SKYLAB ELECTRICAL POWER SYSTEM

By

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SUMMARY

The Skylab electrical power system (EPS) will be composed of the parallel combination of the Airlock Module (AM) and the Apollo Telescope Mount (ATM) EPS's. Each of these subsystems is capable of supplying almost 4000 W of continuous conditioned power, making the Skylab EPS the largest EPS ever designed for operation in space. The operation of the two subsystems in parallel, their unique features, and their capabilities are discussed.

INTRODUCTION

Skylab is a manned Space Station designed to perform multiple experiments of a scientific and medical nature. This modular Space Station will consist of the Orbital Workshop (OWS), the Airlock Module, the Multiple Docking Adapter (MDA), and the Apollo Telescope Mount. The Skylab, shown in Figure 1 with the major features of the electrical power system, will be launched aboard a Saturn V launch vehicle and will be manned by the crew of a Command and Service Module (CSM) spacecraft that will be launched later on a Saturn IB launch vehicle. After rendezvous and docking, the CSM will become a part of the Skylab until the crew departs in it to return to earth. As currently planned, the Skylab will be manned for three different periods of up to 56 days over an 8-month operational life. The ATM and the AM each have an electrical power system consisting of solar array sources, nickel-cadmium batteries, and the necessary charging and conditioning equipment. In addition, there are power sources on the Instrument Unit of the Saturn V launch vehicle and on the CSM. However, these will be used only for short periods at the beginning of the mission and at docking and undocking of the CSM and are not discussed herein. The Skylab EPS has

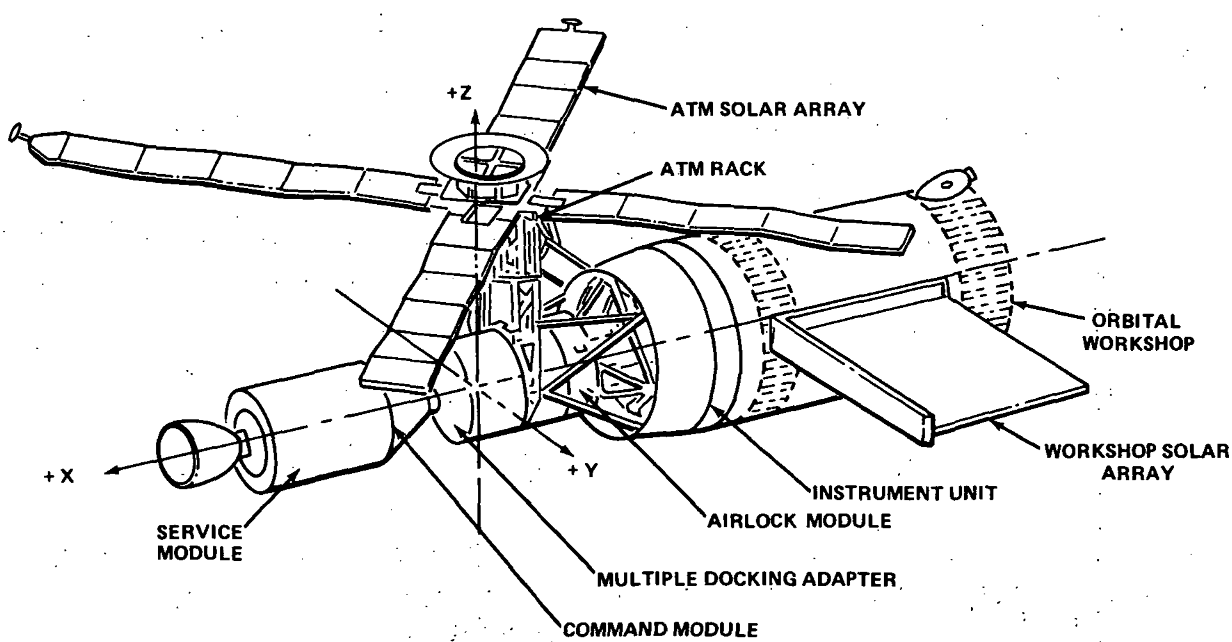


Figure 1. Skylab electrical power subsystems.

evolved from separate developments of the ATM program and the AM-OWS program. As initiated, the two EPS's were developed for different purposes, with different guidelines, and by different NASA centers. However, development and manufacture of both systems are now under the direction of Marshall Space Flight Center (MSFC), and the two operate in parallel. The ATM EPS was originally designed for an 18-month mission. This was later reduced to 2 months, still later increased to 6 months, and finally increased to the current 8-month life requirements. The system was designed to be completely self-dependent during operation, although a man-interface capability was provided. In contrast, the AM EPS was designed for the OWS where man interface was a prime consideration, since one purpose of the OWS experiment was to test the capability of man to operate in space. Furthermore, the AM EPS was designed to operate in parallel and share power with CSM fuel cells. Features designed for this purpose are now used to provide paralleling and sharing between the AM and the ATM EPS's.

MISSION RELATED DESIGN CONSIDERATIONS

The Skylab will operate in a low-earth circular orbit of approximately 385 km with an inclination of 50 deg. Vehicle orientation in a solar inertial mode with all solar arrays directed toward the sun will be the prime mode of operation. During rendezvous and docking maneuvers and during earth resources experiments, however, the vehicle Z-axis will be pointed along the earth local vertical (Z-LV). In the Z-LV mode, the backs of the arrays are directed earthward and the sunlight falls on the arrays at an angle, thus reducing the effective power. The orbit and vehicle orientation impose design considerations on the EPS that affect the sizing and operational restraints of the EPS components. The shadowed portion of the orbit as a function of the beta angle (the angle between the orbit plane and the sun vector) varies from 0 to 36 min. Rechargeable batteries are required for storing energy for use during this eclipse. The orbit time of approximately 94 min means that in the 8-month life of the system, the batteries will experience almost 4000 charge-discharge cycles. Detailed effects of these mission and orbital parameters will be presented in the discussions of particular components.

SKYLAB EPS

Requirements

Basic general requirements for the Skylab EPS have been established at the project level, recognizing the pre-existence of the two subsystems, and are summarized as follows:

1. Configuration — The Skylab EPS shall be comprised of two solar array/battery dc power systems.

2. Power Generation — The Skylab EPS shall have the capability to supply an average of 7530 W to loads while in the solar inertial mode of operation, 6700 W to loads while in the Z-LV earth resources pointing mode of operation, and 1600 W while in the Z-LV rendezvous mode of operation.

3. Power Management — Capability for EPS evaluation and management from the ground station and by the crew shall be provided. Necessary control and display of system functions shall be provided for the astronaut on board.

4. Power Distribution — Power shall be distributed by a two-wire system with no current return througn the vehicle structure. A single-point ground reference to structure shall be supplied. Power to mission critical loads shall be distributed through at least two positive isolated buses. All positive polarity lines in the distribution system shall be protected with circuit breakers or fuses.

5. Power Transfer Across Interfaces — Power feeders capable of carrying 2500 W shall be provided between the ATM and AM power distribution subsystems. Power feeders capable of carrying 2000 W shall be provided between the Skylab and the CSM distribution systems.

Implementation

The ATM and AM EPS's are paralleled through the power feeders provided, as shown in Figure 2, and this parallel combination of the two subsystems satisfies the Skylab EPS requirements. Detail characteristics, capabilities, and limitations of the two subsystems are given in the following.

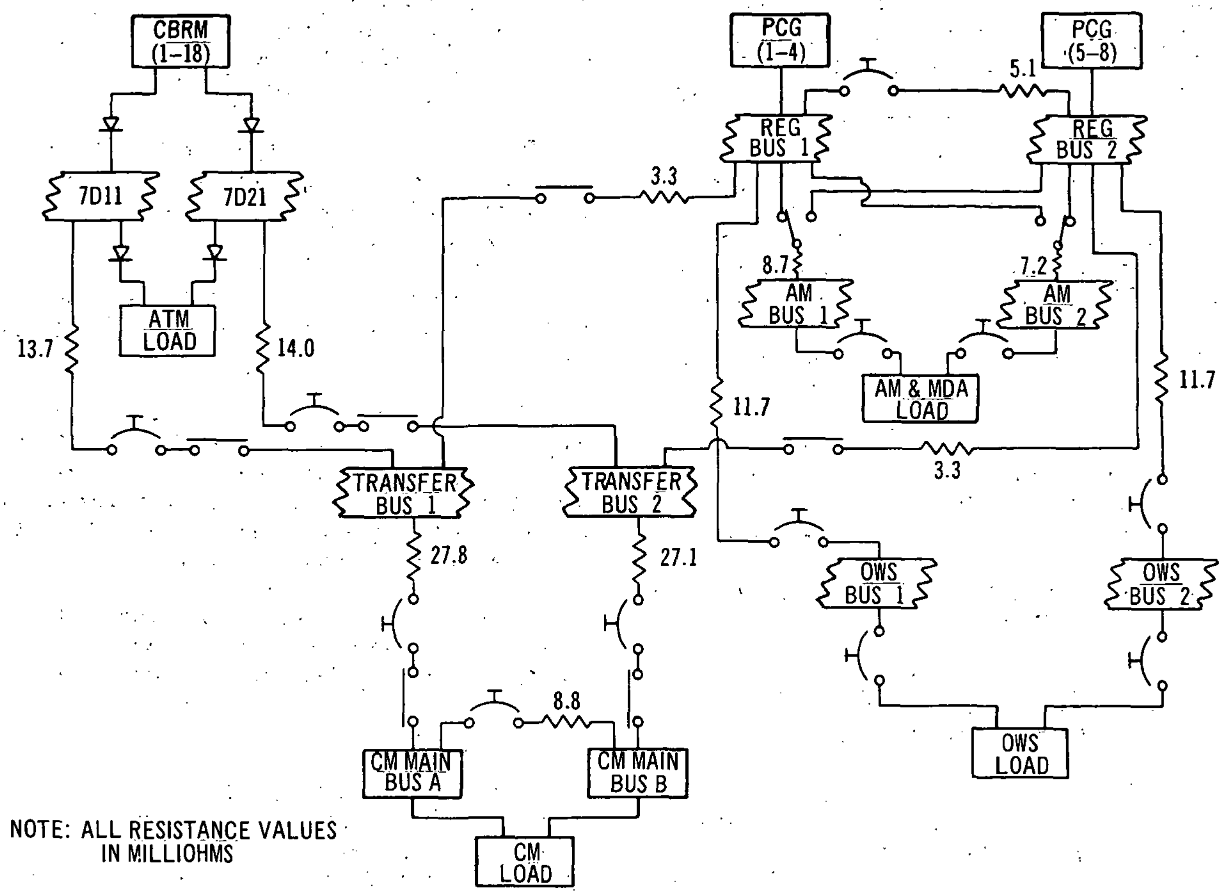


Figure 2. Skylab electrical power subsystems schematic.

AM EPS

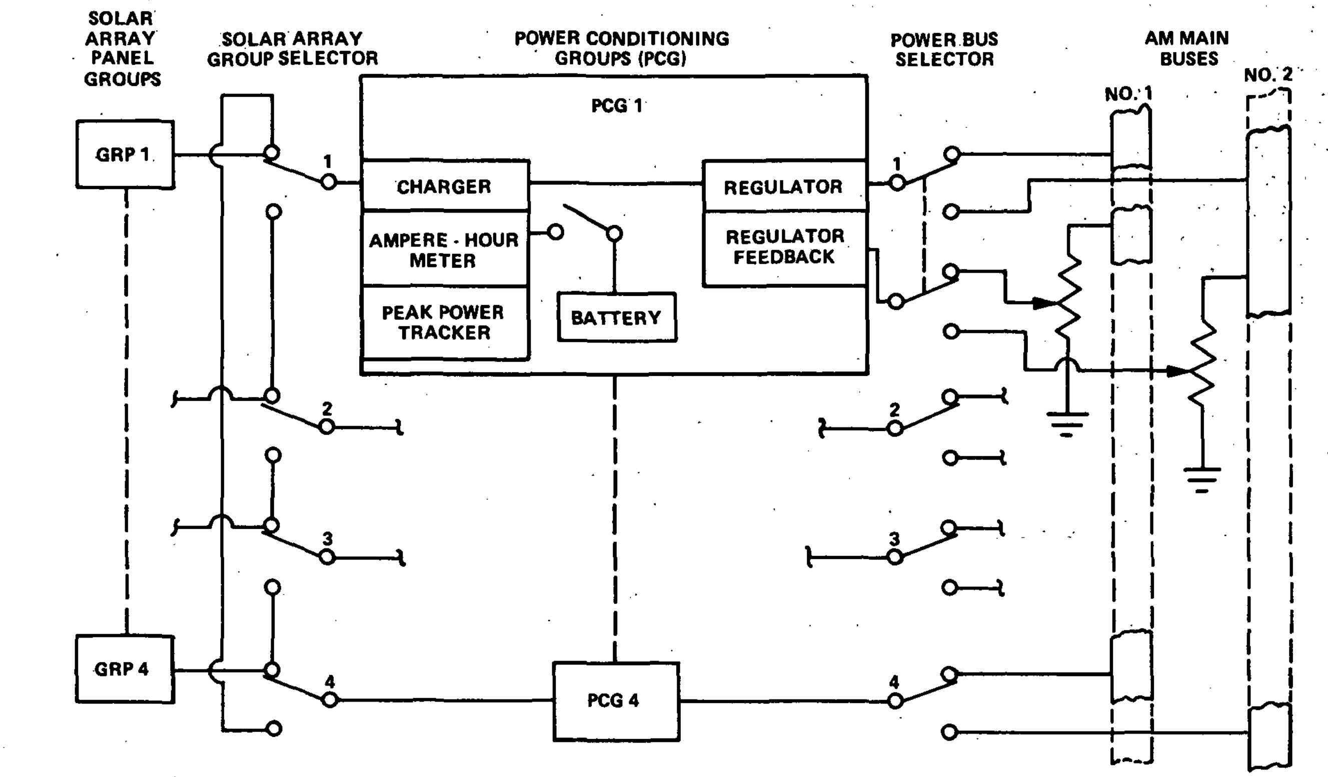
Description

The AM EPS is a modular power system with each module consisting of a solar cell array group that is located on the OWS and a charger, a battery, and a regulator that are located on the AM. The charger, battery, and regulator combination is called a power conditioning group (PCG), and there are eight PCG's with their associated array group source, as shown in Figure 3. The PCG's are located on two PCG modules, each consisting of four PCG's. The PCG modules are mounted on a thermal conditioning plate to provide temperature control. Each PCG regulator feeds, through switches, one of two AM regulator buses.

Power Components

SOLAR ARRAY SYSTEM (SAS)

The SAS for the AM EPS is located on the OWS. It has eight independent power sources, called array groups, mounted on two wings. Each wing contains a half-source for each PCG. Each half-source is composed of 15 modules isolated from each other by diodes. The complete array is rated at 10 496 W in orbit at end of life and at 55°C. Each array group, which feeds 1 of 2 PCG's depending on the position of an array group switch, has 30 solar cell modules connected in parallel. Each module has 616 2- by 4-cm cells with 4 parallel strings of 154 cells each. The solar cell array configuration is shown on the Skylab in Figure 1.



NOTE: GROUPS 1 THROUGH 4 ABOVE TYPICAL FOR GROUPS 5 THROUGH 8.

Figure 3. AM electrical power system.

POWER CONDITIONING GROUP

Battery. The AM battery has 30 Eagle Picher Industries, Inc., RSN-36 nickel-cadmium cells connected in series. The cells have individual self-reseating pressure relief valves set to relieve at 14.8×10^5 N/m^2. The cells are mounted in a magnesium, egg-crate-type case to enable efficient heat removal. The battery case also contains a pressure relief valve set to relieve at 3.4×10^5 N/m^2. The complete battery has a rated capacity of 33 A-h, but the actual capacity is a function of several variables. One of these variables is the cycle life, and tests are currently in progress to establish capacity versus life cycle curves for the battery. However, the fact that the active cooling is available has led to a charge control scheme for the AM battery that is somewhat different from that used for the ATM battery. The major difference is that it allows a greater recharge fraction, particularly at high temperatures, and a trickle charge is provided after the charge is complete. The charge method chosen is a temperature-dependent constant voltage limit charge to a temperature-dependent overcharge as defined by an ampere-hour meter in the charger. The battery is designed for a controlled temperature range of 2°C to 38°C with a combination of passive and active cooling provided by the thermal control panel, and for a range of -23°C to 38°C with total passive cooling during unmanned modes of operation. Testing to verify acceptable operation over these temperature ranges is underway.

Charger. The AM charger is designed to handle the entire solar array group power. It uses a buck-type switching circuit to provide power to both the battery and the regulator with the regulator having priority. Excess power above that required by the regulator is supplied to the battery. The charger also contains a redundant peak power tracker for obtaining maximum utilization of the array group power over a wide range of input voltage and current, and two selectable, redundant ampere-hour meters for battery charge control. The peak power tracker reduces the charger output voltage, and thus the battery charging current, when the array group peak power is exceeded. The peak power tracker functions equally well during both solar inertial and Z-LV modes. During periods when array group power is not sufficient for handling the regulator load, the charger voltage drops to a level at which the battery and array group will share the load. The ampere-hour meter continuously monitors the battery discharge and charge current and requires the charger to return the amount of ampere-hours previously removed from the battery multiplied by a temperature-dependent return factor. The charger switches into a 2-A trickle charge to the battery when the ampere-hour meter signals that the battery has been fully charged.

Regulator. The PCG regulator has a buck-type switching circuit that accepts power from the charger and/or the battery, or directly from the solar array group through a charger bypass switch in a contingency mode. The regulator operates over an input voltage range of 30 to 125 V from these sources. It has a peak output power capability of approximately 1500 W and an output voltage control range of 26 to 30 V no-load, adjustable. Fuses are provided to protect the buses from overvoltage in case of a power transistor short. A shunt load on the bus is electronically switched in when the voltage attempts to go high, thus blowing the fuse and protecting the bus loads from high battery, charger, and solar array voltages. A ganged potentiometer with outputs to all regulators feeding its bus is provided on each of the AM regulator buses. This adjustment feature is used to balance the two buses for sharing of the PCG's and for sharing with the ATM EPS. In addition, a screwdriver adjustment is available to individual regulators for adjustment of their output for sharing with other regulators on the same bus. These manual adjustment features are in contrast to the automatic, fixed voltage power sharing used on the ATM. Each regulator feeds either of the two AM regulator buses, depending on the position of a power selector switch.

Monitoring and Control

As previously noted, the AM was originally designed with plans for a significant astronaut interface from a monitoring and control aspect. This is reflected in the large number of switches and meters provided for astronaut observation and operation. However, except for the voltage adjustment potentiometers previously discussed, these measurements and controls do not interface directly with the PCG's. Instead, they measure the parameters associated with power flow to and from the PCG components and switch this power to the desired buses. In addition to the onboard measurements, various parameters are telemetered to ground for monitoring and control, if desired, and for postflight scientific analysis.

ATM EPS

Description

The ATM EPS is a modular power system with each module consisting of a solar cell array source and a charger, battery, regulator module (CBRM). There are 18 of these separate modules as shown in Figure 4. Each CBRM contains a battery to supply energy during eclipse portions of the orbit, a charger to condition the solar cell array power and control battery charging, and a regulator to regulate battery and/or cell array voltage and to regulate power drain or sharing between batteries. In addition, the CBRM's contain automatic protection and warning circuits, telemetry and astronaut display circuits for monitoring, a heater control circuit, and control circuits. Each CBRM regulator powers both ATM power buses through diodes as shown in Figure 4.

Power Components

SOLAR ARRAY SYSTEM (SAS)

The ATM SAS has 18 independent solar array power sources mounted on 4 solar wings. Each wing has 4 complete power sources containing 20 solar cell modules and 1 half-power source of 10 solar cell modules. The 4 half-sources are paired in parallel to form 2 solar sources making the total of 18 solar sources for the complete system. The complete array is rated at 10 060 W in orbit at the end of life and at 55°C. Each solar source or solar panel has 20 solar cell modules connected in parallel to supply 1 CBRM. There are two different types of solar cell modules on the ATM. One has 684 2- by 2-cm solar cells with 6 parallel strings of 114 cells each. The other has 228 2- by 6-cm solar cells with 2 parallel strings of 114 cells each. The ATM solar cell array will have half of the solar sources made from 2- by 2-cm cell modules and half of the solar sources made from 2- by 6-cm cell modules. The solar cell array configuration and its output capability are shown on the Skylab in Figure 1.

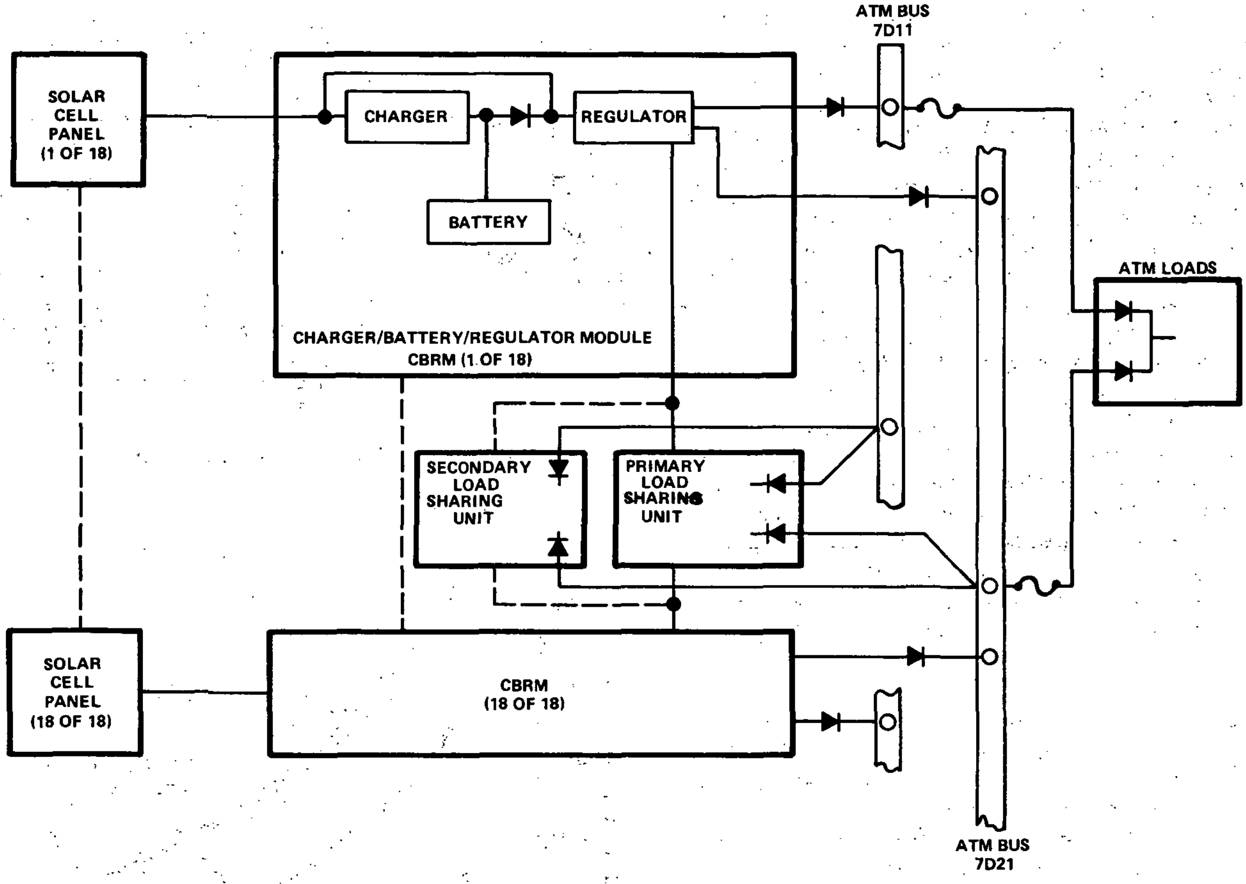


Figure 4. ATM electrical power system.

CHARGER, BATTERY, REGULATOR MODULE

Battery. The ATM battery has 24 General Electric AB-12, nickel-cadmium, 4-electrode, hermetically-sealed cells connected in series. In addition to the normal positive and negative power electrodes, the cells have a third electrode which is used in charge control and a passive fourth electrode which is an oxygen recombination electrode. The battery has a rated capacity of 20 A-h, but the actual capacity at a given time is a function of several variables. The more important of these are temperature, cycle life, and charge control method. The method of charge control is critical to both life and capacity retention, and over 4 years has been spent in testing the AB-12 cell and its predecessors. The charge method chosen is a constant-current charge at 15 A to a temperature-dependent voltage followed by tripback to a constant-voltage charge that is 0.85 V lower. The constant current is usually reduced in actual operation because of the solar panel power limit. The termination of charge is a result of the third electrode cutoff that occurs when the third electrode voltage reaches 200 mV across a 200-Ω load. The third electrode voltage is a function of oxygen partial pressure in the cell. Oxygen is released when the cell is fully charged and recombination of this oxygen results in the third electrode voltage. Battery charge is terminated rather than being reduced to a trickle charge mode. The ATM battery is totally passively cooled, and the heat associated with excessive overcharge cannot be allowed. Thermal control in the form of a proportional heater is provided to prevent the battery temperature from going below 0°C. The battery temperature operating range is 0°C to 30°C. However, operation at 30°C can cause significant capacity loss, and operation at 20°C or lower is desirable.

Charger. The CBRM charger is a buck-type switching circuit designed to provide proper charge control for the battery while achieving maximum utilization of solar power. As may be seen in the CBRM block diagram, the solar panel feeds the charger and regulator in parallel. The regulator, which feeds the buses, has priority on the power. Excess power above that required by the regulator is used to charge the battery. The charger senses total solar panel current and reduces battery charging current to keep the solar panel current at less than 14.0 A. This current closely approximates the solar source peak power current over a wide temperature range. However, during the brief periods of penumbra in each orbit and during Z-LV operation, the solar panel peak power current varies widely and the solar panel voltage rather than current is sensed for charge control. The charger then reduces charging current if the solar panel voltage is less than 38 V. During these periods when the solar panel power is not sufficient to supply regulator requirements, the battery and solar panel share the power. In addition to solar panel current and voltage, the charger senses battery current, voltage, temperature, and third electrode voltage to provide proper charge control.

Regulator. The CBRM regulator has a buck-boost-type switching circuit that accepts power from the solar panel and/or battery and supplies regulated voltage to the ATM power buses. The regulator operates over an input range of 25.5 to 80 V. It has a peak output power capability of approximately 450 W. The output is current limited to prevent damage from overload or short circuit. The circuit provides bus load protection from overvoltage by sensing output voltages and turning the regulator off if the output voltage exceeds 31.8 V. Any failure in the regulator power circuit will result in no output voltage. This protects the buses from high battery and solar source voltages.

Analysis and subsequent tests have shown that, although the regulators were designed with a programed impedance to provide inherent power sharing, voltage and impedance tolerances and line variations cause significant differences in regulator output power between the 18 regulators. The equivalent circuit shown in Figure 5 was used to derive the curves in Figure 6 which show the effect of these variations. This analysis reveals that, although reasonably tight tolerances are imposed on the regulator parameters, a power system degradation of up to 25 percent could exist. The degradation results from the fact that regulator power output is limited to approximately 232 W by solar source capability. In addition, 232 W during eclipse operation represents approximately 30 percent depth of discharge (DOD) for the battery. These factors impose a requirement for some means of sharing between regulators to achieve the maximum bus power capability. The power sharing scheme is discussed in another paper in this report.

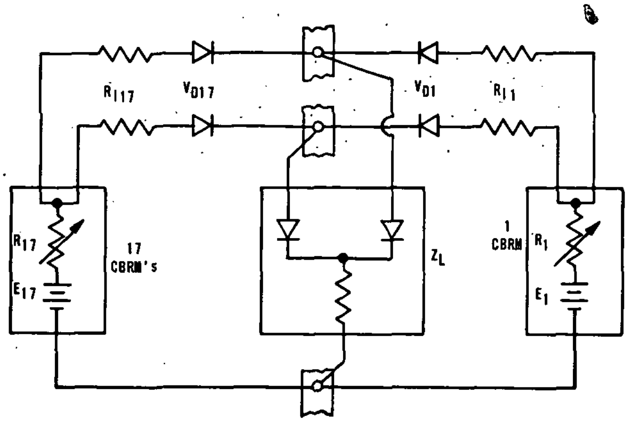


Figure 5. ATM EPS equivalent circuit.

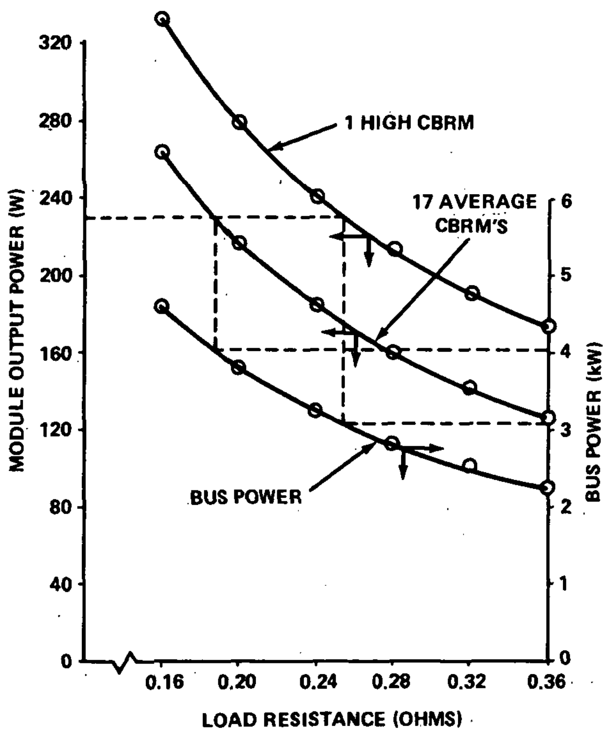


Figure 6. ATM EPS characteristics.

Auxiliary Circuits.

Alert Circuits. Alert circuits are provided to give an astronaut notice of potential problems or changes of state of a component in the CBRM. The alert signals are displayed as black and white striped flags on the EPS control panel. In addition, a light indication is given in a central alert area on the ATM control and display panel.

Protection Circuits. Automatic protection is provided to turn off part or all of a CBRM in case of situations that could cause potential danger to the astronauts and/or damage to equipment.

Telemetry. Conditioning is provided as required for the telemetry signals. The telemetered parameters are used on the ground to monitor and control the ATM EPS during flight and for postflight scientific analysis.

Metering. In addition to signals telemetered for ground monitoring, several parameters are displayed on meters for the astronauts to monitor on the EPS panel. Switches are provided for selecting the CBRM for which monitoring is desired. The status of the charger, battery, and regulator of each CBRM is displayed on the bank of 54 lights in the upper right of the EPS control panel.

Controls. Control of the CBRM is exercised from the ground by a radio frequency (rf) command through the digital address system (DAS), or by an astronaut manually through the DAS keyboard or directly from the EPS control panel rotary and toggle switches. As a result of limited panel space, 1 charger on-off and 1 regulator on-off switch serve all 18 CBRM's. The CBRM being controlled is selected by a rotary and toggle switch combination. The battery is controlled by logic within the CBRM so that it comes on when the charger is turned on but goes off only if both the charger and the regulator are turned off. The CBRM ON switch simultaneously gives a charger-on and regulator-on command to all 18 CBRM's. In addition, there is an ATM POWER OFF switch in a central location on the ATM control and display panel that sequentially removes all loads from the ATM buses and then gives a charger-off and a regulator-off command to all 18 CBRM's. The status of any component in any CBRM may be ascertained by enabling the CBRM status lights. When the light is on, it indicates that the component is off.

Miscellaneous. In addition to the aforementionea auxiliary circuits, there is an auxiliary power supply that generates bias and reference voltages for the other circuits and a battery heater controller that senses battery temperature and proportionally controls battery heater power to keep the battery temperature above 0°C.

SKYLAB EPS PERFORMANCE

Predicted Performance

The Skylab EPS is capable of supplying an average of approximately 7900 W at a beta angle of 0 deg to the ATM and AM primary buses at end of life with all modules working. This approximation is obtained from the energy balance equations for the two subsystems. The energy balance condition is defined as that condition for which the battery's charge is completed at the same time the illumination portion of the orbit is completed. The continuous average power capability of the ATM EPS is 3940 W at the end of mission life, and the continuous average power capability of the AM EPS is 3960 W at the end of mission life. This, of course, assumes no failures. Furthermore, analysis of battery DOD's under these conditions reveals that neither the ATM nor the AM batteries are discharged to depths greater than 30 percent. Failure of two CBRM's or one PCG would allow continued operation at the required load. However, load management provisions allow mission completion with as many as four CBRM's and two PCG's failed.

Z-LV Operation

Analysis of the Skylab available power when operating in the Z-LV modes is somewhat more difficult. Computer programs have been developed that take actual charger utilization of predicted solar source power, solar temperature, and other more accurate assumptions, and calculate actual power outputs and battery DOD for small time increments. These programs are also used to refine solar inertial power predictions. During Z-LV operation, the batteries are allowed to go to 50-percent DOD. During rendezvous Z-LV operation, the vehicle is oriented with the backs of the solar cell arrays pointed toward the earth's local vertical for the complete orbit. For earth resources experiments, Z-LV orientation is required only during performance of the experiments and the vehicle is returned to solar inertial orientation for the remainder of the orbit in order to obtain more solar cell array power. The Skylab EPS is expected to be capable of providing the required power during both of the Z-LV modes of operation.

CONCLUSIONS

The Skylab EPS, as it nears completion, promises to meet or exceed most of the design requirements including those imposed long after the subsystems design was fixed. During solar inertial operation, which is the prime mode of operation, the system has a power output capability of almost 8000 W at the end of the mission. This is the capability at a beta angle of 0 deg, which is the worst dark-light condition. As the beta angle increases, power capability increases substantially in the solar inertial mode. During the Z-LV rendezvous mode of operation, the system has an output power capability greater than 4000 W, as a worst case, which is a substantial margin over the 2600-W requirement. Although the requirement for Z-LV earth resources experiments operation was imposed on the EPS late in the program, the system is expected to meet the requirement. The requirement for parallel operation of the two power subsystems, although imposed late in the program, has been demonstrated at the regulator level. These capabilities promise to provide the Skylab with a modular EPS with maximum flexibility, power utilization, and reliability. The capability of a modular power subsystem to reliably supply power is depicted in Figure 7. Note that a very high probability of success can be obtained by having the capability for losing several modules. In the Skylab, by using power management, up to four CBRM's and two PCG's may be lost without losing the mission. This gives a high probability of mission success. In addition, data from the Skylab EPS, which will be more than any previously obtained, are expected to significantly advance knowledge of large space power system components and operation.

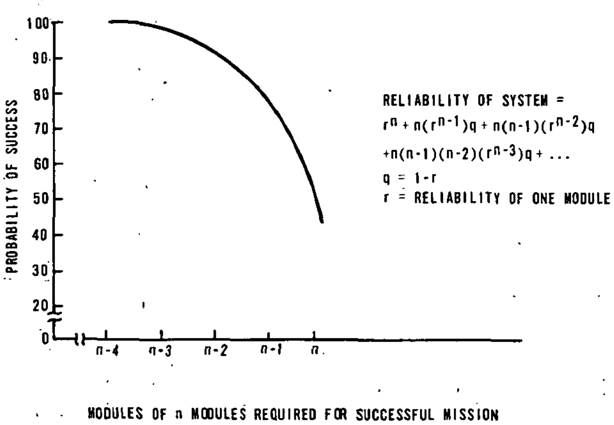


Figure 7. Modular power subsystem reliability.