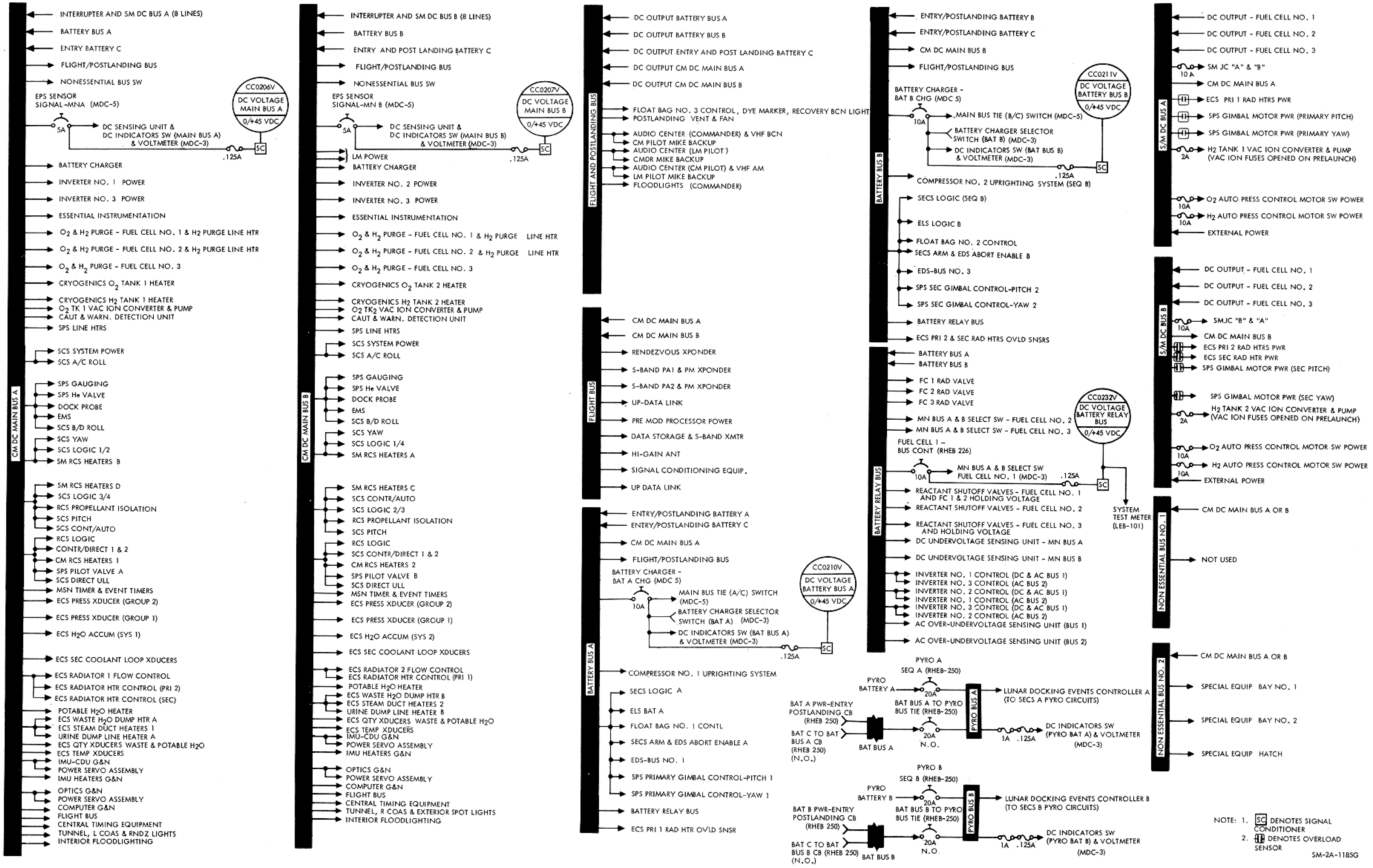
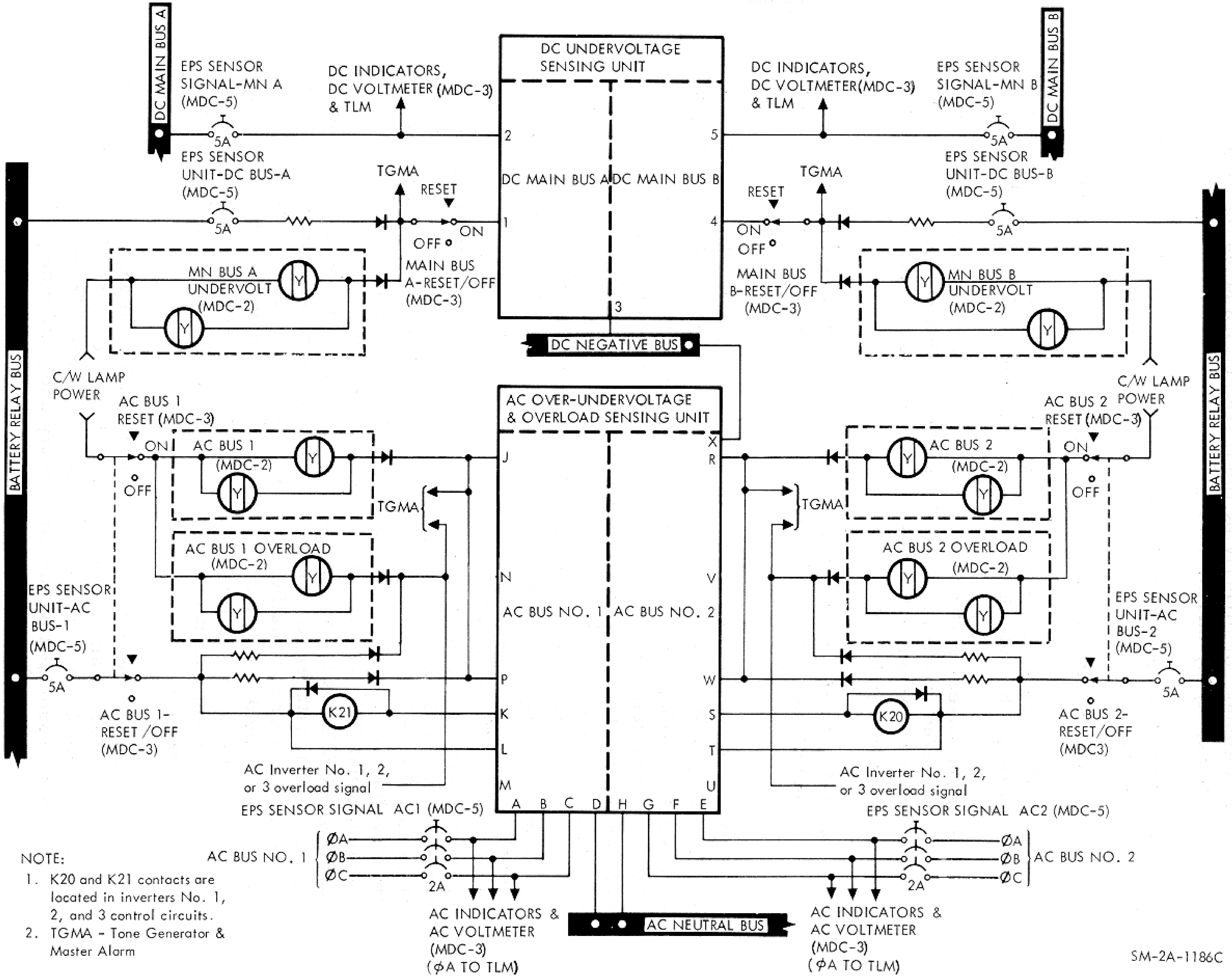


Figure 2.6-12. D-C Power Distribution

- Flight and postlanding bus, powered through both main d-c buses and diodes, or directly by the three entry and postlanding batteries, A, B, and C, through dual diodes.
- Flight bus, powered through both main d-c buses and isolation diodes.
- Nonessential bus, powered through either d-c main bus A or B.
- Battery relay bus, powered by entry and postlanding batteries through the individual battery buses and isolation diodes.
- Pyro buses, isolated from the main electrical power system when powered by the pyro batteries. A capability is provided to connect either entry battery to the A or B pyro system in case of loss of a pyro battery.
- SM jettison controllers, powered by the fuel cell power plants and completely isolated from the main electrical power system until activated during CSM separation.

Power from the fuel cell power plants can be connected to the main d-c buses through six motor switches (part of overload/reverse current circuits in the SM) which are controlled by switches in the CM located on MDC-3. Fuel cell power can be selected to either or both of the main d-c buses. Six talk back indicators show gray when fuel cell output is connected and striped when disconnected. When an overload condition occurs, the overload-reverse current circuits in the SM automatically disconnect the fuel cell power plants from the overloaded bus and provide visual displays (talk-back indicator and caution and warning lamp illumination) (FC BUS DISCONNECT) for isolation of the trouble. A reverse current condition will disconnect the malfunctioning power plant from the d-c system. D-C undervoltage sensing circuits (figure 2.6-13) are provided to indicate bus low-voltage conditions. If voltage drops below 26.25 volts d-c, the applicable d-c undervoltage light on the caution and warning panel (MDC-2) will illuminate. Since each bus is capable of handling all EPS loads, an undervoltage condition should not occur except in an isolated instance; if too many electrical units are placed on the bus simultaneously or if a malfunction exists in the EPS. A voltmeter (MDC-3) is provided to monitor voltage of each main d-c bus, the battery charger, and each of the five batteries. An ammeter is provided (MDC-3) to monitor current output of fuel cells 1, 2, 3, batteries A, B, C, and the battery charger.

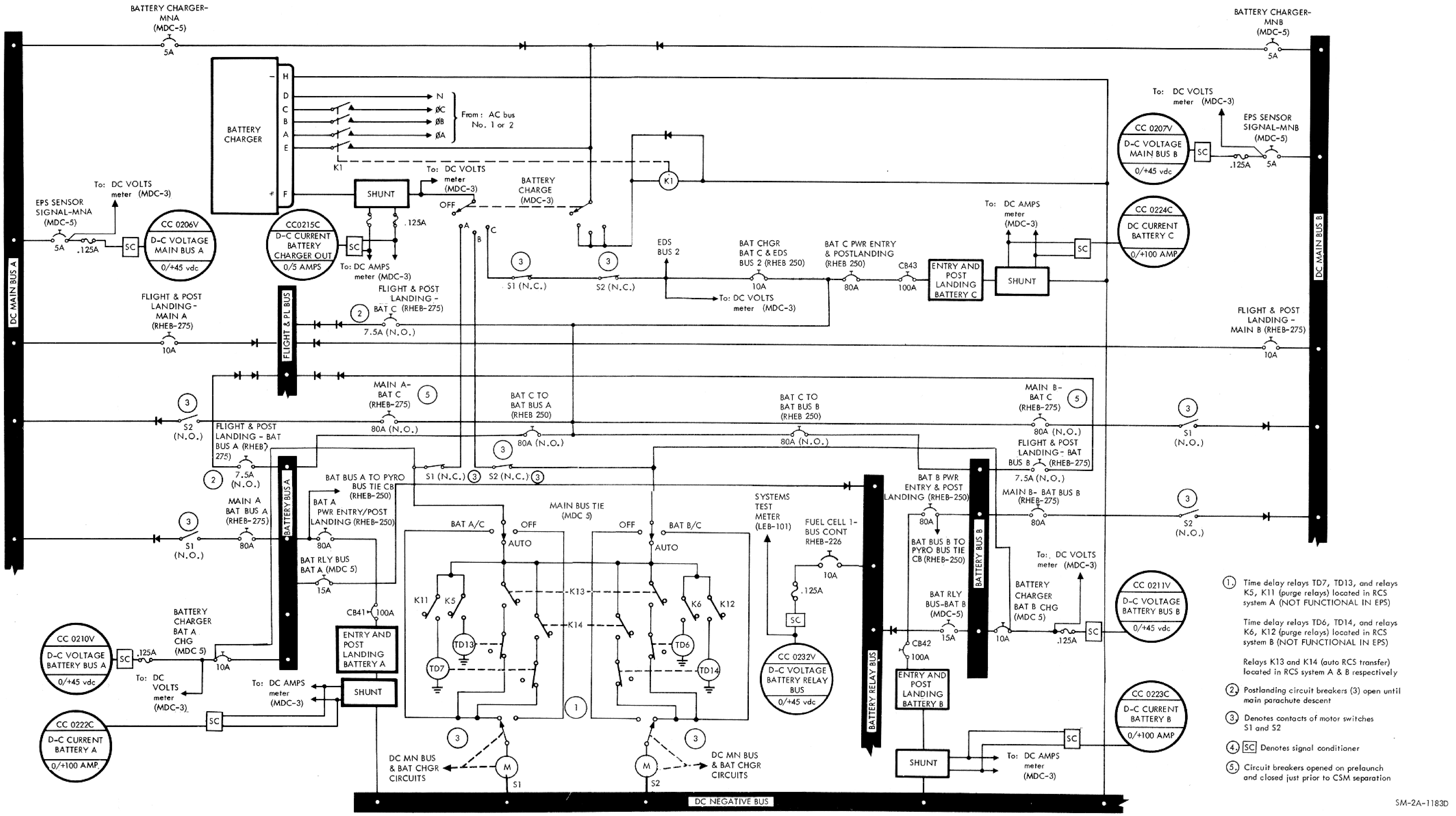
During high power demand or emergencies, supplemental power to the main d-c buses can be supplied from batteries A and B via the battery buses and directly from battery C (figure 2.6-14). During entry, spacecraft power is provided by the three entry and postlanding batteries which



NOTE:

1. K20 and K21 contacts are located in inverters No. 1, 2, and 3 control circuits.
2. TGMA - Tone Generator & Master Alarm

Figure 2.6-13. D-C and A-C Voltage Sensing



① Time delay relays TD7, TD13, and relays K5, K11 (purge relays) located in RCS system A (NOT FUNCTIONAL IN EPS)

Time delay relays TD6, TD14, and relays K6, K12 (purge relays) located in RCS system B (NOT FUNCTIONAL IN EPS)

Relays K13 and K14 (auto RCS transfer) located in RCS system A & B respectively

② Postlanding circuit breakers (3) open until main parachute descent

③ Denotes contacts of motor switches S1 and S2

④ SC Denotes signal conditioner

⑤ Circuit breakers opened on prelaunch and closed just prior to CSM separation

Figure 2.6-14. Battery Charger and CM D-C Bus Control Circuits are connected to the main d-c buses prior to CSM separation; placing the MAIN BUS TIE switches (MDC-5) to BAT A/C and BAT B/C provides this function after closing the MAIN A-BAT C and MAIN B-BAT C circuit breakers (RHEB-275). The switches are manually placed to OFF after completion of RCS purge and closing the FLIGHT AND POST LDG-BAT BUS A, BAT BUS B, and BAT C circuit breakers (RHEB-275) during main chute descent. The AUTO position provides an automatic connection of the entry batteries to the main d-c buses at CSM separation. The auto function is used only on the launch pad after the spacecraft is configured for a LES pad abort.

A nonessential bus, as shown on figure 2.6-12 permits isolating nonessential equipment during a shortage of power (two fuel cell power plants out). The flight bus distributes power to in-flight telecommunications equipment. The flight and postlanding bus distributes power to some of the in-flight telecommunications equipment, float bag No. 3 controls, the ECS postlanding vent and blower control, and postlanding communications and lighting equipment. In flight, the postlanding bus receives power from the fuel cells and/or entry and postlanding batteries through the main d-c buses. After completion of RCS purge during main chute descent, the entry batteries supply power to the postlanding bus directly through individual circuit breakers. These circuit breakers (FLIGHT & POST LANDING-BAT BUS A, BAT BUS B, and BAT C – RHEB-275) are normally open in flight and closed during main chute descent just prior to positioning the MAIN BUS TIE switches to OFF.

Motor switch contacts which close when the MAIN BUS TIE switches are placed to ON, complete the circuit between the entry and postlanding batteries and the main d-c buses, and open the connection from the battery charger to the batteries. The battery relay bus provides d-c power to the a-c sensing units, the fuel cell and inverter control circuits, fuel cell reactant and radiator valves and the fuel cell-main BUS A and B talk-back indicators on MDC-3. The pyrotechnic batteries supply power to ordnance devices for separation of the LES, S-IVB, forward heat shield, SM from CM, and for deployment and release of the drogue and main parachutes during a pad abort, high-altitude abort, or normal mission progression. The three fuel cell power plants supply power to the SM jettison controllers for the SM separation maneuver.

Distribution of a-c power (figure 2.6-15) is accomplished with a four-wire system via two redundant buses, a-c bus 1 and a-c bus 2. The a-c neutral bus is connected to the vehicle ground point. A-C power is provided by one or two of the solid-state 115/200-volt 400-Hz 3-phase inverters. D-C power is routed to the inverters through the main d-c buses. Inverter No. 1 is powered through d-c main bus A, inverter No. 2 through d-c main bus B, and inverter No. 3 through either d-c main bus A or B by switch selection. Each of these circuits has a separate circuit breaker and a power control motor switch. Switches for

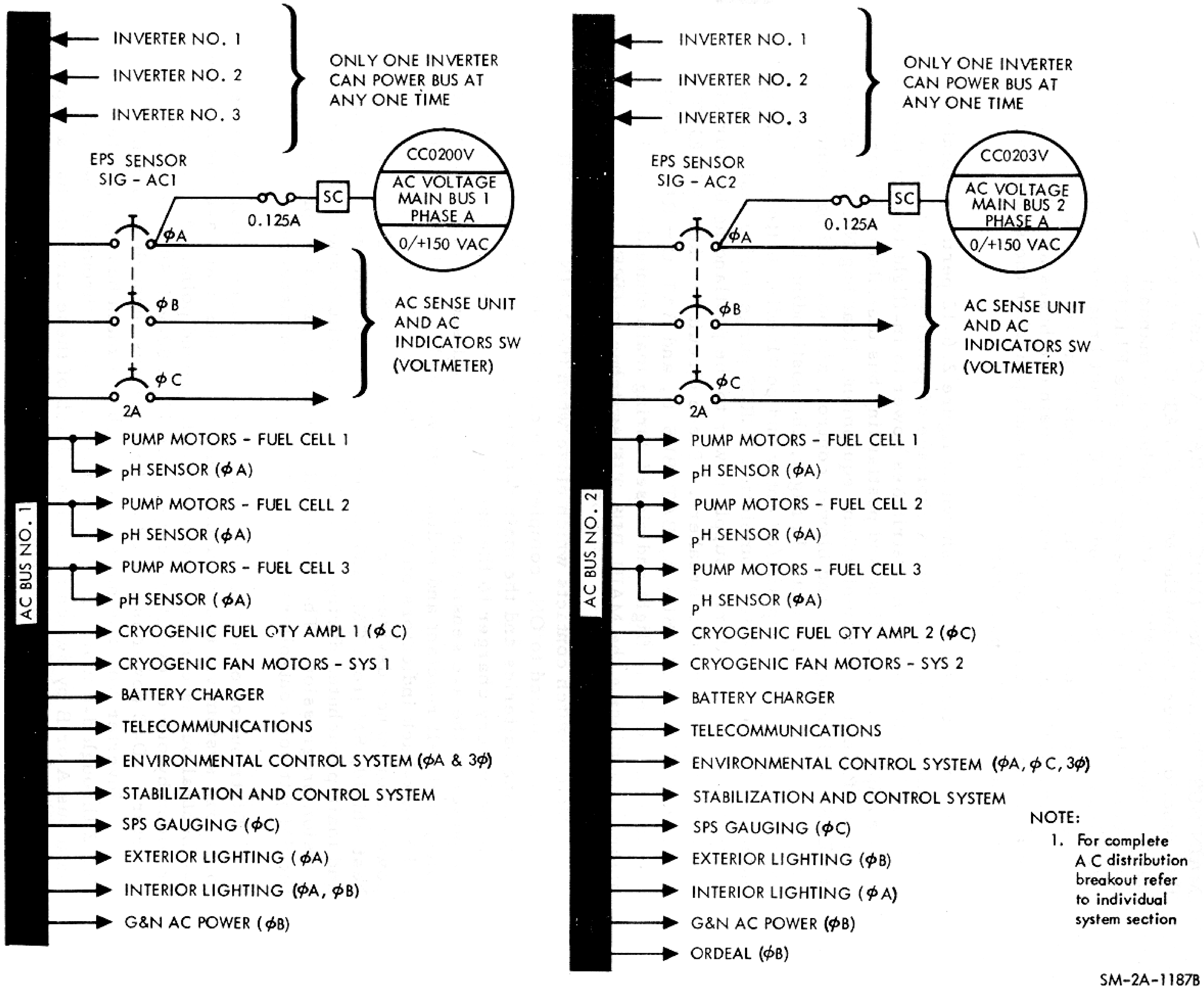


Figure 2.6-15. A-C Power Distribution

applying power to the motor switches are located on MDC-3. All three inverters are identical and are provided with overtemperature circuitry. A light indicator, in the caution/warning group on MDC-2, illuminates at 190° to indicate an overtemperature situation. Inverter output is routed through a series of control motor switches to the a-c buses. Six switches (MDC-3) control motor switches which operate contacts to connect or disconnect the inverters from the a-c buses. Inverter priority is 1 over 2, 2 over 3, and 3 over 1 on any one a-c bus. This indicates that inverter two cannot be connected to the bus until the inverter 1 switch is positioned to OFF. Also, when inverter 3 switch is positioned to ON, it will take inverter 1 off the bus before inverter 3 connection will be performed. The motor switch circuits are designed to prevent connecting two inverters to the same a-c bus at the same time. A-C loads receive power from either a-c bus through bus selector switches. In some instances, a single phase is used for operation of equipment and in others all three. Over-undervoltage and overload sensing circuits (figure 2.6-13) are provided for each bus. An automatic inverter disconnect is effected during an overvoltage. A-C bus voltage fail and overload lights in the caution/warning group (MDC-2) provide a visual indication of voltage or overload malfunctions. Monitoring voltage of each phase on each bus is accomplished by selection with the AC INDICATORS switch (MDC-3). Readings are displayed on the AC VOLTS meter (MDC-3). Phase A voltage of each bus is telemetered to MSFN stations.

Several precautions should be taken during any inverter switching. The first precaution is to completely disconnect the inverter being taken out of the circuit whether due to inverter transfer or malfunction. The second precaution is to insure that no more than one switch on AC BUS 1 or AC BUS 2 (MDC-3) is in the up position at the same time. These precautions are necessary to assure positive power transfer since power to any one inverter control motor switch is routed in series through the switch of another inverter. A third precaution must be exercised to preclude a motor switch lockout when d-c power to inverter 3 is being transferred from d-c main bus A to d-c main bus B, or vice versa. The AC INVERTER 3 switch (MDC-3) should be held in the OFF position for one second when performing a power transfer operation from one main d-c bus to the other.

2.6.4 PERFORMANCE AND DESIGN DATA.

2.6.4.1 AC and DC Data.

AC and dc performance and design data for the EPS is as follows:

AC

Phases	3
Displacement	120±2 degrees

Steady-state voltage	115.5 (+1, -1.5) vac (average 3 phases)
Transient voltage	115 (+35, -65) vac
Recovery	To 115±10v within 15 ms, steady state within 50 ms
Unbalance	2 vac (worst phase from average)
Frequency limits	
Normal (synchronized to central timing equipment)	400±3 Hz
Emergency (loss of central timing equipment)	400±7 Hz
Wave characteristics (sine wave)	
Maximum distortion	5 percent
Highest harmonic	4 percent
Crest factor	1.414±10 percent
Rating	1250 va

DC

Steady-state voltage limits	
Normal	29±2.0 vdc
Minimum CM bus	26.2 vdc
Min Precautionary CM bus	26.5 vdc (allows for cyclic loads)
Maximum CM bus	31.0 vdc
Max Precautionary CM bus	30.0 vdc (allows for cyclic loads)
During postlanding and preflight checkout periods	27 to 30 vdc
Ripple voltage	1v peak to peak

2.6.5 OPERATIONAL LIMITATIONS AND RESTRICTIONS.

2.6.5.1 Fuel Cell Power Plants.

Fuel cell power plants are designed to function under atmospheric and high-vacuum conditions. Each must be able to maintain itself at sustaining temperatures and minimum electrical loads at both environment extremes. To function properly, fuel cells must operate under the following limitations and restrictions:

External nonoperating temperature	-20° to +140° F
Operating temperature inside SM	+30° to 145° F
External nonoperating pressure	Atmospheric
Normal voltage	27 to 31 vdc
Minimum operating voltage at terminals	
Emergency operation	20.5 vdc at 2295 watts (gross power level)
Normal operation	27 vdc
Maximum operating voltage at terminals	31.5 vdc
Fuel cell disconnect overload	75 amperes no trip, 112 amperes disconnect after 25 to 300 seconds
Maximum reverse current	1 second minimum before disconnect
Minimum sustaining power/fuel cell power plant (with in-line heater OFF)	420 watts
In-line heater power (sustain F/C skin temp above 385°F min)	160 watts (5 to 6 amps)
Maximum gross power under emergency conditions	2295 watts at 20.5 vdc min.
Nitrogen pressure	50.2 to 57.5 psia (53 psia, nominal)
Reactant pressure	
Oxygen	58.4 to 68.45 psia (62.5 psia, nominal)
Hydrogen	57.3 to 67.0 psia (61.5 psia, nominal)

Reactant consumption/fuel cell power plant	
Hydrogen	PPH = Amps x (2.57×10^{-3})
Oxygen	PPH = Amps x (2.04×10^{-2})
Minimum skin temperature for self-sustaining operation	+385°F
Minimum skin temperature for recovery in flight	+360°F
Maximum skin temperature	+500°F
Approximate external environment temperature range outside SC (for radiation)	-260° to +400°F
Fuel cell power plant normal operating temperature range	+385° to +450°F
Condenser exhaust normal operating temperature	+150° to +175°F
Purging nominal frequency	Dependent on mission load profile and reactant purity after tank fill.
O_2 purge duration	2 minutes
H_2 purge duration	80 seconds
Additional flow rate while purging	
O_2	Up to 0.6 lb/hr
H_2	Up to 0.75 lb/hr (nominal 0.67 lb/hr)

2.6.5.2 Cryogenic Storage Subsystem.

The cryogenic storage subsystem must be able to meet the following requirements for proper operation of the fuel cell power plants and the ECS:

Minimum usable quantity	
Oxygen	320 lbs each tank (min)
Hydrogen	28 lbs each tank (min)

Temperature at time of fill	
Oxygen	-297°F (approx.)
Hydrogen	-423°F (approx.)
Operating pressure range	
Oxygen	
Normal	865 to 935 psia
Minimum	150 psia
Hydrogen	
Normal	225 to 260 psia
Minimum	100 psia
Temperature probe range	
Oxygen	-325° to +80°F
Hydrogen	-425° to -200°F
Maximum allowable difference in quantity balance between tanks	
Oxygen tanks No. 1 and 2	2 to 4%
Hydrogen tanks No. 1 and 2	3%
Pressure relief valve operation	
Crack pressure	
Oxygen	983 psig min.
Hydrogen	273 psig min.
Reseat pressure	
Oxygen	965 psig min.
Hydrogen	268 psig min.
Full flow, maximum relief	
Oxygen	1010 psig max.
Hydrogen	285 psig max.

EPS

2.6.5.3 Additional Data.

Additional data about limitations and restrictions may be found in the the CSM/LM Spacecraft Operational Data Book SNA-8-D-027, Vol I, (CSM SD68-447).

2.6.6 SYSTEMS TEST METER.

The SYSTEMS TEST meter and the alphabetical and numerical switches, located on panel 101 in the CM LEB, provide a means of monitoring various measurements within the SC, and verifying certain parameters displayed only by event indicators. The following can be measured using the SYSTEMS TEST meter, the respective switch positions, and the range of each sensor. Normal operating parameters of measurable items are covered in the telemetry listing.

SYSTEMS DATA

Systems Test Indication (Telemetry Identity and Code No.)	Switch Positions		Sensor Range
	Numerical Select	Alphabetical Select	
N_2 pressure, psia			0 to 75 psia
F/C 1 SC 2060P	1	A	
F/C 2 SC 2061P	1	B	
F/C 3 SC 2062P	1	C	
O_2 pressure, psia			0 to 75 psia
F/C 1 SC 2066P	1	D	
F/C 2 SC 2067P	2	A	
F/C 3 SC 2068P	2	B	
H_2 pressure, psia			0 to 75 psia
F/C 1 SC 2069P	2	C	
F/C 2 SC 2070P	2	D	
F/C 3 SC 2071P	3	A	
EPS radiator outlet temperature			-50° to +300°F
F/C 1 SC 2087T	3	B	
F/C 2 SC 2088T	3	C	
F/C 3 SC 2089T	3	D	
Battery manifold pressure, psia	4	A	0 to 20 psia
Batt relay bus CC0232V	4	B	0 to +45 vdc
LM power	4	D	0 to +10 amps
SPS oxidizer line temperature SP 0049T	5	A	0 to +200°F
CM-RCS oxidizer valve temperature			-50° to +50°F
-P engine, sys A CR 2100T	6	B	
+Y engine, sys B CR 2116T	5	D	
-P engine, sys B CR 2110T	5	C	
CW engine, sys B CR 2119T	6	D	
CCW engine, sys A CR 2114T	6	A	
-Y engine, sys A CR 2103T	6	C	
Pwr output	XPNDR	A	>1.0 vdc (nominal)

Systems Test Indication (Telemetry Identity and Code No.)	Switch Positions		Sensor Range
	Numerical Select	Alphabetical Select	
AGC signal	XPNDR	B	Test >1.0 vdc Operate 0.0 to 4.5 vdc
Phase lockup	XPNDR	C	Locked >4.0 vdc Unlocked <0.8 vdc

NOTE

Position 7 on the numerical selector switch is an off position.

Conversion of the previously listed measurements to the SYSTEMS TEST meter indications are listed in the following chart. The XPNDR measurements are direct readouts and do not require conversion.

2.6.7 COMMAND MODULE INTERIOR LIGHTING.

The command module interior lighting system (figure 2.6-16) furnishes illumination for activities in the couch, lower equipment bay and tunnel areas, and back-lighted panel lighting to read nomenclature, indicators, and switch positions. Tunnel lighting is provided on SC which will be concerned with LM activity.

Floodlighting for illumination of work areas is provided by use of fluorescent lamps. Integral panel and numerics lighting is provided by electroluminescent materials. Tunnel lights are incandescent. Pen flashlights are provided for illuminating work areas which cannot be illuminated by the normal spacecraft systems, such as under the couches.

Electroluminescence (EL) is the phenomena whereby light is emitted from a crystalline phosphor (Z_NS) placed as a thin layer between two closely spaced electrodes of an electrical capacitor. One of the electrodes is a transparent material. The light output varies with voltage and frequency and occurs as light pulses, which are in-phase with the input frequency. Advantageous characteristics of EL for spacecraft use are an "after-glow" of less than one second, low power consumption, and negligible heat dissipation.

Systems Test Meter Display	N_2, O_2, H_2 Pressure (PSIA)	EPS Radiator Outlet Temperature (°F)	CM-RCS Oxidizer Valve Temperature (°F)	LM Power (Amps)	SPS Temperature (°F)	Battery Manifold Pressure (PSIA)	Battery Relay Bus (VDC)
0.0	0	-50	-50	0	0	0.00	0
0.2	3	-36	-46	0.4	8	0.80	1.8
0.4	6	-22	-42	0.8	16	1.60	3.6
0.6	9	-8	-38	1.2	24	2.40	5.4
0.8	12	+6	-34	1.6	32	3.20	7.2
1.0	15	+20	-30	2.0	40	4.00	9.0
1.2	18	+34	-26	2.4	48	4.80	10.8
1.4	21	+48	-22	2.8	56	5.60	12.6
1.6	24	+62	-18	3.2	64	6.40	14.4
1.8	27	+76	-14	3.6	72	7.20	16.2
2.0	30	+90	-10	4.0	80	8.00	18.0
2.2	33	+104	-6	4.4	88	8.80	19.8
2.4	36	+118	-4	4.8	96	9.60	21.6
2.6	39	+132	0	5.2	104	10.40	23.4
2.8	42	+146	+4	5.6	112	11.20	25.2
3.0	45	+160	+10	6.0	120	12.00	27.0
3.2	48	+174	+14	6.4	128	12.80	28.8
3.4	51	+188	+18	6.8	136	13.60	30.6
3.6	54	+202	+22	7.2	144	14.40	32.4
3.8	57	+216	+26	7.6	152	15.20	34.2
4.0	60	+230	+30	8.0	160	16.00	36.0
4.2	63	+244	+34	8.4	168	16.80	37.8
4.4	66	+258	+38	8.8	176	17.60	39.6
4.6	69	+272	+42	9.2	184	18.40	41.4
4.8	72	+286	+46	9.6	192	19.20	43.2
5.0	75	+300	+50	10.0	200	20.00	45.0

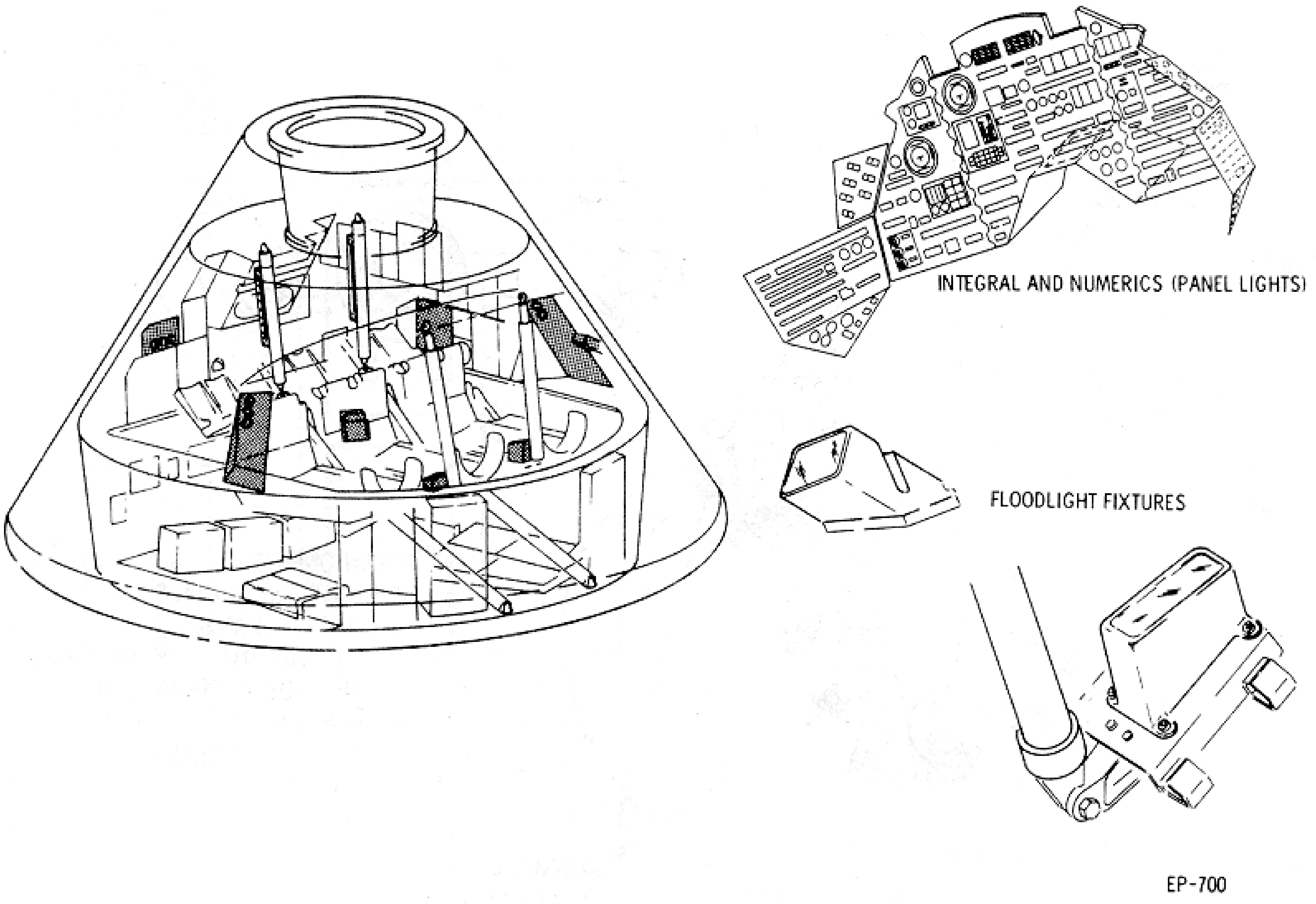


Figure 2.6-16. CM Interior Lighting

2.6.7.1 Floodlight System.

The interior floodlight system consists of six floodlight fixture assemblies and three control panels (figure 2.6-17). Each fixture assembly contains two fluorescent lamps (one primary and one secondary) and converters. The lamps are powered by 28 vdc from main d-c buses A and B (figure 2.6-18). This assures a power source for lights in all areas in the event either bus fails. The converter in each floodlight fixture converts 28 vdc to a high voltage pulsating d-c for operation of the fluorescent lamps.

Floodlights are used to illuminate three specific areas: the left main display console, the right main display console, and the lower equipment bay. Switches on MDC-8 provide control of lighting of the left main display console area. Switches on MDC-5 provide control of lighting of the right main display console area. Switches for control of lighting of the lower equipment bay area are located on LEB-100. Protection for the floodlight circuits is provided by the LIGHTING - MN A and MN B circuit breakers on RHEB-226.

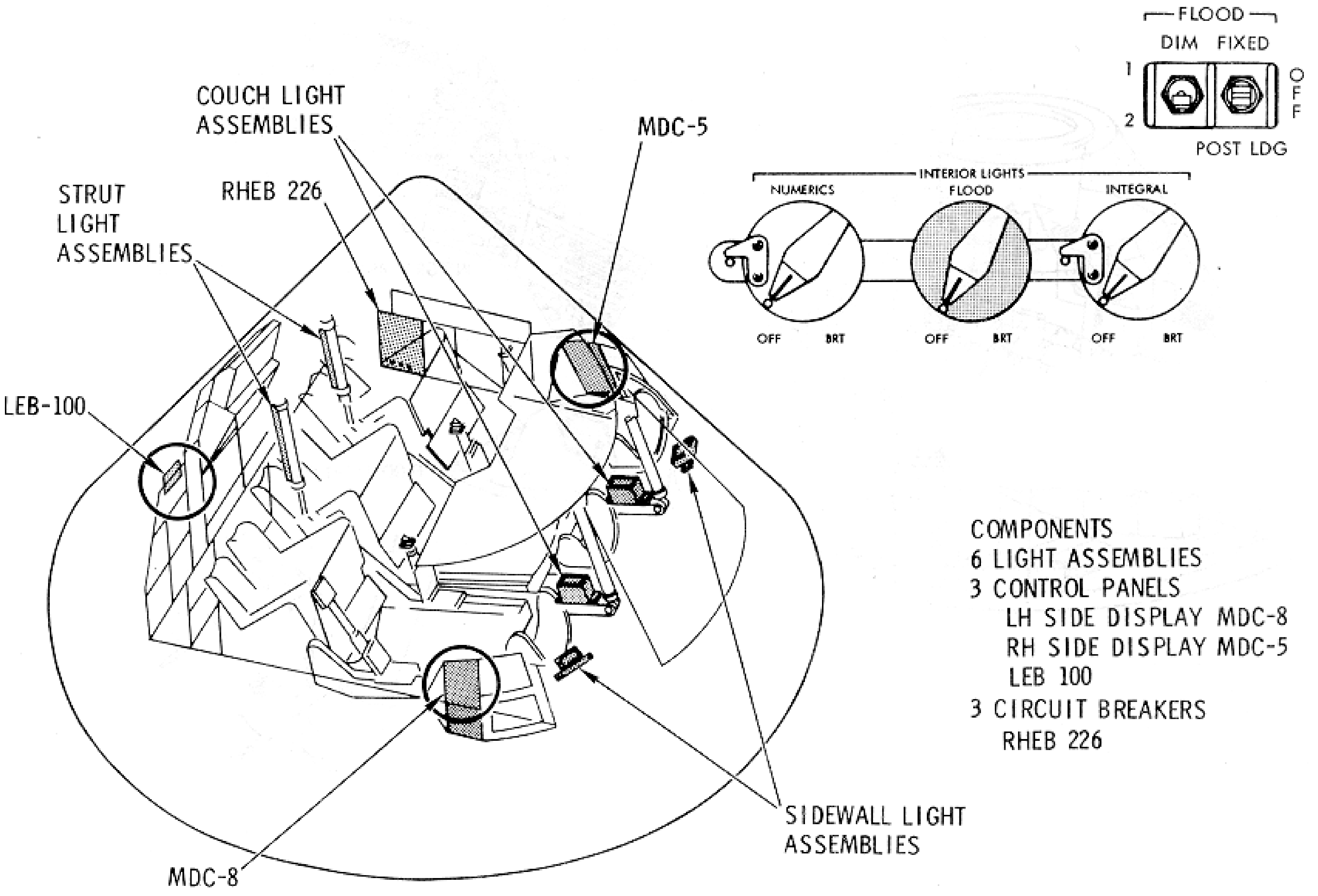


Figure 2.6-17. CM Floodlight Configuration

Each control panel has a dimming (DIM-1-2) toggle switch control, a rheostat (FLOOD-OFF-BRT) control, and an on/off (FIXED-OFF) toggle switch control. The DIM-1 position provides variable intensity control of the primary flood lamps through the FLOOD-OFF-BRT rheostat, and on-off control of the secondary lamps through the FIXED-OFF switch. The DIM-2 position provides variable intensity control of the secondary lamps through the FLOOD-OFF-BRT rheostat, and on-off control of the primary lamps through the FIXED-OFF switch. When operating the primary lamps under variable intensity control (DIM-1 position), turn on of the lamps is acquired after the FLOOD-OFF-BRT rheostat is moved past the mid point. In transferring variable intensity control to the secondary lamps, the FLOOD-OFF-BRT rheostat should first be rotated to the OFF position before placing the DIM switch to the DIM-2 position. The rheostat is then moved to the full bright setting and should remain in this position unless dimming is desired. Dimming of the secondary flood lamps should not be used unless dimming control of the primary floodlights is not available. Dimming of the secondary lamps results in approximately a 90-percent reduction in lamp life. The range of intensity variation is greater for the primary than the secondary floodlights.

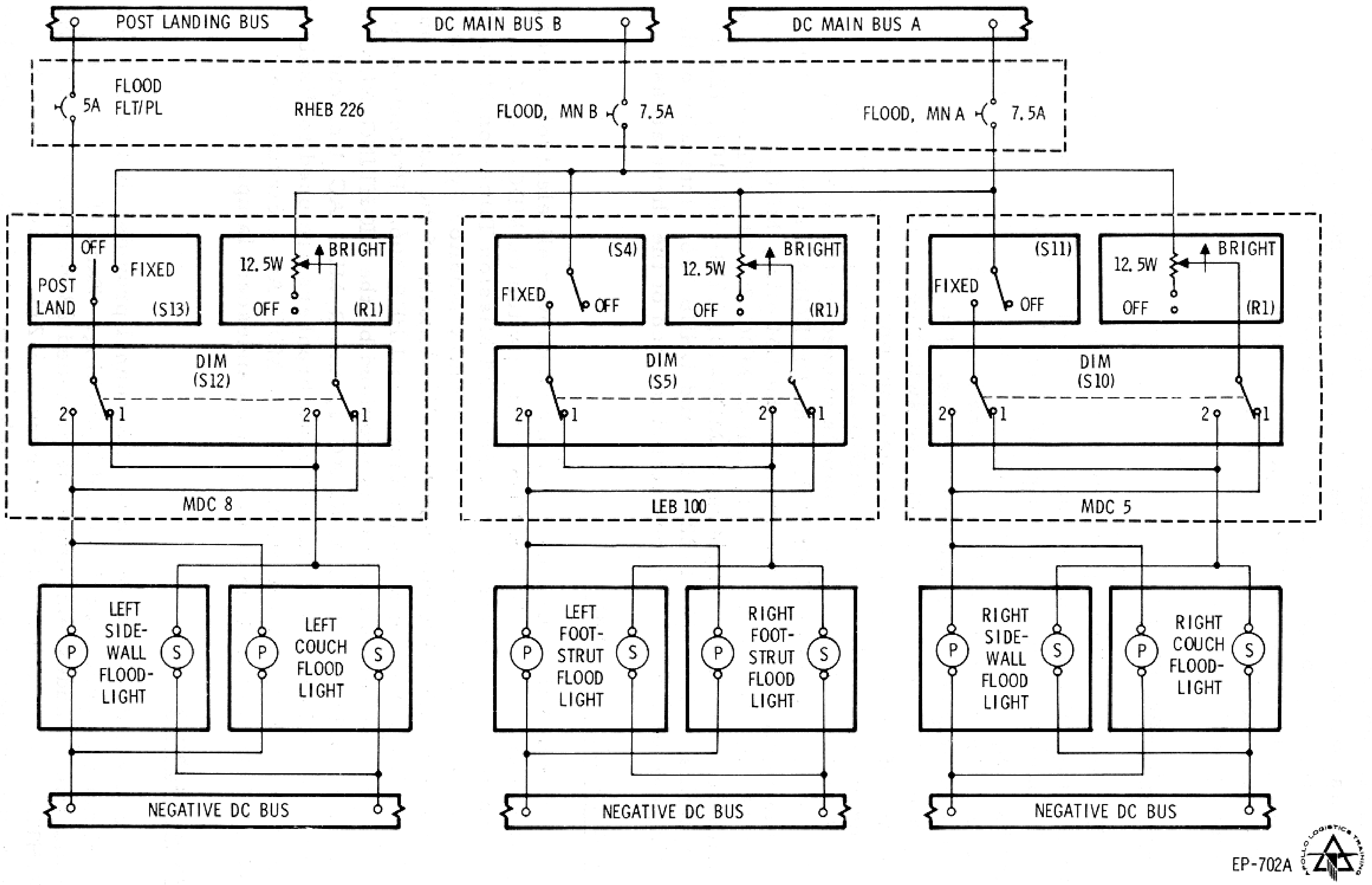


Figure 2.6-18. CM Floodlight System Schematic

The commander's control panel (MDC-8) has a POST LANDING-OFF-FIXED switch which connects the flight and post landing bus to his floodlights (figure 2.6-18). The POST LANDING position provides single intensity lighting to the commander's primary or secondary lamps as selected by the DIM-1 or DIM-2 position respectively. It is for use during the latter stages of descent after main d-c bus power is disconnected, and during post landing.

2.6.7.2 Integral Lighting System.

The integral lighting system controls the EL lamps behind the nomenclature and instrument dial faces on all MDC panels, and on specific panels in the lower equipment bay, left hand equipment bay and right hand equipment bay (figures 2.6-19 and 2.6-20). The controls (figure 2.6-19) are rotary switches controlling variable transformers powered through the appropriate a-c bus. Each rotary control switch has a mechanical stop which prevents the switch being positioned to OFF. Disabling of a circuit because of malfunctions is performed by opening the appropriate circuit breaker on RHEB-226. The INTEGRAL switch on MDC-8 controls the lighting of panels viewed by the commander, MDC-1, 7, 8, 9, 15, and the left half of 2. The INTEGRAL switch on MDC-5 controls the lighting of panels viewed by the LM pilot, MDC-3, 4, 5 and 6, 16, RHEB-229 and 275, and the right half of MDC-2. The INTEGRAL switch on LEB-100 controls the lighting of MDC-10, LEB-100, 101, 122 and the DSKY lights on 140, RHEB-225, 226 and LHEB 306. Intensity of the lighting can be individually controlled in each of the three areas.

2.6.7.3 Numerics Lighting System.

Numerics lighting control is provided over all electroluminescent digital readouts. The NUMERICS rotary switch on MDC-8 controls the off/intensity of numerals on the DSKY and Mission Timer on MDC-2, and the range and delta V indicators of the Entry Monitor System of MDC-1. The switch on LEB-100 controls the off/intensity of the numerals on the LEB-140 DSKY and the Mission Timer on LHEB-306. Protection for the integral and numerics circuits is provided by the LIGHTING-NUMERICS/INTEGRAL-LEB AC 2, L MDC AC 1, and R MDC AC 1 circuit breakers on RHEB-226. These circuit breakers are used to disable a circuit in case of a malfunction. The L MDC AC 1 circuit breakers also feed the EMS roll attitude and scroll incandescent lamps.

2.6.7.4 Tunnel Lighting.

The six light fixtures in the CM tunnel provide illumination for tunnel activity during docking and undocking. Each of the fixtures, containing two incandescent lamps, is provided 28 vdc through a TUNNEL-LIGHTS-OFF switch on MDC-2 (figure 2.6-21). Main d-c bus A distributes power to one lamp in each fixture, and main d-c bus B to the other lamp. Protection is provided by the LIGHTING/COAS/TUNNEL/RNDZ/SPOT MN A and MN B circuit breakers on RHEB-226.

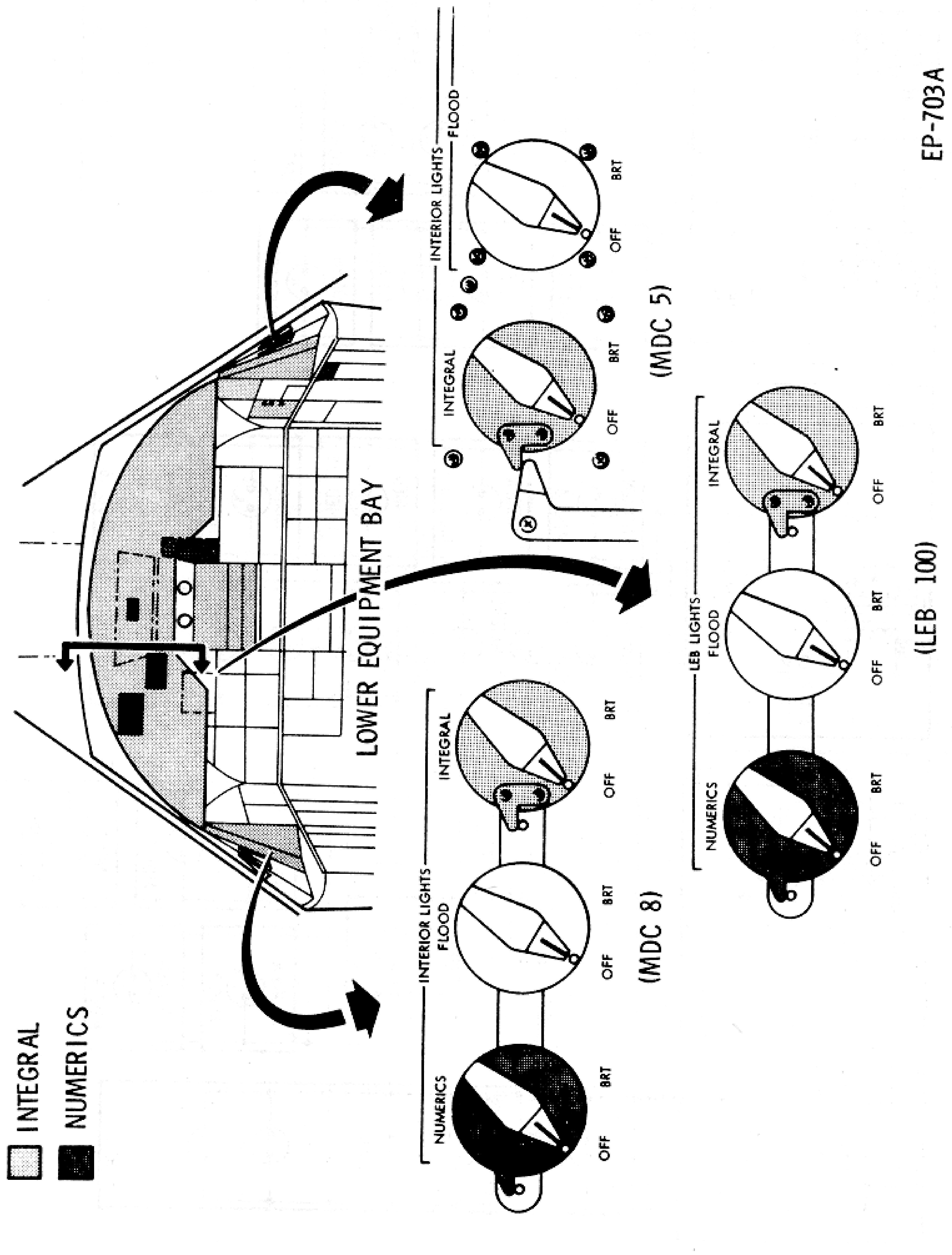


Figure 2.6-19. CM Integral/Numerics Illumination System

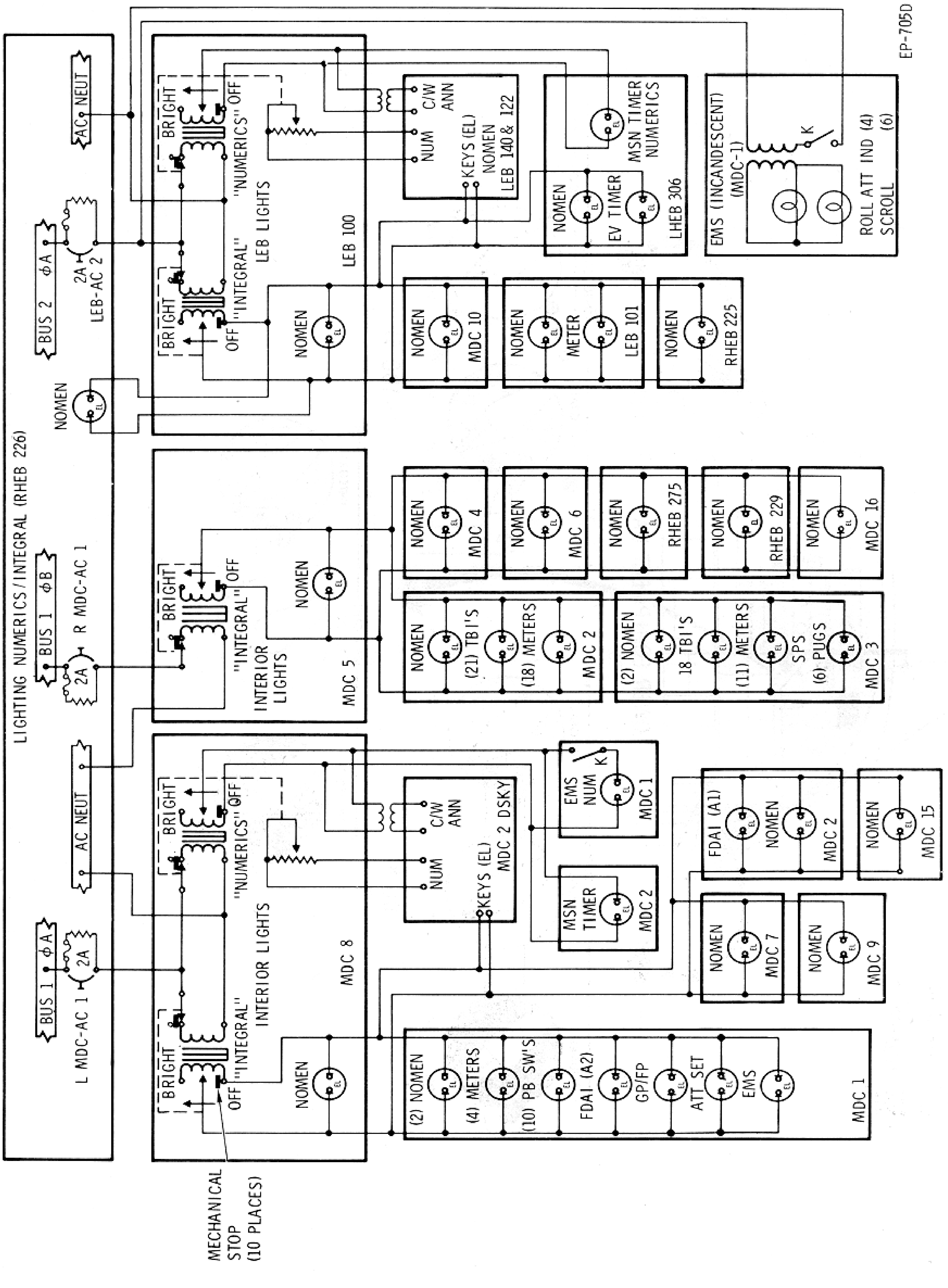


Figure 2.6-20. Integral and Numerics Panel Lighting Schematic

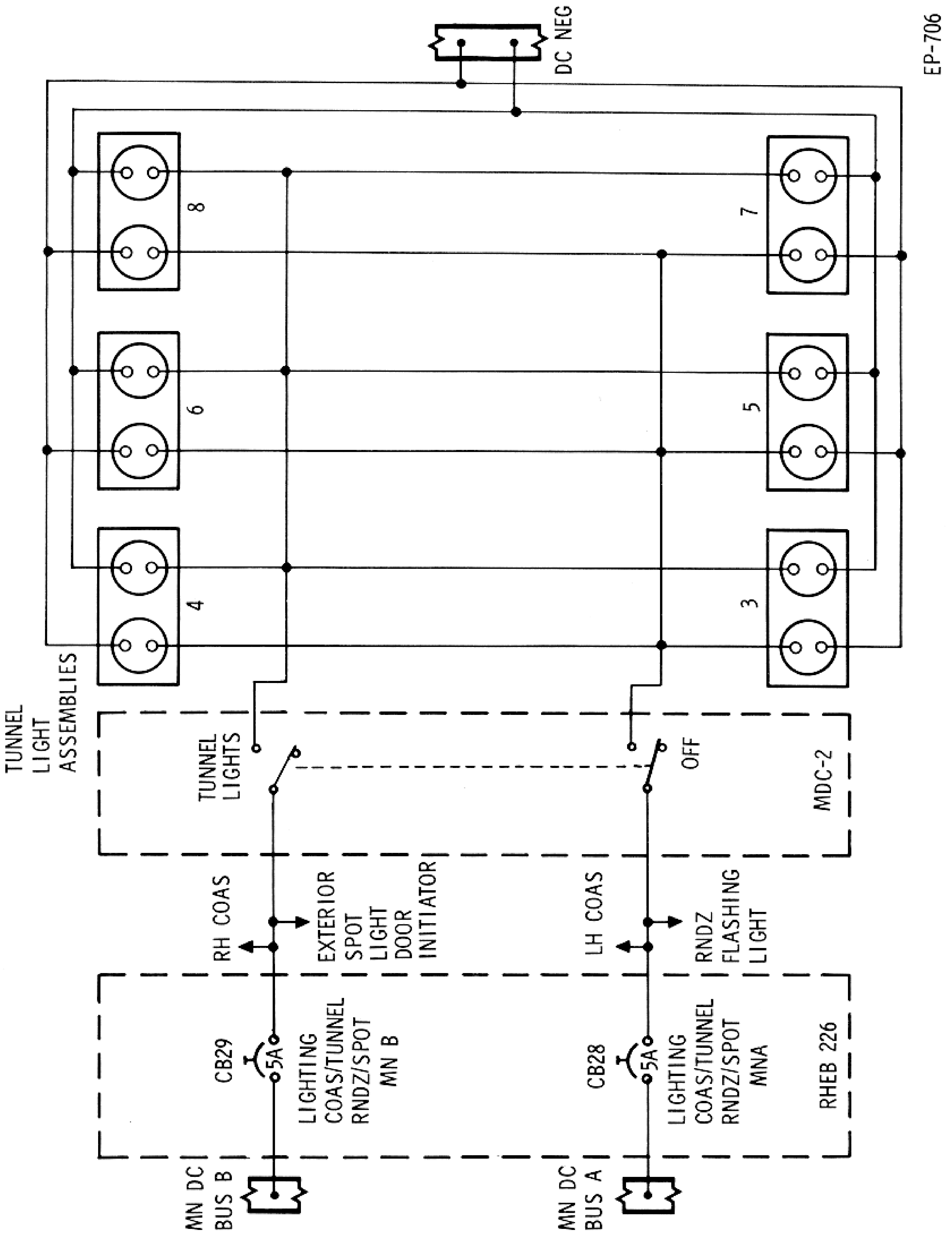


Figure 2.6-21. Tunnel Lighting Schematic