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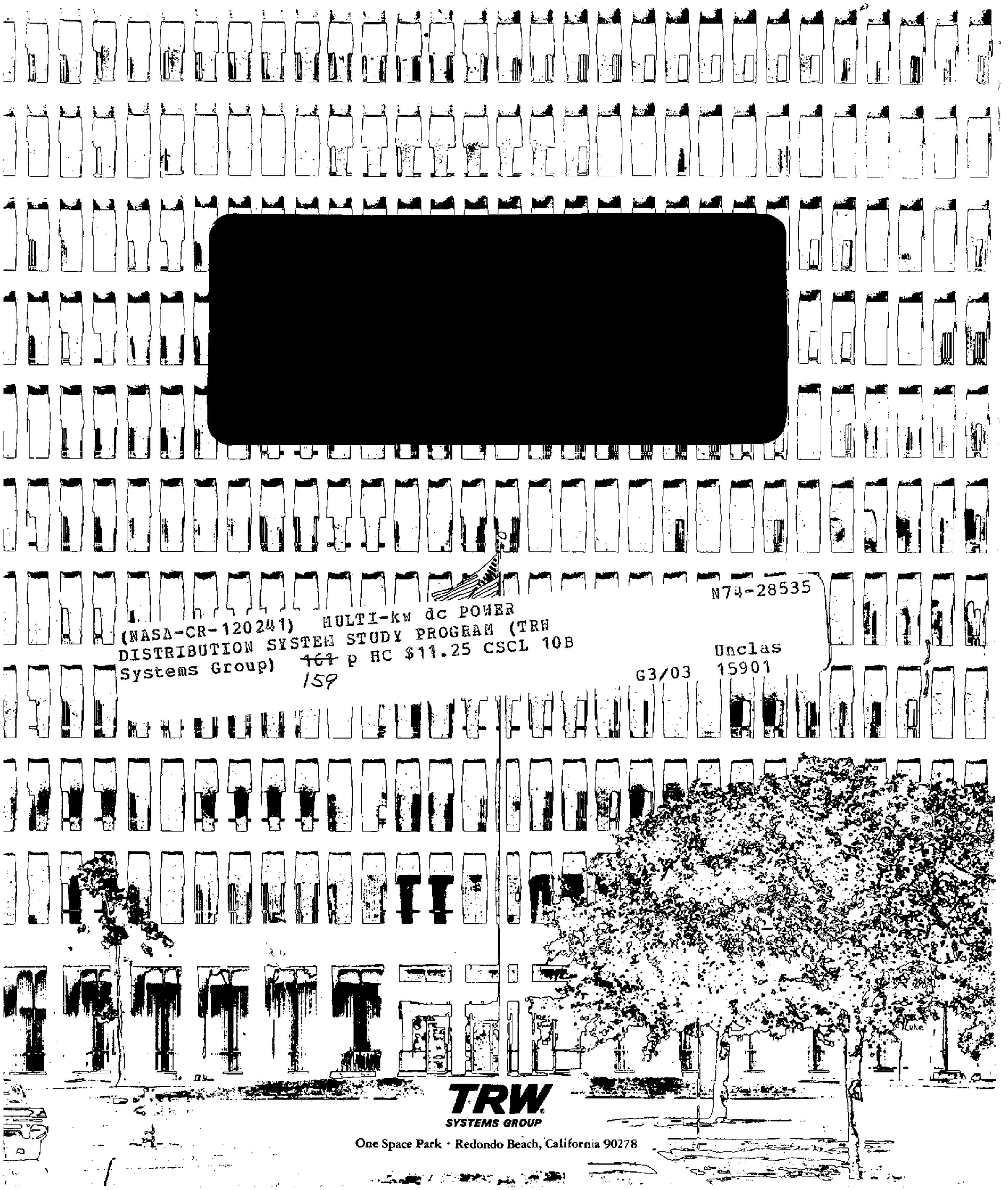

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MULTI-KW DC POWER DISTRIBUTION SYSTEM STUDY PROGRAM

CONTRACT NAS8-28726

BY

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PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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1.0 INTRODUCTION

1.1 BACKGROUND

As part of the NASA space vehicle technology development program, TRW Systems performed a comprehensive "Space Vehicle Electrical Power Processing, Distribution and Control Study" under Contract NAS8-26270 for the Marshall Space Flight Center. This study, which was completed in late 1972 disclosed that significant reductions in weight, greater design flexibility, reliability, and lower cost can be realized for large future aerospace vehicles through use of higher dc distribution and transmission voltage (above 100 Vdc) when compared to conventional 28 Vdc or 115 Vac systems. It also showed that maximum benefit can be obtained when high voltage dc distribution is coupled with use of remotely controlled solid state switchgear and multiplexed computer controlled supervision and checkout of the electrical system. As a result, a supplemental three-phase program which culminates in laboratory demonstration of technology readiness of these advanced design concepts has been planned. This report describes the work performed during the first phase of this program. Subsequent phases are concerned with detailed design and acquisition of a power distribution technology test facility and performance of actual tests aimed at technology readiness demonstration.

1.2 SCOPE OF WORK

The basic purpose of this phase of the Multi-KW Power Distribution Technology Program is definition of a program which involves test and evaluation of a technology breadboard in a specially designed test facility to be located at the Marshall Space Flight Center (MSFC). Its purpose is to demonstrate the static and dynamic performance, fault isolation, reliability, electromagnetic interference characteristics, and operability of high voltage distribution systems in the laboratory in order to gain increased confidence in the high voltage dc (HVDC) approach and encourage its selection for future aerospace vehicles. TRW's contracted effort for this program phase consists of program definition for a technology test facility to be located at MSFC which will provide for both component and subsystem level dynamic performance demonstration test and evaluation of Multi-Kilowatt DC Distribution Systems utilizing suitable power source and load simulators. The effort shall result in recommendations for a program which consists of the following tasks:

1. Detailed definition of the program and associated test objectives.
2. Provide recommendation for selection and sizing of the test article (technology breadboard) and the technology test facility.
3. Recommend test procedures for demonstration of technology readiness of high voltage dc power distribution using the technology test facility and the recommended breadboard components.

A description of the work performed on each of the above tasks constitutes Section 3, "Detailed Technical Description," of this report.

2.0 SUMMARY AND CONCLUSIONS

2.1 TEST OBJECTIVES

The program definition of the detailed test objectives delineates the MSFC program goals, the methods and approaches to be applied, and the specific functions to be evaluated as described in detail in Section 3.1 of this report.

2.1.1 Program Objectives

The basic objective of the Multi-KW DC Distribution System Study and associated NASA/MSFC in-house effort is to demonstrate technology readiness and performance advantages of high voltage dc (HVDC) distribution and control systems for large manned aerospace vehicles. Additional objectives are to evaluate the merits of solid state switchgear and multiplexed computer controlled supervision and control methods in conjunction with HVDC distribution.

The detailed objectives of the present phase of the program can be stated as follows:

Provide recommendations for the design of an HVDC distribution technology breadboard and associated test facility which will be assembled by NASA/MSFC and used during later program phases for the following purposes:

- Serve as a test bed for HVDC electric power system distribution and control components.
- Check dynamic interactions due to operation of solid state and electromechanical switchgear.
- Gain experience with multiplexed and computer controlled supervision and checkout methods.
- Verify transient response and EMI characteristics of a complete HVDC distribution system.
- Gain confidence in the electrical performance and operability of HVDC distribution systems.

The present Study on Multi-KW DC Distribution Systems is the first phase of this program and will concentrate on component requirements and subsystem testing. Component cost analyses and reliability demonstrations will be deferred to subsequent program phases.

2.2 TEST ARTICLE SIZING AND SELECTION

The recommended Multi-KW Distribution System Test Facility is designed to provide a cost effective implementation of the Test Objectives (Section 3.1). The basic elements of the system are illustrated in Figure 2.2-1 and

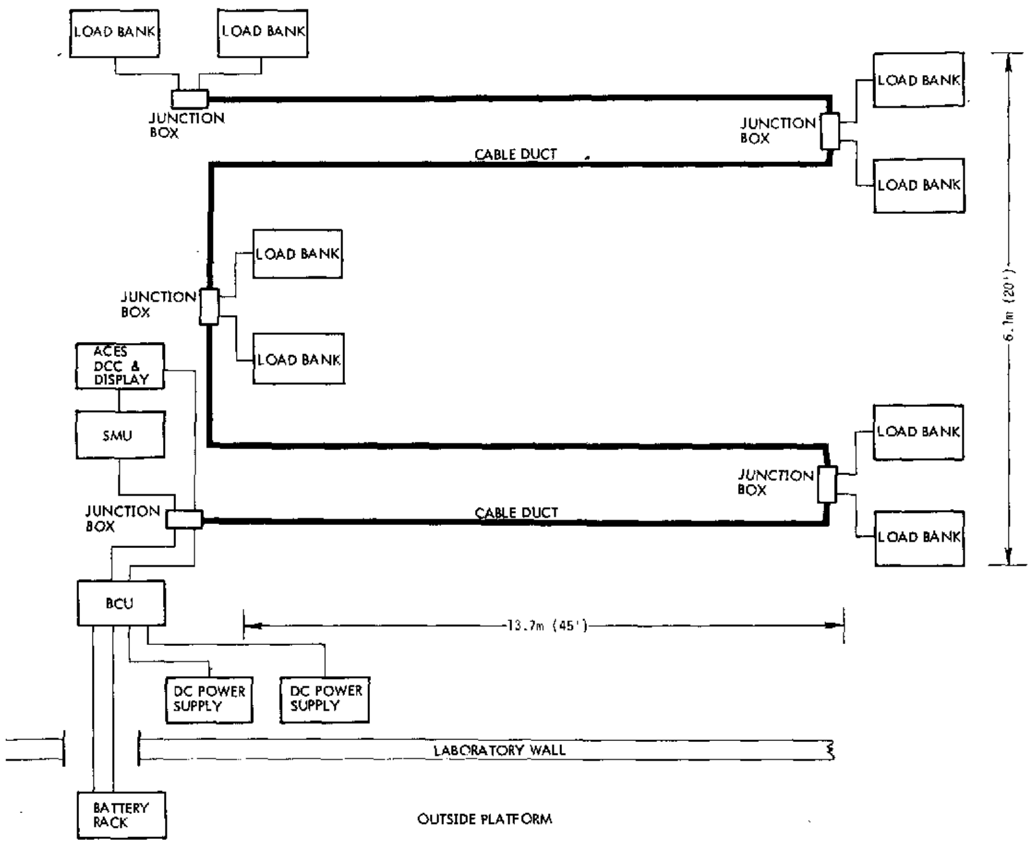

Figure 2.2-1. High Voltage Power Distribution System Test Facility

consist of a power source, bus control panel, supervision and monitor facilities, distribution cable, and loads. The configuration has been designed to simulate a spacecraft electrical power system with a fuel cell capability of 36 KW. The features of the facility include dual redundant (18 KW) power sources and triple redundant, multiplexed digital supervision and monitor equipment. Dual redundant analog/bilevel supervision and monitor control panels are also provided. The load banks provide simulated passive and active spacecraft component interfaces and fault simulation. The design is compatible with digital and analog control, solid state and electromechanical remote power controllers. The hardware has been defined to perform within specification for nominal voltages from 28 Vdc to 120 Vdc. The subsystem configurations have been designed to conform to aerospace specifications and techniques for the majority of the function. Some deviations from flight program design have been included in order to meet the goals of this program; such exceptions are noted in the technical discussion. A summary of the design accomplishments for each element of the test facility will be found in the following paragraphs.

2.2.1 Power Source

Each half of the dual redundant 120 Vdc power source consists of ten series converted 12V lead-acid batteries in parallel with an electronic dc power supply. The batteries are manufactured by ESB Inc. and were selected on the basis of low internal impedance and low cost. The dc power supply (Christie Electric Co.) is rated at 2-135 Vdc at 0-150 amperes and was selected on the basis of performance and cost. The total resistance of each battery pack is 0.075 ohms approximately; the steady-state regulation of the power supply is essentially zero. When simulating a full power line short, both battery packs will operate in parallel with one power supply and be capable of supplying transients up to 800 amperes with approximately 30% regulation. The expected response of a nominal 120V fuel cell to a 150A step load has been modeled approximately as

$$E\ (\text{Fuel Cell}) = 0.965E_1(1 + 0.0187e^{-98t})\ \text{Volts}$$

E_1 = Nominal Source Voltage   t = Time (seconds)

The response of the two battery packs, the dc power supply, and selected additional resistors is

$$E\ (\text{Power Source}) = 0.965E_1(1 + 0.024e^{-67t} - 0.024e^{-18t})$$

The dc power supplies will serve as battery chargers under manual control. Details on the power source selection, capability, and application may be found in Section 3.2.1.

2.2.2 Bus Control Unit

The bus control unit (BCU) consists of a standard equipment rack which contains the manual and remotely controlled switches and circuit breakers which connect the redundant power sources to individual load banks and provides the instrumentation for monitoring voltages, currents, and switch positions. It thus simulates the primary power distribution control elements of an actual spacecraft installation and allows for use of a variety of electromechanical or solid switchgear which are expected to become available in the future. A detailed functional description of the BCU and a simplified schematic circuit diagram are contained in Section 3.2.2. The proposed approach has been chosen to allow simulation of full power transients which occur as a result of power source and feeder faults and to enable operation of power sources and loads isolated or in parallel.

2.2.3 Supervision and Monitor Unit

The Supervision and Monitor Unit (SMU) serves as the operator console which allows manual remote control of all switchgear and contains all display equipment. It thus simulates the cockpit controls in an actual aerospace vehicle. It serves the same purpose as the ACES equipment and thus allows direct experimental comparison between conventional supervision and control and supervision and control by means of a typical multiplexed computer controlled system such as ACES.

2.2.4 Cable System

As will be described in Section 3.3, the cable system can be arranged such that the effect of magnetic and electric field coupling between wires and at various heights above a ground plane can be evaluated for steady state and transient conditions. The cables will be sized to accommodate up to 4 pairs of redundant 100 amp load banks spaced at intervals 15.2 meters (50') with a maximum cable length of 61 meters (200'). Cable ducts will simulate the vehicle structure which serves as a ground plane and will accommodate various wire sizes for maximum flexibility during testing.

2.2.5 Load Banks

The load banks will provide a valid full power simulation of the static and dynamic characteristics of typical power utilization equipment aboard current and future aerospace vehicles. Lumped resistors, capacitors, and inductors which can be interconnected in a variety of ways by means of patch cords are provided. In addition, each load bank will contain a high power electronic pulse width modulator which simulates the dynamic characteristics of typical power conditioning units. As described in Section 3.2.3, provisions are also made for use of solid state remote power controllers (RPC) to connect and disconnect sections of each load bank. In addition, each load bank contains a 300 amp contactor which can be used to apply faults to the system.

2.3 TEST PROCEDURE

The test plan proposed for this program reflects the investigative nature of the study. The detailed discussion of Section 3.3 contains procedures for the simulation of pre-flight system test, the evaluation of power quality for high voltage distribution systems, the performance of solid state switchgear and the effect of major faults on switchgear and a power distribution harness energized by a multi-KW power source. Comparison will be made of the relative performance of analog/bilevel and digital multiplexed monitor and control methods in an environment containing steady state noise and power system transients. The performance of the system will be correlated with the performance of the system elements. The test plan includes procedures for periodic characterization of the system elements in order to maintain control of the system parameters. Necessary test equipment is identified and recommendations are made for specific types. Performance of these tests will provide a valid data base for the analysis and evaluation of projected spacecraft power systems.

2.4 CONCLUSIONS

This phase of the Multi-KW DC Distribution Study has yielded a preliminary design of a technology test facility for laboratory evaluation and analysis of breadboard or prototype components of future high voltage dc power distribution systems and associated solid state switchgear and multiplexed supervision and control methods. The main feature of this facility is that interactions between components will be the same or similar to those which are obtained in an actual flight vehicle. Some components for the technology test facility have already been procured by MSFC. Detailed design of the load banks and other major system elements should proceed on the basis of the approach contained herein.

3.0 DETAILED TECHNICAL DESCRIPTION

3.1 TEST OBJECTIVES AND TEST FACILITY REQUIREMENTS

3.1.1 Introduction

The section summarizes the results of the first task performed under the Study on Multi-KW DC Distribution System entitled "Definition of Detailed Objectives." It describes the basic requirements for a technology test facility which will be established at NASA/MSFC. Subsequent tasks on this program consist of preliminary design of the technology breadboard and development of test procedures.

The previous Space Vehicle Electrical Power Processing, Distribution and Control Study, which was performed by TRW Systems under contract NAS8-26270 for NASA/MSFC, disclosed that significant reductions in weight, cost, and heat dissipation are obtainable for future manned aerospace vehicles through application of the following new system design concepts:

- Electric power distribution at voltages in excess of 100 Vdc
- Use of remotely controlled solid-state switchgear
- Multiplexed computer controlled supervision and checkout.

The basic purpose of this study program and the associated NASA/MSFC in-house effort is to demonstrate the advantages and technology readiness of these concepts through actual laboratory demonstrations, tests, and analyses. Details of this approach are presented herein.

3.1.2 Background

This program is concerned with electric power distribution, processing, and control aboard large aerospace vehicles and encompasses the following functions or types of equipment:

a. Transfer of electric power from a source to a load through wires, cables, and connectors.

b. Power switching and current interruption by means of relays, circuit breakers, fuses, etc.

c. Power processing or conditioning by means of electronic equipment which provides transformation of voltage level, rectification, inversion, regulation, and filtering.

d. Electrical system control and supervision through remote operation of switchgear or power conditioning equipment and use of instrumentation.

The principal design alternatives which determine the technical performance and cost of the distribution and control equipment as well as its impact on the vehicle are:

a. Power distribution voltage and frequency

b. Design and location of voltage regulation and conversion equipment

c. The method of power management and supervision.

In the past, power distribution and control methods which were developed 30 years ago for military aircraft have also been used for manned spacecraft. Thus, conventional 28 Vdc power distribution and mechanical switches and relays were used on the Apollo Program and are planned for Space Shuttle primarily because relays, switches, connectors and electronic power supplies (power conditioners) which have already been qualified for 28 Vdc input per MIL-STD-704 were generally available. The recent NASA Space Vehicle Electric Power Processing, Distribution and Control Study however concluded that high voltage dc distribution (above 100 Vdc) and use of digital control techniques would result in significant performance improvements and cost savings on large future spacecraft. Solid state power controllers and power conditioning circuits which are required for this approach are either currently under development or must be developed for specific applications. Cables, connectors, and display equipment designed for 28 Vdc can be used at higher voltages or can be redesigned for high voltage dc distribution without further design effort. Before a firm commitment can be made for high voltage dc distribution for all future spacecraft, technology readiness must be demonstrated by operating a complete power distribution and control system in the laboratory under closely simulated flight conditions.

3.1.3 Program Objectives

The basic objective of the Multi-KW DC Distribution System Study and associated NASA/MSFC in-house effort is to demonstrate technology readiness and performance advantages of high voltage dc (HVDC) distribution and control systems for large manned aerospace vehicles. Additional objectives are to evaluate the merits of solid state switchgear and multiplexed computer controlled supervision and control methods in conjunction with HVDC distribution.

Technology readiness must be demonstrated before any new design approach or subsystem concept can be adopted as the baseline configuration for the acquisition phase of a new spacecraft. Technology readiness of a new subsystem concept requires the following:

- Availability of components which are capable of passing qualification testing.
- Sufficient hardware life test experience to provide reasonable assurance that reliability goals can be met.
- Analysis and/or laboratory test results to demonstrate the compatibility between components under normal and abnormal conditions; i.e., demonstration of subsystem and system performance requirements and interface compatibility.
- Assurance that all necessary components can be procured at a reasonable cost.
- Confirmation that the new subsystem can be tested prior to and after installation in the spacecraft.

In order to allow NASA to specify HVDC distribution for a specific new spacecraft acquisition program each of the above requirements must be addressed by the three-year technology demonstration which has been planned.

The present Study on Multi-KW DC Distribution Systems is the first phase of this program and will concentrate on component requirements and subsystem testing. Component cost analyses and reliability demonstrations will be deferred to subsequent program phases.

The detailed objectives of the present Phase 1 Study on Multi-KW DC Distribution Systems can be stated as follows:

Design an HVDC distribution technology breadboard and associated test facility which will be assembled by NASA/MSFC and used during later program phases for the following purpose:

- Serve as a test bed for HVDC electric power system distribution and control components.
- Check dynamic interactions due to operation of solid state and electromechanical switchgear.
- Gain experience with multiplexed and computer controlled supervision and checkout methods.
- Verify transient response and EMI characteristics of a complete HVDC distribution system.
- Gain confidence in the electrical performance and operability of HVDC distribution systems.

The design characteristics of the technology breadboard and test facility to accomplish these objectives are described in the following section.

3.1.4 Test Facility Requirement

Requirements for electric power, distribution, and control subsystems aboard future manned aerospace vehicles are determined by the number, type, location, and design configuration of the load utilization equipment. The estimated number of separate load units by type of equipment and the total amount of power which must be delivered to each type of equipment are given in Table 3.1.4-1 for four types of typical vehicles (Reference 1). Total power to be distributed ranges from 10 KW for a typical shuttle vehicle to 200 KW for a large military aircraft.

Table 3.1.4-1. Reference Load Requirements Models

Type of Load	Space Station		Shuttle Orbiter		Transport Aircraft		Military Aircraft	
	Qty	Pwr(KW)	Qty	Pwr(KW)	Qty	Pwr(KW)	Qty	Pwr(KW)
Electronic Equipment								
Analog	304	4.0	106	1.5	60	8	50	5
Digital	248	8.8	97	3.0	60	7	120	10
Electric Motor	84	4.2	38	1.7	60	45	44	26
Electromechanical Actuator	356	1.1	183	1.2	52	5	50	1
Lights	390	3.7	34	0.8	312	20	22	6
Heaters	52	2.4	28	1.6	70	40	25	12
Experiments or Payloads	112	18.0	1	0.5	-	-	14	140
Elec. Energy Storage	18	37.8	0	-	-	-	-	-
Total	1564	80.0	487	10.3	614	125	325	200

The HVDC technology test facility to be provided as a result of the present program must be capable of demonstrating the transient and steady state performance capability of HVDC distribution and control systems designed for any foreseeable future manned spacecraft. In all such vehicles, two, three or four redundant power sources which supply redundant loads are used in order to meet mission reliability and safety requirements. In addition, loads must be disconnected automatically by means of circuit breakers in case of failure in order to prevent failure of power sources which supply unfailed redundant loads as discussed more fully in Reference 1. Since the purpose of

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Reference 1 - Final Report, "Space Vehicle Electrical Power Processing Distribution and Control Study," Contract NAS8-26270, TRW Systems Group, June 1972.

the technology test facility is only to demonstrate technical feasibility of the HVDC distribution and control approach rather than qualification testing for a specific application, it will be sufficient to design the technology breadboard with only two channel redundancy rather than three or four channels, provided adequate switching and protection flexibility are provided. Furthermore, in the interest of economy, it will not be necessary to consider steady state power requirements in excess of 20 KW per channel since larger power requirements are anticipated only for military aircraft rather than manned space vehicles.

The basic layout of a two channel (dual redundance) power, distribution, and control system is shown in Figure 3.1.4-1. Each primary power source which in the actual spacecraft may consist of fuel cells, solar arrays, batteries or rotating dc generators is simulated in the laboratory by the parallel combination of an electronic power supply and a bank of rechargeable battery cells which have the same or similar source impedance, short circuit capability, voltage regulation, ripple and noise characteristics as an actual spacecraft power source. Load utilization equipment and associated power conditioning units are contained in the load centers of Figure 3.1.4-1 and are simulated by electronic or fixed R,L,C load banks. Bus control and load control switchgear is contained in the bus control panel and the load centers. Power distribution cables are contained in a cable raceway or tray which simulates the space vehicle structure. The power system monitoring and control equipment is contained in the switching and monitor panel. The ACES data entry and digital control center (DCC) shown in Figure 3.1.4-1 represent a type of multiplexed supervision and control equipment to be evaluated.

The basic electrical characteristics of the technology breadboard are based on requirement projections consistent with the results of the previous study (Reference 1). Detailed design of the technology test facility (breadboard) constitutes the second task of the current study program.

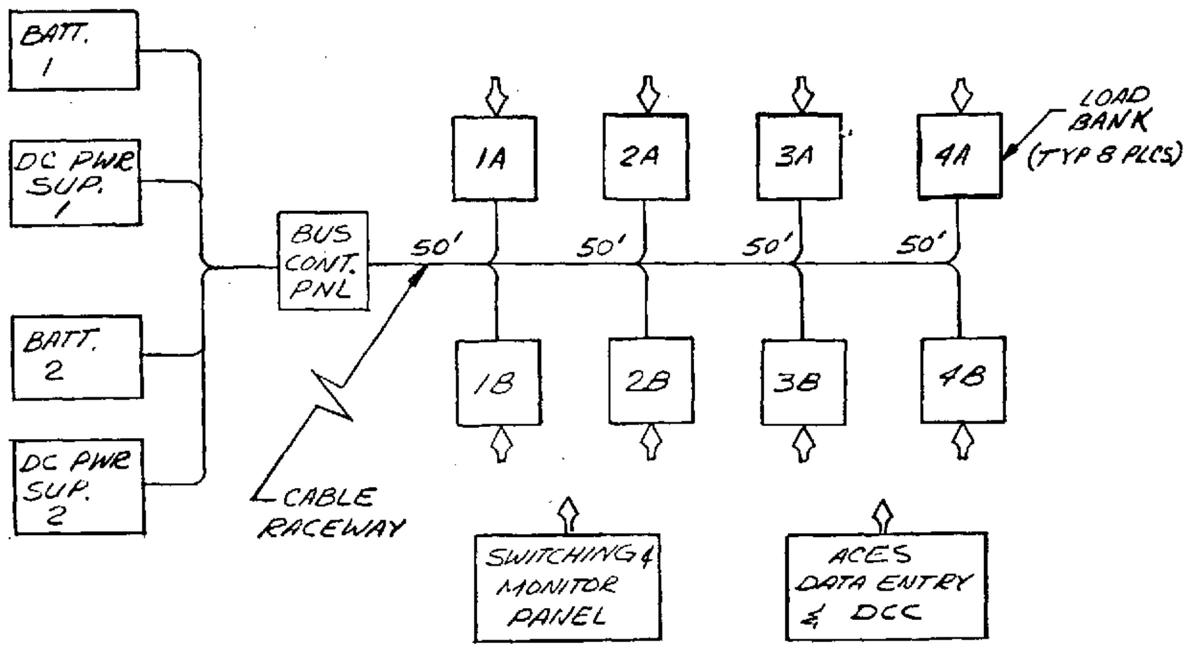


Figure 3.1.4-1. Layout of Technology Breadboard

To demonstrate feasibility of power distribution in excess of 100 Vdc, the test facility design requirements have been chosen to enable performance of tests which demonstrate the following:

- Capability of wires and connectors designed for 28 Vdc to pass established qualification tests for 120 Vdc applications.
- Comparative leakage current between pins in connectors at 28 Vdc and 120 Vdc.
- Elimination of shock hazard at 120 Vdc with suitably designed connectors.
- Interrupt capacity of electromechanical circuit breakers at 28, 56, and 120 Vdc when supplied from a stiff voltage source.

- Comparative radiated interference from circuit breakers in 28, 56, and 120 Vdc circuits when interrupting 150%, 200%, 500%, and 1000% of normal circuit current.
- Comparative susceptibility of power conditioners to inductive or electric field coupled interference when designed for 28 and 120 Vdc input power.
- Comparative efficiency of cables, circuit breakers, and power conditioning equipment at 28, 56, and 120 Vdc at selected levels of power output.

In order to demonstrate technology readiness of solid state switchgear, tests aimed at showing compatibility of solid state remote power controllers (RPC) with switching transients as expected in large systems must be devised. The following shall be demonstrated:

- No RPC failures occur when short circuits are applied at any point in the system.
- Slow increase or decrease in source voltage between zero and 130 Vdc does not degrade switch performance.
- Interference generated during switch operation cannot degrade or inadvertently operate a nearby switch.
- Loss of logic or main supply voltage does not result in any unsafe condition.
- Switch position can be monitored or reset following any single failure.
- Power system transients do not cause inadvertent switch operation.
- Normal temperature excursion and thermal transients do not cause abnormal switch operation.

The test program to demonstrate computer controlled supervision and checkout of the electric power distribution system must yield the following:

- Quantitative data on reduction in crew workload for typical but defined missions and load equipment configurations.
- Absence of interference between switchgear, cabling, power conditioners, and multiplexing equipment.
- Fail-safe characteristics of monitoring and input/output equipment.
- Acceptance of new concept by the astronaut crew.

More detailed test procedures will be developed as part of Task 3 under the present study program.

3.2 POWER DISTRIBUTION TECHNOLOGY DEVELOPMENT FACILITY

The Multi-KW Distribution System test facility serves as a technology breadboard and is designed to provide a cost effective implementation of the test objectives described in Section 3.1. The basic elements of the system consist of a power source, bus distribution panel, supervision and monitoring facilities, distribution cable, and loads. The organization of these elements is illustrated in Figure 3.2-1. The following is a brief discussion to summarize the functions and the capabilities of the elements of the test facility.

a. Power Source

The power source consists of two battery packs and two DC power supplies. Each battery pack is composed of ten lead-acid aircraft batteries and provides a low impedance power source for transient loads at voltages up to 120 volts. The regulated DC power supplies were purchased from Christie Electric and are capable of supplying 150A loads over a range of 2-135V. The two battery packs and DC power supplies are capable of simulating the characteristics of a 36 KW fuel cell source at 120V.

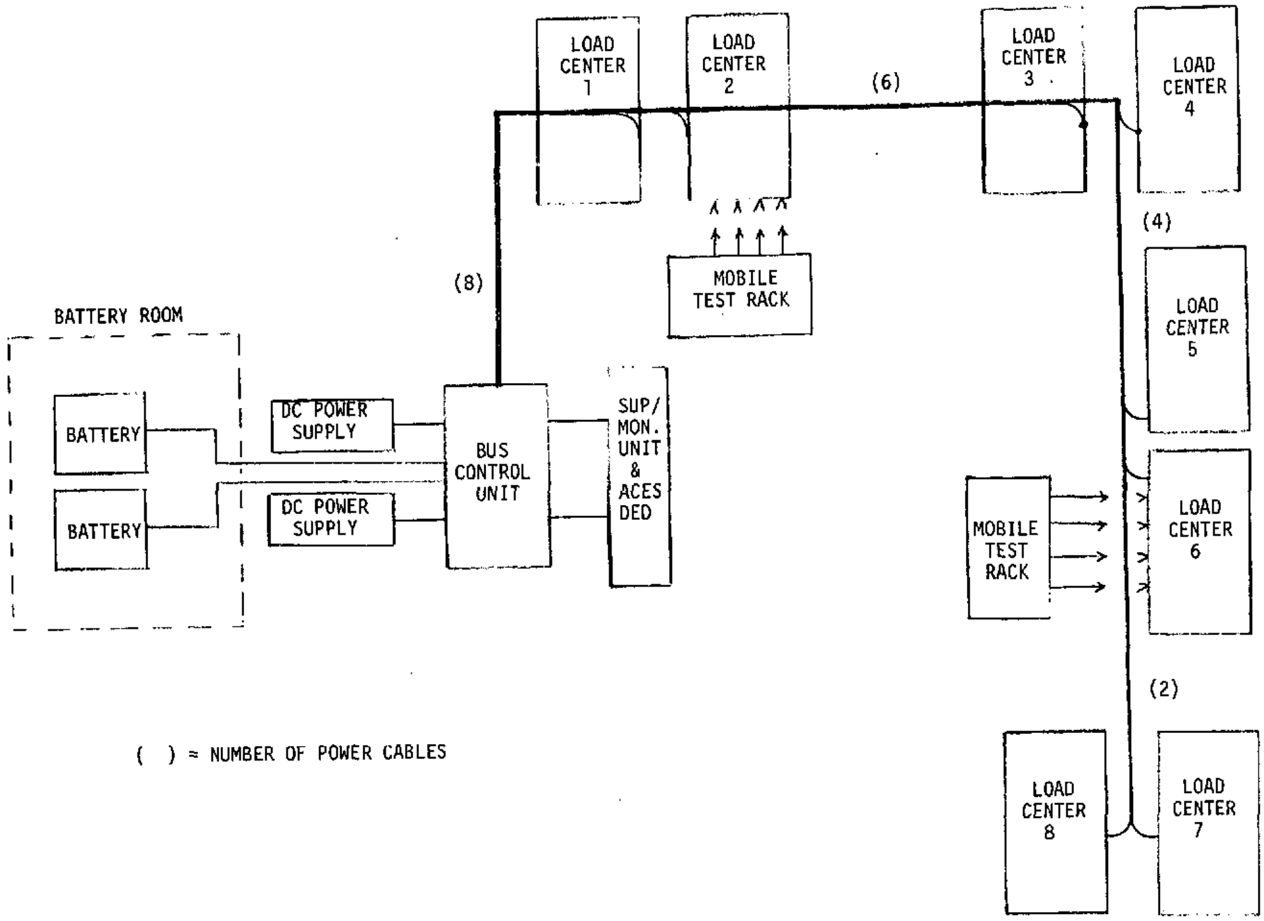


Figure 3.2-1. Test Facility Configuration

The batteries will be located outside and adjacent to the test facility building in order to eliminate any hazard due to accumulated gaseous by-products. During tests simulating "normal" transients the batteries will float on the main bus and will be held close to full charge. Prior to large amplitude transient tests the DC power supplies will perform the battery charging function under manual control to insure that the batteries are at full charge.

b. Bus Control Unit (BCU)

This unit is the interface between the simulated power sources and the power distribution system under test and as such simulates the vehicle breaker or fuse panel. Capability is provided for switching load cables and power sources as well as paralleling power sources. Protective logic has been incorporated to prevent inadvertent paralleling of the power sources. Some monitoring instrumentation appears on this panel for convenience but operations will normally be conducted from the SMU (Supervision and Monitor Unit) and ACES (Automatically Controlled Electrical Systems) panels.

c. Load Banks

The load banks are designed to provide passive loads for steady-state, reactive transient, and power distribution short circuit simulation. In addition, active loads are simulated by a range of pulse width modulator designs. Maximum steady state load current is one-hundred amperes (100A). Currents and voltage are monitored and telemetered (hard wire) to a Supervision and Monitor Unit (SMU). Local test points are provided for all functions to obtain high frequency transient and noise data.

d. Power Distribution Harness

The distribution harness is the major test item. The harness nominally consists of three cables per load bank carrying main dc power, analog telemtry or command signals and digital telemetry and command signals. The main power distribution cable is made up of AWG #8 nickel-plated wire in a twisted lay secured with tie wraps. Extra conductors are included in all cables for test purposes.

e. System Supervision and Data Display

The Supervision and Monitor Unit (SMU) and the Date Entry and Display (DED) panel simulate the cockpit display and control equipment. The DED is part of the ACES (Automatically Controlled Electric System) equipment developed by Westinghouse. It is a triple redundant digital control and monitor system.

The SMU initiates bilevel commands to the power distribution system by switch closures. Bilevel signals (contactor, breaker status) are received and displayed on the status lamp panel; meters are provided on the SMU panel to display analog measurements.

The ACES system initiates digital commands either by depressing keys on the DED panel or from a stored program. Digital data are received and presented on an LED (light emitting diode) display. ACES has additional capability in that preferred turn-on sequences and protective shut-down sequences may be programmed into the system.

f. Mobile Test Rack

Each of the test sets required to perform the critical EMI and transient effect measurements consist of an oscilloscope, camera, wave analyzer, visicorder, and memory voltmeter. In order to facilitate rapid test preparation and to maintain a consistent level of data quality, these instruments will be interconnected and mounted together on a mobile rack or table. This reduces the hazard of faulty test set-up and enables rapid verification of instrument quality by measuring with two or more test sets a known transient response of the facility which has been arbitrarily selected as standard. Test jacks are provided on the load banks to provide access for the test sets to line and load current shunts and line voltage test points.

An outline of the tests which are to be performed during the next phase of this program is presented in Section 3.3.

Further functional requirements and recommended design implementation for each element of the technology breadboard are contained in Sections 3.2.1 through 3.2.4.

3.2.1 Power Source

3.2.1.1 Configuration Requirements

The selection of power sources for the test facility involved consideration of cost and adequate simulation of a large space power plant such as a fuel cell. Since the purpose of this study is to test a power distribution system rather than a power source, the use of an actual fuel cell was not considered due to the cost of procurement, operation, and maintenance. Some typical static and dynamic characteristics for fuel cells are illustrated in Figures 3.2.1-1 and 3.2.1-2. The static and dynamic characteristics of a fuel cell source are estimated from these curves in Section 3.2.1.6. The preferred characteristics of the test facility power source are based on that estimate and the test plan requirements.

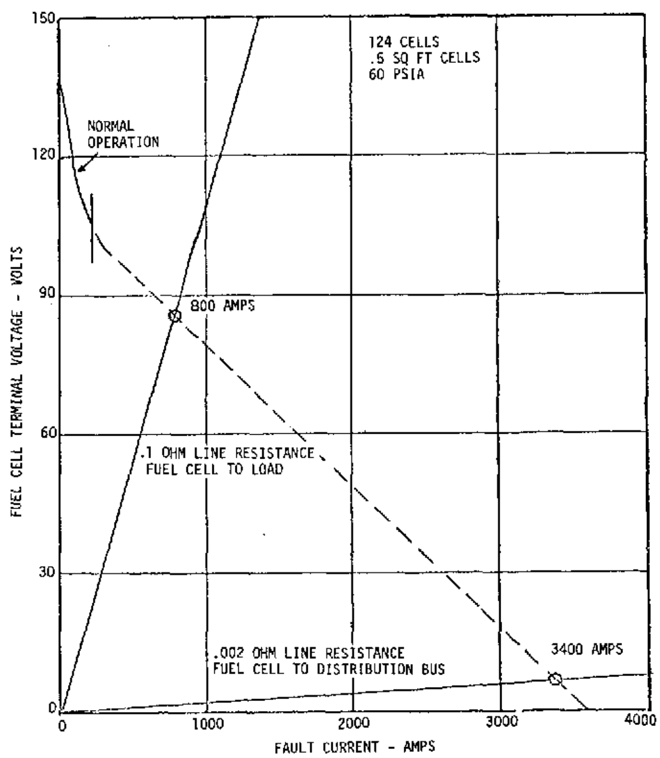


Figure 3.2.1-1. Overload Characteristics of Fuel Cell

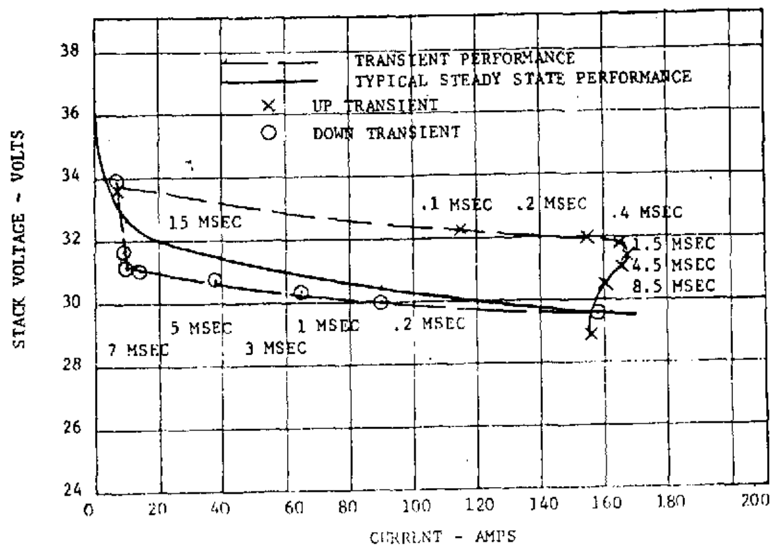


Figure 3.2.1-2. Fuel Cell Transient Response

Voltage	28 - 120 volts
Current	0 - 150 amperes
Response Time	10 msec
Dynamic Impedance	15 m ohms
Static Impedance	30 m ohms

Due to cost considerations, the power sources were to be off-the-shelf commercial/industrial quality equipment. This equipment is available in three basic categories:

a) Electromechanical - Motor Generator Unit
b) Electrical - Regulated DC Power Supply
c) Energy Storage - Batteries, Capacitors

Electromechanical systems were eliminated on the basis of the cost of procurement and installation. Furthermore, the inherent electrical noise of these systems is difficult to control and would interfere with EMI measurements. High current regulated dc power supplies are competitively priced and are readily available from numerous vendors of battery charging equipment. These devices were selected to supply steady state and low amplitude transient load requirements.

Large capacitor banks could be used to supply energy during the initial electrical transient (<2 msec) but could not reasonably provide sufficient energy to observe thermal effects on the distribution cable copper and insulation. Since it is not economical to obtain power supplies capable of supplying high current, low duty cycle loads, electrochemical devices were selected to meet the high peak current demands required by the simulated short circuit tests.

The two obvious candidate types of batteries are Nickel-Cadmium and Lead Acid. Nickel-Cadmium batteries are known to have very low series resistance (i.e., good regulation) for loads with low rates. However, these batteries exhibit an inductive characteristic which appears to predominate at frequencies above a few kilohertz. The presence of this inductance is considered undesirable in this application due to possible resonances with distribution line capacity strongly influencing the noise characteristics to be measured. The data available on Lead-Acid batteries under heavy discharge considerably in excess of design rates leave much to be desired from the standpoint of engineering completeness. However, there is ample evidence that these batteries perform satisfactorily in applications where the load is in a nearly shorted condition (i.e., automotive, aircraft, and diesel starting batteries). The available data will be discussed in more detail in the sections below. These factors together with the competitive pricing of Lead-Acid cells resulted in the selection of Lead-Acid cells as the power source for the high current transient tests.

3.2.1.2 DC Power Supply Selection

The dc power supply should be capable of providing an effective simulation of a large spacecraft power system. Since cost is a major factor in this study, off-the-shelf commercial hardware was considered. A vendor survey was conducted by MSFC with TRW support and requirements were transmitted to twenty-seven major power supply vendors. Five vendors responded and Christie Electric was selected on the basis of low cost and acceptable electrical performance characteristics. The desired parameters and the capability of the Christie Electric dc power supply 2C0135-150E4S purchased by MSFC for this study are compared below:

Parameter	Christie Power Supply	Preferred Parameters
Volts (output)	2-135	28-120
Amperes (output)	0-150	0-150
Load Regulation	<0.1% <10 MV (equiv <0.8 milliohms)	<30 Milliohms
Response Time	50 Milliseconds NL-FL 100 Milliseconds FL-NL	10 Milliseconds
Output Transient NL-FL	10V	<4.5 Volts (30 milliohms)

Note: NL-FL = No load to full load

In addition to the above characteristics, the 2C0135-150E4S power supply has current limiting (at 150A) and selectable voltage limiting features.

A portion of the tests on one unit (E-279) was witnessed at Christie Electric. The data obtained are illustrated in Table 3.2.1-1 below.

Table 3.2.1-1. DC Power Supply-Line and Load Regulation

Input AC Volts	Ripple MV-RMS	DC Volts at 150 Amp	DC Volts at 75 Amp	DC Volts at 0.0 Amp
485	67	120.8	120.8	120.9
440	54	120.8	120.8	120.9
396	56	120.8	120.8	120.8
485	87	27.34	27.34	27.35
440	73	27.34	27.34	27.35
396	70	27.33	27.33	27.34

Output voltage regulation was measured with a digital voltmeter; ripple was measured peak-to-peak on a scope and converted to rms assuming sinusoidal ripple. No fast transients or high frequency components were observed on the scope for load resistance steps from no-load to full-load and full-load to no-load (full load 150 amps). However, the slow transient did exceed the Christie specification (10 volts). Peak deviations and nominal output voltage is given in Table 3.2.1-2.

Table 3.2.1-2. DC Power Supply-Load Transient

Output Voltage (Nominal)	Output Voltage Transient (Max)	
	0 → 150 Amps	150 → 0 Amps
DC Volts	Volts (Peak)	Volts (Peak)
120	-8	+13
28	-7	+14

Transient response, with the exception of 120V NL to FL, was characterized by a ramp reaching a peak in approximately 20 to 40 milliseconds and then decaying in a sinusoidal waveform in two cycles with periods of 360 to 400 milliseconds. The FL to NL transient of 120 volts exhibited a sharp peak and rapid decay with the significant transient completed in approximately 100 milliseconds.

Non-linearities due to operation near the upper voltage limit are probably the cause of the changed response. None of the characteristics observed indicated any problem in utilizing this equipment in the test facility. Christie was reluctant to attempt a short circuit test (current limiting) as they felt this was not required and possible damage could occur to internal devices (primarily SCRs). This may be a problem due to the nature of the tests to be performed on the test facility. It is planned to have the batteries floating on the line with the power supply providing normal load until the line short is applied. This configuration allows the batteries to remain at the optimum full charge condition until the short circuit occurs and maintains a low impedance for high frequencies due to the power supply output capacitance. However, if this configuration proves to be non-feasible during functional testing due to power supply limitations, an additional capacitor bank may be connected across the power line and the DC power supplies will be switched out just prior to applying the short circuit.

The transient response of the DC power supply is controlled primarily by feedback circuitry. Circuit data for analysis was not available at this time. Characterization of the expected transient response of the combined power source transient response is discussed in Section 3.2.1.6.

3.2.1.3 Battery Procurement

The selection of a specific Lead-Acid battery design and/or manufacturer was hampered by a general lack of pertinent data on which to perform trade studies. The nature of the problem is illustrated in Figure 3.2.1-3 based on measurements made at TRW. The sudden application of load current produces an immediate drop in voltage due to equivalent series resistance effect. This drop is followed by a continuing decrease in voltage due to cell discharge. The limited data available do not separate these two contributions to the decrease in battery terminal voltage. Typical data available from

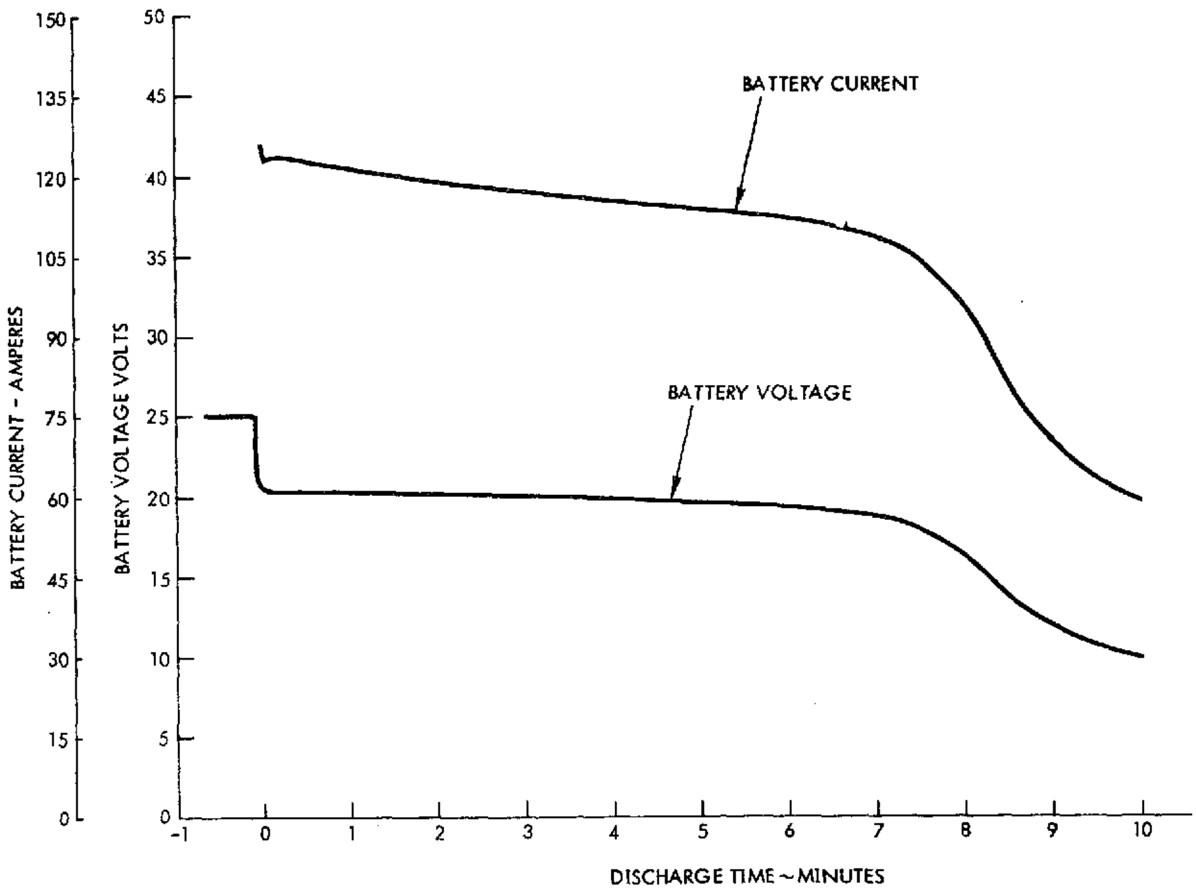


Figure 3.2.1-3. High Rate Discharge-Lead Acid Battery Fixed Load Resistance

suppliers is shown in Figure 3.2.1-4. Some estimate of the equivalent series resistance can be made from the ordinate intercepts but the actual capability for much higher rates is not well defined. Extrapolations by means of Peukert's Formula are regarded as too inaccurate at one minute rates. The few manufacturers who were able to provide data on ampere-hour capability at the high rates under consideration (i.e., one to three-minute rates) used different final voltages as indications of end of capacity. Sources contacted for data and pricing information are listed in Table 3.2.1-3.

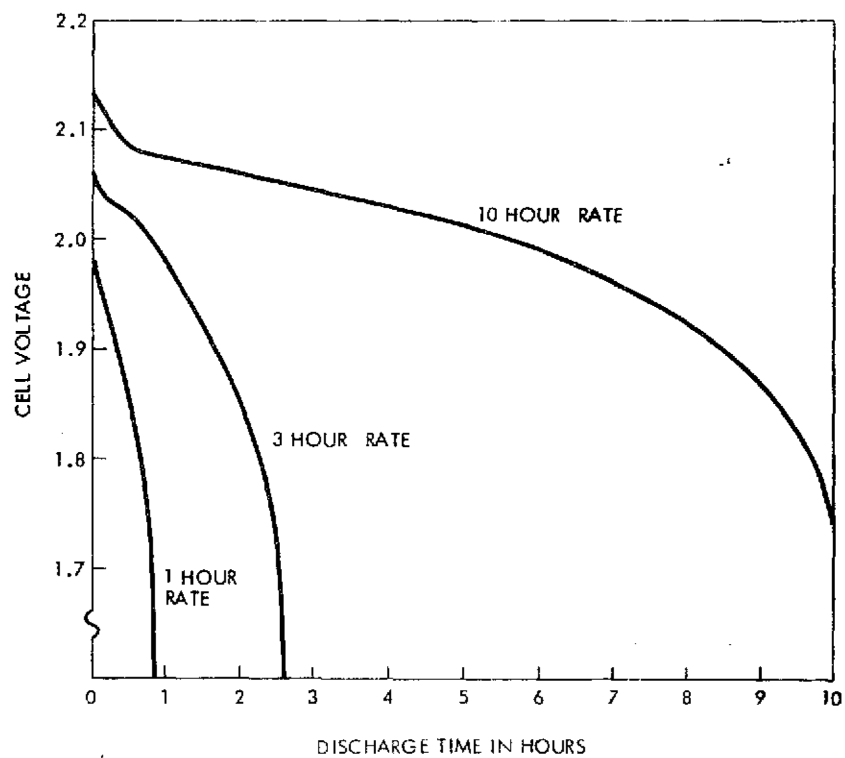


Figure 3.2.1-4. Battery Discharge Characteristics

Table 3.2.1-3. Lead-Acid Battery Trade Study Survey

Source	Response
C&D Battery	Data & Quote (Industrial Battery)
ESB	Data (Aircraft Battery)
Alpha Aero	Data & Quote (Aircraft Battery)
McCulloch Electric	Quote (Golf Cart Battery)
Trojan Battery	Quote (Golf Cart Battery)
Union Carbide	No longer manufacture
Globe Union	No recommendation
Power Inc.	No recommendation
Gates Energy Products	Data & Quote (Sealed, Cylindrical)
Gould	No response
Naval Ammunition Depot - Crane, Ind.	Design Info Only
TRW	Design Info Only
Fort Monmouth Electronics Center	Design Info Only
Flight System Test Inc.	Design Info Only
Martin Marietta	Design Info Only

The battery selected for this application is required to produce high currents for periods which are in general less than 35 seconds. It is known that high discharge rate capability in any one battery design is a monotonic function of the ampere-hour rating. Different designs with similar ratings will produce radically different short term discharge characteristics. High current capability is enhanced by specific gravity in the vicinity of 1.225, increasing the number of plates, the use of thinner plates, and decreasing the separation between plates. Although quantitative data are not available, it is known that these design approaches are used in automotive and aircraft starter batteries. It is expected that use of these batteries under excessive discharge rates would provide good performance but would result in a high mortality rate due to warped plates and melting of terminals. Industrial batteries of equivalent ampere-hour ratings tend to have somewhat higher series resistance but are constructed with heavier connectors and will have better life characteristics under high current discharge.

In order to obtain some comparative data on equivalent series resistance, a figure of merit (F) was established based on the assumption that battery resistance for a particular design configuration is proportional to the number of cells (N) and inversely proportional to the ampere-hour rating (AH) such that

$$R = \frac{F \quad N}{(AH)}$$

Figures of merit for different types of batteries are tabulated below. For any given battery rating, the type with lowest figure of merit (F) will have the lowest equivalent series resistance.

Battery Type	$F = \frac{R(AH)}{N}$	Source
Industrial	0.205	C&D Battery
Automotive	0.1-0.227	Vinal, J. Sanders (MMC)
Aircraft	0.051	ESB
Cylindrical Cell	0.025	Gates Energy Products

In addition to low source resistance, factors of cost and availability also influence the final battery selection. The cylindrical cell is not yet in production and will have a maximum rating of 25 AH. The present cost estimate is $13 per cell but this must be regarded as speculative as the design is still in the development stage.

The figure of merit for the industrial battery is relatively high but ampere-hour capacities and peak currents (one minute rate) are available to almost any desired magnitude (see Table 3.2.1-5). The choice between the automotive and the aircraft battery is in favor of the aircraft type due to the lower figure of merit and comparable price. Furthermore, the lack of definitive data on automotive batteries reflects decreased production process control engendering a lower level of confidence in consistent performance. A cost comparison of the industrial battery and the aircraft battery was performed and is illustrated in Tables 3.2.1-4 and 3.2.1-5.

Table 3.2.1-4. Cost Trade Data - Aircraft Batteries

Battery Type	Voltage	3 Min. Rate	5 Hr. Rate A-H	VA/$	120V Pack Cost
AC 35	12	180	35	61.7	$ 350
AC 25	12	120	25	50.9	281
AC 54M	12	120	25	44.3	325
AC 78M	12	180	37	53.5	404
6-FH-13	12	380	90	77.6	582
12-TAS-11	24	180	42	35.9	603
3150-2	24	200	36	50.7	473
3151-2	24	125	24	34.4	436
3152-A	24	200	36	23.7	512
3154-1A	24	58	11.5	12.9	545
K1(6-GT-13)	12	440	75	21.1	2503

Note: Cost data obtained from Alpha Aero, L.A. Exide representative. Batteries are manufactured by ESB (WISCO Div.).

Table 3.2.1-5. Cost Trade Data - Industrial Batteries

Battery Type	Voltage	1 Min. Rate Amperes	8 Hr. Rate A-H	VA/$	120V Pack Cost
3 DCU-7	6	111	75	16.0	$ 831
2 DCU-9	4	148	100	17.2	1030
3 DCU-9	6	148	100	18.7	950
2 DCU-11	4	184	120	14.1	1560
3 DCU-11	6	184	120	14.9	1480
DCU-13	2	220	150	15.3	1720
DCU-17	2	288	200	11.4	2040
KCU-9	2	408	320	15.2	3228
KCU-11	2	505	400	14.9	4080
KCU-13	2	600	480	15.3	4710
KCU-15	2	693	560	15.8	5260
KCU-17	2	784	640	15.5	6060

Note: Cost data obtained from C&D Battery Catalog

The right hand column (120V pack-Cost $) represents the minimum cost to assemble a 120V power source with each battery type. The column marked VA/$ represents the product of voltage and the maximum rate (amperes) divided by the cost. The highest rate available on the aircraft battery was the three minute rate. Since in almost all cases this figure was identical to the five minute rate, it is regarded as a valid limiting value for these batteries. The VA/$ figure is a more accurate representation of the cost of the battery assembly. It is noted that this value for the 6-FH-13 battery is more than a factor of five greater than the average value for the industrial batteries. The cost significance of this figure is illustrated if comparable battery packs are assembled.

Example:

		Maximum Current	Cost/$
6-FH-13	2-10 battery strings in parallel	760A	1,164
KCU-17	1-60 cell string	784A	6,060

No definitive life or reliability data were found to allow a comparison of confidence in the performance of the industrial and aircraft batteries. However, based on their designs and applications, it may be inferred that the expected life of the aircraft battery will be several months and that of the industrial battery, several years in the test facility application. Since revisions in the design and test program are expected to occur frequently, justification of the longer life, higher cost industrial battery appears questionable. The use of aircraft batteries appears feasible if provision is made for the expected failure of some of the units due to the high peak currents expected in this application. The 6-FH-13 aircraft battery provides a high nominal rate (380 amperes for 3 minutes) at reasonable cost and has been designed for both commercial and military air transport service. Consequently the recommendation for the initial design is to purchase sufficient 6-FH-13 batteries for two 120V packs and one additional set of spares.

Battery	6-FH-13
Manufacturer	ESB Inc.
Vendor	Alpha Aero
Quantity	30
Unit Cost	$58.17
Total Cost	$1,745.10

The use of two parallel 120V aircraft battery packs is recommended for the short circuit test on the power distribution system. The source impedance of the batteries may be estimated from the previously established figure of merit F.

F (Aircraft Battery) = 0.051

Ampere-Hours (6-FH-13) = 90 A-H

Ampere-Hours (Parallel Operation) = 180 A-H

Number (N) of Series Cells = 60

$$R = \frac{N\ F}{(AH)} = 0.037 \text{ ohms}$$

Source resistance will also be a function of the battery cabling and the connectors. Although the contribution from cabling is expected to be negligible, the resistance introduced by connections may be considerable. It is recommended that solid copper bus connectors be fabricated for this purpose and that they be fastened with torque wrenches to appropriate specifications to insure proper contact pressure. The use of bare copper bus will reduce the expected terminal heating during high current transients. Voltage drop across each connection should be checked with a milli-voltmeter prior to each high current test.

Battery state-of-charge is critical only on the infrequent occasions that a power line fault test is to be performed. The battery charging operation will be implemented with the DC power supplies functioning as battery chargers under manual control. This avoids the need for design or purchase of additional charging equipment. Since the present test plan requires only occasional use of the batteries, battery life will be extended by allowing the batteries to stand open circuited and recharging prior to use. These batteries are vented and will be in an exterior ventilated battery shed and there will be no significant hazard associated with the charging operation. The manufacturer will supply recommended charging rates and sequences.

Assembly of 120V pack of batteries will require mechanical operations in the presence of hazardous voltages. The safety hazard may be eliminated by the establishment of appropriate procedures prior to assembly. Aircraft batteries are usually shipped "dry-charged." The electrolyte (sulphuric acid) is a hazardous material and must be added after the battery is in place. Manufacturer's procedures and MSFC safety standards must be observed. Adequate ventilation must be provided in the battery shed to insure that explosive gases (hydrogen, oxygen) are not allowed to accumulate in dangerous quantities.

Cable insulation between the battery shed and the laboratory wall will be exposed to the weather and should be regularly inspected to insure personnel protection. A manual switch capable of carrying currents in excess of 3000 amperes should be located within the shed to permit deactivating all external wiring as illustrated in Figure 3.2.1-5. Personnel should be shielded from all contact closures and manual operations must not be performed with the main contactor closed. The high current available in this system is capable of ejecting solid or molten material from the point of contact.

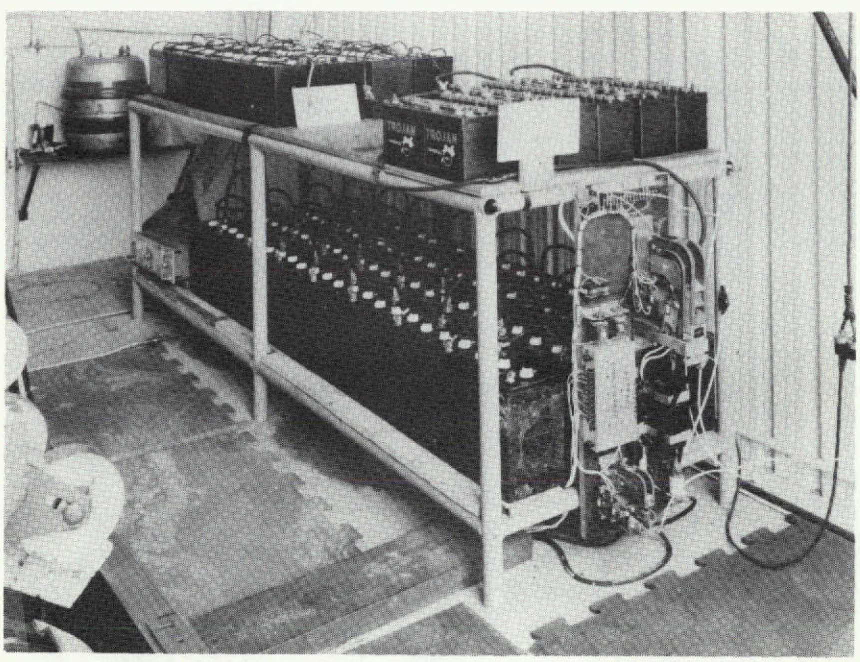


Figure 3.2.1-5. Typical Lead-Acid Battery Pack Assembled from Commercially Available Components

The characteristics and response of the fuel cell power sources are illustrated in Figures 3.2.1-6 and 3.2.1-7. These characteristics indicate a response which may be approximated by an ideal voltage source (E_1) and the network shown in Figure 3.2.1-6.

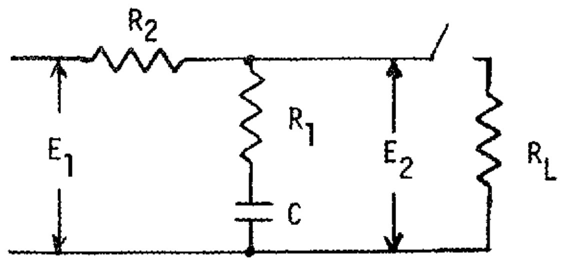


Figure 3.2.1-6. Equivalent Circuit for Fuel Cell

The response of the above circuit to a switch closure is given by

$$E_2\ (t) = A\ E_1\ (1 + B\ e^{-kt})$$

$$A = \frac{R_L}{R_2 + R_L} \qquad B = \frac{R_2^{\ 2}}{R_1\ R_2 + R_2\ R_3 + R_1\ R_L}$$

$$K = \frac{R_2 + R_L}{(R_1\ R_2 + R_2\ R_L + R_1\ R_2)\ C}$$

For $t = 0^-,\ E_2 = E_1$

$$t = 0^+,\ E_2 = \frac{E_1\ R_L\ (R_1 + R_2)}{R_1\ R_2 + R_2\ R_L + R_1\ R_L}$$

$$t = \infty,\ E_2 = E_1\ \frac{R_L}{R_2 + R_L}$$

Considering the voltage and current changes from the initial condition to the condition at the time indicated

$$\frac{\Delta E_2}{\Delta I} \Big/_{t = 0+} = \frac{(E_2 (0^-) - E_2 (0^+))}{E_2 (0^+)} R_L = \frac{R_1 R_2}{R_1 + R_2}$$

$$\frac{\Delta E_2}{\Delta I} \Big/_{t = \infty} = \frac{(E_2 (0^-) = E_2 (\infty))}{E_2 (\infty)} R_L = R_2$$

From the slope and final value of the curves of Figure 3.2.1-2, it may be inferred that

$$R_L = 0.188\Omega$$

$$K = 100$$

$$\frac{\Delta E_2}{\Delta I} \Big/_{t = \infty} = 0.03\Omega$$

$$\frac{\Delta E_2}{\Delta I} \Big/_{t = 0+} = 0.015\Omega$$

$$R_1 = R_2 = 0.03\Omega$$

$$C = 179{,}000 \ \mu f$$

Modifying the input to 120V and the load current to 150a to duplicate the test facility loads

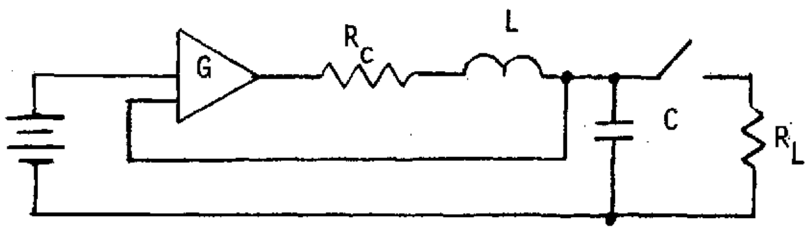
$$R_L = E_1/I = 0.8\Omega$$

$A = 0.065$ $B = 0.0187$ $K = 98.2$

and the expected characteristic of the fuel cell source subjected to the above step load is,

$$E_2 = 0.965 \, E_1 \, (1 + 0.0187e^{-98.2t}) \qquad (1)$$

The configuration of the DC power supply may be represented as in Figure 3.2.1-7(a).



R_c = 0.005Ω
L = 0.8 mh
C = 120,000 μf

Figure 3.2.1-7(a)

Although the filter values are available, the constants which define the loop gain are not. Consequently, this supply will be characterized in a manner similar to that used for the fuel cell. The waveform observed at Christie Electric and the equivalent circuit are illustrated in Figure 3.2.1-7(b).

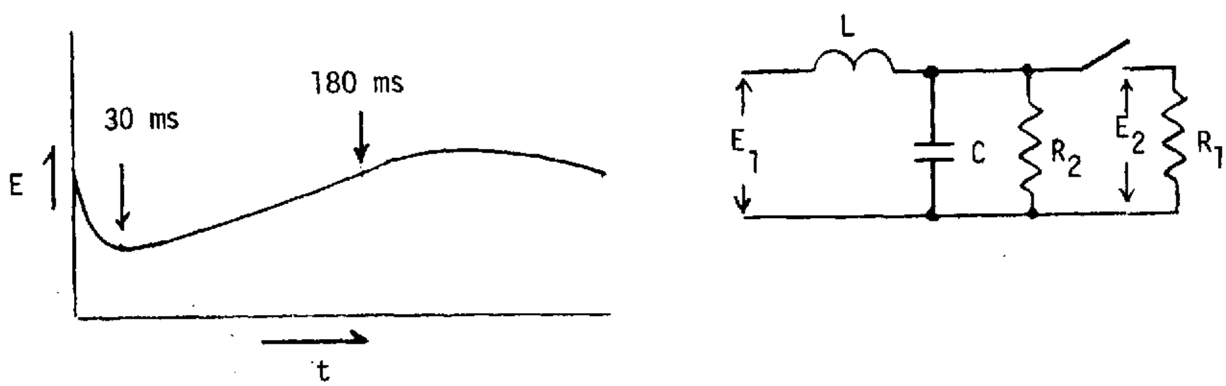


Figure 3.2.1-7(b)

This waveform has the general form of

$$E_2 = E_1 (1 - Ae^{-kt} \text{ Sin } \omega t)$$

$$A = 1/(\omega R_1 C)$$

$$\omega(0.18) = \pi$$

$$\tan \omega t = \frac{\omega}{K} \quad t = 0.03 \text{ seconds} \left(\frac{d E_2}{dt} = 0\right)$$

The resulting equation which describes the performance of the power supply subjected to a 150A step load is

$$E_2 = E_1 (1 - 0.067e^{-30.2t} \text{ Sin } 17.4t) \tag{2}$$

This equation represents a solution to the Lapace transform equation

$$E_2 (s) = E_1 \left(\frac{1}{S} + \frac{1}{R_1 C (S^2 + 2KS + 1/LC)} \right)$$

$$K = \frac{R_1 + R_2}{R_1 R_2 C} \qquad \omega = \sqrt{\frac{1}{LC} - K^2}$$

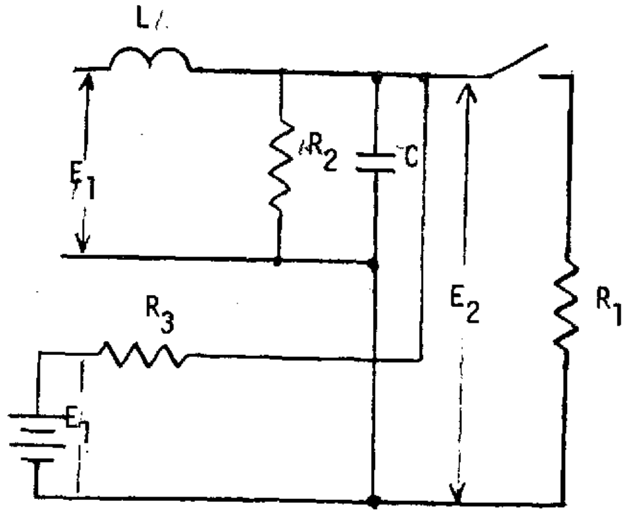
For $E_1 = 120V \quad I = 150A \quad R_1 = 0.8\Omega$

$R_2 = 0.0157\Omega \quad C = 1.075\mu f$

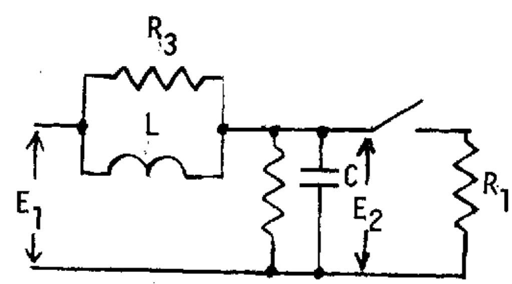
$\omega = 30.2$ rad/sec $L = 0.765mh$

Where these values reflect the performance of the total filter and regulation feedback circuits.

If it is now considered that the battery is floating in parallel with the load, the circuit and the equivalent circuit are shown in Figure 3.2.1-8.



Connection for Transient Test



Equivalent Circuit

Figure 3.2.1-8

From the discussion of the equivalent series resistance of the battery

$$R_3 = 0.037\Omega$$

$$K = \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{2 R_1 R_2 R_3 C}$$

$$= 42.7$$

$$\omega = \sqrt{\frac{1}{LC} - K^2}$$

$$= \sqrt{-1} \quad 24.75$$

The equation in the time domain for the combined power supply and battery responding to a 150A step load becomes,

$$E_2 \text{ (Power Source)} = E_1 (1 - 0.049e^{-42.7t} \text{ Sinh } 24.75)$$

$$= E_1 (1 + 0.025e^{-67.4t} - 0.025e^{-18t}) \qquad (3)$$

The time constant of Equation (3) may be manipulated by adding resistance in series with the battery; however, this is not regarded as significant from the standpoint of the tests to be performed. The major difference between the fuel cell and the simulated power source is the step voltage change which occurs in the fuel cell output. This difference could be eliminated by adding a small amount of resistance in series with the power source such that Equation (3) becomes

$$E_2 \text{ (Power Source)} = 0.965\, E_1(1 + 0.024e^{-67.4t} - 0.024e^{-18t}) \qquad (4)$$

Recalling the response equation of the fuel cell output (Equation (1))

$$E_2 \text{ (Fuel Cell} = 0.965\, E_1\, (1 + 0.0187e^{-98.2t})$$

It may be concluded that the two power sources are sufficiently similar for the intents of the test program and no further modifications are considered.

3.2.2 Bus Control Unit (BCU)

The BCU provides the electrical interface between the simulated power sources and the power distribution cable and simulates the electrical characteristics of a space vehicle power distribution control panel. The functions performed in a flight design panel will consist of power control of major subsystems, power distribution fault removal, and redundancy switching. Instrumentation is minimal and consists of bilevel signals to indicate the state of contactors or circuit breakers and one voltage and current measurement per power source. Displays are located remotely in the pilot's cockpit. There are usually two completely redundant power systems which have interconnection capability so that failure of a power source or a distribution cable will not abort the electrical system. Each portion of the system is capable of performing its function at the full power level required by the load utilization equipment. Mission planning does not normally include the reactivation or attempted reuse of a failed portion of the system. The switching requirements for any one flight system are consequently limited in complexity with only a few switching cycles performed with the main bus RPCs (Remote Power Controllers).

The BCU in the test facility will be able to simulate configurations with redundancy and provide local control and monitor functions; remote control functions are simulated with the SMU (Supervision and Monitor Unit) in combination with the BCU on a logical OR basis. Provision is made for remote monitoring with dual outputs from all BCU instrumentation circuitry. The major elements of the BCU are illustrated in the functional schematic of Figure 3.2.2-1. Since hazards may exist due to the high current and voltage capability of the power sources, logic was designed to prevent inadvertent paralleling of power sources. Override control is provided for tests in which paralleling of power sources is desired and a warning light indicates if this condition is present. Due to the necessarily variable level of the line voltage, all power converters, electronic circuits and relays operate from an ac powered 28 Vdc supply. The 28V is distributed to the load banks where further conversion is performed as needed for control electronics. The details of the BCU elements are discussed in the following paragraphs.

3.2.2.1 BCU Switching

The requirements placed on the test facility BCU are more complex than for a flight system. It is intended to be able to simulate any specified power system configuration and to perform repeated switching functions under major fault conditions. The complexity of the BCU switching is further increased by the necessity of paralleling a battery pack and a dc power supply to simulate a fuel cell. Figures 3.2.2-2 and 3.2.2-3 illustrate a typical flight configuration power distribution control panel and the BCU configuration which simulates that component. Line and load fault protection is provided by main bus breakers (1-2) and line breakers (1-8). It should be noted that additional fault protection is provided by fuses at the load.

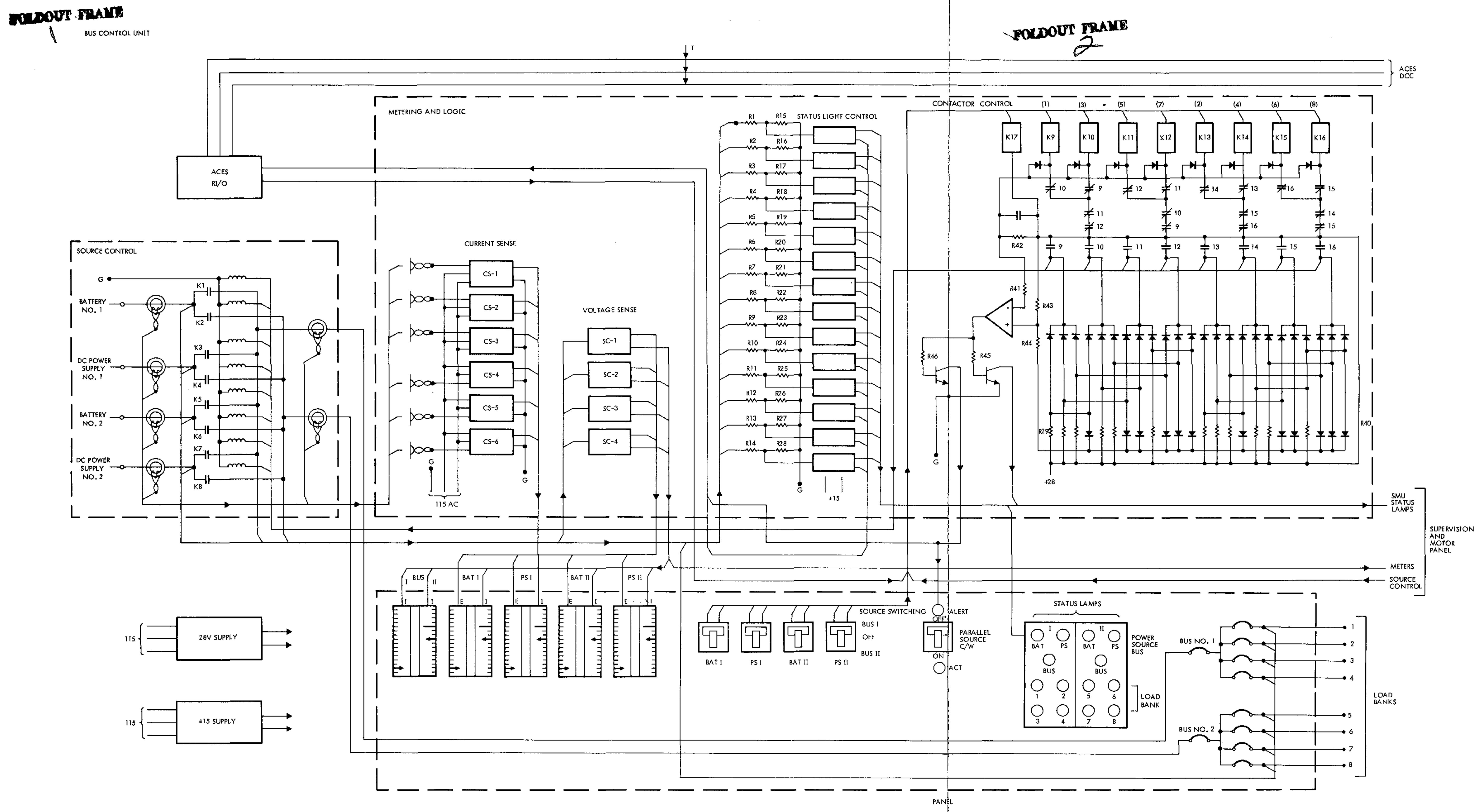


Figure 3.2.2-1. BCU Functional Schematic

POWER DISTRIBUTION SWITCHING

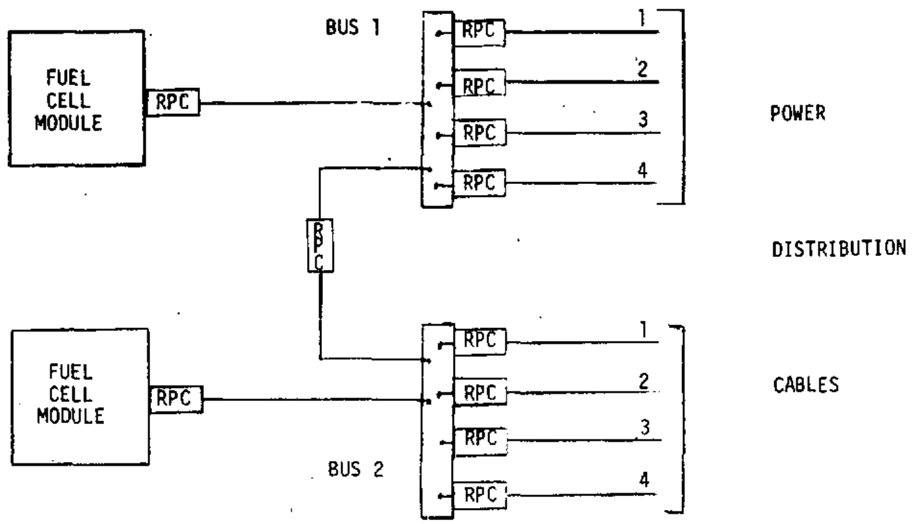


Figure 3.2.2-2. Flight System

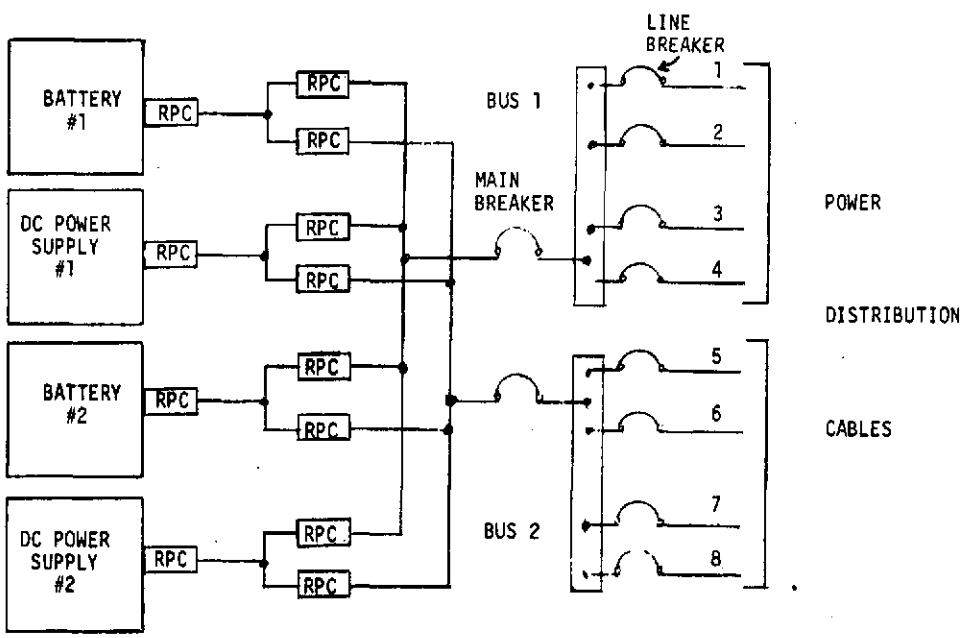


Figure 3.2.2-3. Test Facility

Switching arrangements such as Figure 3.2.2-2 were considered but were rejected due to the lack of flexibility and the specific needs of the test facility. The configuration of Figure 3.2.2-3 can simulate all of the functions of Figure 3.2.2-2 and also reconfigure any selected combination of batteries and dc power supplies to provide power to either line. The BCU configuration also enables the monitoring of power supply and battery voltage prior to paralleling and provides the interconnection for battery charging.

The initial design of the BCU will be implemented with hardware selected on the basis of availability and low cost. These devices do not necessarily represent an optimized selection of flight hardware. The functions and performance characteristics which may influence the quality of the simulation are discussed in the following paragraphs.

Manual reset circuit breakers are used for main bus and line power control since there is, at this time, no specified fault sensing and removal approach and the extensive short circuit testing planned will require frequent, rapid fault clearing.

Power switching under loaded conditions will be performed by the contactors under remote (SMU) control. The contact arcing which occurs under these conditions is of concern due to the resultant EMI and the effect on contact characteristics and life. Measurements will be performed periodically (Baseline DC Tests, Section 3.3.4.1) to monitor contactor conduction characteristics. If significant change of contact resistance or arcing characteristics occur, manufacturer recommended cleaning procedures will be initiated.

Contact arc noise may be reduced and controlled by means of resistance/capacitance circuits strapped across the contacts. It is not possible at this time to specify damping networks for contact/arc protection and this problem will be evaluated by measurements on the BCU during initial tests. A critical factor in this initial evaluation is to establish a correlation between performance at sea level and performance at altitude. The contactors which have been purchased for this program employ magnetic blow-out features for contact protection and arc suppression.

Solenoid control circuitry also produces EMI due to inductive voltage surges. All methods which reduce this effect, increase the contact arcing problem since the speed of the contactor action is decreased. The contactors purchased for this program employ bifilar windings to control this characteristic.

The contactors in the BCU will not be required to open under load for currents in excess of 150 amperes or voltages in excess of 135V. The magnitude of the current carried by the contacts in the closed condition will be determined by the capability of the battery pack and distribution cable utilized in the distribution line short tests. The maximum current with currently recommended procedures will not exceed 500A and time periods of 12 seconds. A full short at the BCU output terminals could conceivably result in currents in excess of 3000A for periods less than one second. This extreme current with its potential hazards to equipment and personnel can be avoided by making effective use of the BCU switching capability and checking all test setups with the DC power supply prior to closing the battery contactor(s). The recommendations for the minimum operating ratings on the contactors and breakers are given below in Table 3.2.2-1.

Table 3.2.2-1

Device	Current Capacity	Break Current*	Voltage*
DC Power Supply RPC	300A	150A	135V
Battery RPC	1500A	150A	135V
Main Bus Breaker	2000A	750A	135V
Line Breaker	2000A	200A	135V

*These values reflect the requirements for the initial effort on the test facility for which one or two load banks and cables with current capacity to 100A each are planned.

3.2.2.2 Instrumentation

A power distribution control panel for a flight program normally utilizes a minimum of instrumentation since the signficant data are primarily "go", "no go" information. Figure 3.2.2-4 represents a typical display for instrumentation of the configuration of Figure 3.2.2-2. This display would likely be located on the "cockpit" panel rather than at the distribution control panel location. The control and display panel for the BCU configuration (Figure 3.2.2-3) is illustrated in Figure 3.2.2-5. This panel is located at the BCU location and is also repeated at the SMU location.

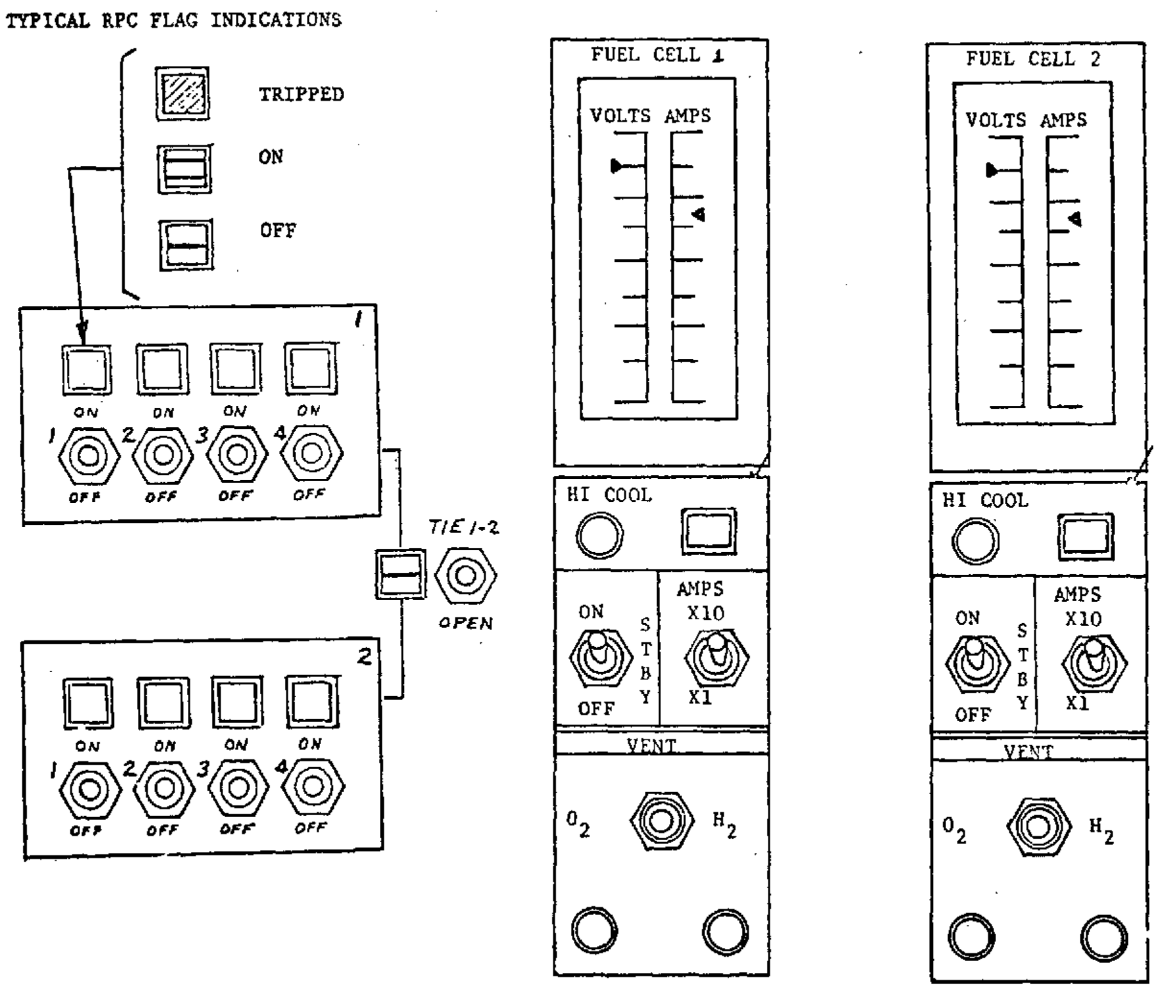


Figure 3.2.2-4. Power Distribution Control Panel for Flight System

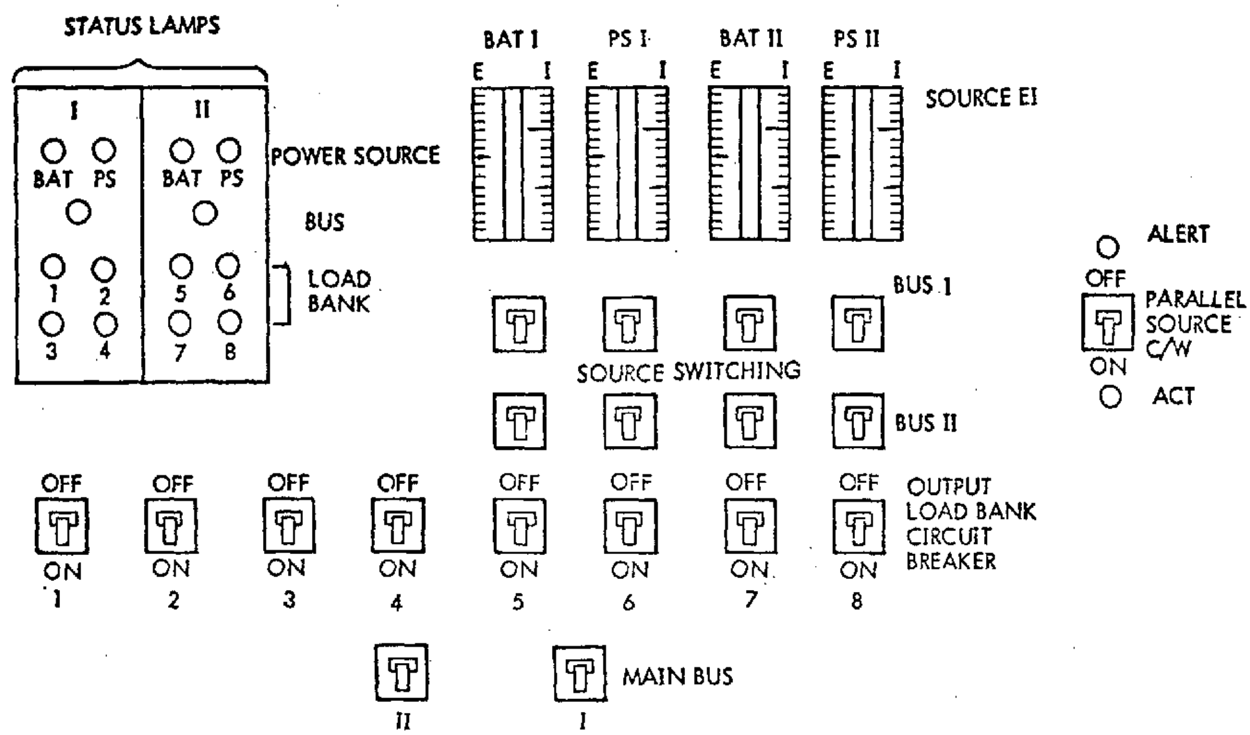


Figure 3.2.2-5. Bus Control Unit Panel

During the simulation of the performance of a power distribution and control system, operations will be conducted from the SMU. When setting up certain test configurations, the test conductor must necessarily operate from the BCU and it is desirable to have the complete display and control functions available at that location.

The displays and controls provided at the BCU reflect the experimental nature of the test facility. The status lamps will light if the voltage at each indicated point exceeds 20 volts. There is built-in hysteresis in the circuitry so that the lamps will remain "on" until the voltage falls below approximately 14V. The circuits are required to function within specification at voltages up to 300V. The line and main bus breakers are manually set devices operating on the hydraulic principle of solenoid operation with magnetic arc quenching. The requirements on the breakers are specified on MSFC drawing 50M02268. Setting the parallel source C/W (caution and warning) switch in the "on" position will prevent paralleling any two or more power sources. The inhibition is removed in the "off" position. The "Alert" lamp will light if two or more power source switches in the same bus group are thrown to the "on" position regardless of whether or not the operation of the RPCs is inhibited. The "ACT" lamp will light when the inhibit switch is thrown to the "off" position. This inhibit control is necessary particularly since power source RPCs may be actuated from the BCU and the SMU panel on a logical "OR" basis and an operator at the BCU may not be aware of the state of the SMU controls. During normal operation, the BCU power source switches will be in the "off" position and control will be from the SMU. The dual scale vertical movement panel meters were selected for ease of reading and were used extensively in the Skylab Program. Figure 3.2.2-6

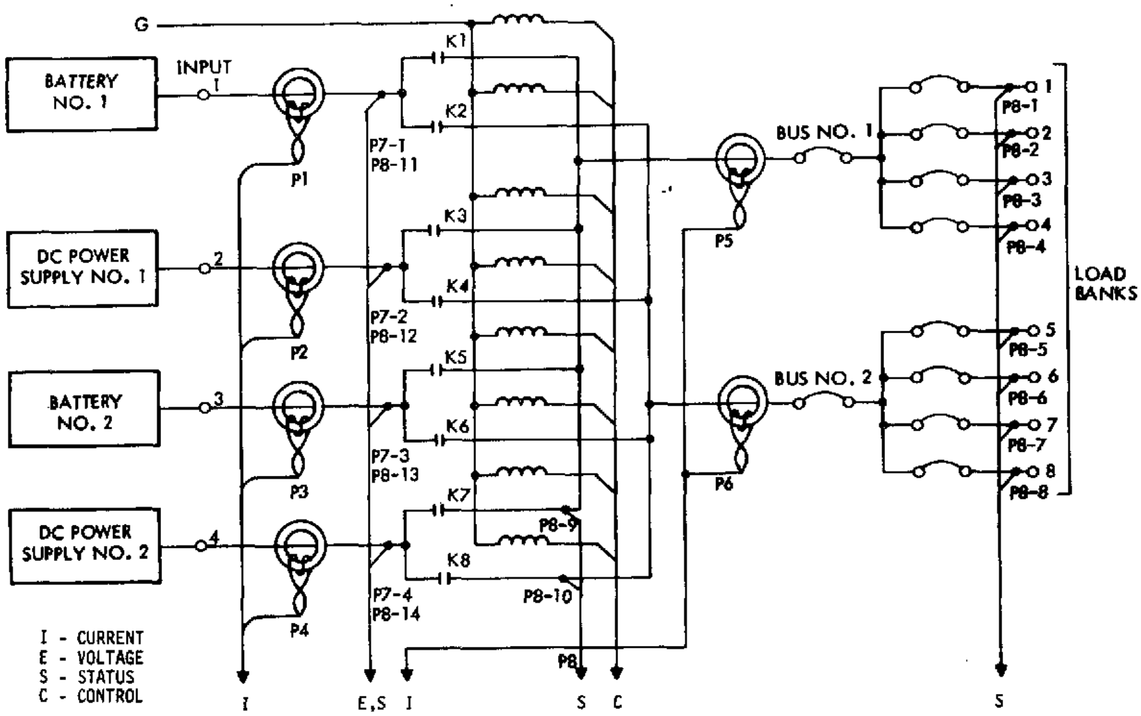
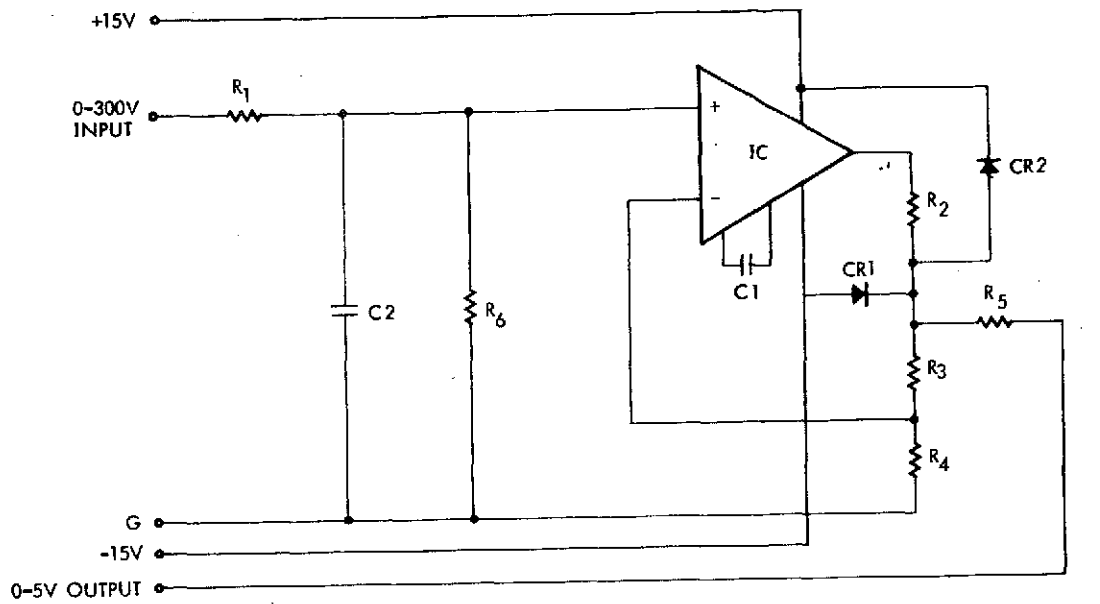


Figure 3.2.2-6. BCU Monitor and Control

illustrates the points of measurement in the switching system. Source voltage, current, and status are sensed on the input side of the RPCs to minimize the number of ammeter connections and provide the operator with voltage and status data prior to connecting the power source to the main bus. These data are necessary prior to paralleling power sources and performing battery charging procedures. Status points P8-9 and P8-10 indicate the presence of voltage on the main bus. Status points P8-1 through P8-8 indicate presence of voltage on the distribution harnesses. Individual harness currents and voltages are measured at the load banks.

Magnetic current sensors are preferred over current shunts for several reasons. Current shunts would insert two more junctions in the low resistance current source power lines. The variable line voltage would increase the complexity of signal conditioning circuits required to actuate panel meters on the SMU and BCU panels. The magnetic sensor responds equally to reversed polarity signals which are normal in this system during battery charging. This measuring device is not subject to damage due to excessive overload currents expected during short circuit transients. The BCU location in the test facility permits the use of an AC powered instrument which could be purchased at reasonable cost (approximately $150).

A feasibility design of the signal conditioning circuit for voltage sensing has been performed and is shown in Figure 3.2.2-7. The LM101 integrated circuit is sufficiently stable with time and temperature so that the signal conditioner output will contain errors of less than 3% and zero adjustment will not be required if resistors R_1, R_6, R_3, and R_4 have 1% tolerance. If parts with greater tolerances are used, calibration may be performed by adjusting the value of R_6.



BCU VOLTAGE SIGNAL CONDITIONING CIRCUIT

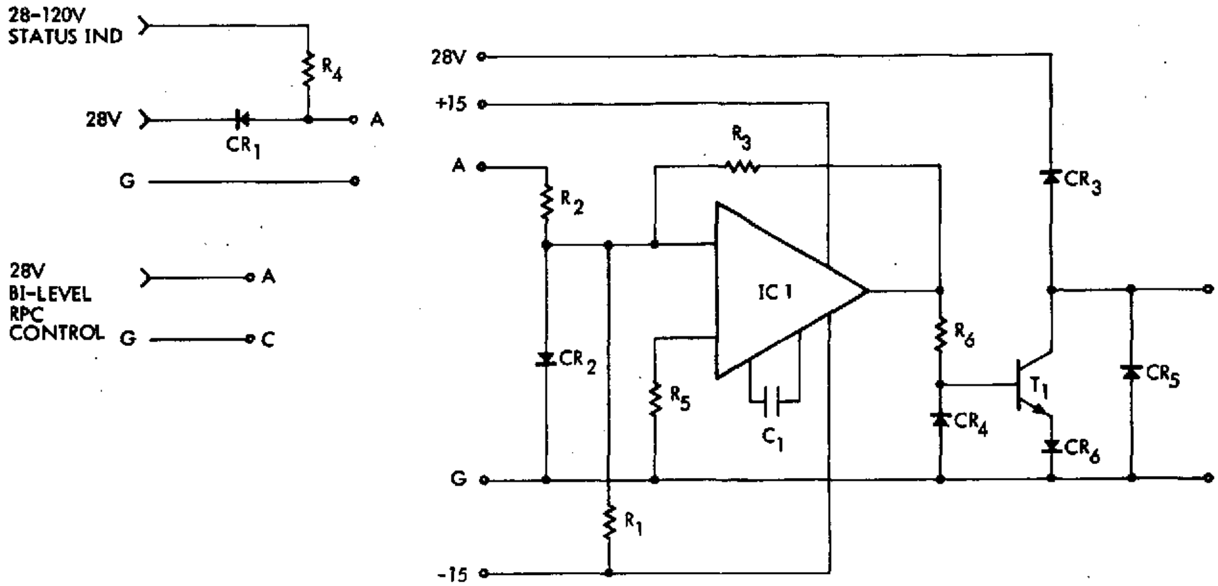
R_1 1.0 MEG, 1/4 W	C_1 90 PF
R_2 10.0K	C_2 0.02 UF
R_3 20.0K	IC LM101
R_4 6.0K	CR1, PT2268
R_5 1.0K	
R_6 33.0K	

NOTE:

(1) ALL RESISTANCES 1/8 WATT UNLESS OTHERWISE NOTED

Figure 3.2.2-7. BCU Voltage Signal Conditioning Circuit

The line voltage status and contactor (RPC) drive circuits use similar configurations (Figure 3.2.2-8) with minor modifications. The contactor drive function may be replaced with a simple toggle switch for the purposes of the BCU and the SMU, but compatibility with the ACES system and the intent to simulate flight program approaches suggest the use of this or equivalent circuits. The status signal conditioner may be used to drive up to four circuits although three is the maximum required (BCU, SMU, ACES).



R_1 1.0 MEG	CR_1-CR_6 PT-2268
R_2 1.0 MEG	C1 30 PF
R_3 3.0 MEG	IC1 LM101
R_4 0.1 MEG 2.0W	R_6 10K (100 MA CONTACTOR DRIVE)
T_1 PT4 7163	24K (LOGIC OR STATUS DRIVE)

Figure 3.2.2-8. Line Voltage Status Indicator or RPC Drive

3.2.2.3 Logic

The possible multiple paths in the BCU which provide the various switching configurations can also produce fault conditions which are a potential hazard to equipment and personnel. This situation can occur whenever two power sources are inadvertently connected in parallel. The possibility of switching errors is increased by the existence of two control panels operating on a logical "OR" basis. Since parallel operation is required and can be performed safely with a minimum of procedural control, it is necessary to provide a parallel source inhibit function with override controls and caution/warning alert panel lamps. A circuit configuration was developed to perform this function and is shown in Figure 3.2.2-9. This circuitry was developed during this phase of the study to demonstrate feasible solutions to test facility design problems and provide a realistic basis for parts count. The final design and worst case analysis is to be carried out at MSFC during the next phase of the program. The following is a brief description of circuit operation.

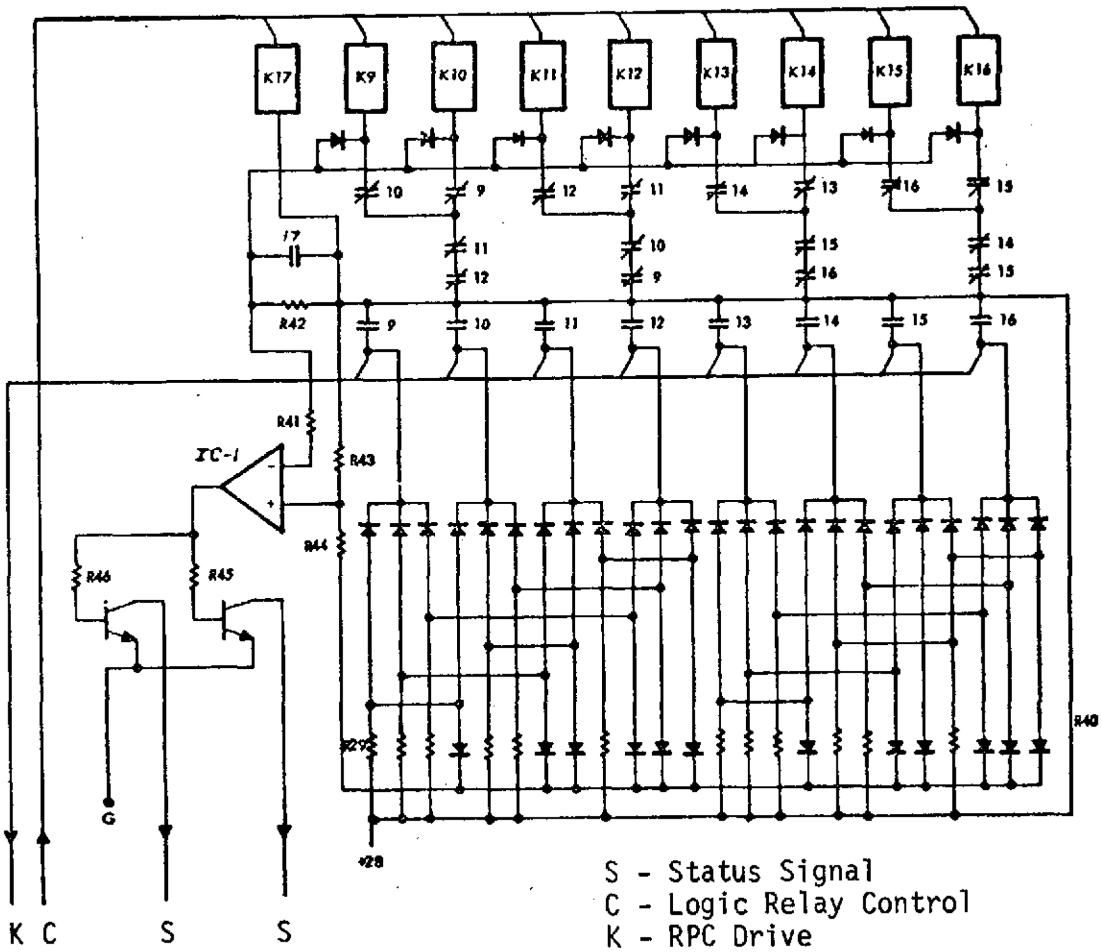


Figure 3.2.2-9. Parallel Source Protection Logic

The eight RPCs which connect power sources to the main bus are energized from 28V through the contacts of relays K9 through K16. Relays K9 through K12 energize RPCs which connect power sources to Bus I. Relays K13 through K16 energize RPCs which connect power sources to Bus II. Each relay is energized through the normally closed contacts of the other three relays in that bus group. Consequently, the operation of one relay prevents the operation of the remaining three relays in the bus group and inhibits the connection of two power sources to one main bus. When it is necessary to operate two power sources in parallel, relay K17 is operated which allows relays K9 through K16 to be operated independently. In this condition any combination of parallel sources may be implemented. The integrated circuit IC-1 provides the signal to the caution/warning panel light. With relay K17 open and all of the relays de-energized, there is sufficient bias on the negative input of IC-I to hold the panel light "off". Operation of relays which are not inhibited by the logic results in 28V being applied to one side of the blocking diodes which go to the relay solenoids. An attempt to operate a relay which is inhibited by the logic provides a low resistance path through the diodes, modifying the bias on IC-1 and energizes the C/W panel lamp. When the parallel source inhibit is removed, the bias on IC-1 is shifted (relay K17 operated), the C/W logic operates off the RPC solenoid voltages and is energized if two or more power sources are connected to the same bus. The effects of this logic on panel operation are summarized below:

- Inhibit Control On
  - Only one power source may be connected to each Bus
  - C/W panel lamp will operate if the attempt is made to connect two or more power sources to the same Bus
- Inhibit Control Off
  - All power sources may be connected to any Bus
  - C/W panel lamp will operate if two or more power sources are connected to either Bus

3.2.2.4 BCU Power

An auxiliary power bus is required in the BCU and load banks since the use of the 28-120 Vdc main bus would create an unrealistic circuit design problem. A 28V bus will be used to power all electrical and electronic circuitry and will be derived from a power supply located in the BCU. Where additional levels of voltage are required (±15 volts for LM101) a small dc/dc converter may be purchased. Converters which provide isolated, regulated outputs, with sufficient power to meet the requirement for the electronics in the BCU or a load bank are supplied by several vendors (Power/Mate Corp., Intronics Inc.) at a cost of $69.00 (EEM Catalog 1972-1973).

3.2.3 Load Banks

The load banks shall provide the power utilization equipment characteristics necessary to demonstrate the steady state and dynamic performance of the Power Distribution System for line voltages from 28 to 120 Vdc. The load banks must also serve as a test bed for state-of-art RPCs (Remote Power Controllers) and ACES (Automatically Controlled Electrical System). The design of the load banks will provide a valid simulation of the characteristics of spacecraft equipment which is in current use or proposed for future applications. Surplus or spare components will be used for loads where available since the direct purchase of qualified hardware is not consistent with planned program funding.

Solid state switchgear will become available from NASA sponsored development programs (Solid State Switchgear Technology Development, LeRC, NAS3-17771; Solid State Remote Power Control, MSFC, NAS8-29965) as well as from several industrial vendors. Equipment is also being developed specifically to simulate spacecraft load characteristics (Modular, High Power, Variable R Dynamic Electrical Load Simulator, NAS9-13495; High Power AC/DC Variable R Dynamic Electrical Load Simulator, NAS9-13524). Cooperative test and evaluation activities with these programs on the Multi-KW Power Distribution Test Facility would enhance the value of the total effort.

During the current phase of this study, a pulse width modulator has been designed to provide steady state active load simulation. Passive R, L, and C elements and available switchgear have been selected for evaluation of the distribution system transient dynamics and to provide steady state dc loads. Control interface configurations have been selected which are compatible with the ACES hardware currently available at MSFC.

3.2.3.1 Load Bank Configuration

The configuration of the power circuits in the load banks consist of a set of eight paths in parallel, each containing a fuse, RPC and load impedance. The relationship of these elements to the power distribution system is illustrated in Figure 3.2.3-1. Complexity has been restrained to a minimum since measurement accuracy and the capability to be responsive to new options as they occur are principle objectives of the configuration design. The functional schematic of Figure 3.2.3-2 illustrates the basic design areas of the load banks.

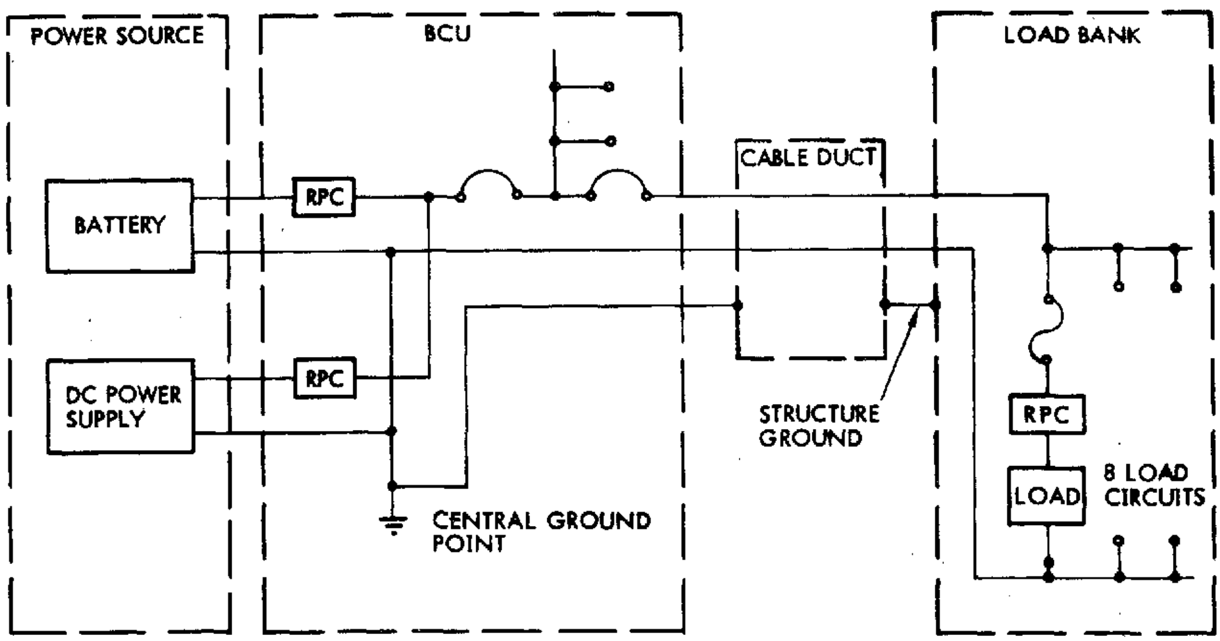


Figure 3.2.3-1. Power Distribution Circuit Elements

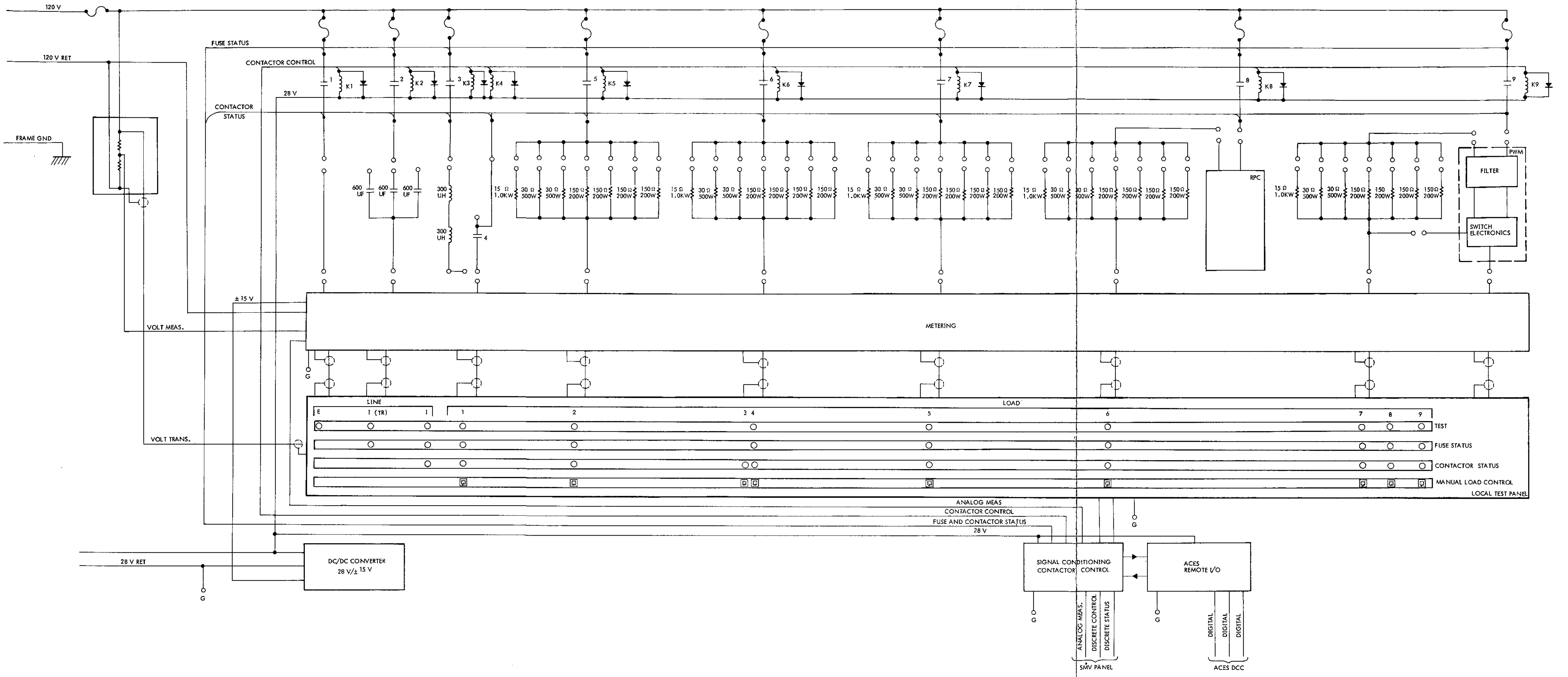


Figure 3.2.3-2. Load Bank Functional Schematic

The pulse width modulator was designed as part of this program to simulate dynamic loads which generate continuous perturbations of the distribution power; passive elements are used to simulate the majority of vehicle loads. In addition to the normal load switching transients, a full short circuit will be provided by the load bank to simulate a major power distribution fault. Loads are easily modified or combined to obtain any required configuration by the use of patch cords. Metering circuitry includes signal conditioning for remote panel displays and direct coupling from the meter shunts to the local test panel via coaxial cable to insure accurate transient measurements. Auxiliary dc/dc converters provide ± 15 volts for the integrated circuits and are discussed in Section 3.2.2.4 (BCU). The remote control interface includes analog and digital telemetry and command signals utilized by the SMU (Supervision and Monitor Unit) and ACES (Automatically Controlled Electrical System components) respectively. The load bank framework is bonded to the metallic cable duct which is grounded at the common ground point in the BCU to simulate the spacecraft structure.

The basis for the selection of this configuration and the technical details required are discussed in the following sections.

3.2.3.2 Interface Requirements

The definition of an electrical interface is comprised of a specification of impedance and signals crossing the interface. Spacecraft equipment input (interface) characteristics may be characterized by evaluating the behavior of each type of component on the basis of initial (turn-on) transient, steady state characteristics, and load profile. General characteristics of some typical loads as observed from the input terminals of each device are shown in Table 3.2.3-1. This listing of equipment is not all inclusive; however, the characteristics do typify the majority of load characteristics which will be encountered in a flight program.

Table 3.2.3-1. Spacecraft Load Characteristics

Equipment	Initial Transient	Load Profile	Simulation
Lights/Heaters	Inrush current 2-5 times steady state rating	Essentially constant resistance	Incandescent lamps
Digital Electronics	Step function	Constant current	Resistance
Analog Electronics	Step function	Load cycles from 10% to 100% at rates <10 Hz	Resistance cycle RPCs
RF Electronics	Step function	Load cycles from 10% to 100% at rates <110 Hz	Resistance cycle RPCs
Conversion, Regulation Equipment	Inrush current 2-3 times steady state rating	Load dependent	Pulse width modulator
Contactors, Solenoids	Inductive Transient	Constant resistance	Series inductance and resistance
Pyrotechnics	Rectangular Pulse/Arcing	0.05-0.1 sec duty cycle	Series resistance and fuse
Motors	Inrush current 3-5 times steady state rating	Duty cycle from seconds to minutes	Motors as available at MSFC

The effort to simulate the loads of Table 3.2.3-1 is considerably reduced by the standard practice of interposing EMI filters between the power line and the load impedance. In addition, for spacecraft in which a single voltage is distributed for power, the majority of subsystems normally require regulation and conversion equipment.

Components such as gyros, ac motors, fluorescent lighting and induction heaters all require dc/ac conversion. The power distribution interface for these components is then primarily determined by the input characteristics of the power conditioning equipment. Regardless of the type of power conversion equipment, the input characteristics will in general consist of the reactive impedance of the input filters and electrical noise with amplitude and frequencies within the spectral distribution permitted by the appropriate MIL specification. The simulation of all such equipment for this study is provided by the pulse width modulator.

3.2.3.3 Pulse Width Modulator (PWM)

The pulse width modulator is designed to be capable of functioning at frequencies from 5 KHz to 20 KHz. Manual potentiometer adjustments of frequency and pulse width control may be easily modified to provide remote voltage level control. Optimized filter designs can be provided for any parameter set of pulse width, frequency, input voltage, and power.

The functional schematic of the PWM is shown in Figure 3.2.3-3. Amplifiers IC-1 and IC-2 are connected in bistable and integrator configurations respectively. The positive feedback path (R_4) causes this circuit to function as a free running sawtooth generator. Transitions occur when the current in R_4 is essentially equal and opposite to the current in R_1; the sawtooth slope is controlled by resistor R_5. Since both the slope and the triggering point are linear functions of the saturation voltage of IC-1,

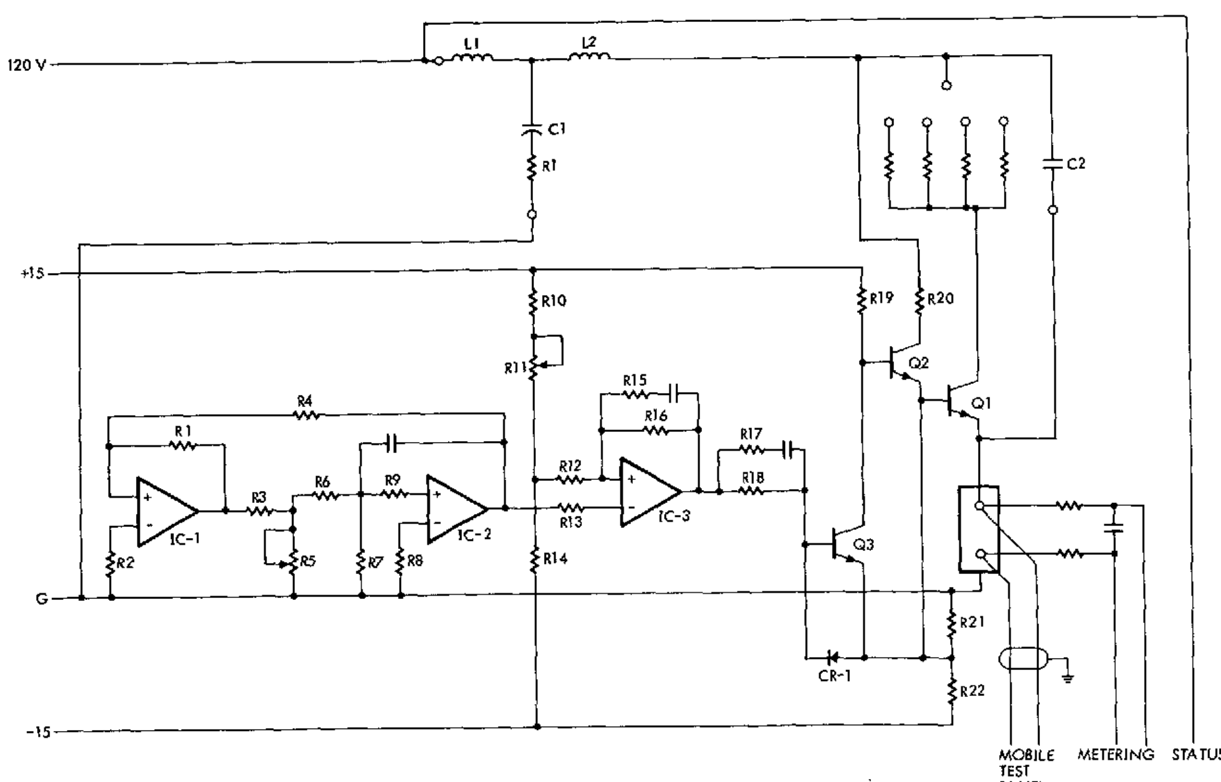


Figure 3.2.3-3. PWM Functional Schematic

variations of this voltage do not affect frequency. The pulse is generated by threshold detector IC-3 and width is controlled by R_{11}. The remainder of the electronics is a straightforward power amplifier with 1.5 to 2.0 amperes drive to the final stage. Circuits for metering and the local mobile test panel are tapped off the current shunt. Since no load output is required from the PWM (only input characteristics are of importance), the grounded emitter switching transistor (Q1) is an acceptable configuration and will greatly facilitate achievement of the sharp switching transitions required for the upper frequency limit (20 KC) and high power. The use of resistive loads in the collector of Q1 provides a limitation on peak dissipation and reduces the tendency for secondary breakdown during transitions. There are a number of transistors with advertised characteristics which are in excess of the capability required for this program. For example, the present Solitron designs (SDT 5855-SDT 5858) withstand collector voltages in excess of 400V and would be able to draw a 30 ampere load (60A peak) at 50% duty cycle. This would effectively provide a 3.6 KW converter interface with a 120 Vdc line voltage. The faster response types (SDT 5820-SDT 5823) would provide a 100 ampere (200A peak) load but are marginal (200V max.) in collector breakdown voltage rating when 120 Vdc line and input filter overshoot (180V peak) is considered.

The combination of these transistors could provide a possible 2.5 KW power conditioning load to the power distribution system over the range of line voltage (28 - 120 Vdc) to be used in the system testing. Practical consideration of transistor time constants and drive circuit design reduce the maximum power which can be obtained in a reasonably economical laboratory development. It is estimated on the basis of the transistor characteristics supplied by Solitron that PWM designs which would provide a 500 watt simulated power conditioning load over the full range of line voltage could be implemented with the configuration of Figure 3.2.3-3.

The filter for the PWM must be designed for each combination of line voltage, power, and operating frequency. A filter design computer program has been assembled based on work previously performed at TRW in the area of optimum coil design and PWM filter design. The program accepts inputs of voltage, power and frequency and calculates all the necessary design criteria for a weight optimized PWM filter. The details of this design program are given in Appendix A. The electrical properties of PWM filters for several combinations of line voltage power and frequency are given in Table 3.2.3-2.

Table 3.2.3-2. PWM Filter - Electrical Parameters

			FILTER DESIGN					
Line Voltage Volts	Freq KHz	Power W	L_1 uH	L_2 uH	I Amps	C_1 uF	C_2 uF	R_1 Ohms
120	20	138	633	316	1.15	30	3	6.8
120	20	300	345	172	2.5	90	9	2.9
120	20	600	322	161	5.0	150	15	2.2
120	20	1200	280	140	10.0	270	27	1.5
120	20	2400	233	116	20.0	510	51	1.0
120	10	138	435	217	1.15	60	6	4.0
120	10	300	279	140	2.5	150	15	2.0
120	10	600	238	119	5.0	270	27	1.4
120	10	1200	195	97.6	10.0	510	51	0.92
120	10	2400	152	75.9	20	1020	102	0.57
28	20	100	195	97.4	3.57	200	20	1.46
28	20	250	141	70.3	8.93	500	50	0.79
28	20	500	123	61.3	17.9	900	90	0.55
28	20	750	103	51.3	26.8	1400	140	0.40
28	20	1500	83.7	41.8	53.6	2700	270	
28	20	2500	70.2	35.1	89.3	4500	450	0.19
28	10	100	130	65.2	3.57	400	40	0.85
28	10	250	103	51.5	8.93	900	90	0.50
28	10	500	80.1	40.1	17.9	1800	180	0.31
28	10	750	69.2	34.6	26.8	2700	270	0.24
28	10	1500	54.1	27.0	53.6	5400	540	0.15
28	10	2500	45.2	22.6	89.3	9000	900	0.11

3.2.3.4 Solid State Remote Power Controller (SSRPC)

Although SSRPCs are not part of the design effort of this effort, the inclusion of these devices in the test facility is one of the principle objectives of this program. SSRPCs are electronically controlled semiconductor switches. The designs include specified overload trip characteristics, reset capability, and remote trip indication. These devices are the logical means for implementation of switching in an automated power system with centralized control. The considerable potential advantages include stability of trip characteristics, contact life, and low transition noise due to elimination of contact bounce, arcing, and inductive transients. Historically, electronic switches have been used in low (signal) power or specialized power switching applications. During recent years, the increased capability of the switching elements to withstand higher voltages and conduct larger currents together with the need to obtain improved switching characteristics has accelerated efforts to realize the potential gains of the solid state switch. A functional block diagram of an SSRPC is illustrated in Figure 3.2.3-4. The functions of this device include on/off control, control of overload trip characteristic, status indication, and a timing signal. The latter is used to reset the switch to the on position at a specified time after an overloap trip. This may be repeated two or three times; if the overload condition persists, the switch locks open and transmits a load fault indication.

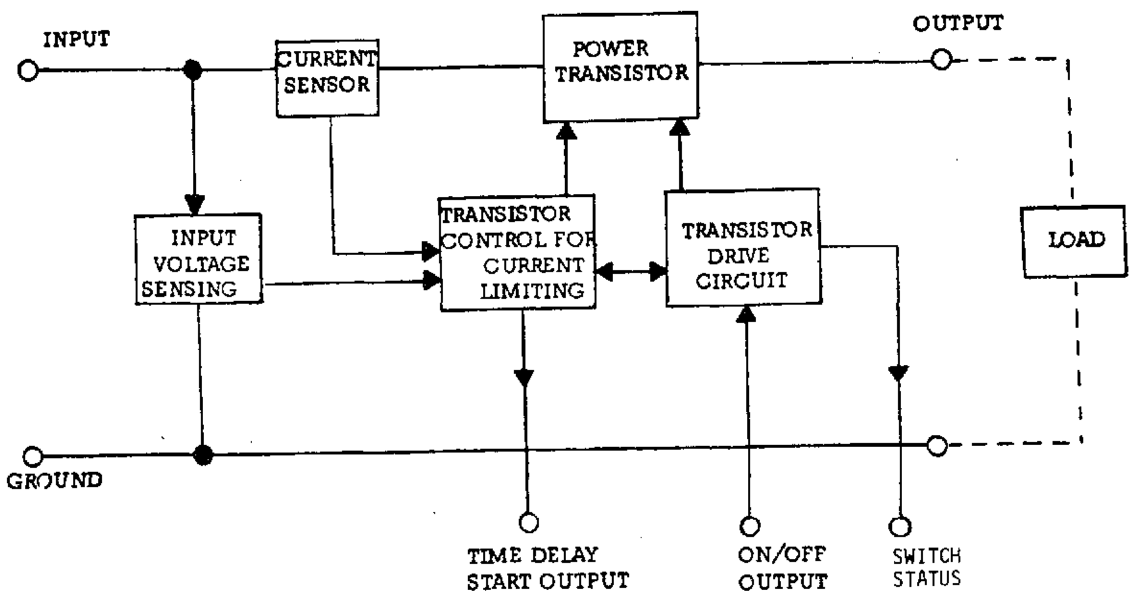


Figure 3.2.3-4. SSRPC Block Diagram

Some of the basic considerations which must be resolved for SSRPCs are the effect of transient and noise spikes on the switch and control circuitry, the ability to withstand major fault conditions, and the compatibility of this approach with other power control devices which can exist in spacecraft power distribution systems. It is necessary to obtain operating experience and life test data to evaluate and establish confidence in the performance of the SSRPC.

At the present time, Westinghouse is under contract with NASA Lewis Research Center to develop three SSRPC designs. The requirements placed on this development are given in Tables 3.2.3-3, -4, and -5. The design effort on this contract (Solid State Switchgear Technology Development, NAS3-17771) will be completed 7-26-74.

MSFC has been actively pursuing the development of solid state switches. This effort has resulted in designs which are manufactured by Spacecraft Inc. (Huntsville, Ala.). These devices are well beyond the breadboard stage and are planned for flight qualification in 1974.

MSFC has been actively pursuing the development of solid state switches. This effort has resulted in 5 and 10 ampere, 28 Vdc designs which are manufactured by Spacecraft Inc. Qualification of these units is planned for 1974. Current development at MSFC includes 5 and 10 ampere, 120 Vdc designs. Initial designs are expected to be completed May 1, 1974. The next phase of this study will result in qualification models with tests starting early in 1975. With the exception of the nominal voltage/current rating, the electrical characteristics of all units are identical and are represented by the requirements for the 28 Vdc, 5 ampere unit given in Table 3.2.3-6.

3.2.3.5 Passive Loads

The dynamic transient performance of the power distribution system will be evaluated with passive loads. These will primarily consist of heavy power resistors. Inductors and capacitors will be added in series or parallel to simulate the input filtering. The major function of these loads will be to

Table 3.2.3-3. Detailed Performance Requirements (LeRC) Type I Solid State Switch

Voltage Rating	120 ± 12 VDC steady state
Voltage Transients	+200V peak and -65 V peak for 50 microseconds
Current Rating	5 amperes dc
Load Protection Characteristics . .	3X current limiting
Trip Time	$T = \frac{20}{I^2 - 6^2}$
ON Voltage Drop	1.0 volts at rated current
OFF Leakage Current	5 milliamps
Output Rise & Fall Time. . . .	10^{-5} to 10^{-2} seconds at rated load
Power Consumption	"shall be minimized" (Westinghouse design goal, 12 watts max. on and 2.5 watts max. off worst case.)
Operating Temperature	$-55^{\circ}C$ to $+ 100^{\circ}C$
Control Input Voltage	15 Vdc ± 10%
Reset.	By relaxing input control signal or by optional automatic reset (3 times)
Control Input Current	Not specified. Westinghouse design goal 10 milliamps at 15 Vdc.
Status Indication.	"Sinking" type. 10 milliamp capability. Will indicate open or closed state of switchgear.
Dielectric Isolation	100 VAC between power and control terminals.

Table 3.2.3-4. Detailed Performance Requirements (LeRC)
Type II Solid State Switch

Voltage Rating	120 ± 12 VDC steady state
Voltage Transients	+200V peak and -65V peak for 50 microseconds
Current Rating	5 amperes dc
Load Protection Characteristics	3X, 4X or 5X Instant Trip, Selectable
Trip Time	$T = \frac{5}{I^2 - 6^2}$
ON Voltage Drop	1.0 volts at rated current
OFF Leakage Current	5 milliamp
Output Rise & Fall Time	10^{-5} to 10^{-2} seconds at rated load
Power Consumption	"shall be minimized" (Westinghouse design goal, 17 watts max. on and 2.5 watts max. off worst case)
Operating Temperature	$-55^{o}C$ to $+100^{o}C$
Control Input Voltage	15V dc ± 10%
Reset	By relaxing input control voltage or by optional automatic preset (3 times)
Control Input Current	Not specified, Westinghouse design goal is 10 milliamps at 15 volt
Status Indication	"Sinking" type, 10 milliamps capability. Will indicate open or closed state of switchgear
Dielectric Isolation	1000 VAC between power and control terminals

Table 3.2.3-5. Detailed Performance Requirements (LeRC)
Type III Solid State Switch

Voltage Rating	120 $\pm$ 12 VDC steady state
Voltage Transients.	+200V peak and -65V peak for 50 microseconds
Current Rating	30 amperes dc
Load Protection Characteristics .	2X or 3X Instant Trip, Selectable
Trip Time.	$T = \frac{100}{I^2 - 36^2}$
ON Voltage Drop	1.0 volts at rated current
OFF Leakage Current	5 milli-amp
Output Rise and Fall Time . .	10^{-5} to 10^{-2} seconds at rated load
Power Consumption.	"shall be minimized" (Westinghouse design goal, 40 watts max. on and 2.5 watts max. off worst case)
Operating Temperature	-55°C to +100°C
Control Input Voltage	15 Vdc $\pm$ 10%
Reset	By relaxing control input or by optional automatic reset (3 times)
Control Input Current	Not specified, Westinghouse design goal 10 milliamps at 15 Vdc
Status Indication	"Sinking" type, 10 milliamp capability Will indicate open or closed state of switchgear
Dielectric Isolation	1000 Vac between power and control terminals

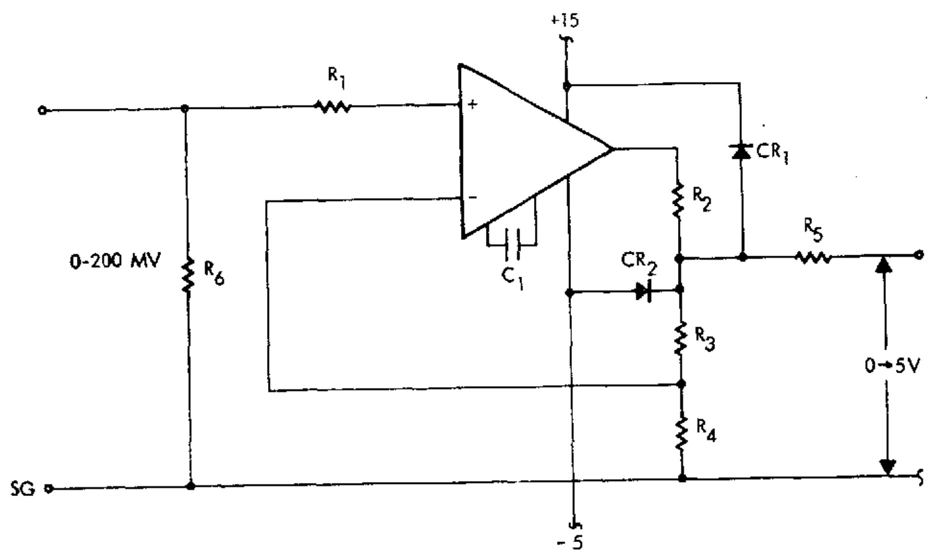
Table 3.2.3-6. Electrical Characteristics Solid State Switch (MSFC)

Rated operating voltage	28 ± 4 Vdc
Output current rating	5 amperes
Control voltage nominal	28 ± 4 Vdc
Turn-on voltage minimum	18 Vdc
Turn-off voltage maximum	5 Vdc
Turn-on time maximum	2.5 milliseconds
Turn-off time maximum	2.5 milliseconds
Output rise time maximum	700 microseconds
Output fall time minimum	700 microseconds
Control/reset input current maximum	50 milliamperes
Control/reset frequency rejection maximum	50 μsec time base
Output voltage drop (maximum)	250 millivolts
Power dissipation - ON (Maximum)	7.5 watts
Power dissipation - OFF (Maximum)	175 milliwatts
Power dissipation - Tripped (Maximum)	700 milliwatts
Output leakage current (Maximum)	100 microamperes
Fail safe current maximum	700% time rated current
Fail safe current minimum	500% time rated current
Power output status indication current rating maximum	15 milliamperes
Power output status indication OFF leakage (maximum)	10 microamperes

generate on/off transients over a sufficient range of current and voltage to provide an adequate field of data for the evaluation of 28 to 120 Vdc broadband EMI. These elements will also supply the correct impedance interface during the evaluation of dynamic loads and major fault (short circuit) transients.

3.2.3.6 Metering and Control

Line voltage will be measured and line voltage, fuse and RPC state will be sensed. The recommended circuitry for these functions and for RPC control is identical to the similar functions in the BCU (Section 3.2.2.2). Current measurements for remote monitors and sensing of current transients for local test equipment are performed with a current shunt. A typical signal conditioning circuit for current measurement is illustrated in Figure 3.2.3-5.



R_1 = 1.0K
R_2 = 25K
R_3 = 25K
R_4 = 1.0K
R_5 = 1.0K
R_6 = 1.0K
C_1 = 30 PF

Figure 3.2.3-5. Signal Conditioning Circuit
Current Measurement

Based on the published characteristics, maximum output offset will be less than 3%; drift with time and temperature will be negligible. This tolerance should be adequate for the purposes of the remote monitor (SMU). Signal ground (SG) for these signal conditioners is derived from the secondary circuit of the 28/±15 Vdc converter. The only connection to the 28V ground and/or main bus return is through the shunt for the main bus current as will be shown in Figure 3.2.3-6. There will be no direct connection of SG to the central ground point of the BCU.

An overview of the elements required for each of the eight load circuits in a load bank is shown in Figure 3.2.3-6. Elements which perform one function per load bank or provide a common function to all load circuits are marked Ⓑ.

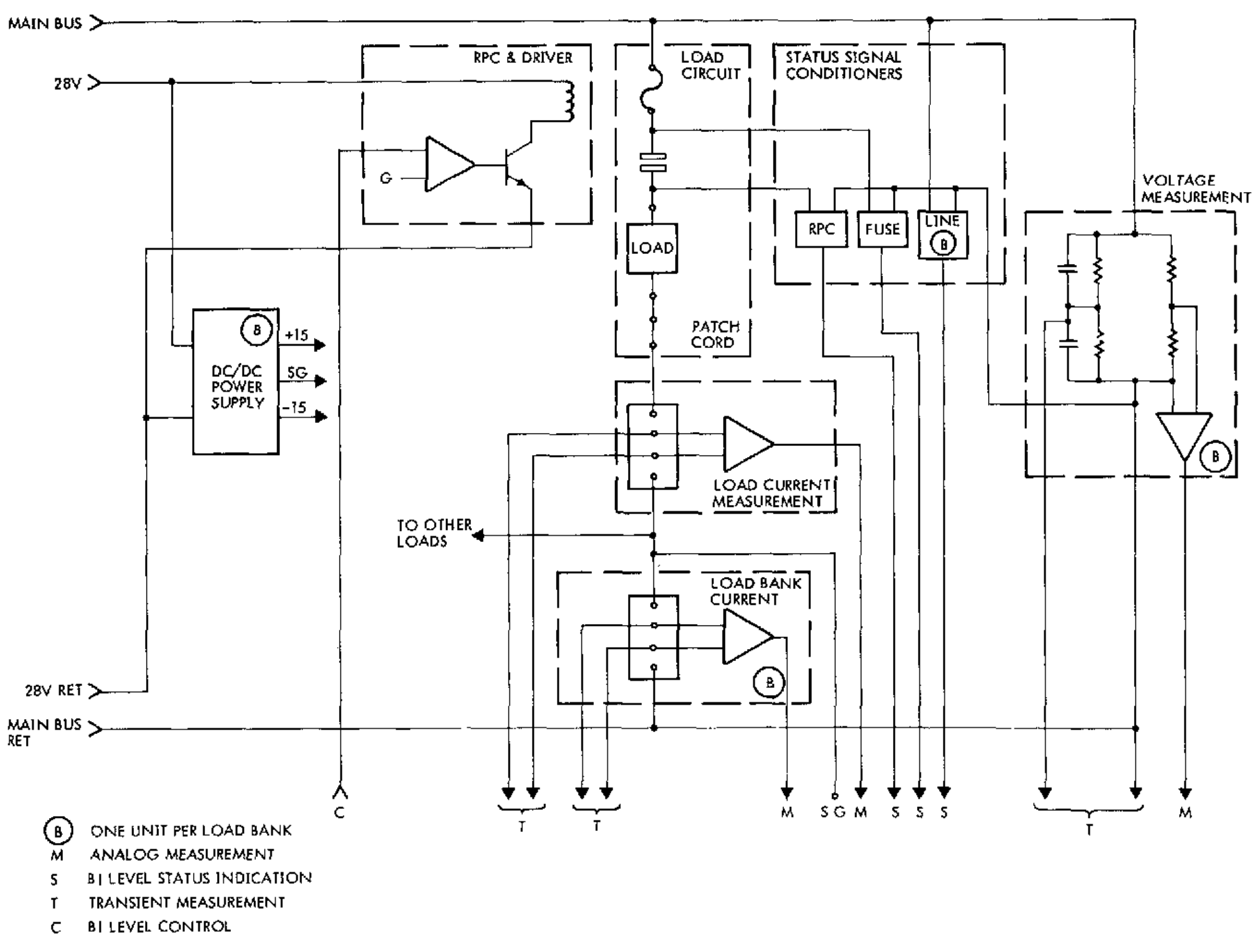


Figure 3.2.3-6. Functional Schematic for One Load Circuit

3.2.3.7 Piece Part Estimate

Piece part estimates based on the above discussions are shown in Tables 3.2.3-7 and -8. The parts list for the power circuits assumes a 100 ampere capability per load bank and is considered an accurate estimate. The electronics parts required for instrumentation and T/C circuitry is an estimate based on the model control and signal conditioning circuits illustrated in Section 3.2.3.6 and Section 3.2.2.2 (BCU).

Table 3.2.3-7. Load Bank Parts Requirement
Power System Loads

QTY	PART	DESCRIPTION	COMMENTS
5	RESISTOR	15 Ω, 1 KW	MANF., GLOBAR, MILWAUKEE
10	RESISTOR	30 Ω, 0.5 KW	MANF., GLOBAR, MILWAUKEE
25	RESISTOR	150 Ω, 200 W	(ORDERED)
4	LAMP	120 VOLT, 250 W	
2	INDUCTOR	300 UH, 5 AMP	
3	CAPACITOR	600 UF, 400 VDC	PAPER/PYRANOL, PAPER/MYLAR
1	CONTACTOR	400 AMP, 120 VDC	(ON ORDER)
6	CONTACTOR	40 AMP, 120 VDC	(ON ORDER)
1	CONTACTOR	50 AMP, 120 VDC	(ON ORDER)
8	METER SHUNT	30 AMP, 200 MV	(ON ORDER)
1	METER SHUNT	300 AMP, 200 MV	(ON ORDER)

Table 3.2.3-8. Load Bank Electronics and Controls
Estimate (Information Only)

QTY	PART	DESCRIPTION	COMMENTS
130	RESISTOR	1/8 WATT	MISCELLANEOUS VALUES
20	RESISTOR	1.0 WATT	MISCELLANEOUS VALUES
20	CAPACITOR	30-90 PF, 50V	IC STABILIZATION
40	CAPACITOR	0.1-1.0 UF, 50V	FILTERING
30	DIODE	- -	PT4-2268 OR EQUIVALENT
30	TRANSISTOR	- -	PT4-7163 OR EQUIVALENT
20	IC OP AMP	- - -	LM-101 OR EQUIVALENT
4	IC OP AMP	- -	LM-106 OR EQUIVALENT
4	TRANSISTOR	400V, 40 AMP	SDT5855 OR EQUIVALENT
1	DC/DC CONVERTER	28/±15V, 0.1 AMP	INTRONICS, POWER MATE
1	ACES REMOTE I/O	- -	WESTINGHOUSE

3.2.4 Cable, Harness and Wiring

3.2.4.1 Introduction

The cabling subsystem transmits power and control signals to the load banks and returns measurement data to the control panels. The selected configuration provides a simple and economical simulation of the electrical/ electromagnetic characteristics of a distribution harness for a large space vehicle and provides sufficient access to accommodate a flexible test program. The configuration of the cabling harness meets the requirements established by MSFC Specification 40M39582, "Harness, Electrical Design Standard." The following sections discuss the cable design details based on that specification.

3.2.4.2 Cable Design

(a) Classification - Type IV - Open Bundle

This classification is for general use outside the crew compartment area. The electrical characteristics of this cable will be similar to those of a crew compartment area cable and the economical open construction provides better access for test and inspection than the enclosed designs.

(b) Style - Style B

Spot ties were selected for reasons of economy and ease of fabrication.

(c) Lay of Wire - Configuration T - Twisted

This configuration minimizes radiated and coupled EMI. Random lay would provide better access and ease of fabrication but does not have the desired characteristics for simulation of a flight harness.

(d) Wire

The wire shall be stranded wire nickel plated copper or copper alloy.

(e) Insulation

The selection of wire insulation will be dependent on cost or availability at MSFC but will provide an effective simulation of the dielectric constant of 300V flight cable.

(f) Current Carrying Capacity

The allowable current capacity of wire in an aerospace design program is constrained by allowable temperature rise and voltage drop, optimization requirements and specific application conditions. It is necessary to establish constraints on the test facility in order to perform adequate simulation of a flight harness and provide baseline conditions for comparison of distribution harnesses at various line voltages. The current allowed in bundled cable with a maximum temperature rise of 50° in an exposed space environment is specified in 40M39582 (Section 4.1.3.2, Table I). Due to the high current to be used in this facility, it is planned to use AWG #8 which is not included in this table. An extrapolation of the current values in the table was performed to include AWG #10 and AWG #8. The revised current constraints are shown in Table 3.2.4-1.

Table 3.2.4-1

Wire Size	Maximum Design Current (Amperes)
24	1.5
22	3.0
20	4.0
18	5.0
16	6.0
14	8.0
12	11.0
10	14.5
8	20.0

Optimization of line voltage drop or losses is usually performed with respect to the total system weight as follows:

$W_s = W_c + W_g$	W_s	=	System Weight
	W_c	=	Cable Weight (Kg)
	W_g	=	Generator Weight (Kg)
$W_c = w_c \ell A$	w_c	=	Copper density (Kg/M^3)
	ℓ	=	Cable length (M)
$W_g = w_g P$	A	=	Copper Cross-section (M^2)
	w_g	=	Generator Weight Factor (Kg/watt)
$P = P_L + I^2R$	P	=	Total Power (watts)
	P_L	=	Load Power (watts)
	I	=	Line Current (amp)
	R	=	Line Resistance
	G	=	Copper Resistivity (ohm-meters)

$$W_s = w_c \ell A + w_g \left(P_L + \frac{I^2 G \ell}{A}\right)$$

System weight is a minimum when

$$A/I = \sqrt{\frac{w_g G}{w_c}} \quad \frac{\text{Meter}^2}{\text{Amp}}$$

Substituting numerical values indicates that the generator weight factor for which a twenty (20) ampere current in AWG #8 cable provides an optimum system design is

$$w_g = 0.06 \text{ Kg/watt}$$

Since this value lies within the range of large power source weight factors (0.03 to 0.3 Kg per watt), the indicated current density (240 amperes/cm^2) will be regarded as minimum for this program.

The voltage drop incurred in the power line bus and ground at the above current density for a sixty-one meter line is 5.9 volts or approximately a 5% power loss for a 120V bus. The loss for a 28V bus is greater than 20%. Since none of the power loads are voltage sensitive, no recommendation will be made to plan a maximum constraint on voltage losses during this phase of the program. Based on the above discussion, Table 3.2.4-2 is modified for primary power distribution.

Table 3.2.4-2

Maximum Current for Primary Power Distribution

AWG	Maximum Design Current Amperes
12	7.9
10	12.6
8	20

3.4.2.3 Short Circuit Conditions

During the test program it is expected to perform short circuit tests on the primary power distribution of the test facility. Although the performance of a power distribution harness under these conditions is not well known and is the purpose of the tests, a brief description of some of the obvious and expected results is appropriate to this section. A more detailed analysis of short circuit conditions will be made in later sections of this report.

Under steady state high-current conditions, the conductor will heat to the melting point (1083°C) where temperature will remain constant until the metal in that region is completely melted. Heating then continues until the vaporization temperature is reached (3300°C). Beyond this temperature arcing occurs. As the temperature in the wire increases the

3.2.4.4 Cable Configuration

The general configuration of the cable harnesses is shown in Figure 3.2.4-1. Two battery racks and two dc power supplies comprise the power sources for power distribution tests. Current for the main power distribution bus flows from the power source to the load banks via the BCU, cable duct and junction boxes. There will be no splices or junctions in the cable wires for the purpose of conducting power currents although the conductors may be exposed and terminals attached for test voltage measurements. The lengths of the power distribution cables are in increments of approximately fifteen meters (50') with a maximum of sixty-one meters (200'). The main power distribution harness will be separate from secondary power, telemetry and control distribution harnesses but will be routed through the same duct.

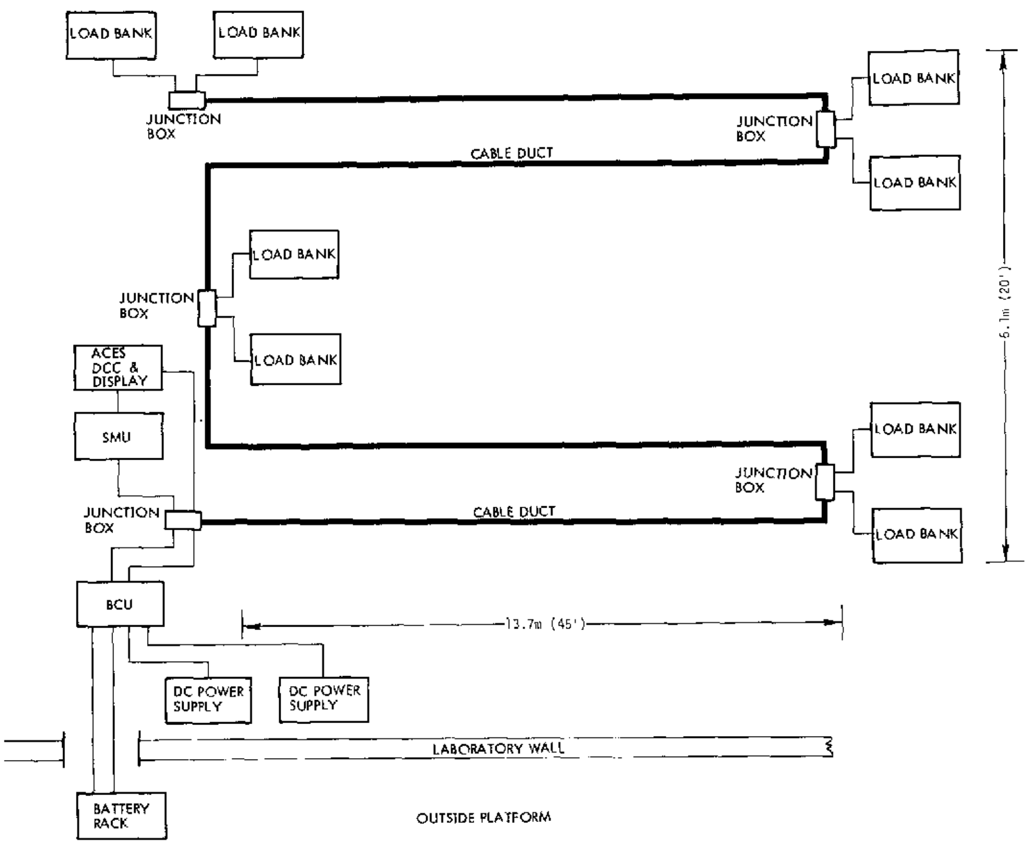


Figure 3.2.4-1. High Voltage Power Distribution System Test Facility

The cable duct provides support for the cable, simulates vehicle structure and provides protection from arcing for the operating personnel. The cross-section of the duct should provide 9.7 cm^2 for each (100A) load bank served; cable weight is approximately 1.0 kg/m for each (100A) load bank served. Although the present planned capability of the power supplies is three hundred amperes (300A), it is assumed that six load banks with one hundred ampere capability may be used in the facility. On this basis, the requirements for the cable duct are

Conductor Carrying Cross-Section	58 cm^2
Support Weight	6.25 kg/m

3.2.4.5 Cable Configuration

The routing of each cable required for the test facility is shown in Figure 3.2.4-2. It should be noted that the cables in the cable duct are representative of the cables for one load bank and will be repeated for each additional load bank. Table 3.2.4-3 provides general information for each cable.

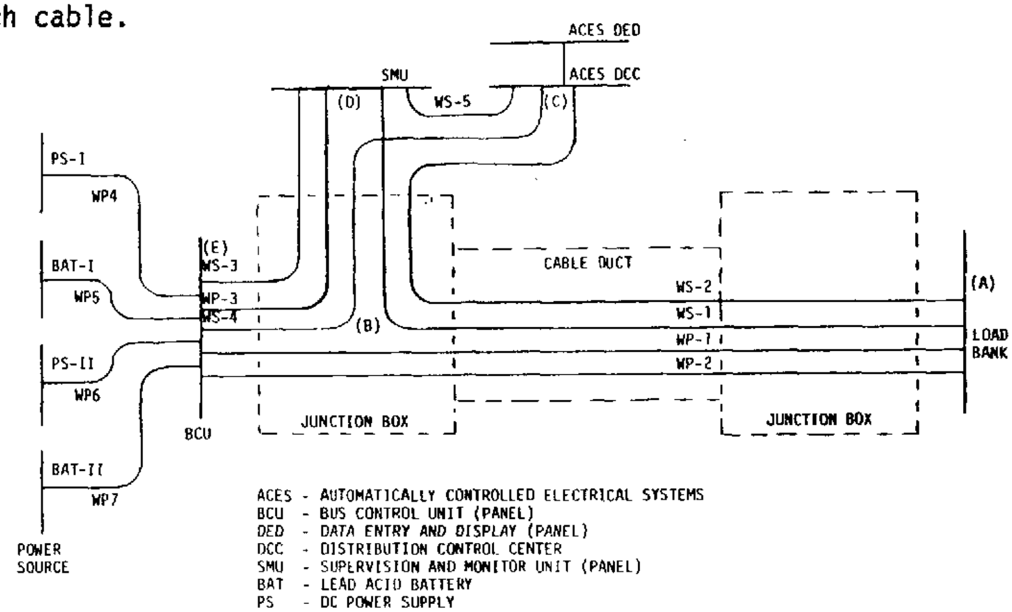


Figure 3.2.4-2. HVDC Power Distribution System Cable Connection Diagram

Table 3.2.4-3

Cable	Function	Make/Buy	Source
WP1	Main Power Distribution	M	Wiring List
WP2	Secondary Power Distribution	M	Wiring List
WP3	Auxiliary Power Distribution	M	TBS (1)
WP4	Main Power Distribution	B	Vendor/Christie Electric (2)
WP5	Main Power Distribution	B	Vendor (3)
WP6	Main Power Distribution	B	Vendor/Christie Electric (2)
WP7	Main Power Distribution	B	Vendor (3)
WS1	Telemetry/Command	M	Wiring List
WS2	Telemetry/Command	M/B	Westinghouse Drawing (4)
WS3	Telemetry/Command	M	Wiring List
WS4	Telemetry/Command	M/B	Westinghouse Drawing (4)

(1) WP3 - Spare power cable carrying ac and/or dc to supply for needs for auxiliary instruments, ACES, etc. to be determined at time of installation.

(2) WP4, WP6 - DC Power Supply Cables - Lengths to be determined at time of installation.

(3) WP5, WP7 - DC Battery Supply Cables - Lengths to be determined at time of installation. Since these cables will supply large surge currents, inductance, stray fields and pair resistance should be minimized and controlled. Welding cable is commercially available in sizes up to 4/0 and rated at 550 amperes. Procurement of this cable for this application is recommended.

(4) WS2, WS4 - ACES data and command cables are defined in the ACES manual. These cables may be made to MSFC standards (40M39582) or purchased to commercial standards (see below).

Commercial sources are available for all cables with the exception of WP1 if the nickel-coated requirement is waived. Since the tests to be undertaken primarily involve the main power distribution, this would represent an economical implementation without compromising the intent of the program.

3.2.4.6 Wiring Lists

The wiring lists for cables WP1, WP2, WS1, and WS3 are presented in Tables 3.2.4-4 through 3.2.4-7. It should be noted that cable WP1 is designed for 100 amperes, the maximum current considered for a single load bank. For designs which have decreased current requirements, one pair of #8 wire may be deleted for each decrement of 20 amperes from 100 amperes.

Table 3.2.4-4. Component-Cable, Ident. #WP-1, Routing A-B-E

ITEM	AWG GAUGE	CURRENT AMPS	VOLTAGE VOLTS	SIGNAL	FUNCTION	DESTINATION	ORIGIN
1	8	20	300	DC	POWER-MAIN BUS	LB-FUSE BLK	BCU BRKR
2							
3							
4							
5			300		POWER-MAIN BUS	LB-FUSE BLK	BCU BRKR
6			-		POWER-MAIN RET	LB-MAIN RET	BCU-CGP
7			-				
8			-				
9			-				
10	8	20	-	DC	POWER-MAIN RET	LB-MAIN RET	BCU-CGP
11	12	-	-	-	TEST SPARE	LB-TERM	BCU-TERM
12	12	-	-	-	TEST SPARE	LB-TERM	BCU-TERM

Table 3.2.4-5. Component-Cable, Ident. #WP-2, Routing A-B-E

ITEM	AWG GAUGE	CURRENT AMPS	VOLTAGE VOLTS	SIGNAL	FUNCTION	DESTINATION	ORIGIN
1	22	2	30	DC	POWER 28V BUS	LB-FUSE BLK	BCU-28V PS
2	22	2	-	DC	POWER 28V RET	LB-28V GRND	BCU-CGP
3	22	-	-	DC	SEC PWR GRND	LB-SEC PWR GRND	BCU-SEC PWR GRND
4	22	-	-	-	TEST SPARE	LB-TERM	LB-TERM
5	22	-	-	-	TEST SPARE	LB-TERM	LB-TERM

Table 3.2.4-6. Component-Cable, Ident. #WS-1, Routing A-B-D

ITEM	AWG GAUGE	CURRENT AMPS	VOLTAGE VOLTS	SIGNAL	FUNCTION	DESTINATION	ORIGIN
1	24	0.040	28	BI-LEVEL	STATUS-FUSE	SMU PL	LB-FUSE #1
2							LB-FUSE #2
3							LB-FUSE #3
4							LB-FUSE #4
5							LB-FUSE #5
6							LB-FUSE #6
7							LB-FUSE #7
8							LB-FUSE #8
9	24	0.040	28	BI-LEVEL	STATUS-FUSE	SMU PL	LB-FUSE #9
10	24	0.040	28	BI-LEVEL	STATUS-CONTACTOR	SMU PL	LB-K1
11							LB-K2
12							LB-K3
13							LB-K4
14							LB-K5
15							LB-K6
16							LB-K7
17							LB-K8
18	24	0.040	28	BI-LEVEL	STATUS-CONTACTOR	SMU PL	LB-K9
19	24	0.025	28	BI-LEVEL	COMMAND CONTACTOR	LB-CD1	SMU-SW
20						LB-CD2	SMU-SW
21						LB-CD3	SMU-SW
22						LB-CD4	SMU-SW
23						LB-CD5	SMU-SW
24						LB-CD6	SMU-SW
25						LB-CD7	SMU-SW
26						LB-CD8	SMU-SW
27	24	0.025	28	BI-LEVEL	COMMAND CONTACTOR	LB-CD9	SMU-SW
28	24	< 0.01	28	ANALOG	MEAS VOLTAGE	SMU-METER	LB 28V BUS
29	24	< 0.01	15	ANALOG	MEAS VOLTAGE	SMU-METER	LB +15V BUS
30	24	< 0.01	15	ANALOG	MEAS VOLTAGE	SMU-METER	LB -15V BUS
31	24	< 0.01	30	ANALOG	MEAS VOLTAGE	SMU-METER	LB MAIN BUS SC 10
32	24	< 0.01	5	ANALOG	MEAS CURRENT	SMU-METER	LB SC1
33							LB SC2
34							LB SC3
35							LB SC4
36							LB SC5
37							LB SC6
38							LB SC7
39							LB SC8
40	24	< 0.01	5	ANALOG	MEAS CURRENT	SMU-METER	LB SCD
41	24	1.0	28	DC	POWER	SMU-SW	LB 28V BUS
42	24	0.1	-	DC	28V RET	SMU-SW	LB 28V RET
43	24	0.1	-	DC	±15V RET	SMU-SW	LB ±15V RET
44	24	-	300	DC	MAIN BUS RET	SMU-SW	LB MAIN BUS RET
45	24	-	300	-	TEST SPARE	SMU TERM	LB TERM
46	24	-	300	-	TEST SPARE	SMU TERM	LB TERM

Table 3.2.4-7. Component-Cable, Ident. #WS-3, Routing C-B-E

ITEM	AWG GAUGE	CURRENT AMPS	VOLTAGE VOLTS	SIGNAL TYPE	FUNCTION	DESTINATION	ORIGIN
1	24	0.04	28	BI-LEVEL	STATUS PS 1	SMU PL	BCU-SLC
2					BAT 1		
3					PS 2		
4					BAT 2		
5					MAIN BUS 1		
6					MAIN BUS 2		
7					LOAD BUS 1		
8					LOAD BUS 2		
9					LOAD BUS 3		
10					LOAD BUS 4		
11					LOAD BUS 5		
12					LOAD BUS 6		
13					LOAD BUS 7		
14					LOAD BUS 8		
15					PARALLEL ALERT		
16	24	0.04	28	BI-LEVEL	STATUS PARALLEL ACTIVE	SMU PL	BCU-SLC
17	24	<0.01	5	ANALOG	MEAS CURRENT PS 1	SMU METER	BCU CS1
18					CURRENT BAT 1		BCU CS2
19					CURRENT PS 2		BCU CS3
20					CURRENT BAT 2		BCU CS4
21					CURRENT MAIN BUS 1		BCU CS5
22					CURRENT MAIN BUS 2		BCU CS6
23					VOLTAGE PS 1		BCU SC1
24					VOLTAGE BAT 1		BCU SC2
25					VOLTAGE PS 2		BCU SC2
26	24	<0.01	5	ANALOG	MEAS VOLTAGE BAT 2	SMU METER	BCU SC3
27	24	0.1	28	BI-LEVEL	COMMAND BAT 1/MAIN BUS 1	BCU K9	SMU SW
28					BAT 1/MAIN BUS 2	BCU K13	
29					PS 1/MAIN BUS 1	BCU K10	
30					PS 1/MAIN BUS 2	BCU K14	
31					BAT 2/MAIN BUS 1	BCU K11	
32					BAT 2/MAIN BUS 2	BCU K15	
33					PS 1/MAIN BUS 1	BCU K12	
34	24	0.1	28	BI-LEVEL	COMMAND PS 1/MAIN BUS 2	BCU K16	SMU SW
35	24	0.04	28	BI-LEVEL	COMMAND PARALLEL SOURCE	BCU K17	SMU SW
36	22	2	28	DC	POWER 28V PS	SMU 28V BUS	BCU 28V PS
37	22	2	-	DC	POWER 28V RET	SMU GRND	BCU CGP
38	24	-	-	-	TEST SPARE	SMU TERM	BCU TERM
39	24	-	-	-	TEST SPARE	SMU TERM	BCU TERM

Connectors

The preferred connectors for all cables with the exception of the main power distribution (WP1) and the power source cables (WP4-WP7) are specified by 40M39569 (MSFC specification). However, procurement may be guided by availability and cost since use of other connectors would not compromise the intent of the program. Connectors for WP1 and WP4-WP7 will be soldered terminal lugs which may be secured to the appropriate bus by a nut and bolt and lock washer. Nuts and bolts shall be tightened with a torque wrench to provide adequate and uniform contact. All main power connections shall be checked with a millivoltmeter under full load current to insure adequate conductivity.

3.2.5 System Supervision and Control

The monitor and control functions are performed by the Supervision and Monitor Unit (SMU) and the Automatically Controlled Electrical System (ACES) equipment. These are functionally duplicate equipments which will provide a comparison of the performance of conventional hardwired and multiplexed digital control approaches. The monitor and control requirements of the test facility are shown in Table 3.2.5-1.

Table 3.2.5-1. Test Facility Control and Monitor Functions

Unit	Control	Monitor Functions	Interface
LOAD BANK	8 Load Circuit RPC	1 Line Voltage Status 8 Fuse Status 8 Contactor Status 8 Load Current Measurements 1 Line Current Measurement 1 Line Voltage Measurement	⇄ CONTROL CENTER: Supervision and Monitor Unit; ACES, Data Entry and Display
BUS CONTROL UNIT	8 Power Source RPC	4 Power Source Status 2 Main Bus Status 8 Distribution Cable Status 4 Power Source Voltage Measurements 4 Power Source Current Measurements 2 Main Bus Current Measurements	⇄ CONTROL CENTER: Supervision and Monitor Unit; ACES, Data Entry and Display

As discussed in Section 3.2.2, the BCU has control and monitor capability only for the purpose of test setup. Operations will normally be conducted from the control center (SMU or ACES) to simulate the cockpit control function. The system compatibility and relative susceptibility to electrical disturbances of the two control approaches will be evaluated. The design approach and capability of these approaches are discussed in the following paragraphs. A detailed description of the ACES system may be obtained from the ACES System and Operational Description Manual available at MSFC.

3.2.5.1 Supervision and Monitor Unit

The SMU receives analog 0-5 volt signals for all current and voltage measurements. Bilevel status signals are implemented by an effective ground (i.e., saturated transistor) in the BCU or load bank. Control signals are implemented with a manual switch. All data signal conditioning and control signal processing are performed at the location of the function; the SMU provides display only.

Power for status lamps (28V) and grounds for the analog measurements are provided with the signals from the BCU and load banks to eliminate ground and power circuit loops and to permit independent operation of portions of the test facility. The controls and display panel is illustrated in Figure 3.2.5-1.

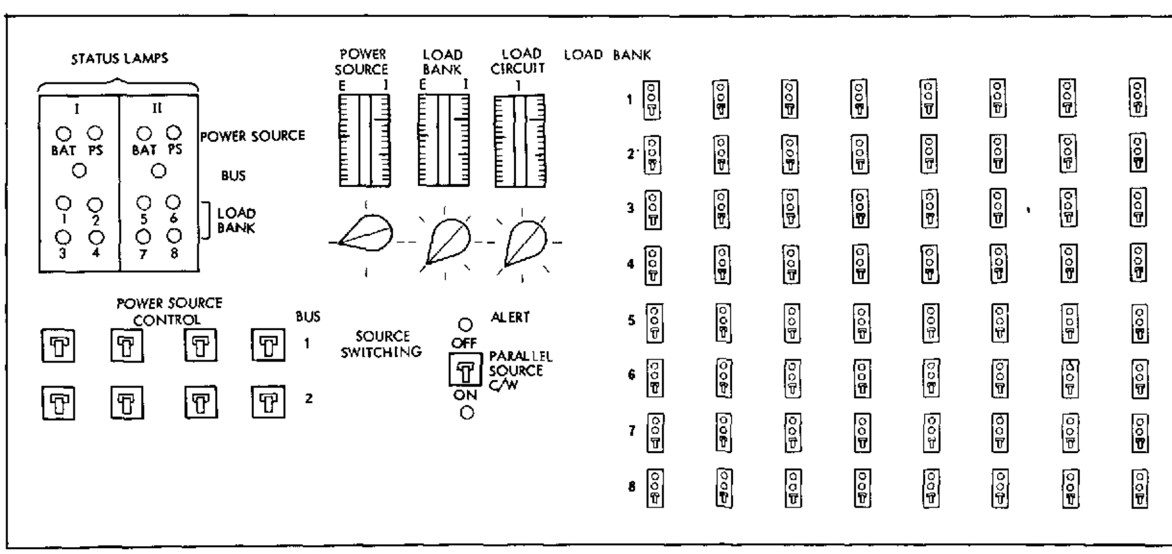


Figure 3.2.5-1. Supervision and Monitor Panel

Two dual face vertical scale meters have been selected to display power source and load bank voltage and current. A single face vertical scale meter displays the individual load cirucit current. The desired measurement is selected with a rotary switch. The load bank selector switch automatically shifts the load circuit ammeter to that load bank. The BCU controls and displays for RPCs and status lamps are duplicated on the left side of the panel. The controls for the load bank load circuit RPCs and status lamps for load bank bus, fuses, and RPCs are located on the right side of the panel. The use of ganged switches to select RPC control and status lamps for each load bank were considered earlier in the study; however, the obvious advantage of having continuous status display and control of all load circuits is significant in the test facility.

3.2.5.2 Digital Control

The ACES system developed by Westinghouse utilizes a digital command and data acquisition approach to control remote power switching devices and monitor binary data which describe the state of a power distribution system.

Signals are transmitted on a redundant data bus which provides weight and reliability advantages over the classic separately wired approach. Control of the system is maintained with a small general purpose computer using time multiplexed signals. In addition it may be programmed for self checkout, automatic fault sensing and control and power sequencing. The functional elements of the system are the general purpose computer which is designated Distribution Control Center (DCC), the local interface equipment designated Remote Input/Output unit (RIO) and the operators panel designated Data Entry and Display (DED). The system is designed with the intent to interface with solid state RPCs but is compatible with electronic/electro-magnetic power switchgear. The general configuration of the system is illustrated in Figure 3.2.5-2. The RIO provides all interfaces between the DCC, the power distribution system and the DED. The system is actually connected in a triply redundant configuration as illustrated in Figure 3.2.5-3. The internal circuits in each RIO are also triple redundant.

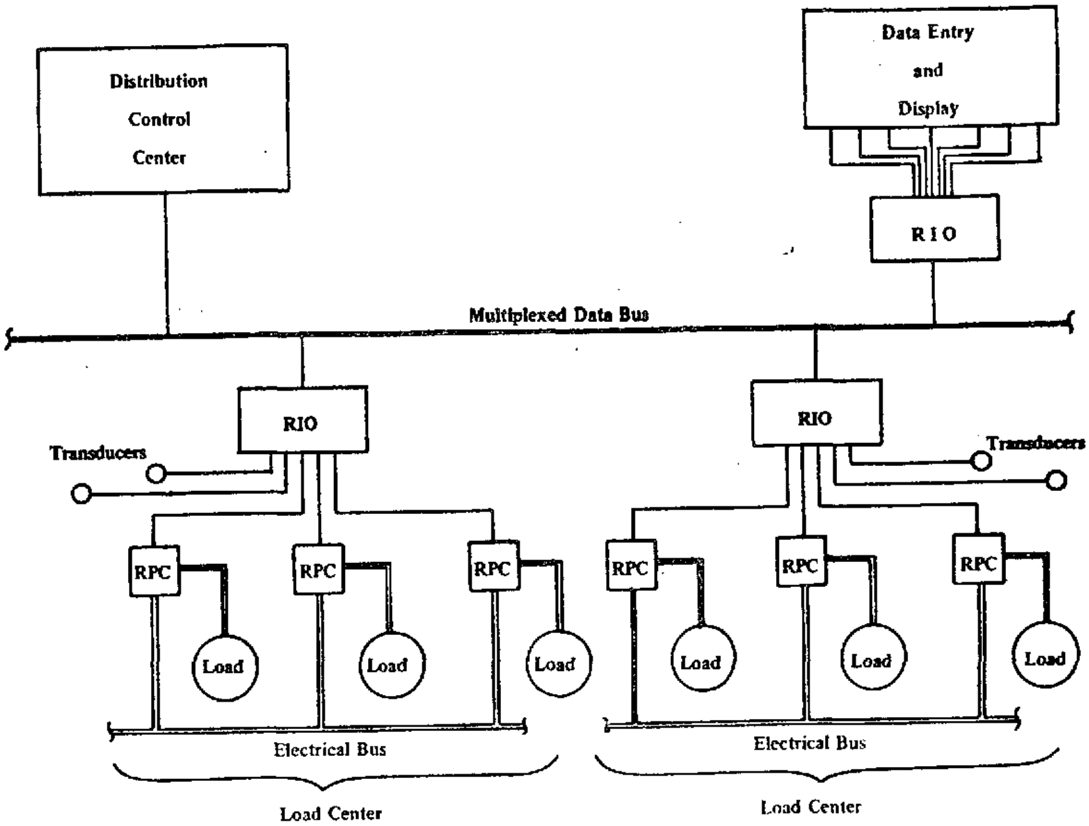


Figure 3.2.5-2. System Schematic

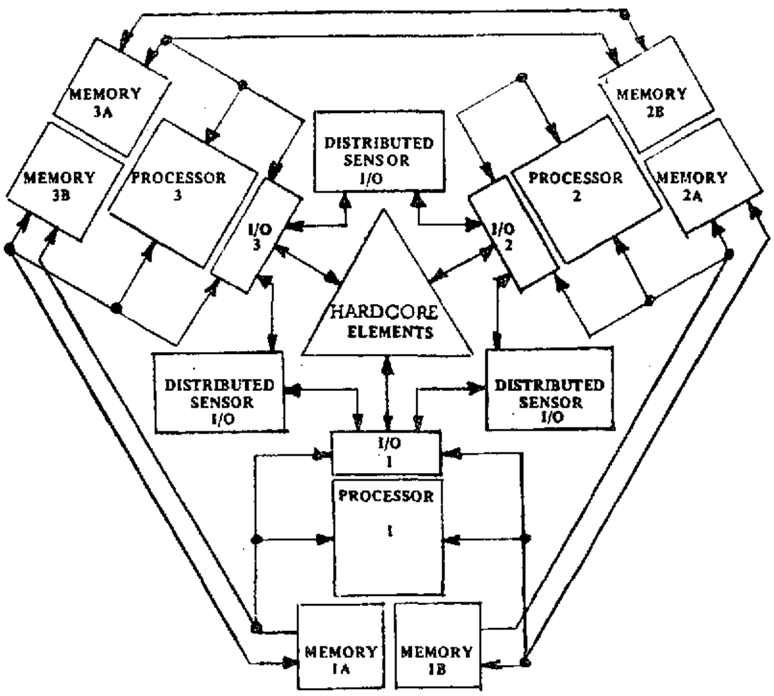


Figure 3.2.5-3. Triple Redundant System - ACES

A set of ACES equipment is available at MSFC for use in the test facility. The following is a brief description of the elements of the system. Complete details may be found in System and Operational Description Manual provided by Westinghouse at MSFC.

3.2.5.3 Distribution Control Center (DCC)

The DCC is a small general purpose military type computer of modular design and uses standard transistor-transistor-logic (TTL) integrated circuit devices of medium scale integration (MSI) complexity to maximum advantage. It is composed of control, arithmetic, memory and input/output units.

The control unit operates with 16 single-address instructions, all indexable and capable of using any one of eight general purpose registers. A computing speed of over 300,000 instructions per second is obtained with magnetic core memory.

The arithmetic unit features parallel arithmetic logic on the 16 bit words. It uses fixed point, fractional two's complement notation. It contains eight general purpose registers.

The magnetic memory is in 4096 word modules and is expandable to 16 modules; cycle time is 1.0 microsecond. The approximate memory requirement for this system is 1K words per RIO; this includes all software functions.

The DCC input/output unit contains a serial data transmission capability for multiplexed communication with the RIOs, a real time clock, and additional input/output mode control. The buses which interconnect the DCC with the RIOs are in triplet, with provision in the DCC for built-in test to verify the integrity of each bus individually. The unit can withstand a data bus short circuit to ground on any one bus, or a short between DATA I and DATA II without damage.

3.2.5.4 Data Entry and Display Panel (DED)

The DED contains a 10 digit keyboard, a numerical display and several switches and indicating lamps. An operator can open or close an RPC by keying in the appropriate three digit RPC address and pressing the "open" or "close" switch. The DCC is programmed to permit keyboard control of only selected RPCs. If an incorrect address or an address of an RPC not subject to keyboard control is keyed in, the "invalid address" lamp will light.

If an RPC trips, the "RPCs tripped" lamp lights. The addresses of the tripped RPCs can be displayed by switching to the "RPCs trip" mode and pressing the "clear/update" switch.

If the system goes into an automatic load shedding mode, the "loads shed" lamp will light. The addresses of the RPCs controlling the shed loads can be displayed in a manner similar to that for tripped RPCs by switching to the "loads shed" mode.

3.2.5.5 Remote Input/Output Units (RIOs)

Each RIO will accommodate up to 64 transistors, status lamps, RPCs or any combination thereof. Each has 64 command output and 64 status inputs. The control outputs provide signals which activate an RPC or the panel indicator. The status inputs accept signals from transducers, limit switches, and the status indicator output of an RPC.

The RIOs are assigned an address via a permanently wired mating connector, so each RIO in the system has a unique address code. Random access to the RIOs in the system is thus provided with only one part number RIO.

Each RIO is constructed in triplet in such a manner that it is essentially three input/output units, each one driven by a separate data bus. Each unit is completely self-contained with its own power supply, each power supply provided with three sources of power. Thus a failure in one unit will not propagate into another unit. The outputs of the units are joined at a buffer which drives the RPCs. Each RPC has its own buffer unit. A failure in any portion of the individual units has no affect on system performance. A failure in the buffer affects only one RPC. Each buffer can be current limited so that the output may be short circuited without disturbing the rest of the control system.

3.3 FACILITY TESTS

3.3.1 General Test Objectives

Tests will be performed on the technology breadboard to define static and dynamic performance and EMI characteristics and to provide a basis for evaluating relative performance of 28 to 120V distribution levels. In addition, a direct comparison between manual and computer controlled multiplex methods for supervision and control will be possible.

The transmission of large amounts of power over significant distances results in a distribution system which is a major element in determining the performance of the total spacecraft electrical/electronic system. The weight of distribution and control systems increases rapidly with increasing power. High current capability can result in damage to the spacecraft and excessive EMI during severe load transients. The length of the distribution system introduces significant transmission delays which influence the dynamic performance of the system. Evaluation of the performance of high power distribution systems tends to be limited since large spacecraft are designed by several contractors and testing performed on the total system during the pre-launch period is highly constrained.

Test sequences normally performed on spacecraft are intended to verify that each subsystem meets its specifications. Out of specification conditions are either ruled as acceptable or eliminated by redesign. The objective of the measurements to be performed on the technology breadboard is investigative in nature and is intended to provide a quantitative basis for the synthesis of large aerospace power distribution systems. Since the test environment is not subject to the stringent controls encountered in pre-flight testing, greater flexibility is possible in methods for test implementation and procedural format. However, in keeping with the investigative intent, there must be effective test planning with some formal preparation, implementation, and documentation procedures in order to maintain the validity and retrievability of the test data. The purpose of this section is to provide an initial definition of a test plan and to establish minimum standards of performance.

There are three general classifications of tests to be performed on the test facility site. These are defined as follows:

a. Initial System Assembly Tests - These tests are primarily concerned with establishing that the configuration of the test facility and the functional performance of the components and system conforms with the plan and manufacturers specifications.

b. Facility Maintenance Tests - Performed at regular intervals to verify the integrity of the test facility and components.

c. Technology Breadboard System Performance Tests - Performed to investigate the feasibility of high voltage dc power distribution and multiplexed supervision and control of solid state switchgear. In addition to the measurements necessary to obtain required data, tests will be performed to establish system and environmental baseline parameters after initial setup and prior to each test.

Separate test data logs will be maintained for System Tests and Maintenance/Set-up Tests. Each block of data will be dated and initialed. A log will be maintained by the Test Conductor which will identify all tests and participating personnel. Data recorded in the logs should not be limited to minimum requirements of the test plan. All observations which may be pertinent to system performance should be recorded and appropriately identified and qualified. Since some of the tests will place severe stress on the test facility, it is anticipated that some deviation of baseline parameters will occur. Specific changes may not be anticipated and the recording of all significant deviations from expected performance is essential to maintain the validity of the system baseline. Analysis of deviations from predicted performance represents a prime objective of the test program.

3.3.2 Assembly Tests

The purpose of the assembly tests is to eliminate defective or improperly installed equipment prior to performing functional system tests. Tests on purchased equipment will generally be provided in the supplier's Operating Instructions. Discussion of these tests here is intended to provide a preliminary assessment of the scope of the tests and the instrumentation required.

3.3.2.1 Batteries

Detailed battery test procedures will be provided by the supplier. These tests will consist of the following:

a. Voltage, Open Circuit

1. With all batteries (or cells) connected and the battery contactor open, measure voltage across each battery (or cell)
2. Measure voltage across full assembly of batteries (or cells)
3. End-to-end voltage should correspond to sum of individual batteries or cells. (Note: It may be necessary to apply a small load; i.e., C/10, in order to overcome contact effects at cell or battery terminals.)

b. Initial Charge

1. Charge batteries at supplier recommended rate and time (batteries are usually shipped dry-charged but should be re-charged when installed).
2. Voltage - Charge battery (or cell) and verify that voltage conforms to supplier specification for the nominal design specific gravity. Incorrect readings will indicate defective battery (or cells), incorrect electrolyte or high resistance contacts.

c. <u>Test Equipment</u>

1. Voltmeter 0-150 volts
2. Ammeter 0-10 amperes
3. Millivoltmeter 0-0.01-0.1-1.0 volts
4. Hydrometer

3.3.2.2 <u>DC Power Supply</u>

Initial set-up and verification tests have been established by the supplier (Christie Electric) and may be found in the data package provided with the equipment.

3.3.2.3 <u>Bus Control Unit (BCU)</u>

a. <u>28 Volt Supply</u> - Tests will be provided by supplier and should include measurements of

1. Voltage adjustment range
2. Line regulation
3. Load regulation
4. Output ripple voltage

b. <u>Power Circuit Verification</u> - The design of the BCU permits 32 individual paths (Figure 3.3.2-1) and combinations thereof between input power sources (1-4) and output distribution cables (1-8). The integrity of these paths may be verified by means of open-circuit and short-circuit measurements described below:

1. All breakers and switches in open position and 28V power supply "off"
2. Verify open circuit conditions as indicated in Table 3.3.2-1

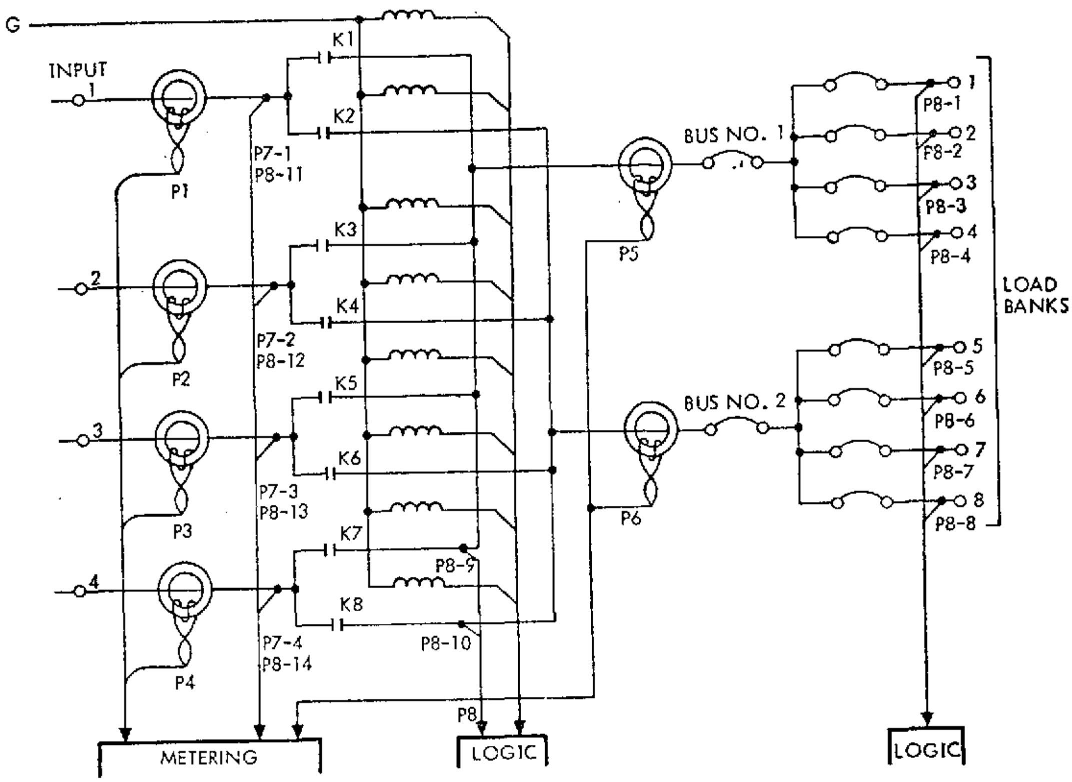


Figure 3.3.2-1. BCU Power Distribution Switching

Table 3.3.2-1. Open Circuit Test

From		To	
		In Sequence	
Input	Output	Input	Output
1		2-4	1-8
2		3-4	1-8
3		4	1-8
	1		2-8
	2		3-8
	3		4-8
	4		5-8
	5		6-8
	6		7-8
	7		8

3. 28V power "on" verify open and short circuited conditions as indicated in Table 3.3.2-2. Columns 1-3 identify BCU elements to be placed in the "on" condition. All other elements are to be "off".

Table 3.3.2-2. Logic Verification

Contactor	Main Breaker	Line Breaker	From Input	To Output	Read
K1	1		1	1	OC
K1		1	1	1	OC
	1	1	1	1	OC
K1	1	1	1	1	SC
K1, K4	1,2	1	2	5	OC
K1, K4	1	1,5	2	5	OC
K1	1,2	1,5	2	5	OC
K1, K4	1,2	1,5	2	5	SC
K1, K4	1,2	1,5	1	5	OC

4. Activate "Parallel Source Enable"

5. Verify short circuit conditions indicated in Table 3.3.2-3.

Table 3.3.2-3. Continuity Test

Contactor	Main Breaker	Line Breaker	From Output	To Output	Read
K1, K2	1,2	1,5	1	5	SC
K3, K4	1,2	2,6	2	6	SC
K5, K6	1,2	3,7	3	7	SC
K7, K8	1,2	4,8	4	8	SC

6. 28V supply "on", all switches and breakers "off"

7. Check proper operation of status lamps with the following cumulative sequence

"On" Sequence	Panel Light
28V to Input 1	Input 1
K1	Bus 1
K2	Parallel Source C/W
Parallel Source Enable	Bus 2
K3, K5, K7	Input 2, 3, 4
Main Breakers 1, 2	-
Line Breakers 1-8	Output 1-8

8. Verify that current into Input 1 is less than 1.0 ma

c. Test Equipment

1. Differential Voltmeter
2. Ammeter 0-5-10-20 Amperes
3. AC Millivoltmeter 0-0.1-1.0 Volts
4. AC Voltmeter 0-150 Volts
5. Wireman's Continuity Indicator

It is not recommended that an ohmmeter be used to check open circuit/short circuit conditions since the presence of eighteen status circuits, each contributing -0.7 volts from a 1.0 megohm source could cause erroneous indications.

3.3.2.4 Load Banks

The load banks consist of the main power circuits, switchgear monitor and control circuits and the telemetry interface. The integrity of the main power circuits will be verified in the DC Baseline Tests (Section 3.3.4.1). The remaining elements of the load banks are functionally independent and will be adequately checked out in MSFC component assembly.

3.3.2.5 Supervisory and Monitor Unit (SMU)

The SMU design contains passive circuits which consist of switch contacts and panel lamps for bilevel control and display and meters for analog display. Checkout of this unit will require connecting the appropriate cables and performing the procedures indicated below.

1. All breakers, switches on BCU, SMU, Load Banks to "off" position. DC power supply "off".

2. Connect cables as indicated below:

Power Supply #I - BCU	WP4 (BCU - Input #1)
BCU-SMU	WS3, WP3
BCU-Load Bank	WP1, WP2 (BCU - Output #1)
SMU-Load Bank	WS1

3. Perform the following sequence verifying operation of the indicated SMU status light:

Test Sequence	SMU Status Lamp
BCU 28V Supply On	
Main DC Power Supply #1 On	Input #1
SMU-K1 "On"	Bus #1
SMU K2 "On"	Parallel C/W
BCU Parallel Source Enable "On"	Bus #2
BCU-Main Breaker #1	Line #1
Line Breaker #1	Load Bank #1
	Load Bank Fuses 1-8
SMU Load Contactors 1-8	Load Contactors 1-8
SMU K3, K5, K7 "On"	Input #2, 3, 4
SMU K3, K5, K7 "Off"	
SMU K4, K6, K8 "On"	Input #2, 3, 4

Test Equipment - None Required

3.3.2.6 ACES

Tests to be performed as described in the Westinghouse manual available at MSFC.

3.3.3 Maintenance Tests

3.3.3.1 Battery

Tests to be performed as specified by supplier.

3.3.3.2 DC Power Supply

Measure performance of the power supply for the following conditions:

1. Output Regulation	0-150A	120, 28 volts
2. Output Ripple	150A	28 volts
3. Response	0-150A, 150A-0; 28, 120 volts	
4. Output Voltage Adjustment Range	Fixed Load Resistance 2.0Ω	

These data will be compared with previous data to detect change in performance. Test will be performed after each major transient test and as required at regular intervals by the test conductor.

3.3.3.2 ACES, SMU

None required. Performance is monitored continuously in normal course of tests.

3.3.3.3 BCU, Power Distribution System, Load Banks

Tests will be required to maintain the parametric baseline. These tests are fully described in the baseline tests (Sections 3.3.4.1 to 3.3.4.3 inclusive).

3.3.4 System Performance Tests

The objective of the performance tests is to provide a detailed characterization of a high voltage power distribution system. Ideally, these tests would provide a valid data base from which the performance of similar distribution systems may be predicted for a range of nominal voltages and a variety of expected load conditions. Both ac and dc power lines have been analyzed thoroughly in standard power transmission applications, however, those transmission lines have been optimized for utility power systems and have reasonably predictable parameters. The distributed parameters in a space vehicle are influenced by the variable physical environment along the cable duct, the complex geometry required by the structure, the presence of relays, breakers, fuses, ferromagnetic components and wire plating. Present designs of distribution cables in this application rarely reflect a control of the distributed parameters which determine the characteristic performance under steady-state, transient and fault conditions. The parameters of concern include distributed R, L and C as a function of frequency, cable to cable electric and magnetic field coupling, characteristic impedance of the distribution cable, source/ load impulse response and transfer functions. The objectives of the System Performance Tests will be met by measuring and correlating these parameters with EMI measurements and the dynamic response of the power distribution system. The nominal tests which will be performed to achieve these objectives are listed below:

a. DC Baseline - Resistance measurements, steady state line voltage characteristics, distribution, and structure return currents.

b. AC Baseline - Inductance, capacitance, coupling, transmission parameters, source and load response.

c. EMI Baseline - Test facility environment, power sources, steady state (resistive load) conditions, model transient response.

d. System Dynamic Performance - System response to full load DC, periodic and transient loads. Radiated and conducted EMI under these loads with switching transients implemented with contactors, breakers, and fuses.

e. Fault Simulation - Radiated and conducted EMI, response of breakers and fuses, cable thermal characteristics with distribution system under shorted conditions.

f. Transmission Parameters - DC to RF measurement to determine characteristic impedance and propagation constants.

Two additional tests are recommended in Section 3.3.4.5 but cannot be completely defined at this stage of the program.

Tests a, b, and c or portions thereof may be rerun during the course of tests d and e in order to maintain an accurate system baseline. Measurements will be performed with standard flight test equipment and techniques. Where such approaches modify the power distribution system due to the insertion of equipment, the effects of this modification will be evaluated in order to provide the desired correlation between flight testing and actual system performance.

3.3.4.1 DC Baseline

The purpose of the DC baseline tests is to establish a data base which will enable the prediction of an accurate voltage drop budget during any steady-state condition of the test facility. The configuration of the test facility for these measurements is illustrated in Figure 3.3.4-1. BCU inputs (1-4) and outputs (1-8) are as shown. Current from the power supply may then flow through any selected element. Due to the series configuration care should be exercised to prevent test current for one element flowing through another element (i.e. fuse) for which the second element is not rated. When this condition can occur the lower rated element should be strapped out. The functional schematic (Figure 3.3.4-1) should be annotated with the actual current ratings of all elements for reference prior to turning power on. Nominal test points are shown for reference; the test conductor should verify that no resistive connections are included between actual test points. Meters should be open circuited except during actual measurement to protect the instrument. An ammeter should be connected in the power source lead to obtain accurate current setting. All reading should be accurate to at least ±2% of actual reading. When this tolerance is exceeded, the estimated tolerance should be recorded.

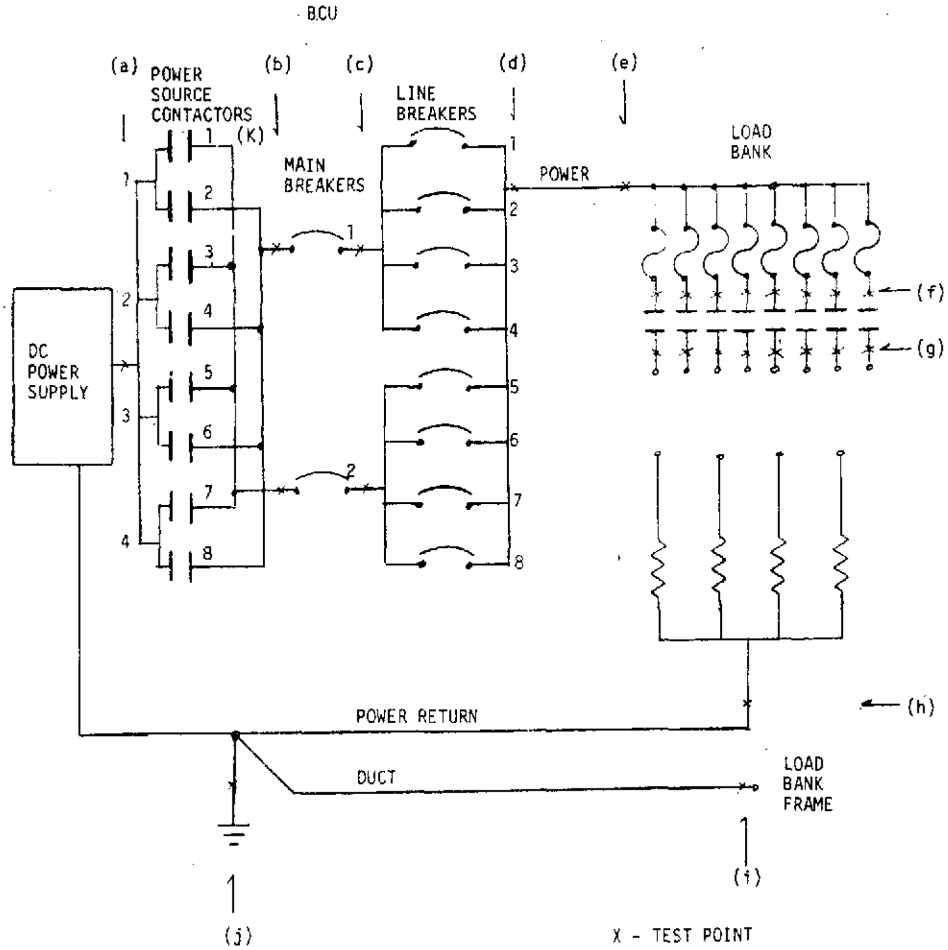


Figure 3.3.4-1. DC Baseline Measurements

a. DC Measurements

1. Measure voltage drop across each breaker (b-c,c-d), contactor (a-b,f-g) and fuse (e-f) at one-tenth (1/10) rated current.
2. Measure voltage drop across each contactor (a-b,f-g) and breaker (b-c,c-d) at rated current.
3. Measure voltage drop across each fuse at one-half (1/2) rated current.

4. Cycle each switching device three (3) times at one-tenth (1/10) rated current and repeat 1. and 2. above for each breaker and contactor.

5. Measure line drop (d-e,h-j) at 100 amperes.

6. With a clamp-on ammeter, measure current in each wire.

7. Disconnect four (4) pairs of the main cable.

8. Measure line drop in the remaining pair (d-e,h-j) at one (1) ampere and at twenty (20) amperes. Allow line to heat for fifteen minutes before reading voltage drop at 20 amperes.

9. Repeat 7. and 8. for each pair of power lines.

10. Reconnect full (5 pair) main bus.

11. Load system to 100 amperes at 120V input.

12. Measure voltage between frame and circuit ground (use suitable filter if AC component is present.

13. Measure input (a-j) and output (g-l) voltage

14. Repeat 12. and 13. for each BCU input (1-4) and output (1-8) path.

3.3.4.2 AC Baseline

The purpose of this test is to establish the AC and transient characteristics of the elements of the test facility. These data will be correlated with measurements made with the total system operating under comparable conditions.

a. Line Capacitance. In this test and in the inductance measurements which follow, it is expected that reactance will not vary significantly from wire to wire. Consequently the tests do not always measure every possible combination of reactances. The test conductor should use his discretion based on the results as the test progresses to increase or decrease the actual number of measurements.

1. Open line breakers in BCU and contactors in load bank

2. Connect impedance bridge as shown in Figure 3.3.4-2

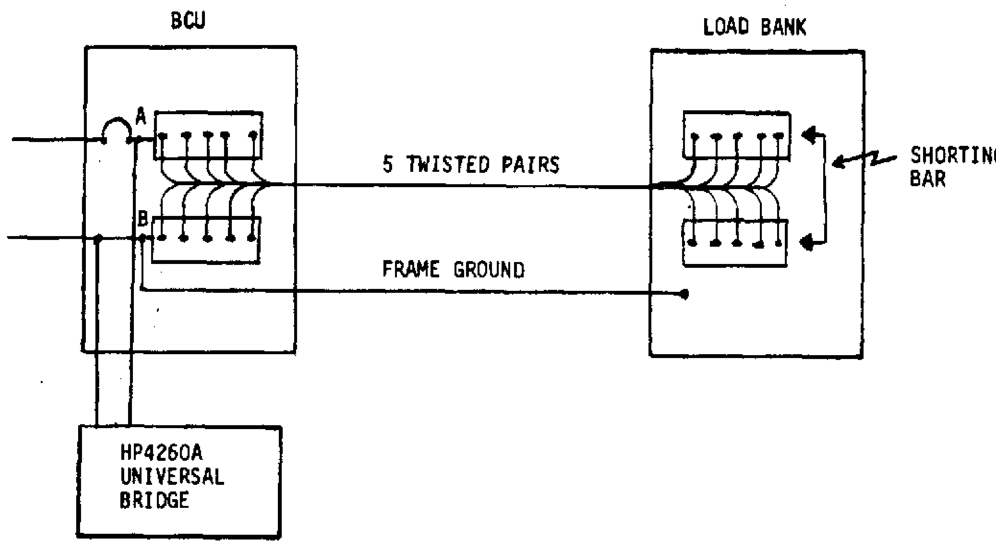


Figure 3.3.4-2. Impedance Measurement

3. Measure capacitance between power bus and return of each pair

4. Measure capacitance between each pair and frame ground

5. Connect all pairs in parallel

6. Measure capacitance between power bus and return

7. Measure capacitance between power bus and frame ground and between return and frame ground

b. <u>Line Inductance</u>

1. Connect shorting bar at load bank

2. Measure inductance of each pair

3. Measure inductance with all pairs in parallel

c. <u>Mutual Inductance</u>

1. Connect AC signal generator to terminals A, B

2. Connect shorting bar at load bank

3. Disconnect 4 of the 5 wire pairs of the main bus in the BCU

4. Measure AC signal current with a clamp-on current sensor

5. Measure AC voltage on open-circuited pairs with AC millivoltmeter or oscilloscope

6. Short circuit each pair successively at the BCU and measure current with a clamp-on current sensor

7. Perform 4, 5, and 6 at 1 KHz and at successive octave intervals to 64 KHz.

d. <u>Mutual Coupling - Transient</u>. The objective of this test is to provide data which correlate the capacitance and inductances measured above with the coupled signal under closely controlled transient conditions. Since the coupled signal is a function of voltage (capacitive coupling) and current (inductive coupling), two voltages and currents are used in this test. During the course of the test, it may become apparent that additional conditions are necessary. These should be added at the test conductor's discretion.

1. Disconnect 4 of the 5 wire pairs at the BCU.

2. Lift corresponding pairs at the load bank and short the load termination of each pair.

3. Connect Memory Voltmeter, Visicorder, and Oscilloscope as indicated in Figures 3.3.4-3, -4, and -5.

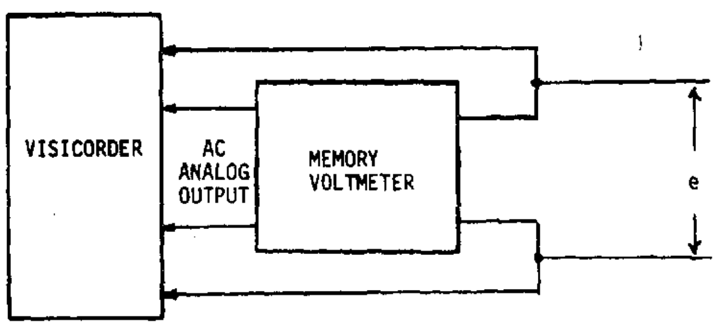


Figure 3.3.4-3. Memory Voltmeter and Visicorder Connection

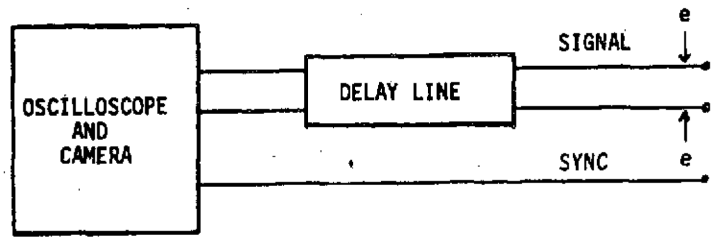


Figure 3.3.4-4. Oscilloscope Connection for Observing Transient

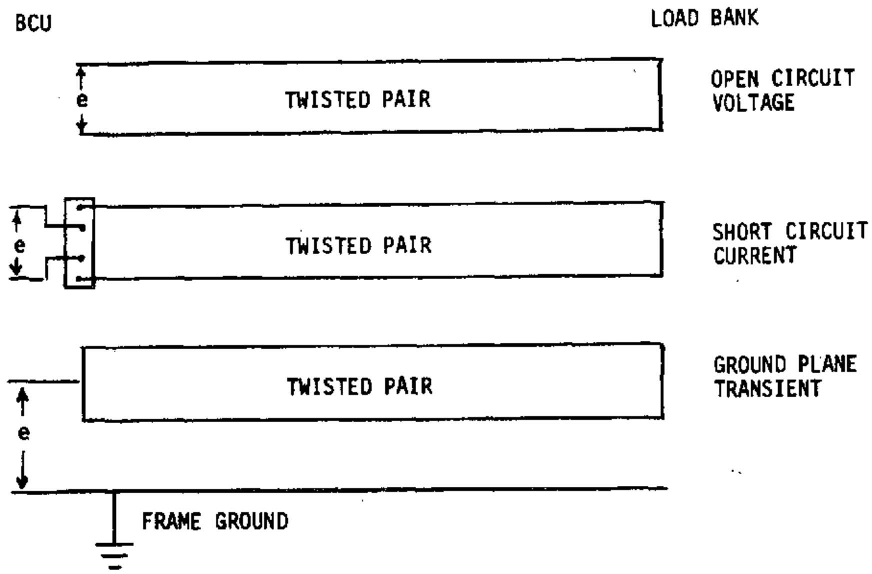


Figure 3.3.4-5. Connections for Transient Measurement

4. Set up DC power supply and loads to produce resistive turn on transients of 5.0A and 20.0A at 28V and 120V (four conditions).

5. Prepare the four open circuited pairs for the three measurements indicated in Figure 3.3.4-5.

6. Perform the indicated measurements for each of the four voltage and current conditions specified in item 4. above.

Note: The delay line shown in Figure 3.3.4-4 is to insure that the oscilloscope sweep is initiated before the signal reaches the instrument. The delay line may consist of a length of coaxial line.

e. Contactors and Breakers. The purpose of these tests is to isolate the characteristics of power switching devices. The effects of interest are contact bounce and arcing during the switching transients. These effects are voltage and current sensitive and several nominal values of voltage and current are suggested. The drive circuits for the contactors should be the same or similar to the circuitry to be used in the final design. The parameters of the drive circuitry significantly influence contactor dynamics and variations in performance can be expected with deviations of drive source voltage, resistance, and damping techniques. These tests will be repeated with solid state as they become available.

1. Set up DC power supply and resistive loads to obtain 5.0A and 20.0A at 28V and 120V.

2. Set up test equipment and loads as indicated in Figure 3.3.4-6. The DC power supply and load must be connected through the switching element by short leads. The distribution power line must not be used.

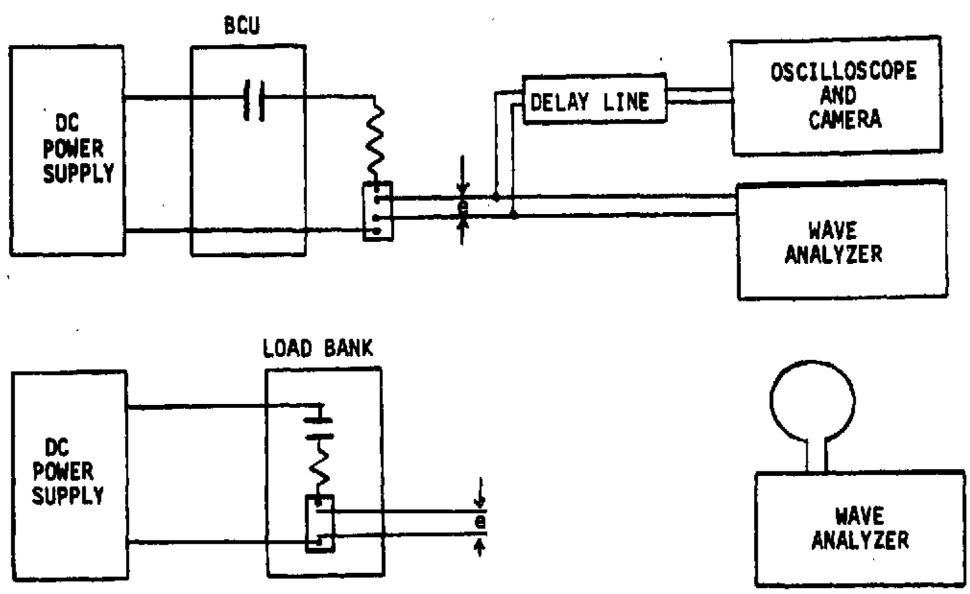


Figure 3.3.4-6. Test Equipment and Loads Setup

3. Operate each contactor and breaker at the loads indicated. Obtain photographs and broadband noise measurements of turn on and turn off transients.

f. Fuses. The purpose of this test is similar to that of sequence e. above. The observed signal however will necessarily include the contactor or breaker turn on characteristic. The tests suggested here are limited to keep expenditures low. If significant trends are not established by the six transient measurements below, it is recommended that the test series be expanded. Selection of the fuse should be governed by availability and usage in test facility overload tests.

1. Select six fuses of one type and rating.

2. Measure voltage drop on each fuse at 10% and 50% of rated current.

3. Connect fuse in series with contactors or breakers with circuits and test equipment as in sequence e above.

4. Prepare loads at 200% and 500% of fuse rating with 28V and 120V source voltages.

5. Blow three fuses at 28V at 200% and 500% of rated load and with a full short circuit.

6. Blow three fuses at 120V at 200% and 500% of rated load and a full short circuit.

7. Photograph signal and record broadband noise measured across current shunt and at the radiated EMI receiver.

3.3.4.3 EMI Baseline

These tests will establish levels of background noise in the test facility environment due to functions which are unrelated to the operation of the test facility and represent uncontrolled signal sources, and functions which are required for test facility operation but are not elements of the test article. Expected noise sources are heavy power equipment such as vibrators and presses, nearby high power lines, flourescent lighting, and welding equipment. Obviously some of these sources may not be active at the time these measurements are made. It will be necessary at selected points in later test sequences to re-evaluate the EMI baseline.

a. Environmental Background Noise. The intent of this test is to measure the noise level present in the test facility area and establish if possible simple and effective means of monitoring and controlling the noise sources.

1. With all unnecessary facility equipment shut down, measure radiated broadband and narrowband EMI levels at selected locations.

2. Compare simultaneous measurements made at different locations and determine from their fluctuations, if they represent the same noise source. It may be necessary to make strip chart recordings of simultaneous measurements to accomplish this comparison. One of the results of this test should be the selection of one preferred location which will provide a good estimate for the ambient noise level in the facility. It may be desirable during later tests to maintain a continuous monitor of background noise.

3. Operate in succession all electrical and electronic equipment (lights, test equipment, etc.) not directly involved with the power distribution system. Observe and record transient and steady state, broadband, and narrowband radiated EMI.

b. Test Facility Background Noise. The objective of this test is to measure noise present in the power distribution system due to external sources. During this study, the instrument measuring radiated EMI will be operated continuously at the location selected in a-2 above.

1. Measure broadband and narrowband conducted EMI on the main power bus, the main power return, and on the frame ground return near the central ground point in the BCU.

The above tests should be performed for the test facility states in Table 3.3.4-1 below:

Table 3.3.4-1

Battery	Main PS	28V PS	Load Contactors
0	0	0	0
0	1	0	0
0	0	1	1
0	1	1	1

0 = Test facility element deactivated

1 - Test facility element activated

Note: Throughout this test the main breakers remain open and the distribution cable is shorted at the load side of the main breakers. The main power supply should be loaded (100A, 120V) on the input side of the main breakers. The load banks should be configured for 100A loads with maximum parallel capacitance.

2. Repeat measurements 1. with all electrically powered instruments or auxiliary equipment on and connected in typical test positions.

3. Repeat broadband measurements while cycling the main power supply contactor.

4. Open main power supply contactor. Repeat broadband measurements while cycling the battery source contactor.

3.3.4.4 System Dynamic Performance

The purpose of these tests is to characterize the response of the power distribution system over the full range of line voltage and load current permitted by system capability. A typical system configuration for these tests is illustrated in Figure 3.3.4-7. Measurements of conducted EMI and

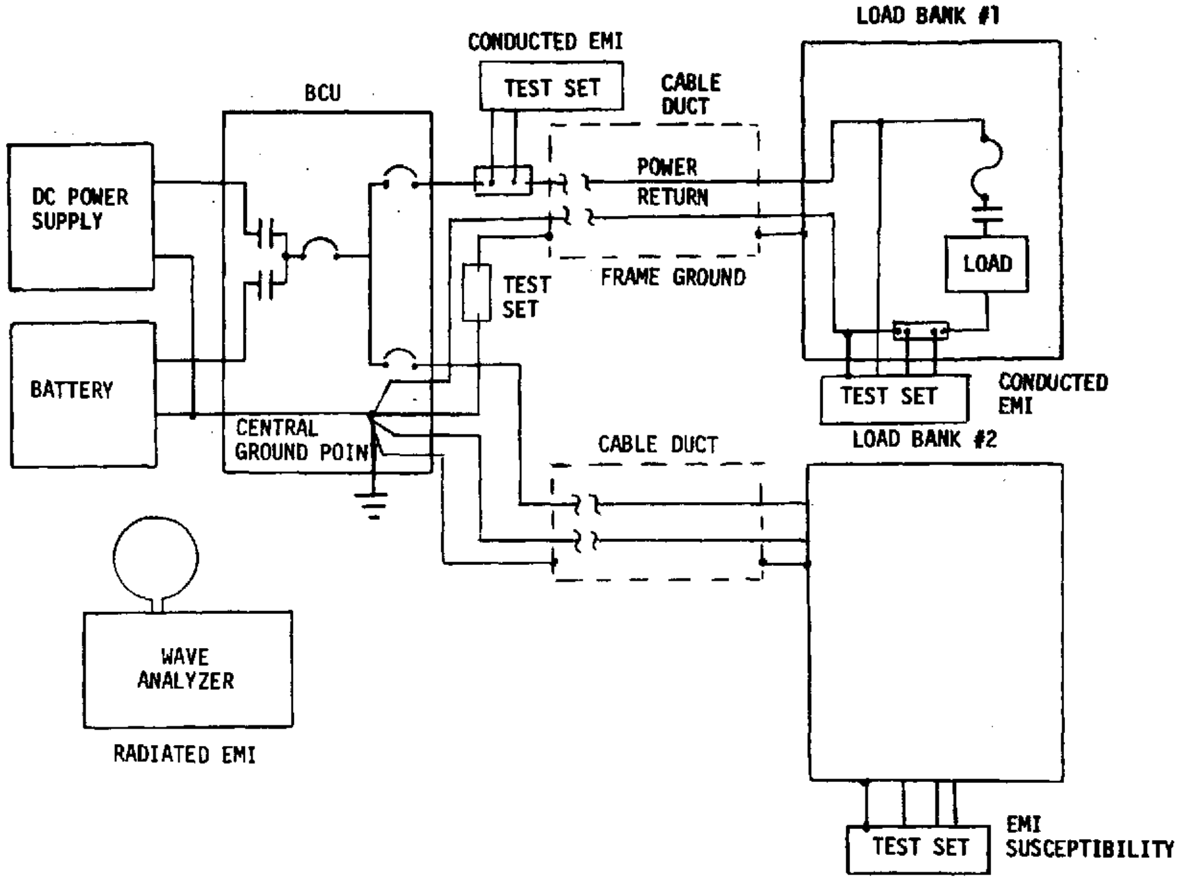


Figure 3.3.4-7. System Dynamic Performance - Test Configuration

transients are made at the load bank and on the power distribution cable near the BCU. Measurements of hardwire coupled interference (approximating susceptibility tests) are made at a second load bank. Since there are no vulnerable components in the load banks, a formal susceptibility test cannot be performed with the present facility concept. Radiated EMI measurements are recorded for each test. Voltage and current will be continuously monitored by the memory voltmeter/visicorder test set. The complete test set configuration is shown in Figure 3.3.4-8. Elements of this configuration may be deleted as permitted by the reduced testing requirements at some test locations. Further discussion of the requirements and capability of the test equipment may be found in Section 3.3.5.

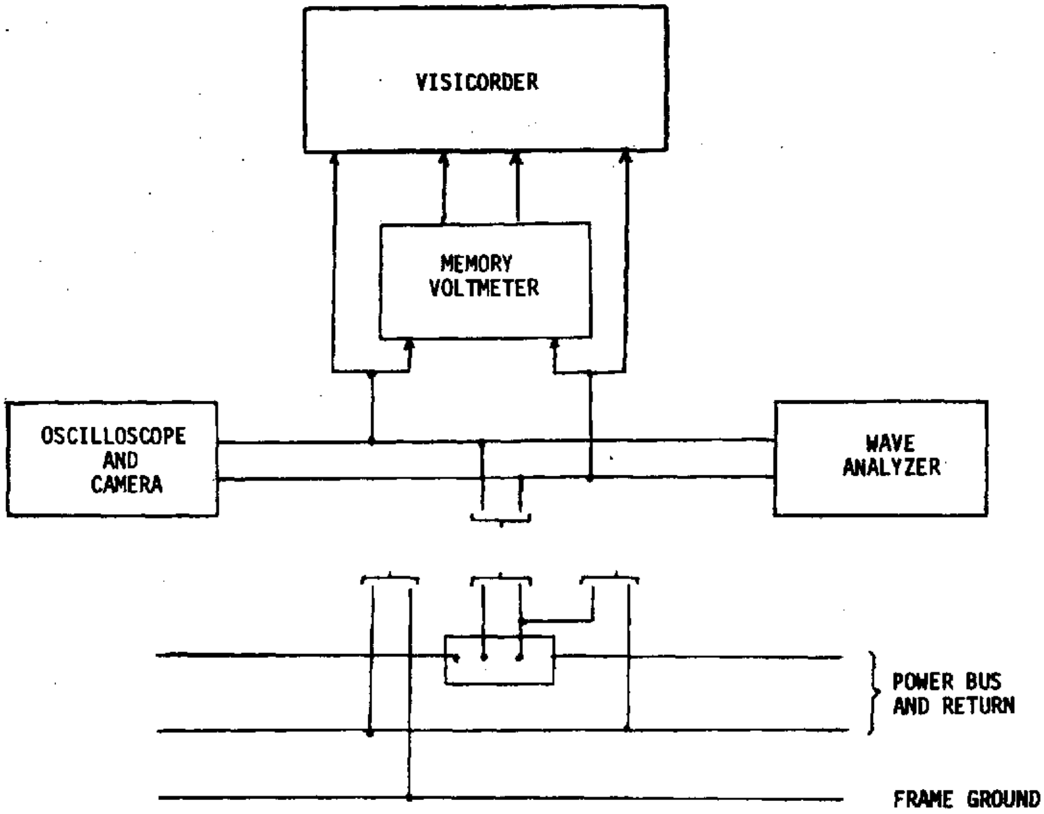


Figure 3.3.4-2. System Dynamic Performance - Test Set

Simultaneous photographs of current and voltage waveforms are taken during the transient tests. In addition open and short circuit measurements on spare test wires in the cable (not connected to the power system) will be made for each test condition. Measurements on these wires will be similar to those performed on the main bus except voltage and current may not be measured simultaneously.

The total number of measurements will be ultimately dependent on the discretion of the test conductor and the observed performance of the system. The following test conditions are recommended for the initial tests.

a. <u>Load Type</u>

1. Resistance
2. Parallel capacitance and resistance
3. Series inductance and resistance
4. Pulse width modulator
5. Pulse width modulator in parallel with capacitance

b. <u>Load Current and Voltage</u>

1. Current: 25, 50, 100 amperes
2. Voltage: 28, 60, 120 volts

c. <u>Measurements</u>

1. <u>Passive Load</u>. Conducted and radiated, narrowband and broadband EMI, DC voltage drop.
2. <u>Active (PWM) Load</u>. Conducted and radiated, narrowband and broadband EMI, oscilloscope photographs of line current and voltage.
3. <u>Transient (On-Off Cycling of Above Loads)</u>. Conducted and radiated, broadband EMI, oscilloscope photographs of line voltage and current.

d. <u>Short Circuit Tests</u>. Short circuit tests should be conducted after the above sequence since disturbance to the baseline parameters is possible. Test conditions are described below:

1. Voltage: 28, 60, 120 volts
2. Instrumentation: Conducted and radiated broadband EMI, oscilloscope photographs of line voltage and current transients, memory voltmeter/visicorder continuously monitoring line voltage and current.

Insulation leakage, power harness, contactor and breaker voltage drops should be checked after each shorting test since the high currents in each operation could modify the noise characteristics in subsequent tests. In general, short circuits will be applied by load contactors and opened by fuses. Applying power to a shorted line with a line breaker should modify the transient waveforms and should be investigated if time permits. Since there are at least two contactors in series with the short circuit, it is recommended that the contactor which does not perform the short circuit closure be paralleled by a low amperage fuse (i.e., 5 amperes) and be used as a manual safety switch in the event that the system fails to open. At 120V the operator will have approximately 12 seconds before the harness insulation is jeapordized. When simultaneous transient observations are made, oscilloscope test leads with equal or known delay should be used. It may be necessary to add timing calibration pulses to the oscilloscope display in order to correlate the time relationship of transients. A single beam intensity modulation pulse may be adequate for this purpose.

3.3.4.5 Recommended Future Testing

The tests outlined in the preceding section with such increased detail as may be considered necessary are sufficient to define the general performance of the facility power distribution system in normal operation. Two additional types of tests are recommended to more fully define the total performance of the distribution harness.

a. Fault Simulation. The current carrying capacity of a harness is defined on the basis of allowable maximum temperature. Currents which may cause this temperature rise are not very well known for the majority of specific applications. The effect on a spacecraft harness of a sustained short does not appear to have been studied. The tests in the preceding sections specify some measurements of voltage drop after sustained current at various levels. Temperature rise and heat loss may be calculated from these data. It is then possible to evaluate the effect of a sustained (order of 10-20 seconds) low resistance short circuit on the power line. This effect is significant with respect to line protection as well as analysis of fault damage to power distribution systems during test and flight. Therefore, it is recommended that a program of sustained short circuit tests be implemented. Since these tests will result in cable damage, testing of the full harness must follow all other required tests. However it is possible to perform tests on a short length of harness assembled for that purpose and which would not interfere with the system testing. The pairs making up the harness may be placed in series rather than parallel. This has the effect of reducing the required current to simulate a full short by a factor of five for the harness under consideration. The comparison of harness lengths and currents required to simulate identical conditions is shown below:

Maximum Current - Simulated Short at 120 Volts

Harness	Length - Feet	Peak Current - Amperes
System Harness	200	2390
Test Harness	40	478

The current required for the test harness is within the capability of the battery power pack selected for this program. The data to be derived from this test are:

1. Time temperature profile
2. Evaluation of effects on insulation due to combinations of temperature, normal stress due to harness construction, and thermally induced mechanical stress
3. Survivability of the harness under fault conditions

b. Transmission Line Characterization. It will be advantageous if power distribution lines could be fully characterized as a distributed transmission line over a broad range of frequencies from DC up the rf transmission frequencies (i.e., 10 GHz) currently in use. Such an evaluation would enable a computerized analysis and simulation of the power system characteristics. Extrapolation of measurements made on the test facility cable to a specific application may not be valid due to the variable physical environment encountered in spacecraft. However, the broad characteristics would provide greater insight into the coupling between large power systems and the electrical/electronic environment of the spacecraft. Furthermore, the techniques developed would enable the implementation of this measurement in pre-flight testing. The transmission properties which need to be determined as a function of frequency are

1. Characteristic impedance
2. Propagation constants

There are numerous types of test instruments and techniques employed in obtaining these properties. It is recommended that those available at MSFC be obtained to implement an initial effort to perform these tests.

3.3.5 Test Instrumentation

A tentative list of equipment to implement the tests described in the preceding sections is shown in Table 3.3.5-1.

Table 3.3.5-1. Test Instrumentation

Quantity	Instrument	Comments
1	Impedance Bridge	HP4260A
2	Low Freq. Wave Analyzer	Fairchild EMC-10
2	High Freq. Wave Analyzer	Fairchild EMC-25
3	Oscilloscope	Tektronix 547
3	Scope Camera	HP196A
2	Visicorders	Honeywell 1508
2	Galvanometer Amplifiers	Honeywell T6A
2	Memory Voltmeters	Micro Instruments 5208, 5201C
2	DC Millivoltmeter	Digital
2	AC Millivoltmeter	Digital
1	AF Signal Generator	As available
1	RF Signal Generator	As available
4	Multimeters	As available

In addition all normal accessories such as EMI antennas, current probes, oscilloscope plug-in amplifiers, and calibrated test leads used with the above will be required.

The test equipment listed above have been selected as representative models of the instruments required based on measurement needs and general availability. The quantities listed are considered minimum for maintaining the quality of the data base. This is not intended to restrict the use of other instruments which perform equally well. Since availability of equipment at MSFC will influence the final selection of test equipment, it is pertinent at this time to discuss the measurement requirements and instrument capabilities.

1. <u>Impedance Bridge</u>. The principle requirement is to be capable of measuring reactances down to the values expected in the distribution cable. These values are at present unknown but they are expected to fall in the vicinity of 0.3 microhenries and 10 picofarads per foot. The capability of the Hewlett Packard Model 4260 Universal Bridge is given in Table 3.3.5-2. This bridge can also perform resistance measurements which may be useful but are not necessary. Measurements are normally performed with an internal 1 KHz oscillator but may be implemented with an external oscillator functioning between 20Hz and 20 KHz. It is desirable to perform these measurements over a range of frequencies but the above range is not sufficient to provide significant added value to the measurements at 1 KHz. If an instrument can be obtained at MSFC which can perform the impedance measurement at frequencies up to 50 MHz, the definition of the distributed parameters of the power distribution harness will be considerably improved.

Table 3.3.5-2. Specifications - Model 4260 HP Universal Bridge

<u>CAPACITANCE</u>

Range: 1 pF to 1000 μF, in 7 ranges.

Accuracy:

±(1% + 1 Digit), from 1 nF to 100 μF.

±(2% + 1 Digit), from 1 pF to 1 nF and 100 μF to 1000 μF.

Residual capacitance ≈ 2 pF.

<u>INDUCTANCE</u>

Range: 1 H to 1000 H, in 7 ranges.

<u>ACCURACY</u>

±(1% + 1 Digit), from 1 mH to 100 H.

±(2% + 1 Digit), from 1 μH to 1 mH and 100 H to 1000 H.

Residual inductance ≤ 1 μH.

<u>DISSPATION FACTOR</u>

Range: Low D (series C): 0.001 to 0.12.
High D (parallel C): 0.05 to 50.

Accuracy (C greater than 100 pF):

Low D: ±(5% + 0.002) or one dial division, whichever is greater.

High D: ±(5% + 0.05) or one dial division, whichever is greater.

<u>QUALITY FACTOR</u>

Range: Low Q (series L): 0.02 to 20.
High Q (parallel L): 8 to 1000.

Accuracy (L greater than 100 μH):

Low Q: ±(5% + 0.05) or one dial division, whichever is greater.

High Q: ±(5% + 0.002) or one dial division, whichever is greater.

2. Wave Analyzers. The Fairchild EMC-10 and EMC-25 provide coverage from 20 Hz to 1.0 GHz, and are standard EMI measuring instruments. Any instruments capable of measurements to current specifications such as MIL-STD-461/462 are adequate for this function.

3. Memory Voltmeters and Visicorders. These instruments represent a practical method for monitoring of steady state and transient noise. Depending on the model, most visicorders are able to accommodate from 12 to 36 galvanometers which exceed the requirements of this program. The response of the visicorder galvanometer is flat down to pulse widths of approximately 40 microseconds (M-13000 galvanometer) which is adequate for measuring general transients and monitoring broadband noise as sensed by a wave analyzer. The effectiveness of the visicorder is considerably enhanced by operating in combination with a memory voltmeter. This instrument has a fast response (30-50 nanoseconds) and is either automatically or manually reset. The output is held by the memory voltmeter long enough (40 milliseconds) for the visicorder or other strip chart recording instrument to respond. For low energy signals, galvanometer power amplifiers are available to improve the data presentation. A typical configuration for simultaneous presentation of multiple signals is illustrated in Figure 3.3.5-1. The resulting data presentation is illustrated in Figure 3.3.5-2 (increasing time is from right to left). The general characteristics and capabilities of these instruments are summarized in Table 3.3.5-3.

4. Oscilloscope and Camera. The principle requirement on these instruments is to be capable of photographing transient (single sweep) waveforms at sweep speeds up to one centimeter per microsecond. The spectrum of the transients to be observed is not known but it is estimated that signals with fundamental frequencies of 2.5 to 5.0 MHz will be generated on the 200 foot distribution cable

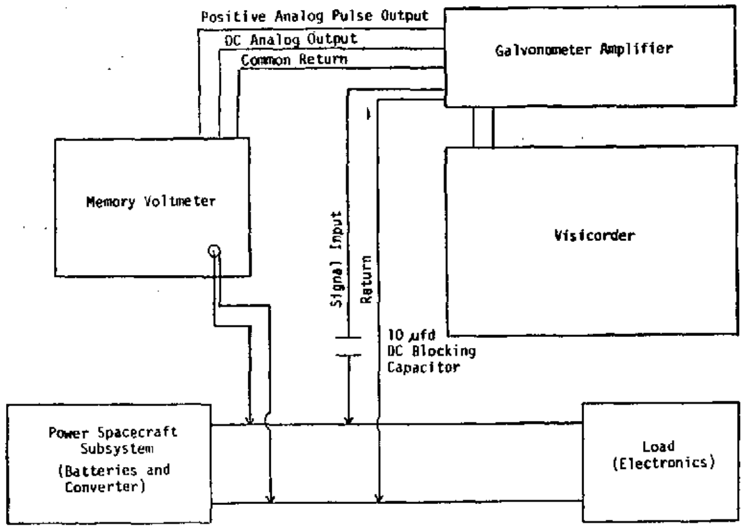


Figure 3.3.5-1. Transient Monitoring Test Setup

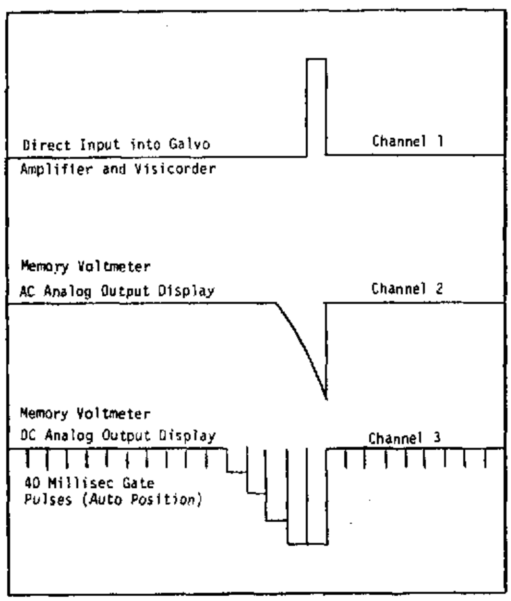


Figure 3.3.5-2. Typical Presentation of Pulse Displayed on Visicorder Using Direct Input and Memory Voltmeter Outputs

Table 3.3.5-3. Equipment Characteristics Memory Voltmeter (Micro Instrument Co. Model 5201C)

Input Impedance	30K ohms minimum (3.0V range)
Pulse Width Range	DC - 50 nano seconds
Accuracy	±3% of full scale
Operating Modes	Reads peak positive
	Reads peak negative
	Reads peak positive or negative

Outputs: DC analog 0-3.0 volts output on 3.0; 30.0; and 300 volt range 0-1.0 volts on 10 and 100 volt ranges. A 40 milli-second timing pulse is also present on this output.

AC Analog Output:

Simultaneous positive and negative outputs. 2.5 volt nominal, decay to zero in 100 μsec at full scale.

VISICORDER HONEYWELL MODEL 1508

Speed Button	1, 2, 4, 8 cps
Range Buttons (times speed button)	X.01; X1.0; X10
Galvonometer Selection	Accepts all M series galvonometers

GALVONOMETERS

Model	Freq. Response	Maximum Pk-Pk Deflection		Load Resistance Required
M-13000	0-13000 Hz	2.0"		0
M-8000	0-5000 Hz	2.0"		0
M-3300	0-2000 Hz	8.0"	Series	22 ohms
M-1650	0-1000 Hz	8.0"	Series	24 ohms

GALVONOMETER AMPLIFIER HONEYWELL MODEL TG 6A-600

Frequency Response	DC to 20,000 Hz
Input Impedance	47K ohms
Input Voltage	1.0 volt to ±50 volts
Output Impedance	1 ohm DC -5000 Hz
Nominal 10 AD impedance	37 ohms
Gain	0 to Unity
DC Blocking Capacitor	10 μfd for minimum distortion

due to echoes from the mismatched terminations. Noise due to contactor and fuse arcing will have lower energy density and broader spectrum than the cable resonance effects and will be measured by the broadband wave analyzer which has capability up to 1 GHz. All other significant noise effects on the cable then can be adequately observed with an oscilloscope with response up to 50 MHz. The characteristics of a Tektronix 547 oscilloscope with a 1A5 plug-in unit is:

Deflection	2 mv/cm to 20 v/cm
Bandwidth	DC to 45 MHz
Rise Time	8 nanoseconds

The Tektronix Model 544 and 546 oscilloscopes provide slightly better performance. Any of these units would probably be adequate. A dual beam oscilloscope would be quite advantageous in providing a comparison of transients; however, the response of dual beam oscilloscopes which have been reviewed do not appear to be adequate for the purposes of the test program.

5. Miscellaneous Instrumentation. Ammeters and voltmeters used should have scales and tolerances so that measurement accuracies approach 1%. Digital meters are far preferable where many measurements are to be performed. Due to the multiple ground systems in the test facility and the necessity for careful measurements, battery operated test equipment is preferred.

APPENDIX A
PULSE WIDTH MODULATOR DESIGN

1.0 INTRODUCTION

Evaluation of the performance of the Multi-KW Power Distribution System requires the use of some dynamic load which will provide a realistic simulation of a distribution system/power conditioning equipment interface. The two fundamental classes of power conditioning components which produce significant noise are converters and pulse width modulated regulators. The operation of dc/dc or dc/ac converters generates noise at the switching frequency primarily due to various types of imbalance in the electrical characteristics of the hardware. Spikes and bursts of noise with broad spectral characteristics are generated by the switching transients in the primary and rectification transitions in the secondary windings of transformers. These noise sources are relatively unpredictable since they are due to basically second order characteristics, such as leakage inductance, stray capacitance, and semiconductor impulse response.

The pulse width modulator (PWM) regulator normally performs its function by alternately applying line voltage and ground to the input of an inductance input filter (Figure A-1). The output voltage of the filter is the average value (neglecting IR losses) of the input voltage. The current from the input filter flows in rectangular pulses with a small superimposed ripple. Noise is conducted to the power line through the input filter and is a function of the filter parameters, pulse width, magnitude, and frequency. Since these functions are relatively easy to control, the PWM was selected to simulate power conditioning equipment in the load bank.

The requirements on the PWM as a simulated load are concerned only with the input characteristics. In order to minimize the development and test time, the basic regulator design was modified to the configuration shown in Figure A-2. The details of the design are shown in Figure A-3. Although no useful output may be derived from this circuit, the load on the input filter is similar to that of the standard regulator configuration with the exception of second order ripple effects and low frequency transients associated with

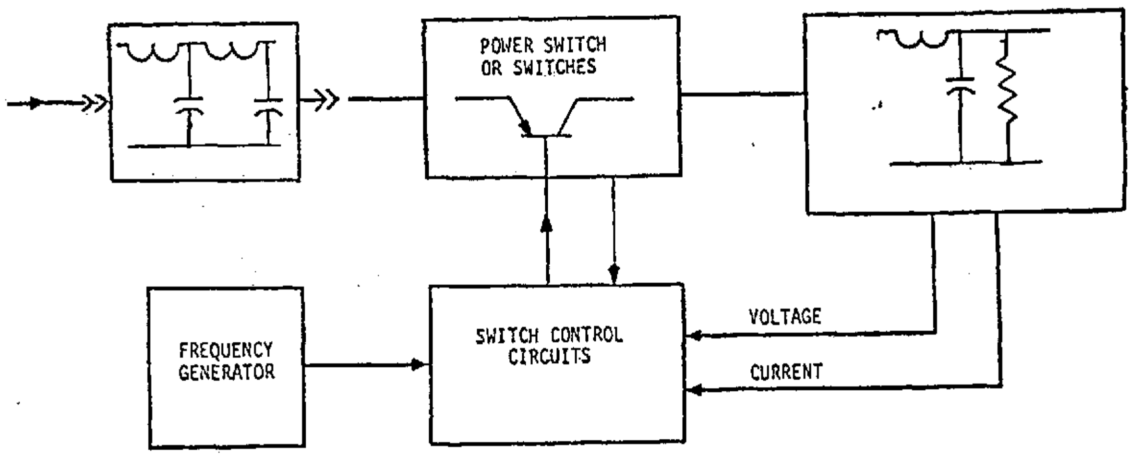


Figure A-1. Standard PWM Buck Regulator Configuration

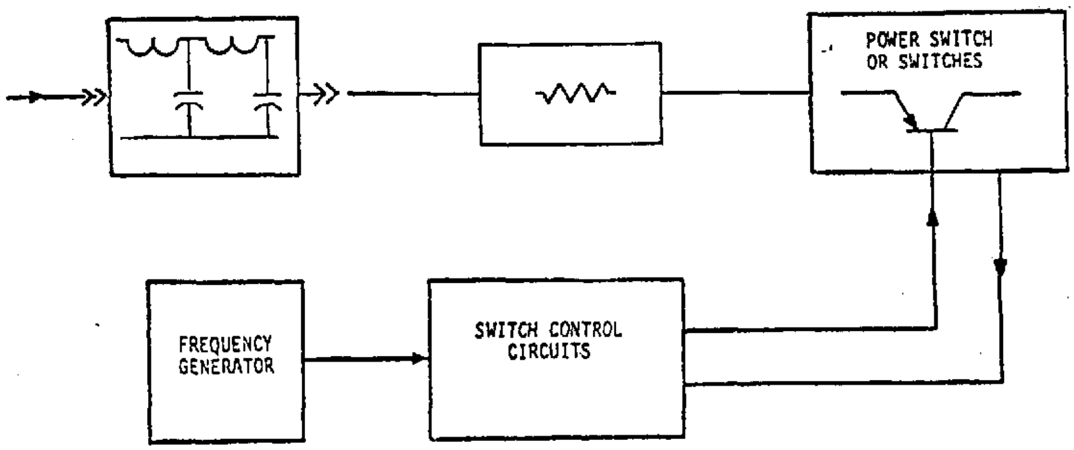


Figure A-2. Simulated PWM Configuration

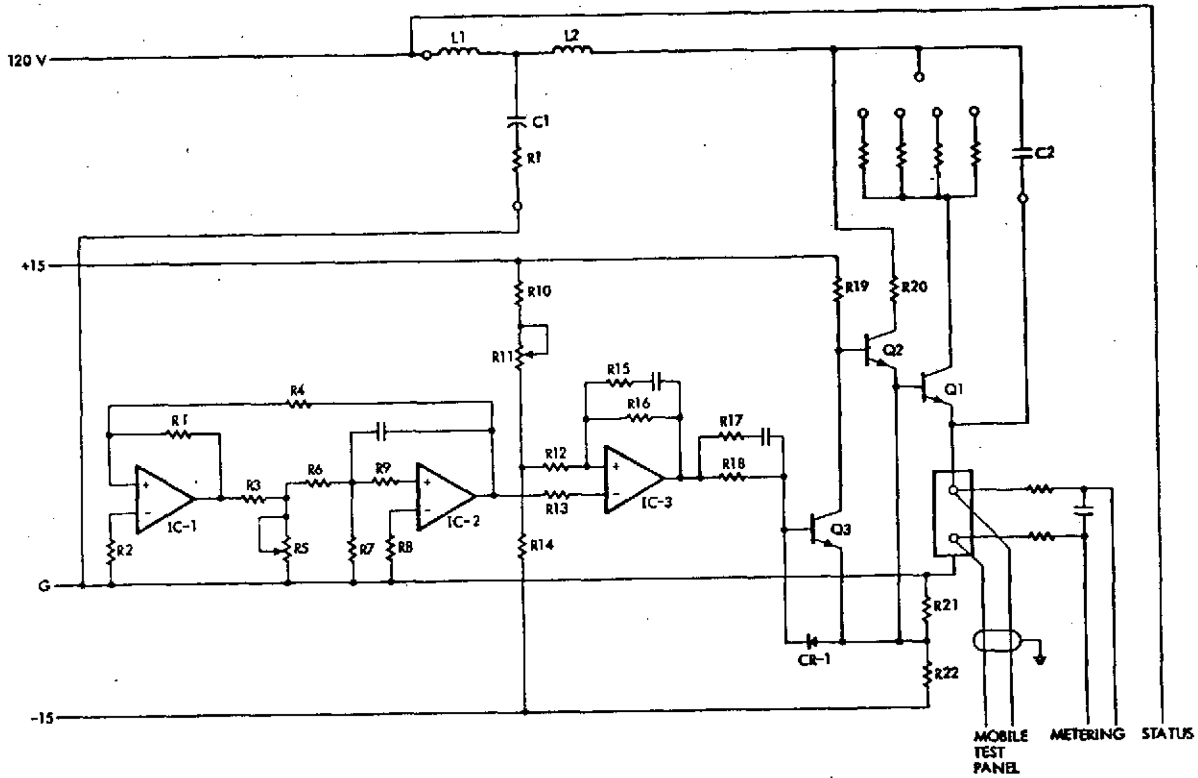


Figure A-3. Simulated PWM Functional Schematic

the deleted output filter characteristics. The performance of the NPN switching element with a positive voltage line, grounded emitter and resistive load is predictable and less subject to breakdown phenomena associated with the inductive load of the normal configuration. A single control circuit design will fulfill the circuit requirements for all variations of line voltage and load. It will be necessary to change switching transistors to accommodate the full voltage and power range required in the tests. In order to provide an adequate comparison of performance for all conditions, an input filter must be designed for each combination of line voltage and load current.

2.0 FILTER CONFIGURATION

Filters are required at the input of a PWM switching regulator to provide the low non-inductive source impedance required by the switching element and shield the input power line from the ac component of current drawn by the switch. The degree of filtering is determined by the tolerance of the power source and parallel loads to pulsed line current and allowable losses due to the increased RMS value of that current. Spacecraft filter designs are required to maintain the magnitude of the ripple current on the input line within the values designated in the appropriate specification. The requirements on a PWM regulator input filter address the following characteristics:

a. Input ripple current
b. Output voltage variation
c. Transient characteristics.

In addition to the above, interactions with the output filter, weight, and size are design considerations.

The requirements for the input filter of the simulated PWM are based on two considerations:

1. Meet MIL-STD-461A, Note 4, for all combinations of line voltage, current and PWM operational frequency.
2. Provide a realistic common basis for the comparison of size, weight, and electrical properties for all combinations of line voltage, current, and PWM operational frequency.

Selection of filter configurations was limited to inductance input (to meet turn-on transient noise requirements) and capacitance output (to meet switching element requirements. A single stage filter may then be completely defined from the calculation of capacitance required to limit the output ripple voltage to the value which may be tolerated by the output capacitor and the switching element, and the inductance required to limit the ripple current to within the specification of MIL-STD-461A. However, with this simple configuration it is not possible to effectively constrain the initial transient peak voltage applied to the PWM switching element. The use of a two-stage inductance input filter does provide control of the transient peak voltage and also is improved from the weight standpoint. The two-stage filter configuration illustrated in Figure A-4 was selected on this basis.

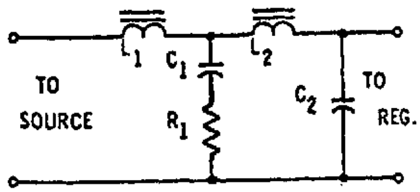


Figure A-4. Two-Stage Input Filter with Controlled Damping Factor

3.0 FILTER ELECTRICAL DESIGN

The electrical parameters of the PWM input filter are based on work performed at TRW and documented in Reference (1). The design criteria in that analysis place constraints on input line ripple current, output capacitor peak-to-peak voltage, resonant peaking (audio susceptibility), and initial transient overshoot. The design procedures provided were adopted for this program and programmed on the remote terminal. Modifications were incorporated to provide the automated selection of filter attenuation required by the range of power system voltage and current parameters, PWM frequency and the constraints of MIL-STD-461A. The output of this program provides all the resistor, inductor, and capacitor values for the filter.

4.0 COIL DESIGN

The mechanical design constraints on the filter inductances were based on analytic results presented in Reference (2). These equations provide complete design factors for a minimum weight coil design derived with variational calculus methods. The terms used in the analysis are defined below.

A : Core sectional area, meter ^{2}

A_c : Copper conductor area per turn based on a given efficiency requirement, meter^2

B_s : Saturation flux density of the core material, weber/meter^2

D_c : Density of the copper conductor, kg/meter^3

D_i : Density of the magnetic core, kg/meter^3

F_w : Window fill factor

F_c : Ratio of mean length per turn of copper conductor to circumference of the core cross-section

I_p : Peak current expected in inductor winding, ampere

L : Inductance, henry

N : Number of turns

μ : Permeability of core material in MKS units. To convert to gauss/oersted, divide by $4\pi x 10^{-7}$

Z : Mean length of the circular magnetic path, meter

W_m : Minimum inductor weight, kg

Core cross-sectional area, number of turns, mean circumference of the core, and core permeability are given by the following equations:

$$A = (1/3)[LI_pA_c/B_s\pi F_w]^{1/2}S$$

$$N = 3[LI_p\pi F_w/A_cB_s]^{1/2}(1/S)$$

$$Z = 2\sqrt{3}\,\pi[LI_pA_c/B_s\pi F_w]^{1/4}(S^{-1/2}+\frac{S^{1/2}}{6}$$

$$\mu = (2\pi/\sqrt{3})(B_s/I_p)^{5/4}(A_c/F_w)^{3/4}L^{-1/4}S^{1/2}$$

$$\cdot(1 + \frac{S}{6})$$

where

$$S = 1 + \frac{12F_cF_wD_c}{D_i} - 1$$

The weight of the optimized coil is

$$W_m = (2\pi D_c/\sqrt{3})(LI_pA_cB_s\pi F_w)^{3/4}(S)^{-1/2}\,[6F_cF_w+(D_i/D_c)(S + \frac{S^2}{6})]$$

The design equations were programmed at TRW and made available to this study (Reference (3)). Modifications were added to provide variable current density to obtain comparable efficiency for constant PWM power at all input line voltages. These design procedures assume the availability of arbitrary values of permeability (powdered iron core), core dimensions, and wire cross section. Since an actual design will use available piece parts, the final hardware will be suboptimum. However, the variational calculus indicates that optimized functions have shallow minimums and maximum curves in the vicinity of the solution and negligible deviation from the optimum weights are anticipated.

5.0 CAPACITOR SELECTION

Capacitor values are standard catalog piece parts. The output capacitor (C2) is required to withstand initial voltage transients with 30% overshoot and currents equal to 50% of the line current. The continuous ac current rating of capacitors used in this circuit must be adequate or catastrophic (explosive) failure will occur. Recommended capacitor types are ceramic, mylar, teflon, polystyrene, polycarbonate, and metalized versions of these designs. These capacitors were compared on the basis of volume with data derived from the Balco Electronics Catalog. The results of this trade are listed in Table A-1.

Table A-1

Capacitor Type	$in^3/\mu f$ at 100V
HT Teflon and Foil	4.51
KT Polycarbonate and Foil	0.83
PT Polystyrene and Foil	4.5
QT Mylar and Foil	1.05
HTM Metalized Teflon	0.91
KTM Metalized Polycarbonate	0.47
PTM Metalized Polystyrene	1.47
QT Metalized Mylar	0.3

Metalized polycarbonate was selected on this basis together with additional considerations of ac current capability and successful past experience. Capacitor values, rating dimensions, and weight were selected from the Component Research Co. Catalog G. The largest capacitor value in each voltage rating was selected.

Capacitor C1 (filter first stage) is required to withstand low magnitude ac currents and voltages less than 5% in excess of the actual line voltage. Polarized plain foil capacitors were selected on the basis of weight and volumetric efficiency and available voltage ratings. The Sprague Catalog (Bulletin 3601C) was used as source data for capacitance values, ratings, weight, and volume.

A file of capacitor values, voltage rating, and weight was assembled and programmed on the remote terminal. With a given input voltage, a plain foil and a polycarbonate capacitor is selected with 100% dc voltage margin; if capacitors with 100% margin are not available, capacitors with 50% margin are selected and the actual voltage margin is printed on the terminal; if capacitors with 50% margin are not available, the program will abort and issue a "no capacitor in file" statement. With a line current input, the program will calculate the maximum current in C2 and store a sufficient number of the selected polycarbonate capacitors to stay within 50% of that capacitor's ac rating.

6.0 FILTER DESIGN PROGRAM

The three programs for capacitor selection, filter design, and coil design were assembled into one program in that order. The input requirements to the assembled program are line voltage, power, and PWM operational frequency. The program will then print out complete electrical and physical design parameters, dissipations, weight, and volume for each part of the two-stage filter as well as total weight volume and efficiency. A listing of the program and the program output for a 600 watt PWM operating at 120 and 28 Vdc and 5, 10, 15 and 20 KHz is attached to this Appendix. The typical transient response of these filters is represented by the ICAP plot of Figure A-5 for a 120 Vdc, 600 watt, 15 KHz PWM input filter. The voltages across capacitor C1(*) and capacitor C2($) are shown. The peak voltages indicate 2.2% and 27.5% overshoot for the respective capacitors. Wire size or current density are not printed out in this program but are easily calculated from

$$A = 300I^{1.4}$$

A = Area in circular mils
I = Line Current

This relationship was found empirically to result in reasonably consistent power efficiencies for the range of power, voltage, and frequencies of interest in the test facility.

REFERENCES

(1) Input Filter for CADP High-Voltage Converter, Interoffice Correspondence 7237.16-41, 4 Jan. 1971, Y. Yu to B. F. Farber.

(2) Some Design Aspects Concerning Input Filters for DC-DC Converters, Yuan Yu, John J. Biess (TRW Systems, Redondo Beach, California), PSCS'71 Record, pp 66-76.

(3) Basic Program File, IND, G. T. Inouye (TRW Systems, Redondo Beach, California).

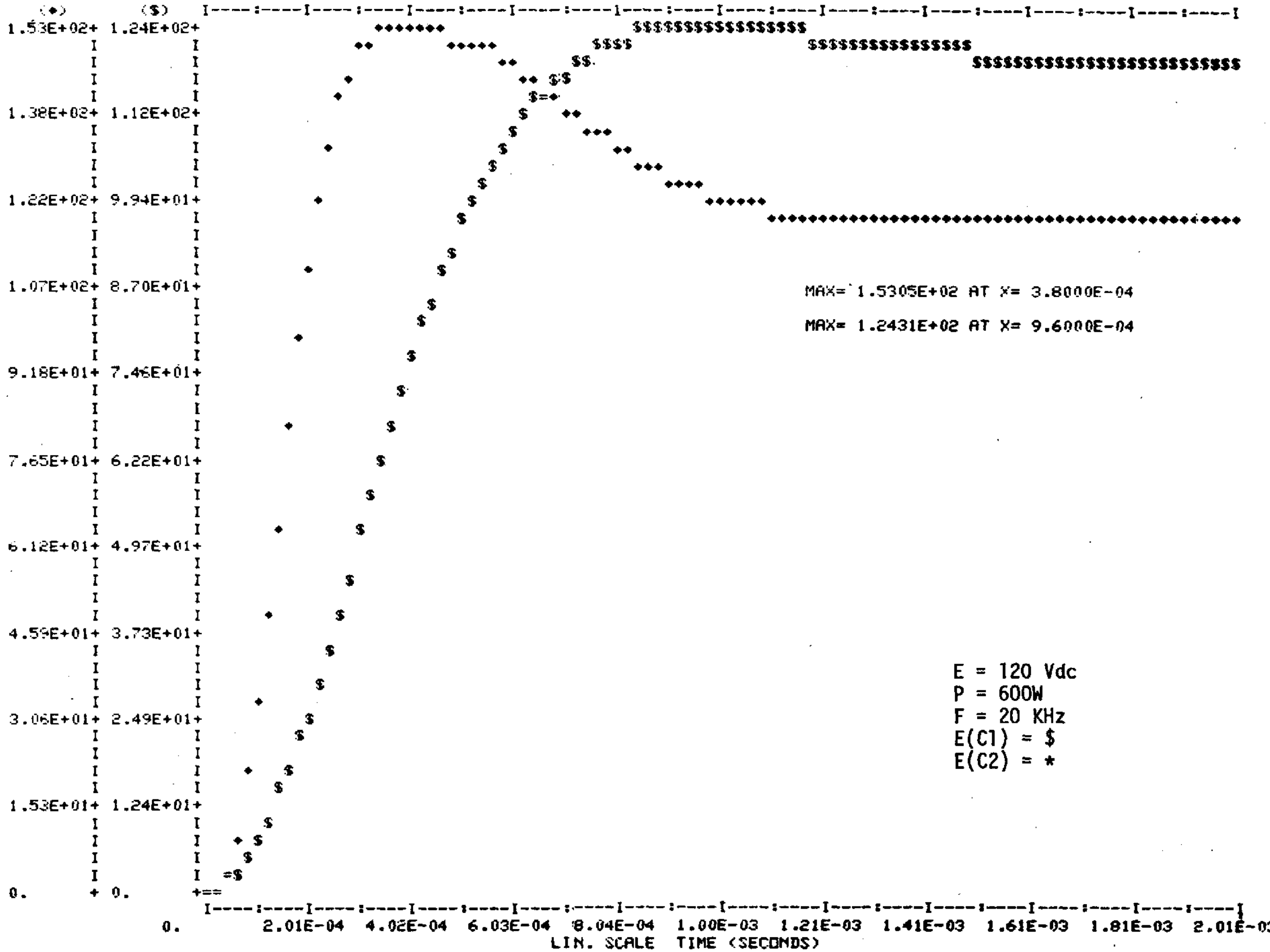


Figure A-5. Turn-On Transient Voltage

PWM FILTER DESIGN PROGRAM (Page 1 of 3)

```
100 PRINT "ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC"
110 INPUT E1,P4,F0
115 I1=P4/E1
120 E2=.055*E1+3.333
121 J=E1
205 E1=1.25*E1
210 IF E1>400 THEN 845
215 T=E1
220 E1=1.2*E1
225 IF E1>400 THEN 325
230 IF E1>375 THEN 335
235 RESTORE 345
240 IF E1>300 THEN 335
245 RESTORE 350
250 IF E1>250 THEN 335
255 RESTORE 355
260 IF E1>200 THEN 335
265 RESTORE 360
270 IF E1>150 THEN 335
275 RESTORE 365
280 IF E1>100 THEN 335
285 RESTORE 370
290 IF E1>75 THEN 335
295 RESTORE 375
300 IF E1>60 THEN 335
305 RESTORE 380
310 IF E1>50 THEN 335
315 RESTORE 385
320 GO TO 335
325 Y=400-T
330 PRINT "C2 SURGE VOLTAGE MARGIN,VOLTS    =";Y
335 READ X1,C1,E5,C2,E6,W1,W2
340 DATA 1,6,450,3,400,2.747,65
345 DATA 2,12,375,3,400,4.214,65
350 DATA 3,18,300,3,400,4.214,65
355 DATA 4,30,250,3,400,5.385,65
360 DATA 5,35,200,5.6,200,5.385,56
365 DATA 6,47,150,5.6,200,5.385,56
370 DATA 7,70,100,10,100,5.385,56
375 DATA 8,88,75,10,100,5.385,56
380 DATA 9,100,60,10,100,5.385,56
385 DATA 10,120,50,10,50,5.385,21.5
```

```
390 V1=2.61*W1
395 V2=.787*W2-1.75
445  C5=(1000*I1)/(2*F0*E2)
450  M=INT(C5/C2+1)
460  C2=M*C2
465  E2=(1000*I1)/(2*F0*C2)
470  I2=1.273*I1
475  I3=3.16*((2/F0)↑2.5)
490  A=I2/I3
495  B=(29.64*A)↑(1/3)+.988
520  F1=F0/B
525  C6=10*C2
526  K=INT(C6/C1+.999)
528  C1=K*C1
530  L1=1000/(C1*((6.28*F1)↑2))
550  L2=L1/2
555  D=1.482
560  Z=1000*L1/C1
565  R1=1.482*SQRT(Z)
566 V1=K*V1
567 V2=M*V2
568 W1=K*W1
569 W2=M*W2
570 I=I1
575 L=L1/1000
580 G=1
585 GO TO 610
590 L=L2/1000
595 GO TO 610
610 A1=300*(I1↑1.4)
615 A2=A1
620 B=.3
625 F1=.3
630 A1=A1*5.067E-10
635 D1=8.94E3
640 D2=8.4E3
645 F2=2
650 S=((1+(12*F2*F1*D1)/D2)↑.5)-1
655 R=(L*I*A1)/(B*3.1416*F1)
660 T=1/(S↑.5)+(S↑.5)/6
665 A=(R↑.5)*S/3
670 N(G)=(3/S)*(((L*I*3.1416*F1)/(A1*B))↑.5)
```

PWM FILTER DESIGN PROGRAM (Page 3 of 3)

```
675 Z=10.3828*(R↑.25)*T
680 U=3.6276*((B/I)↑(5/4))*((A1/(3.1416*F1))↑(3/4))*(1/(L↑.25))*S*T
685 W=3.6276*D1*(R↑(3/4))*(1/(S↑.5))*(6*F2*F1+(D2/D1)*(S+(S↑2)/6))
690 A(G)=A*1E4
695 Z(G)=Z*1E2
700 U(G)=U*(1/(4*3.1416*1E-7))
705 W(G)=W*1E3
710 V(G)=(Z(G)↑3)/39.48
715 R(G)=2.72*N(G)*(A(G)↑.5)/A2
720 P(G)=(I↑2)*R(G)
725 G=G+1
730 ON G-1 GO TO 590,732
732 W5=W(1)+W(2)+W1+W2
733 W6=W5/453.6
734 V5=V(1)+V(2)+V1+V2
735 V6=V5/16.39
736 P5=P(1)+P(2)
737 Q=100*P5/P4
740 L(1)=L1
741 L(2)=L2
750 SIGNIFICANCE 3
755 PRINT ΞINDUCTANCE(L1,L2),MH=  Ξ,L(1),L(2)
760 PRINT ΞAREA,SQ-CM=            Ξ,A(1),A(2)
765 PRINT ΞNUMBER OF TURNS=       Ξ,N(1),N(2)
770 PRINT ΞMEAN MAG LENGTH,CM=    Ξ,Z(1),Z(2)
775 PRINT ΞPERMEABILITY=          Ξ,U(1),U(2)
780 PRINT ΞWEIGHT,GRAM=           Ξ,W(1),W(2)
785 PRINT ΞVOLUME CU-CM=          Ξ,V(1),V(2)
790 PRINT ΞDISSIPATION WATTS=     Ξ,P(1),P(2)
795 PRINT ΞRESISTANCE OHMS=       Ξ,R(1),R(2)
800PRINTΞ               Ξ
805 PRINTΞ    Ξ
810 PRINTΞCAPACITANCE(C1,C2),UF=  Ξ,C1,C2
815 PRINTΞWEIGHT,GRMS=            Ξ,W1,W2
820 PRINTΞVOLUME,CU-CM=           Ξ,V1,V2
821 PRINTΞ  Ξ
822 PRINTΞ  Ξ
823 PRINTΞ RESISTANCE(R1),OHMS=   Ξ,R1
825 PRINTΞ Ξ
830 PRINTΞ Ξ
835 PRINTΞTOTAL WEIGHT,GRMS,LBS=  Ξ,W5,W6
840 PRINTΞTOTAL VOL,CU-CM,IN-CU=  Ξ,V5,V6
841 PRINTΞTOTAL DISSIPATION,WATTS=Ξ,P5
842 PRINTΞEFFICIENCY,%=           Ξ,Q
844 GO TO 850
845 PRINT ΞNO CAP IN FILE FOR THIS VOLTAGEΞ
850 END
```

PWM FILTER DESIGN

```
RUN
ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC
? 120,600,20
INDUCTANCE(L1,L2),MH=              .276E+00        .138E+00
AREA,SQ-CM=                        .545E+00        .385E+00
NUMBER OF TURNS=                   84.5            59.8
MEAN MAG LENGTH,CM=                9.48            7.97
PERMEABILITY=                      53.5            63.6
WEIGHT,GRAM=                       108             64.2
VOLUME CU-CM=                      21.6            12.8
DISSIPATION WATTS=                 1.49            .883E+00
RESISTANCE OHMS=                   .594E-01        .353E-01


CAPACITANCE(C1,C2),UF=             175             16.8
WEIGHT,GRMS=                       26.9            168
VOLUME,CU-CM=                      70.3            127


 RESISTANCE(R1),OHMS=              1.86


TOTAL WEIGHT,GRMS,LBS=             367             .809E+00
TOTAL VOL,CU-CM,IN-CU=             232             14.1
TOTAL DISSIPATION,WATTS=           2.37
EFFICIENCY,%=                      .395E+00

LINE 00850
END
$
```

PWM FILTER DESIGN

```
RUN
ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC
? 120,600,15
INDUCTANCE(L1,L2),MH=                 .31E+00        .155E+00
AREA,SQ-CM=                           .577E+00       .408E+00
NUMBER OF TURNS=                      89.6           63.3
MEAN MAG LENGTH,CM=                   9.75           8.2
PERMEABILITY=                         52             61.8
WEIGHT,GRAM=                          118            70
VOLUME CU-CM=                         23.5           14
DISSIPATION WATTS=                    1.62           .963E+00
RESISTANCE OHMS=                      .648E-01       .385E-01


CAPACITANCE(C1,C2),UF=                175            16.8
WEIGHT,GRMS=                          26.9           168
VOLUME,CU-CM=                         70.3           127


 RESISTANCE(R1),OHMS=                 1.97


TOTAL WEIGHT,GRMS,LBS=                383            .843E+00
TOTAL VOL,CU-CM,IN-CU=                235            14.3
TOTAL DISSIPATION,WATTS=              2.58
EFFICIENCY,%=                         .43E+00

LINE 00850
END
$
```

PWM FILTER DESIGN

```
RUN
ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC
? 120,600,10
INDUCTANCE(L1,L2),MH=                    .23E+00         .115E+00
AREA,SQ-CM=                              .497E+00        .351E+00
NUMBER OF TURNS=                         77.1            54.5
MEAN MAG LENGTH,CM=                      9.05            7.61
PERMEABILITY=                            56              66.6
WEIGHT,GRAM=                             94              55.9
VOLUME CU-CM=                            18.8            11.2
DISSIPATION WATTS=                       1.29            .77E+00
RESISTANCE OHMS=                         .518E-01        .308E-01


CAPACITANCE(C1,C2),UF=                   280             28
WEIGHT,GRMS=                             43.1            280
VOLUME,CU-CM=                            112             212


 RESISTANCE(R1),OHMS=                    1.34


TOTAL WEIGHT,GRMS,LBS=                   473             1.04
TOTAL VOL,CU-CM,IN-CU=                   354             21.6
TOTAL DISSIPATION,WATTS=                 2.06
EFFICIENCY,%=                            .344E+00

LINE 00850
END
$
```

PWM FILTER DESIGN

```
RUN
ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC
? 120,600,5
INDUCTANCE(L1,L2),MH=             .17E+00       .849E-01
AREA,SQ-CM=                       .427E+00      .302E+00
NUMBER OF TURNS=                  66.3          46.9
MEAN MAG LENGTH,CM=               8.39          7.06
PERMEABILITY=                     60.4          71.9
WEIGHT,GRAM=                      74.9          44.5
VOLUME CU-CM=                     15            8.9
DISSIPATION WATTS=                1.03          .613E+00
RESISTANCE OHMS=                  .413E-01      .245E-01


CAPACITANCE(C1,C2),UF=            525           50.4
WEIGHT,GRMS=                      80.8          504
VOLUME,CU-CM=                     211           381


 RESISTANCE(R1),OHMS=             .843E+00


TOTAL WEIGHT,GRMS,LBS=            704           1.55
TOTAL VOL,CU-CM,IN-CU=            616           37.6
TOTAL DISSIPATION,WATTS=          1.64
EFFICIENCY,%=                     .274E+00

LINE 00850
END
$
```

PWM FILTER DESIGN

```
RUN
ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC
? 28,600,20
INDUCTANCE(L1,L2),MH=              .103E+00        .517E-01
AREA,SQ-CM=                        1.91            1.35
NUMBER OF TURNS=                   38.7            27.3
MEAN MAG LENGTH,CM=                17.7            14.9
PERMEABILITY=                      51.1            60.8
WEIGHT,GRAM=                       709             422
VOLUME CU-CM=                      142             84.2
DISSIPATION WATTS=                 3.05            1.81
RESISTANCE OHMS=                   .664E-02        .395E-02


CAPACITANCE(C1,C2),UF=             .12E+04         110
WEIGHT,GRMS=                       53.9            237
VOLUME,CU-CM=                      141             167


 RESISTANCE(R1),OHMS=              .435E+00


TOTAL WEIGHT,GRMS,LBS=             .142E+04        3.13
TOTAL VOL,CU-CM,IN-CU=             533             32.5
TOTAL DISSIPATION,WATTS=           4.86
EFFICIENCY,%=                      .81E+00

LINE 00850
END
$
```

PWM FILTER DESIGN

```
RUN
ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC
? 28,600,15
INDUCTANCE(L1,L2),MH=               .886E-01        .443E-01
AREA,SQ-CM=                         1.77            1.25
NUMBER OF TURNS=                    35.8            25.3
MEAN MAG LENGTH,CM=                 17.1            14.4
PERMEABILITY=                       53.2            63.2
WEIGHT,GRAM=                        631             375
VOLUME CU-CM=                       126             75
DISSIPATION WATTS=                  2.71            1.61
RESISTANCE OHMS=                    .591E-02        .351E-02


CAPACITANCE(C1,C2),UF=              .156E+04        150
WEIGHT,GRMS=                        70              323
VOLUME,CU-CM=                       183             228


 RESISTANCE(R1),OHMS=               .353E+00


TOTAL WEIGHT,GRMS,LBS=              .14E+04         3.08
TOTAL VOL,CU-CM,IN-CU=              611             37.3
TOTAL DISSIPATION,WATTS=            4.33
EFFICIENCY,%=                       .721E+00

LINE 00850
END
$
```

PWM FILTER DESIGN

```
RUN
ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC
? 28,600,10
INDUCTANCE(L1,L2),MH=              .71E-01          .355E-01
AREA,SQ-CM=                        1.58             1.12
NUMBER OF TURNS=                   32               22.6
MEAN MAG LENGTH,CM=                16.2             13.6
PERMEABILITY=                      56.2             66.8
WEIGHT,GRAM=                       535              318
VOLUME CU-CM=                      107              63.5
DISSIPATION WATTS=                 2.3              1.37
RESISTANCE OHMS=                   .5E-02           .298E-02


CAPACITANCE(C1,C2),UF=             .228E+04         220
WEIGHT,GRMS=                       102              473
VOLUME,CU-CM=                      267              334


 RESISTANCE(R1),OHMS=              .261E+00


TOTAL WEIGHT,GRMS,LBS=             .143E+04         3.15
TOTAL VOL,CU-CM,IN-CU=             771              47
TOTAL DISSIPATION,WATTS=           3.66
EFFICIENCY,%=                      .611E+00

LINE 00850
END
$
```

PWM FILTER DESIGN

```
RUN
ENTER LINE VOLTAGE,VOLTS;POWER,WATTS;FREQ,KC
? 28,600,5
INDUCTANCE(L1,L2),MH=                 .488E-01      .244E-01
AREA,SQ-CM=                           1.31          .928E+00
NUMBER OF TURNS=                      26.6          18.8
MEAN MAG LENGTH,CM=                   14.7          12.4
PERMEABILITY=                         61.7          73.4
WEIGHT,GRAM=                          404           240
VOLUME CU-CM=                         80.6          47.9
DISSIPATION WATTS=                    1.73          1.03
RESISTANCE OHMS=                      .378E-02      .225E-02


CAPACITANCE(C1,C2),UF=                .444E+04      440
WEIGHT,GRMS=                          199           946
VOLUME,CU-CM=                         520           668


 RESISTANCE(R1),OHMS=                 .155E+00


TOTAL WEIGHT,GRMS,LBS=                .179E+04      3.94
TOTAL VOL,CU-CM,IN-CU=                .132E+04      80.3
TOTAL DISSIPATION,WATTS=              2.77
EFFICIENCY,%=                         .461E+00

LINE 00850
END
$
```

APPENDIX B

CABLE DESIGN FACTORS

1.0 INTRODUCTION

The rated current capacity for wire in a cable when exposed to the space environment is given in Section 4.1.3.2, Table I, of MSFC Specification 40M39582, "Harness, Electrical Design Standard," and is repeated below for reference:

Table B-1

Wire Size	Maximum Design Current (amperes)
24	1.5
22	3.0
20	4.0
18	5.0
16	6.0
14	8.0
12	11.0

The currents specified are expected to generate a temperature rise of approximately 50°C. This standard may be modified depending on ambient temperature conditions, local thermal boundaries such as a cable duct, the presence of some atmosphere characteristics of manned space environment or the use of short lengths for which heat conduction along the wire becomes a significant factor. The majority of these factors can only be evaluated by tests in the actual environment. Additional constraints may be placed on the current capacity of the wire due to restrictions on allowable voltage drop, efficiency or conductive coupling due to cable impedance. The lowest current defined by any of the above constraints forms the basis for the specification of the cable under steady state conditions. The difficulty of establishing a valid analytic base to evaluate these constraints and the concern for crew safety and mission success frequently result in assumption of conservative design factors which impose a severe weight penalty on both large and small spacecraft.

The specification for wire current capacity addresses the steady state problem only. Fault removal techniques require the specification of time-temperature characteristics for fuses, breakers, and overload current sensors. These devices when located at the power source are intended to protect the power source and/or to prevent the occurrence of severe power transients. When located at the load, integrity of the cable is a prerequisite and the protective device must operate before the cable fails. In either case, the time/temperature characteristics of the cable are a factor. It is conceivable that a wire in a long cable could reach a resistance condition which would not trip a fault removal device but could result in damage to one pair and possibly to adjacent pairs of wires which do not at that time have a fault condition. Another consideration which does not appear to receive sufficient attention is the evaluation of the integrity of a portion of a power distribution system subsequent to experiencing a fault. Presuming that it can be established that the fault has been removed, it is desirable to determine if the loads which still may be served by that cable can be safely reactivated. The use of redundant power systems and the care and conservatism with which power systems are installed, while imposing a weight penalty, usually make this question academic since there would not be the intent to reactivate that portion of the system which has experienced failure. However, as the size of the power systems and the total life of multiple mission vehicles increase, the increased probability of a major fault and the loss of redundant protection becomes a significant factor. It thereby becomes expedient to develop a more detailed basis for an in-flight decision with respect to the continued use of power distribution systems which have experienced faults since the obvious alternative of triple redundancy incurs undesirable weight penalties. The necessarily empirical form of a data base to specify current capability or to estimate the condition of a cable which has been over-stressed, limits an initial effort to designating anticipated tests required and possible failure modes.

2.0 STEADY STATE TEMPERATURE CONDITIONS

The maximum temperatures allowable for teflon insulated wire are 205°C (FEP) and 260°C (TFE). The limitation is imposed on FEP due to loss of mechanical strength; the limitation on TFE is due to the onset of measurable decomposition weight loss. It may be noted that the temperature limitation on the preferred TFE insulation is in general more than 200°C higher than normal ambients associated with space vehicles. Table B-2 gives some characteristics of insulation and wire over this temperature range.

Table B-2. TFE "Teflon" Mechanical Characteristics

	Temperature			
Property	23°C	100°C	204°C	260°C
Ultimate Tensile Strength (PSI)	3850	2500	1500	900
Compressive Stress (PSI)				
5% Strain	1850	800	430	260
Linear Expansion %	0.0	0.9	2.7	4.3
Relative Resistance (copper cable)	1.0	1.37	1.77	2.00

The decrease in insulation strength is a major factor in favoring the lower temperatures in applications where severe mechanical stress environments exist.

Power distribution systems which are not required to function at full capacity during launch or re-entry may be permitted to operate at temperatures close to the 260°C value. Assuming a 23°C ambient, this would increase the cable capacity more than 50% above the specification value in the absence of other constraints.

There is no particular concern about the effect of transients briefly raising the temperature since decomposition proceeds at a sufficiently slow rate that negligible gases are evolved. Table B-3 gives some of the characteristics of teflon at elevated temperatures.

Table B-3. TFE "Teflon" Weight Loss

Temperature °C	Initial Weight Loss % per Hour	Comments
230	0.001 to 0.002	Lower limit of measurement techniques
260	0.0006	
290	0.0015	
320	0.0045	
340	0.014	
370	0.032	
400	0.08	Trace amounts of HF
425	0.15	Trace amounts of Perfluroisobutylene (toxic)

Since the actual temperature rise is a function of the distributed coefficients of emissivity, thermal conductivity and the electrical conductivity of the copper, it is desirable to perform some tests under reasonably simulated flight conditions (i.e., atmospheric pressure, temperature of the surroundings). Cable temperature could be measured by means of wire resistance or imbedded temperature sensors. Infra-red sensors may be used to detect "hot spots" due to irregularities in cable resistance and exposed insulation flaws.

3.0 TRANSIENT TEMPERATURE CONDITIONS

High temperature transients may occur due to major fault conditions on a power distribution system energized by a low impedance power source. This condition is represented in the basic circuit of Figure B-1.

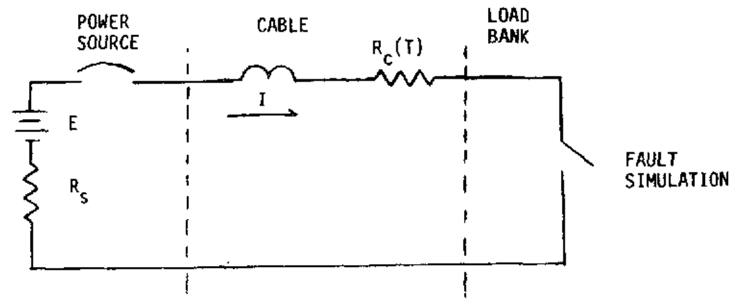


Figure B-1.

Initial current rises at a rate determined by the cable parameters of distributed inductance, capacitance and resistance. The initial rise is completed in approximately 0.5 ms for 200', AWG #8 twisted pair cable before any significant heating takes place. As the temperature rises, the increase in cable resistance causes a decrease in current and associated thermal input. Assuming conductive heat dissipation, the equations governing the temperature rise are given below:

$$E = L\frac{dI}{dt} + I(R_s + R_c) \qquad (1)$$

$$\frac{dT}{dt} = \frac{\left(\frac{E}{R_s + R_c}\right)^2 R_c - B\,(T - T_o)}{J} \qquad (2)$$

T_o = Cable Duct Temperature

T = Copper Temperature

B = Thermal Conductivity

J = Thermal Capacity of Copper Cable

$R_c(T)$ = Cable Resistance

R_s = Source Resistance

Both equations were programmed using iterative techniques with variable time increments.

A decrease in the magnitude of the current increments below a preset value signals the end of the initial primarily reactive transient. The program then shifts to the solution of the purely thermal solution of Equation (2). Input data required are line voltage, line length, cable conductor area in circular mils, rated current and rated temperature rise. All other parameters are calculated in the program. The program outputs time, current, resistance, temperature, and ampere-hours. The last variable was required to provide specifications for the power source battery. A listing of the program is shown in Table B-4 and a typical output in Table B-5. Outputs are approximate due to the iterative method, but sufficiently accurate to provide quick evaluation of significant cable parameters.

Under normal source impedance conditions (i.e. low reactance), Equation (2) is adequate. A closed solution for this equation may be obtained with zero source impedance. This equation was programmed and requires inputs of source voltage, pair length conductor area in circular mils, initial temperature, rated current, and rated temperature rise. The program outputs maximum cable temperature (fusion processes ignored) and the time from the initiation of the cable fault to specified temperatures. A listing of the program is shown in Table B-6 and some tabulated outputs in Table B-7.

It should be noted that the output of Table B-5 and the last column on the right of Table B-7 represent the same conditions. The differences in elapsed time represent cumulative error in Table B-5 due to the iterative approach. Table B-7 provides an overview of the effect on elapsed time to reach critical temperatures (i.e. 260°C, rated temperature; 330°C, teflon gel temperature; 690°C, decomposition products inflammable; 1083°C, copper melting point). The conclusion which may be reached from the data is that the time for a cable to reach a temperature state which determines the degradation of the power distribution system is a function of length, source resistance, and cable cross-section. Furthermore, major faults can exist for significant periods before serious damage to the insulation or the conductor occurs. Since these programs assume linear (conductive) heat dissipation neglecting convection and radiation, the iterative program was modified to simulate a power distribution cable with no capability for heat dissipation under major fault conditions. The result of this run is contained in Table B-8. It is noted that the difference in time for the cable to reach 690°C (flammable temperature) is 101.77 seconds in Table B-8 (no heat dissipation capability) and 106.45 in Table B-5 (rated heat dissipation capability). The difference of approximately 5% indicates that for all practical purposes dissipation capability is not a factor in determining major fault damage. Partial faults, under certain conditions, can result in complete failure of the cable. It may be noted that in Table B-5, the line current just prior to fusion is less than 90 amperes. Since the cable is rated at 20 amperes, a fault which draws four and one-half (4.5) times the rated current will cause the cable to melt after an extended period of time. Smaller fault currents will cause the cable to reach temperatures which will cause degradation of the insulation.

The general solution to the problem of evaluation involves several more areas which have not been investigated. These consist of the following:

a. The ability of the insulation to resist cut-through under varying time-temperature profiles.

b. Stress on the insulation due to harness construction.

c. Stress on the insulation due to the significant change in length of long cables at elevated temperatures.

It is recommended that further studies in this program should address the measurement of these factors.

Power distribution subsystem life, reliability and capability to withstand various fault conditions are dependent on a considerable number of distributed thermal, mechanical and electrical parameters which are unique to each cable harness. Classic approaches which treat these subsystems as simple lumped constant components with poorly defined nominal characteristics impose significant weight penalties on the spacecraft and may not obtain the assumed reliability and performance. It is recommended that further tests and simulations be performed to provide a more precise basis on which to establish the actual capability and limitation of spacecraft power distribution subsystems.

Table B-4. Cable Electrical/Thermal Transient
(Page 1 of 2)

```
005   PRINT"E,D,A,I,T"
010   INPUT E,D,A,I,T
015   R2=10.36/A
020   R1=R2*2*D
021  U=0
025   A=A*(3.1416/4)*1E-6
030   V4=A*12*(2.54↑3)
035   J=3.76*V4
037  VAR=ZERO
045   K=(I↑2)*R2/T
056   N=L
060   R=R1
062   Z=0
065   T=20
070   I1=0
140   M=INT(E/(R*20))
150   L=.32*D*1E-6
160   V1=0
170   V2=M*L/E
200   T2=T
221 PRINT""
222 PRINT""
223  PRINT"TIME","AMPS","LINE R","TEMP","DEL I"
224 PRINT""
225   SIGNIFICANCE 5
240   PRINT V1,I,R,T,I1
250   I1=(E-I*R)*V2/L
260   T1=((I↑2)*R2-K*T)*V2/J
270   R=R1+R1*(T-T2)/235
280   R2=.5*R/D
290   I=I+I1
295   Z1=I*V2
297   Z=Z+Z1/3600
300   T=T+T1
310   V1=V1+V2
320   IF I1<M/10 THEN 360
330   IF ABS(I1)>M THEN V2=.75*V2
340   IF ABS(I1)<M/4 THEN V2=2*V2
341  U=U+1
342  IF (U/5-INT(U/5))>0 THEN 250
350   GO TO 240
360   PRINT ""
```

Table B-4. Cable Electrical/Thermal Transient
(Page 2 of 2)

```
361  READ T(1),T(2),T(3),T(4),T(5)
363  DATA 235,260,330,690,1083
366 PRINT""
367  PRINT""
368  PRINT "TIME","AMP","LINE R","TEMP","AMP-HR"
369 PRINT""
370   PRINT V1,I,R,T,Z
380   T1=((I↑2)*R2-K*T)*V2/J
390   R=R1+R1*(T-T2)/235
400   R2=.5*R/D
410   I=E/R
412   Z1=I*V2
416   Z=Z+Z1/3600
420   T=T+T1
425  IF N=6 THEN 470
430   V1=V1+V2
435  IF (T+2*T2)>T(N)  THEN 445
440   IF T1<20  THEN V2=2*V2
445  IF (T+T1)>T(N)  THEN 452
450  GO TO 370
452  V2=(T(N)-T)*J/((I↑2)*R2-K*T)
454  N=N+1
460   GO TO 370
465   PRINT""
470   PRINT"                    FUSION"
480   END
```

Table B-5. Distribution Cable Major Fault Transient
(Page 1 of 2)

Source Voltage ~120V   Pair Length ~200 feet

Wire Size ~AWG #8   Rated Current/Temp Rise ~20A/50°C

E,D,A,I,T
? 120,200,16510,20,50

TIME	AMPS	LINE R	TEMP	DEL 1
0	20	.251E+00	20	0
.61333E-04	120.09	.251E+00	20	18.093
.12267E-03	198.3	.251E+00	20	14.14
.184E-03	259.43	.251E+00	20	11.051
.24533E-03	307.2	.251E+00	20.001	8.6364
.30667E-03	344.54	.251E+00	20.001	6.7494
.38027E-03	378.99	.251E+00	20.002	10.55
.50293E-03	418.33	.251E+00	20.003	6.3613
.72373E-03	455.11	.251E+00	20.006	5.4725

TIME	AMP	LINE R	TEMP	AMP-HR
.13125E-02	477.61	.25101E+00	20.014	.14472E-03
.15088E-02	478.06	.25101E+00	20.017	.17078E-03
.19013E-02	478.05	.25102E+00	20.023	.22291E-03
.26864E-02	478.04	.25102E+00	20.035	.32716E-03
.42565E-02	478.02	.25104E+00	20.058	.53564E-03
.73968E-02	477.97	.25106E+00	20.105	.95258E-03
.13677E-01	477.88	.25111E+00	20.199	.17863E-02
.26238E-01	477.68	.25121E+00	20.387	.3453E-02
.51361E-01	477.3	.25141E+00	20.762	.67838E-02
.1016E+00	476.54	.25181E+00	21.512	.13435E-01
.20209E+00	475.03	.25261E+00	23.009	.26695E-01
.40307E+00	472.04	.25421E+00	25.994	.53047E-01
.80502E+00	466.2	.2574E+00	31.926	.1051E+00
1.6089	455	.26374E+00	43.639	.20671E+00
3.2167	434.39	.27625E+00	66.493	.40071E+00
4.8246	399.12	.30066E+00	88.291	.57897E+00
6.4324	370.44	.32394E+00	108.3	.74441E+00
8.0402	347.52	.34531E+00	126.84	.89962E+00
11.256	328.66	.36512E+00	161.6	1.1932
14.471	298.33	.40223E+00	194.39	1.4597
15.62	274.43	.43727E+00	205	1.5472
17.918	267.5	.44859E+00	224.48	1.718

Table B-5. Distribution Cable Major Fault Transient
(Page 2 of 2)

20.215	255.64	.4694E+00	243.44	1.8811
22.319	245.07	.48966E+00	260	2.0243
26.525	236.53	.50734E+00	291.68	2.3007
30.731	221.74	.54118E+00	322.17	2.5597
31.888	209.15	.57374E+00	330	2.6269
34.201	206.15	.5821E+00	344.74	2.7594
38.827	200.72	.59785E+00	373.75	3.0173
43.453	190.83	.62883E+00	401.9	3.2626
48.08	182.12	.6589E+00	428.55	3.4966
52.706	174.58	.68736E+00	453.87	3.721
57.332	167.97	.71441E+00	478.05	3.
61.959	162.11	.74023E+00	501.2	4.1451
66.585	156.87	.76497E+00	523.46	4.3467
71.211	152.14	.78873E+00	544.9	4.5423
75.838	147.85	.81163E+00	565.6	4.7323
80.464	143.93	.83375E+00	585.64	4.9172
85.09	140.33	.85514E+00	605.05	5.0976
94.343	137	.87588E+00	642.75	5.4497
103.6	130.98	.91615E+00	679.3	5.7863
106.45	125.63	.95519E+00	690	5.8861
112.17	124.14	.96661E+00	710.41	6.0833
117.89	121.41	.98841E+00	730.49	6.2761
123.61	118.83	1.0099	750.03	6.4648
135.04	116.42	1.0307	788.05	6.8346
146.48	112.01	1.0713	824.99	7.1904
157.91	108.03	1.1108	860.13	7.5336
169.35	104.5	1.1483	893.64	7.8655
180.78	101.34	1.1841	925.68	8.1874
192.22	98.495	1.2183	956.4	8.5003
203.65	95.912	1.2511	985.91	8.8049
215.09	93.555	1.2827	1014.3	9.1021
226.52	91.392	1.313	1041.7	9.3924
237.96	89.399	1.3423	1068.2	9.6764
	FUSION			

Table B-6. Cable Thermal Transient

```
100   PRINT"E,D,A,I,T,R(EX)"
110   INPUT E,D,A,I,T,R3
120   R2=10.36/A
130   R1=R2*2*D
140   A=A*(3.1416/4)*1E-6
150   V4=A*12*(2.54↑3)
160   J=3.76*V4*2*D
170   VAR=ZERO
180   K=(I↑2)*R1/T
190   Y=1/235
200   T2=20
210   Q1=(R3+R1)/(Y*R1)-T2
230   S1=(E↑2)/(Y*R1*J)
240   S2=K/J
250   S3=S2*(Q1+T2)
260   S4=S3/(2*S2)
270   S5=S1/S2+(S3↑2)/((4)*(S2↑2))
280   S6=SQR(S5)
290   T3=S4+S6
300   PRINT""
320   PRINT""
330   PRINT"MAX TEMP";(T3-Q1)
340   PRINT "T0,TF,MODE"
350   INPUT T(1),T(2),G
360   N=1
370   T1=Q1+T(N)
380   X1=(T1-S4)/S6
390   X2=1-X1↑2
400   X3=SQR(X2)
410   X4=X1/X3
420   X5=ATN(X4)
430   X6=LOG(X3)
440   X7=TAN(X5/2+PI/4)
450   X8=LOG(X7)
460   X(N)=X8*S4/(S2*S6)-X6/S2
470   N=N+1
480   IF N<3 THEN 370
490   PRINT (X(2)-X(1));"  SECONDS"
510   ON G GO TO 100,340,520
520   END
```

Table B-7. Time (Seconds) to Reach Temperature from 23°C with Short Circuit at Load AWG #8 Wire Pair

Source Voltage (Volts)	28	28	28	120	120	120
Cable Length (Feet)	50	100	200	50	100	200
Temperature °C						
73	4.3	17.3	70.2	0.23	.94	3.7
260	27.8	114.7	524.4	1.5	6.0	24.2
330	39.8	166.3	830.0	2.1	8.6	34.6
425	58.9	252.4	1560	3.1	12.6	51.1
690	131.1	635.2	-	6.8	27.4	113.4
1083	301.6	3119.1	-	14.6	59.4	258.0

Table B-8. Distribution Cable-Major Fault Transient
(Page 1 of 2)

Source Voltage ~120V

Wire Size ~AWG #8

Pair Length ~200 feet

Rated Current/Temp Rise ~20A/50°C

```
E,D,A,I,T
? 120,200,16510,0,50
```

TIME	AMPS	LINE R	TEMP	DEL I
0	0	.251E+00	20.	0
.61333E-04	104.45	.251E+00	20	18.883
.12267E-03	186.09	.251E+00	20	14.758
.184E-03	249.89	.251E+00	20	11.533
.24533E-03	299.74	.251E+00	20.001	9.0134
.30667E-03	338.71	.251E+00	20.001	7.0441
.368E-03	369.16	.251E+00	20.001	5.5051
.49067E-03	412.4	.251E+00	20.003	6.9924
.68693E-03	449.83	.251E+00	20.005	6.7325

TIME	AMP	LINE R	TEMP	AMP-HR
.13248E-02	477.61	.25101E+00	20.014	.14499E-03
.15211E-02	478.06	.25101E+00	20.017	.17106E-03
.19136E-02	478.05	.25102E+00	20.023	.22318E-03
.26987E-02	478.04	.25102E+00	20.035	.32743E-03
.42688E-02	478.02	.25104E+00	20.058	.53592E-03
.74091E-02	477.97	.25106E+00	20.105	.95285E-03
.1369E-01	477.87	.25111E+00	20.199	.17865E-02
.26251E-01	477.68	.25121E+00	20.387	.34533E-02
.51373E-01	477.3	.25141E+00	20.762	.67841E-02
.10162E+00	476.54	.25181E+00	21.513	.13435E-01
.20211E+00	475.03	.25262E+00	23.011	.26695E-01
.40308E+00	472.04	.25422E+00	25.999	.53047E-01
.80504E+00	466.19	.25741E+00	31.936	.1051E+00
1.6089	454.98	.26375E+00	43.662	.2067E+00
3.2168	434.35	.27627E+00	66.552	.40069E+00
4.8246	399.04	.30072E+00	88.404	.57891E+00
6.4324	370.3	.32406E+00	109.48	.74429E+00
8.0402	347.32	.3455E+00	127.11	.89941E+00
11.256	328.41	.3654E+00	162.06	1.1928
14.471	297.97	.40273E+00	195.1	1.4589
15.533	273.96	.43802E+00	205	1.5397
17.657	267.5	.44859E+00	223.2	1.6975
19.78	256.39	.46804E+00	240.98	1.8487

Table B-8. Distribution of Cable-Major Fault Transient
(Page 2 of 2)

21.904	246.39	.48702E+00	258.02	1.9941
22.161	237.52	.50522E+00	260	2.0111
22.676	236.53	.50734E+00	263.83	2.0449
23.705	234.64	.51142E+00	271.44	2.112
25.764	230.96	.51956E+00	286.56	2.2441
29.882	224	.53571E+00	316.32	2.5003
31.834	211.46	.56749E+00	330	2.6149
35.738	206.15	.5821E+00	355.83	2.8385
39.643	196.82	.6097E+00	381.02	3.052
43.547	188.5	.6366E+00	405.06	3.2564
47.451	181.19	.66228E+00	428.09	3.4529
51.356	174.7	.68688E+00	450.23	3.6424
55.26	168.89	.71052E+00	471.57	3.8256
59.164	163.64	.73332E+00	492.21	4.003
63.069	158.87	.75535E+00	512.2	4.1753
70.877	154.5	.77671E+00	551.01	4.5105
78.686	146.67	.81817E+00	588.76	4.8286
86.495	139.78	.85849E+00	624.6	5.1318
94.304	133.81	.89676E+00	658.76	5.422
101.77	128.58	.93324E+00	690	5.6886
109.23	124.14	.96661E+00	720.02	5.9459
116.69	120.16	.99868E+00	749.01	6.195
124.15	116.55	1.0296	777.07	6.4365
131.61	113.25	1.0596	804.28	6.6713
139.08	110.23	1.0887	830.72	6.8998
146.54	107.44	1.1169	856.46	7.1225
154	104.86	1.1444	881.55	7.3398
161.46	102.46	1.1712	906.03	7.5522
168.92	100.22	1.1974	929.95	7.7599
176.39	98.127	1.2229	953.35	7.9633
183.85	96.162	1.2479	976.27	8.1627
191.31	94.312	1.2724	998.72	8.3581
198.77	92.567	1.2964	1020.7	8.55
206.24	90.918	1.3199	1042.4	8.7385
213.7	89.355	1.343	1063.6	8.9237
	FUSION			