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DESIGN GUIDE: DESIGNING AND BUILDING HIGH VOLTAGE POWER SUPPLIES

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NOTICE

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This report contains an accumulation of publications and analyses aimed at developing guidelines for improving both high voltage and low voltage power supplies for the U.S. Air Force systems command. It is the intent of the report to supply good design and manufacturing techniques for the packaging and the building of high quality, reliable, long-life power supplies. These data are based on the wealth of engineering practices established by design and manufacturing engineers.

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FOREWORD

This Interim Technical Report covers the work performed on contract Nos. F 3360187 M 7499 through F 3360187 M 8081, project 2418, entitled, "High Voltage Power Supply Design and Reliability Handbook," for the period 20 July 1987 through 19 July 1988.

This contract was performed by the Space Power Institute, Auburn University, Auburn, Alabama 36849 for the U.S. Air Force Materials Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433. The Program was under the technical direction of Dr. Bill Dobbs, AFWAL/MLSA with assistance from Mrs. Lavera Floyd and Mr. John Price of ASD/ENA. The Program Manager for Auburn University was Dr. M. Frank Rose. Other key personnel were William G. Dunbar, Research Associate, Space Power Institute and Lt. Chris Tarvin, AFWAL/MLSS.

TABLE OF CONTENTS

TABLE OF CONTENTS (concluded)

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I
SCOPE

The U.S. Air Force has emphasized the use of new development electronic components and designs, materials technologies, manufacturing, and test techniques for power supplies to reduce the manufacturing and maintenance cost of airborne and ground-based systems and increase system reliability. The U.S. Air Force has sponsored many manufacturing technology programs that have contributed significantly to the development and manufacture of many new development parts, printed circuit boards, and components. The results of these programs are reflected in smaller volume, lower weight, and reasonable cost power supplies.

This document contains the executive summary which outlines many requirements and specifications that are either overlooked or taken for granted during the assessment and procurement of power supplies. Volume II is a high voltage design guide for airborne equipment, which is applicable to ground-based equipment. In that volume are details on insulations, selection and application, packaging, and design details, with emphasis on manufacturing, test, and maintainability.

For current industry production to make rapid strides toward more reliable, longer life, cost-effective power supplies, a better understanding and implementation of tests for electrical performance, mechanical, thermal, and environmental stresses must be imposed by the statement of work and applicable specifications. Most military specifications and standards are well written and, if properly applied, the manufactured power supplies will meet the desired objectives for flight readiness.

SECTION II
INTRODUCTION

There is an urgent need for long-life, affordable, high-energy density power supplies to maintain the flight readiness of U.S. Air Force flight and ground support systems. Manufacturing technology, standardization programs, and workshops that have been implemented to emphasize the need for lighter weight, smaller volume, increase reliability, and, in many cases, lower cost. Initially, many programs appeared to bring breakthroughs toward higher reliability and longer life, only to find that life and reliability were good for the few power supplies delivered for the development program. Two reasons exist for the reliability and life dropping from its initial state. First, the initial orders were procured using special manufacturing techniques to build a few previously designed power supplies. Second, the supplier did not include the required modifications for the developed design in the manufacturing and test procedure because of cost and schedule. Because of this, improvements in design, manufacturing, and test must be either specified at contract initiation or a new contract for subsequent modified power supplies must be issued.

Electrical design, packaging, materials and processes, manufacturing, and test are equally important to the life, reliability, and cost effectiveness of a compact power supply. So far, no single electrical or packaging design has all the ideal electrical, thermal, and structural properties for all applications; therefore, the engineer must recognize that each application has a set of designs that must both satisfy the electrical performance and meet the environmental and structural constraints.

For example, many materials with good electrical properties have poor thermal or structural properties. In others, it may be difficult to procure materials without voids, which are the principal source of partial discharges and eventual arcing. In addition, the more compact the packaging design, the more closely spaced are the parts and interconnects. This implies that insulation must adhere to all surfaces of the parts within the enclosed volume without voids, cracks, or delamination to ensure a nearly corona-free, long-life design.

The designer must evaluate compromises when selecting the correct packaging techniques for electrical insulation and processing for a reliable, compact, lightweight, high voltage power supply.

SECTION III
BACKGROUND

Current U.S. Air Force high voltage power supplies require sophisticated electronics design, packaging, and electrical insulation to achieve the dense packaging constraints of modern airborne and ground support weapon system requirements. It is the application of these requirements that increases power supply manufacturing and test costs.

Power supplies can no longer be assumed to be simple circuits. Early airborne and ground power supplies were simple, operating either from a 60-Hz power source or a dc power source with a very low frequency electromechanical multivibrator. At best, most early power supplies consisted of a transformer, rectifier, and simple filter with little or no feedback control. Little emphasis or design time was allocated to yesteryear's power supplies. Some managers and executives believe the same to be true for the complicated electronic power supplies for modern equipment. As a result, too little design, packaging, and manufacturing time is allocated to the power supplies with respect to the time allocated to the electronic circuit. This results in poorly conceived designs, circuitry, and packaging for expensive electronic hardware.

In most cases, the modern power supply is a complicated electronic circuit. The designer may start with either an alternating or direct voltage source, but to save weight and volume he must immediately convert the input energy to radio frequency energy, often to frequencies between 100 kHz to 1.0 MHz or higher. To do this radio frequency magnetic components and capacitors require special selection and application, wiring must be kept short, coupling between circuits must be minimized, and all components and parts must be life derated for high-frequency applications. Older power supplies accepted large voltage swings and transients; current hardware must be well regulated and have controls for over and under voltage, over and under current, temperature, short-circuit protection, and frequency control. In addition, they must be electromagnetic interference compatible and many designs must be electromagnetic pulse hardened. Current power supplier designers must be multi disciplined in power, power electronics, radio frequency, thermodynamics, structure and materials and processes. They must also be given ample time and budget to do their designs so the government will be able to obtain high-quality, long-life flight power supplies for the aircraft electronics system.

SECTION IV
EXECUTIVE SUMMARY

4.1 Introduction

The purpose of this document is to provide the U.S. Air Force Systems Program Office (SPO) and Associate Air Logistic Center (ALC) personnel a more realistic insight when developing new electrical and electronic systems or when upgrading existing systems. The objective of these recommendations is to relieve SPO and ALC personnel of some ambiguities that have existed concerning weight, volume, form, fit, and function of one key item in the electronic system: the power supply.

When the system is being planned, the SPO must include the PRAM and ALC office personnel to obtain high-reliability, long-life and maintainable hardware for the system to be contracted. This planning must include all the form, fit, function, and test equipment requirements for the system. Many older systems did not require built-in test equipment (BITE) or automatic test equipment (ATE) for their circuits. These circuits must become a part of the electronics package. This implies that new ALC test equipment must be developed to ensure the ATE or BITE are functioning properly in addition to the other electronic or powertrain circuits.

This information, although directed to the design and manufacture of high voltage power supplies, applies equally to low voltage power supplies, inasmuch as each high voltage power supply is merely a low voltage power supply with a high voltage converter, filter, and output connector.

Topics that should be emphasized are insulating materials, manufacturing materials processing, assembly, and test. Topics on design criteria, power and volume densities, and environmental screening are well defined in the U.S. Navy document NAVMAT P4885-1, "Navy Power Supply Reliability Document". A considerable amount of redundant material between this document and NAVMAT P4855-1 is necessary to emphasize the importance of those articles.

4.2 **Program Management**

Program management personnel must address design, development, manufacturing time, and cost for power supply procurement. A power supply is an electronic circuit; it must be designed, developed, and manufactured with the same precautions as its electronic load. The first recommendation is that the power supply design be given equal design, development, and manufacturing time as its electrical or electronics load. After all, haven't we been designing and manufacturing the electronics as long as the power supplies? Modern power supplies also operate at radio frequencies as well as power frequencies.

Realistic technical capability must be demonstrated by both the U.S. Air Force program management and the contractor. For instance, environmental test constraints have been a source of waivers and subsequently for shortened life. Temperature and cooling waivers are intolerable and should cease for long-life equipment procurement.

The U.S. Air Force management and contractor must both understand the design specifications, the airplane environment, the maintainability of the power supply, and its input energy source and output load before a statement of work can be agreed. Likewise, contractor management must relay all the specified data to selected subcontractors and insist on high-quality workmanship and quality control to obtain better flight hardware.

4.2.1 Development and Cost

There are two categories of power supplies and many types of power supplies. The two categories are (1) identical or similar and (2) new development power supplies. Identical or similar power supplies may follow the traditional idea that the power supply can wait until the host electronic circuit is completely developed and then accept an off-the-shelf power supply. That premise is acceptable as long as the power supply is not upgraded to include better regulation, more circuits for BITE or ATE, computer logic control, or improved electromagnetic interference (EMI) filtering.

New development power supplies include changes to:

- o EMI filtering or hardening for electromagnetic pulse
- o New power input-output power or voltage characteristics
- o Upgraded BITE, ATE, or logic functions
- o New form or fit for missile versus airplane, helicopter operations
- o Higher altitude or other environmental changes
- o Heat removal system changes
- o Upgraded parts
- o Upgraded tests to obtain long life

A traditional, similar or identical power supply can be developed in very short order if the original power supply to be modified is a long-life, maintenance-free design.

New development reliable power supplies require a development time of 18 months to 4 years from specification release and design start to first production unit. The short time is for minor changes such as improving a filter, BITE, or ATE circuit. Longer time is required to develop a new system with complicated voltage, high-power conversion techniques, such as the multikilowatt to megawatt systems.

Short development time, less than 18 months, usually means the supplier has modified an existing power supply. This implies that all the existing failure modes and marginal parts of the previous supply will be coupled to the new failure modes of the modification.

Buying from the lower bidder usually results in a hurried design that neglects fundamental problems that exist with --

- o Environmental test and evaluation
- o Structural integrity between potted insulation and metallic surfaces
- o High electric field stresses in electrical insulation or between traces in a board, which lead to short life
- o Poor test procedures and inadequate tests

The initial cost saving is very poor compared to the cost of resupply, maintenance, repair, and system downtime to replace failed power supplies. A low power, high voltage power supply with long life, high reliability, and low maintenance costs up to 60 percent more to improve life, from a few hundred hours to over 10,000 hours, which is very cost effective.

4.2.2 Standardization

Power supplies for ground support as well as some airplanes can be custom designed for the host system. Many airborne and spaceborne power supplies are difficult to standardize. Ground support equipment can use a power supply operated at 75 percent to 100 percent output capacity without endangering the host system, as long as the output voltage characteristics meet the host system voltage requirements. In some cases the host system may require a simple modification to meet a standard power supply output characteristic.

Flight power supplies, especially for small missiles, have form and fit constraints that make standard rectangular power supply designs impractical. Spacecraft and small airplanes have restricted volumes for the power supply and its host system. Therefore, it may be impractical to standardize for form and fit, but practical to standardize for function.

Some computer programs develop power supply circuits by storing and selecting the proper subcircuit for the supply to be developed. Subcircuits that can be stored in computer memory include:

- Input power characteristics
- Input filters
- Switches
- Transformation and rectification
- Output filters
- Output power characteristics
- Control
- ATE and BITE
- Thermal control

Using the following parameters, compatible subcircuits can be selected and developed for the complete power supply:

(a) Where practical standardization allows one power supply design for several applications, the power supply may be overrated for some loads and correct for others.

(b) It eliminates designing many power supplies for growth to meet future host circuit requirements.

(c) Basic requirements for the host circuits are compatible with the power supply provided the host circuit power input requirement is specified for the standard power supply.

(d) Reduces development costs.

(e) Heat removal is standardized as either cold plate or air cooled.

4.2.3 Life and Reliability

There is good correlation between life and reliability when the parts are used in accordance with the specified characteristics that were used to obtain the reliability numbers. In addition, all parts must have a meaningful reliability number. It is estimated that 30 percent to 50 percent of failures in high voltage power supplies can be contributed to misapplication and workmanship for electrical insulation; yet the reliability numbers for electrical insulation and workmanship are 1.0: a complete error. There are many ways to obtain the life in hours for electrical insulation; some empirical, some by test. Whichever method is used, the reliability of electrical insulation and workmanship should not be 1.0. Low voltage power supplies have less trouble with voltage breakdown than do high voltage power supplies, but they have problems with corrosion, overheating, and circuit board trace breakage.

4.2.4 Tests

Tests are mandated to verify compliance with the specified electrical, environmental, and insulation performance criteria set forth in the military specifications and the power supply specifications. Power supplies are generally tested to meet the tests shown in Table 1.

TABLE 1. ELECTRICAL AND ENVIRONMENTAL TESTS

Test	Test procedure
Vibration	MIL-E-5400, applicable paragraph
Shock	MIL-E-5400, applicable paragraph
Temperature	MIL-STD-202E, Method 107
Altitude	MIL-E-5400, applicable paragraph
Humidity	MIL-STD-202, Method 106
Sand and dust	MIL-STD-202, Method 110
Salt spray	MIL-STD-202, Method 101
Flammability	MIL-STD-202, Method 112
Explosion	MIL-STD-202, Method 109
Life	MIL-STD-202, Method 108
	MIL-E-5400, applicable paragraph
Electrical compliance	MIL-E-5400
	MIL-STD-202
Materials and Processes	MIL-STD-454

Several tests should be imposed on the parts, materials, circuits, subassemblies, and assembly. Each QPL part should be evaluated for tolerances and use by Engineering. Parts with special tolerance requirements should be given special instructions or test procedures to ascertain high quality. High voltage parts and assemblies require special high voltage tests for dielectric withstanding voltage and partial discharge or corona in addition to continuity and electrical characteristics. Incoming materials should be given materials characterization tests to determine quality control by the supplier. Assembly line tests must be in cooperation with Quality Control to determine shorts, opens, cracks, handling damage, soldering corrosion, and excessive solder flux.

Each power supply must be given an acceptance test to verify it will meet the electrical performance requirements. Qualification test units and specified acceptance units must be tested to meet all environmental, materials, and electrical performance. High voltage power supplies should be made to pass the partial discharge test and dielectric withstanding voltage tests in addition to all other tests. All qualification units and specific acceptance units should be tested for life to determine the integrity of the insulation.

The corona or partial discharge test is not fully understood by most designers, consequently it is waived. Actually, it is one of the best tests to verify void-free or crack-free electrical insulation. If there are insulation flaws, most insulations will pass the dielectric withstanding voltage test and insulation test but not the corona test. However, the test must be properly performed by trained personnel using qualified test equipment. Advantages to the partial discharge test are:

- It is a nondestructive test operated at 110 percent to 125 percent rated voltage

- Small voids and cracks that may take months to break down and cause arcing can be found in a few minutes

- Test equipment may be an initial expense but will pay for itself in a short time by failing marginal parts and power supplies

The insulation test is also nondestructive. It indicates short circuits, open circuits, and low resistance or burned insulation in a system.

The dielectric withstanding voltage test or "high pot" test may affect longevity of a power supply. Most compact packaging has electric field stresses near the surfaces of small wires and parts that exceed 150 volts/mil. If tested to two times voltage or greater, some dielectric materials will become overstressed. This shortens the insulation life. All insulation systems should have a field stress analysis before a destructive test is performed.

Life tests should be imposed on at least two high voltage power supplies and critical assemblies. The parts can be accelerated life tested by increasing temperature, increasing frequency of components and circuits or by overvoltage stressing. Life varies: (1) as the inverse of frequency increases, (2) inversely with temperature; that is, half life for every 8° to 10°C rise, and (3) inversely with voltage; that is, 10 percent voltage increase shortens life one magnitude time. Accelerated life is good for up to three to seven times. Above seven times, the data are unreliable because of other influences with parts and insulation.

4.2.5 Design Reviews

Design reviews are very powerful tools that enable the program manager to evaluate the status of the system and hardware quality. No waivers to military specifications and standards, ASTM standards, and the certified specification should be granted because they foreshorten life; cause low reliability; and add cost because of system downtime, maintenance, and repair.

The design review must be staffed with experts who have designed, maintained, repaired, or tested high-quality equipment. It is recommended that the U.S. Air Force design review team have assisting personnel from the ALCs, the PRAM office, and the technical design branches, who understand the design details required for high-quality hardware.

The design review team should plan several meetings with the supplier. In addition to the preliminary design review (PDR), the critical design review (CDR), the production readiness review (PRR), and the production reliability design review (PRDR), several technical exchanges are recommended to discuss the following topics:

- Program objective
- Definition and understanding of the flight environment
- Power supply evaluation and analyses
- Reasons for each drawing change and material and process change
- Benefits to be derived from these changes by reduced EMI and increased life
- Application of technology from other power supply and electronic circuit designs to this power supply
- Retention of the power supply's original form, fit, and functions
- Benefits of environmental and high voltage tests, including corona testing
- Capabilities of the supplier's corona test facility
- Questions on each change from the original specification and its impact on the assembly and test for the specific power supply
- Ensuring the manufacturer understands the requirement for complete accountability of all part and manufacturing failures, failure analyses,

and the retraining of personnel to do the failure analysis and special tests

- o Discussions with key personnel of such items as field stress analysis, solder balling, and high voltage testing

  Determination of test requirements, test procedures, and test equipment at the manufacturer's facility
- o Determination of the type of corona test procedure for each high voltage power supply and the criteria for passing or failing

Engineering technical exchanges should be made with the manufacturer when the first power supply assembly is completed. This technical interchange (1) provides assistance with potting, and testing; (2) approves design changes, procedure changes, and drawing updates; and (3) obtains the final approved production dates for the power supplies. A list of data that must be passed upon by review team follows:

(a) Drawing reviews: All drawings within the drawing tree must be examined for inclusion of parts changes, materials and processes changes, circuit board design and configuration changes, materials and processes compliance, and test compliance.

(b) Module and circuit board assembly: Uninsulated and unpotted circuit boards and assemblies must be examined for workmanship design configuration, packaging compliance, and parts compliance.

(c) Potting: Module and small inductor potting should be easily accomplished by the manufacturer. Large inductors with multiple layers of insulation and very small wires although difficult to impregnate with a single vacuum pressure potting procedure, must be shown to have complete encapsulation and pass corona by the supplier's test and materials department personnel. A change to multiple cycles of vacuum pressure may resolve the problem.

(d) Testing: Special corona test sets may be developed to test the high voltage modules and the circuit. Most magnetics may be tested with commercial corona test sets, high voltage insulation test sets, and megohmeters.

(e) Program review: The program must be reviewed for schedule; contract compliance; and form, fit, and function before PPR.

These technical reviews should be made by a select group of specialists after the CDR and before the PRR. These specialists are not on the team to find fault. Their purpose is to inspect, review, and determine if the power is ready for production and eventual inclusion in flight systems.

The formal design review teams made up of management, Design and Test Engineering, Contracts, and Materiel differ from the technical design review team. They should interface with the technical team to re-evaluate schedules and costs. The formal review team must have a program schedule and the agenda must be followed. The technical review team has a more open schedule, which is designed to assist the manufacturer with problem areas as required to develop a high-quality power supply.

4.2.6 Subcontractor, Contractor, and U.S. Air Force Review

Many U.S. Air Force power supplies and power supply circuits are manufactured by third to fifth order removed suppliers. This makes it difficult to impossible for the SPO to control the design reviews or to determine if all design, manufacturing, and tests comply with the proper specifications and standards. It is recommended that the technical review team have contractor permission to cooperate in the technical exchanges and reviews with the manufacturer and have authority to impose compliance to drawings, test procedures, materials, and manufacturing.

4.3 Design

A long-life, reliable power supply requires several engineering disciplines to obtain goals of over 10,000-hours flight operating time for airplane power supplies and over 40,000-hours life for ground support power supplies. The lesser lifetime for airborne power supplies is attributed to higher electric field stresses between parts and conductors and higher operating temperature for critical parts and insulation. Design engineers must be expert in the disciplines of electronic design, materials and processes, thermodynamics, packaging, power electronics, electromagnetics, grounding and bonding. The thermodynamist must include "hot spot" or maximum operating temperatures in his analyses and tests. Most engineers understand and can measure average temperature. Hot spot temperatures rapidly degrade insulation and shorten predicted life. A rule of thumb for insulation life is halflife for every 8°C to 12°C rise and one decade less life for every 10 percent electric field overstress.

Many failure analyses are made by engineers who look only at the failed part and predict that changing or increasing the part size will suffice. This technique works for most parts failures, but a few failures are caused by overheating or excessive field stress caused by transients during startup, stopping, or intermittent shorts and opens. The failure analysis must include materials, processes, thermal overloads, and excessive field stress. Many items can lead to damage and failures in a power supply, as shown in Tables 2 and 3. For a long trouble-free life, a power supply must be operated at low temperature and moderate field stress, which are not synonymous with high-density packaging and airplane environmental conditions.

4.4 Output Power Density

All military power supplies must use standard parts and the most recent state-of-the-art for design, manufacturing, and test. Output density depends on several design features that are built into the power supply. Some power supplies are built for high efficiency regardless of cost; others are built on a cost-competitive basis, provided they meet functional requirements. Actually, all power supplies should be built to meet functional requirements, high efficiency, and long life.

The first, simplest power supplies merely contain a voltage stepup or stepdown power transformer. A second type is a transformer-rectifier filter that takes power from an ac line and delivers dc. A third type is an invertor, which takes power from a dc source and has an ac output. The fourth type is a converter that converts ac or dc to a different value or several values dc. Each type of power supply has specific functions and should be designed for (1) maximum efficiency to reduce cooling; (2) compact packaging without sacrificing life, reliability, and maintainability; (3) and least cost. These criteria conflict; for example, high efficiency and low weight or compact units with long life at low cost. Because of this, the contractor and supplier must

TABLE 2. POWER SUPPLY FAILURE MECHANISMS

- Instability
- Skin effects
- Voltage peaks
- Current peaks
- Thermal peaks
- Ripple currents
- Common-mode noise
- Leakage inductance
- Non-QPL parts
- Poor grounding techniques
- Poor packaging techniques
- Electrostatic interaction
- Differential noise effects
- Electric noise effects
- Electric field interaction
- Secondary breakdown limits
- Worst-case tolerance effects
- Instantaneous power dissipation
- Equivalent load characteristics
- Stray capacitance
- Magnetic interactions
- Poor phase-gain margin

- Source impedance effects
- Interaction and propagation effects
- Uncontrolled powerup and powerdown
- Parasitic impulses and oscillation effects
- Interaction between systems on the same power source
- Corrosion
- Debonding
- Moisture-proof connectors
- Cracks and voids
- Corona and partial discharges
- Inadequate high voltage testing
- No corona test
- High voltage parts, non-MIL-STD-833C
- High voltage transients
- Short-circuit protection
- Low-temperature waiver
- Poor potting workmanship
- Potting materials selection
- Poor wire routing
- Insufficient cooling
- High pot test overstress

TABLE 3. PART OPERATING TEMPERATURE CRITERIA

<3 watts:	40°C rise from the part ambient with a maximum absolute temperature of +110°C.
>3 watts:	55°C rise from the part ambient with a maximum absolute temperature of +125°C.
Transformers:	30°C rise from the part ambient with a maximum absolute temperature of +100°C for MIL-T-27 Class S insulation.
Capacitors:	10°C rise from the part ambient with a maximum absolute temperature of +85°C.

understand compromises for specific weight, life, and cost. The power supply manufacturer must specify the following details:

- o Power output
- o Type of power conversion required
- o Power characteristics, input, and output
- o Form and fit
- o Regulations
- o Efficiency
- o Heat removal technique
- o EMI and electromagnetic pulse (EMP) requirements

Variations in these parameters can change power density from 0.5 W/in^3 to over 2 W/in^3 in for small, low-power units. Likewise, the weight can vary from 10 W/lb to over 75 W/lb for large inverters. Some very large megawatt class resonant inverters will exceed 100 W/lb. Very low voltage outputs and very high voltage output units will have very poor power density compared to mid-range voltage units that require less copper or insulation.

By modernizing filter systems using properly derated filters, MOSFETS, and recent hybrid techniques on multilayer boards with improved solder techniques, weight and volume can be improved for all power units. For instance, in small power supplies up to a few hundreds of watts, high-frequency planar transformers are a great advantage over core wound and ferrite cores with wire wound cores.

4.5 Power Input Characteristics

The U.S. Air Force needs power supplies for ground support equipment, airplanes, helicopters, missiles, and spacecraft. Each type of vehicle and ground base test unit has its own specific power input characteristics. Some ground support equipment is designed to operate from a 400-Hz input rather than a commercial power line of 60 Hz. On airplanes, the generated voltage may be 115 to 200 volts, 400 Hz, but many power supplies operate from conditioned power or batteries with outputs of 28 volts. With newer equipment there may be new voltages and frequencies to choose from. Typical power system voltages are as follows. The military specifications for some of the voltages give the characteristics of the input power sources described.

- o 115 VAC (+21 percent, to -11.5 percent) single-phase, 47.5 to 440 Hz
- o 115 VAC 3-phase, wye or delta, 400 Hz
- o 115 VAC 3-phase, wye or delta, 50 or 60 Hz, and 115 VAC single-phase, 50 or 60 Hz (MIL-E-4158, paragraph 3.2.30.3)
- o 220 VAC 3-phase, wye or del , 50 or 60 Hz (MIL-E-16400, paragraph 3.5.1.2)
- o Type I 115 VAC single-phase, 60 Hz, and Type 3 115 VAC 3-phase, wye or delta, 400 Hz (DOD-STD-1399, section 300, paragraphs 5 and 6)
- o 220 VAC +/-20 percent, single-phase, 47 to 64 Hz
- o 220 VAC +/-20 percent, single-phase, 360 to 440 Hz
- o 220 VAC +/-20 percent, 3-phase, wye or delta, 360 to 440 Hz
- o 28 VDC +/-20 percent
- o 270 VDC +/-20 percent
- o 115 to 200 VAC 3-phase, wye or delta, 20 kHz (proposed voltage for the NASA Space Station)

Operation of a power supply from more than one of these voltage sources increases the complexity of the design approach, making it more difficult to meet the objectives of high power density and long life. It also increases cost, adds more parts, and decreases reliability. If multiple input power and voltage sources are required, let it be for the ground support equipment used to test and evaluate the flight hardware. Ground support equipment has more space and is not as limited as to weight and volume as flight equipment. Flight power supply input power characteristics should be based on the following:

(a) Flight vehicle power system requirements. Airplanes and helicopters may have interchangeable power supplies. Missiles and spacecraft may require dedicated power supplies.

(b) Power supply input characteristics should be developed to meet as few variables as possible; for instance, do not select 400-Hz and 60-Hz input voltage frequencies. A better selection is 200 VAC at 60 Hz, 400

Hz, or 20 kHz and 270 VDC. It is much easier and cost effective to change 200 VAC to 270 VDC using rectifiers and filters.

(c) The power source must meet a specific military specified power source requirement and that must be an essential input parameter.

An uninterruptible power requirement levied in the power supply design requires the power supply to have energy storage capability. The longer the time, in milliseconds, the greater the energy storage requirement and the more impact to specific weight and cost. Computers and other flight-critical hardware need this uninterruptible requirement, otherwise the specified minimum voltage requirement may be endangered.

4.6 Manufacturing

The real test of a long-life power supply is manufacturing.

Each worker must be encouraged to use his best skills when constructing, assembling, or testing a high-density power supply. Manufacturing management must understand that cleanliness is very important. This includes the amount of dust particles in the air, the relative humidity, temperature, application of qualified parts, boards and wiring, use of new encapsulating and coating materials, and certified test equipment operated by qualified personnel. Quality control personnel obtain training from the design engineers to understand all failure mechanisms and what causes failures, in addition to excellent shop practices by the manufacturing personnel. A shop assembler or test person should not qualify his own construction, assembly, or test.

SECTION V

POWER SUPPLY ACQUISITION

This section concerns the general aspects for the power supply requirements. Included will be the following topics:

- o Statement of work objectives
- o Design and technical requirements
- o Manufacturing practices
- o Fabrication and test
- o Reliability and life

5.1 Statement of Work Objectives

The program can include the power supply as a part of a line replaceable unit (LRU) or a subpart of a larger system. The ultimate goal of the power supply is to produce power of a specified quality to a subsystem or a host electronics package. Small power supplies in an airplane are usually dedicated to a specific host load, such as a computer (low voltage) or a radar (high voltage). The objective of the program should be stated, along with the criticality of the host subsystem or electronic load. Each power supply is essential, or it would not be required. But in some cases, flight success depends on the host load being operational at all times. This is important from the reliability and life aspects of the unit. Redundancy of the power supply as a unit or for specific circuits in the power supply must be stated in the objectives. For instance, if two or more power supplies are required for redundancy, are they totally independent in separate shop replaceable units (SRU), or do they have a common mainframe? If they are in a common mainframe, do the units share a common cooling loop or separate cooling loops? And do the units share common electronic sensors, BITE, ATE, or computer control circuits? The objectives and scope for the statement of work should include all these items as well as specifics for the particular power supply. Other topics that must be included in the objectives and scope are as follows:

- o Cooling technique and temperature
- o Type of mainframe or form and fit size and shape allocations in special host electronic mainframe, LRU, or SRU

- Power density requirements to meet the form and fit characteristics
- Input power quality
- Output power quality
- Military specifications and standards, government handbooks and standards, and civilian specifications and standards that apply to design, manufacturing, and test
- Operating environment; that is, airplane, helicopter, missile, or ground support, including altitude and temperature where applicable
- Use of new materials, parts, and tests
- Manufacturing processes and control
- Reliability and life requirements
- EMI and EMP requirements
- Test requirements for electrical performance and life compliance

All items addressed in the objectives, scope, and background of the statement of work must be detailed in the technical requirements section of the statement of work.

5.2 Development Costs and Schedule

Most power supplies are subcontracted by the prime contractor, often to a power supply manufacturer by the subcontractor. The true cost for the power supply development is often mixed in with the system cost. For instance, the prime contractor must include the basic requirements in the electronic system specification, the subcontractor must obtain detailed data for the power supply inputs, and the host load output detailed specification and the power supply manufacturer must develop, manufacture, and qualify the power supply to comply with the power input system and the host electronics requirements. Often the subcontractor will develop a breadboard and give the manufacturer the circuit design and specifications to develop into a qualified power supply. This multiplies the development costs considerably, especially if the subcontractor has a design team to monitor the supplier design and manufacturing team.

5.2.1 Cost

Power supply cost differs according to the life, reliability, and application. High-power designs cost much more than low-power state-of-the-art designs.

Manpower costs for the development of a typical low-power, low voltage, state-of-the-art and new development power supplies are shown in Table 4.

The labor costs for a new development power supply assumes a new requirement statement be written, all circuits be modified, new parts are used, and the unit is packaged for 20 to 30 W/in^3 instead of the normal 0.5 to 5 W/in^3. Efficiency must be increased to over 80 percent to meet the new power density requirement.

System manufacturers who manufacture and purchase their power supplies estimate state-of-the-art low voltage power supply development cost at 5 percent to 10 percent of the total electronic system development cost, excluding software. Individual power supply costs may be estimated to be 2.5 to 5 times greater then the bill of material, these additional costs are imposed as a result of production environmental testing, parts screening, and specialized procedures.

Development costs may be estimated on the basis of anticipated labor hours plus material, which often includes subcontracted environmental and EMI testing.

Space system power supplies for aerospace planes will require much more emphasis on reliability and life testing. This could double or triple the development cost.

5.2.2 Schedule

A schedule may vary from 9 months to over 3 years for power supply development. A 9 month schedule is usually for a simple circuit redesign, parts update, simple mainframe modification, or improvement of life and reliability by adding more stringent material process and test requirements to an existing design. A new circuit state-of-the-art design usually takes 18 months to 2 years. A high voltage design or high-power design may take upwards of 2 years to develop the special magnetics, materials and processes, cooling, and packaging designs.

TABLE 4. TYPICAL APPLIED LABOR FOR CUSTOM POWER SUPPLY

State-of-the-Art Labor Manhours:

Electronics Engineer*	1,200	Manufacturing Engineer	400
Engineering Technician	600	Drafting (full documentation)	1,200
Mechanical Engineer	450	Assembly	300
Designer	600	Quality Assurance Inspection	100
Reliability Engineer	200	Qualification Testing	500
Components Engineer	300	Special Test Equipment	200
Servo Analyst	50	Project Engineer	400
Thermal Analyst	100		
Material costs must be added to the manhour costs			
		TOTAL HOURS:	6,600

Typical Labor HVPS (New Design, Difficult):

Electronics Engineer*	3,100
Engineering Technician	3,200
Drafting	3,000
Thermal Analyst	150
Assembly	1,000
Inspection (QC)	300
Mechanical Engineer	1,500
Manufacturing Engineer	300
TOTAL HOURS:	12,550

*Includes materials and processes.

A typical development schedule for a state-of-the-art low voltage, low-power power supply is shown in Figure 1. This schedule assumes all design criteria, without modification, has been correctly specified by the subcontractor. A typical new development design high voltage power supply is shown in Figure 2.

When a new development power supply is required, time to develop and qualify the power supply is typically 24 months. Such new development designs often include use of custom integrated or hybrid microcircuits, use of multilayer interconnect boards or metal core boards, switching frequencies over 100 kHz, and other techniques aimed at increasing reliability and the power output density to in excess of 20 W/in^3.

Development and qualification time for a custom power supply design can be shortened to 12 months if (1) the circuits are packaged in building blocks or modules that do not require new layout and detail design, (2) if an existing design can be used for new requirements, or (3) if the design is linear rather than switching-mode. The schedule then may be limited primarily by part procurement leadtimes, which often approach 12 months for critical military power supply parts.

5.3 Design and Technical Requirements

Electronic, structural, materials, manufacturing, and test personnel must remember that they cannot do today's job with yesterday's methods and be in business tomorrow. New power supplies must keep up with the new trends in electronics. Current power supplies are allocated 20 percent to 25 percent volume as compared to 75 percent to 80 percent for the host electronic load.

As electronics designers use more very large scale integration (VLSI) circuits and components, power supplies must increase in power density to maintain the present power ratio. For some cases that may be impractical. For instance, increasing frequency and using higher density packaging with higher density parts has been the past technique to minimize weight and volume. As frequencies increase, better methods for controlling EMI and radio frequency interference (RFI) must be derived. The new trend may be in the circuits, parts, materials and processes, efficiency, and circuitry. One of the new power density reduction techniques is magnetics, but more reduction

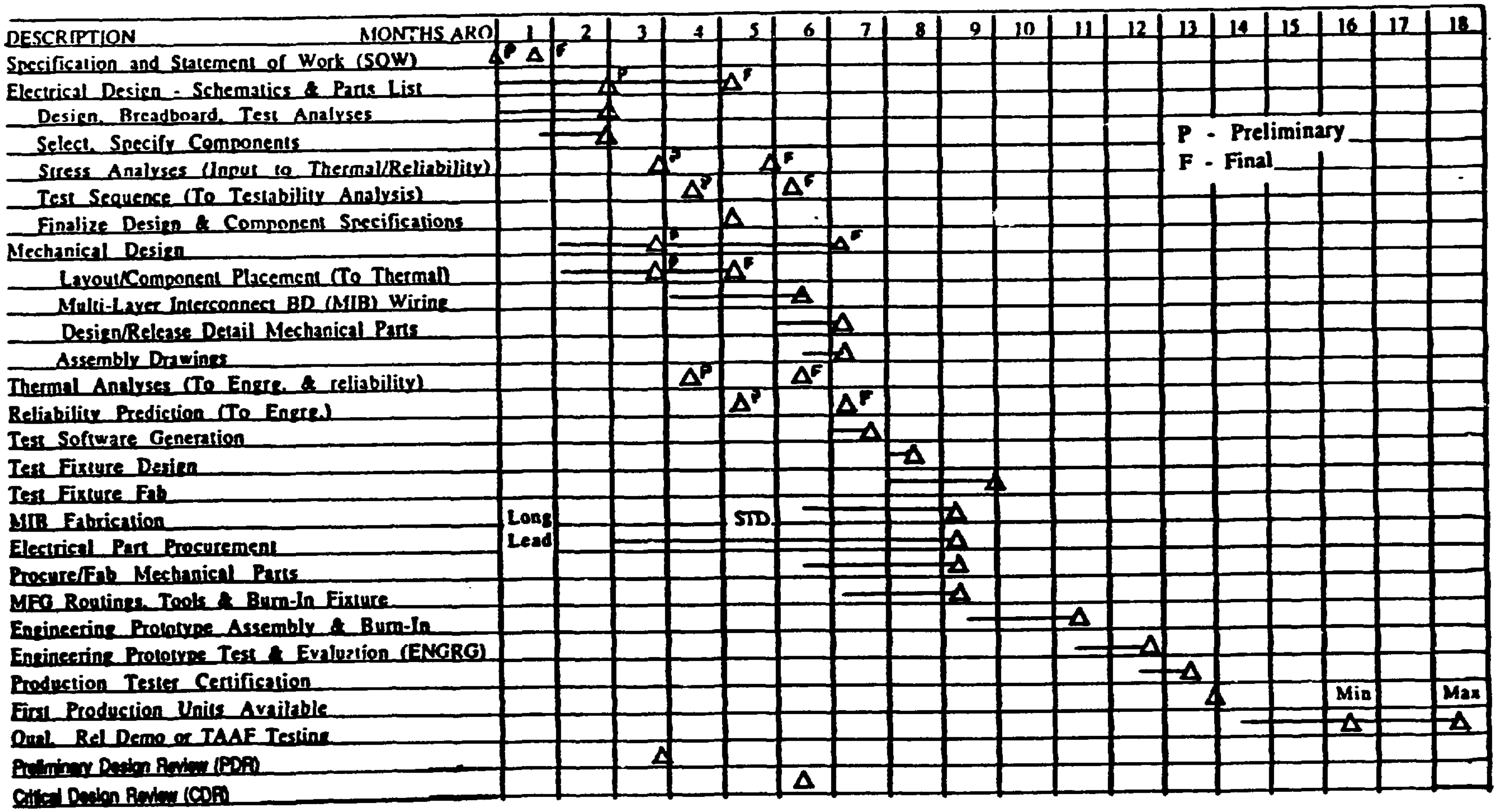

Figure 1. Typical Development Schedule for Custom Switching Mode Power Supply

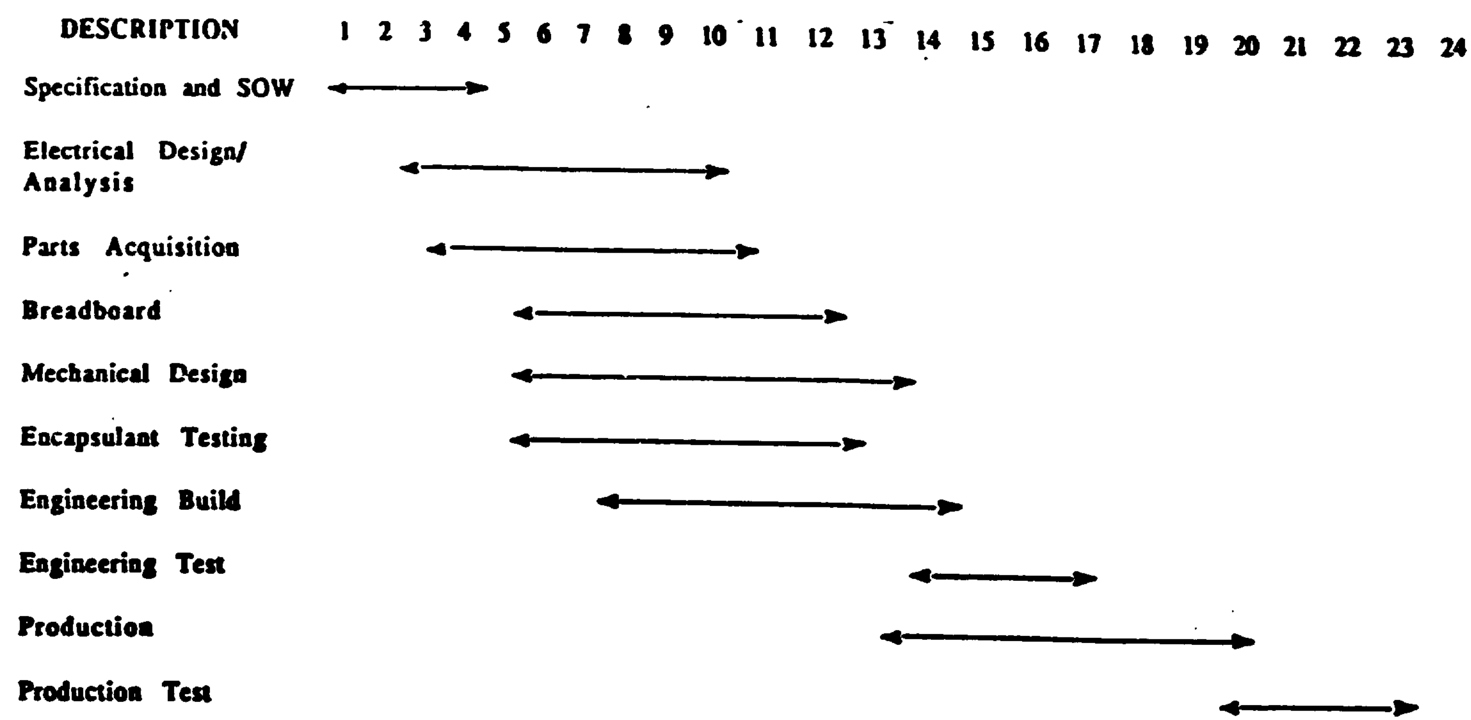

Figure 2. Typical New Design High Voltage Power Supply

may take time without compromising life, reliability, and performance. A final criterion is that a power supply continuously in the shop has poor flight history and has very high system cost.

5.3.1 Description

There are many ways to describe a power supply. First, there are many types, such as:

- o Regulating transformers, which are the simplest case, and raise or lower voltage
- o Ac input dc output transformer rectifier units with little or no regulation with capacitive filtering
- o Frequency changers with 60 Hz or 400 Hz input and either a constant or variable frequency output
- o Converters that have dc inputs and one or more dc outputs
- o Inverters with dc input and ac output, both single-phase and 3-phase

Second, switching mode, pulse width modulated, resonant, and voltage multipliers are some of the many circuits that may be used. Figure 3 shows a typical military power supply block diagram. Essential features shown in Figure 3 are the EMI and EMP differential and common mode filters built into the power supply instead of added later. These filters add weight, volume complexity, and cost but make the circuit more reliable, with improved input and output characteristics. The power supply should include the weight of all EMI, RFI, and EMP shields and input filters. That includes the boxes and their attachment structures. Another item often neglected is the thermal control that includes special air louvers in the LRU or liquid-cooled cold plates mounted on the power supply.

For high-powered, power supplies with very high voltages, the output connectors are often neglected. Each connector may weigh several pounds. Often two or more high voltage connectors are required. With all the equipment and circuitry described, including the liquid in the cold plate, the weight and volume of the power supply is much larger than that of the circuits parts and mounting boards often described.

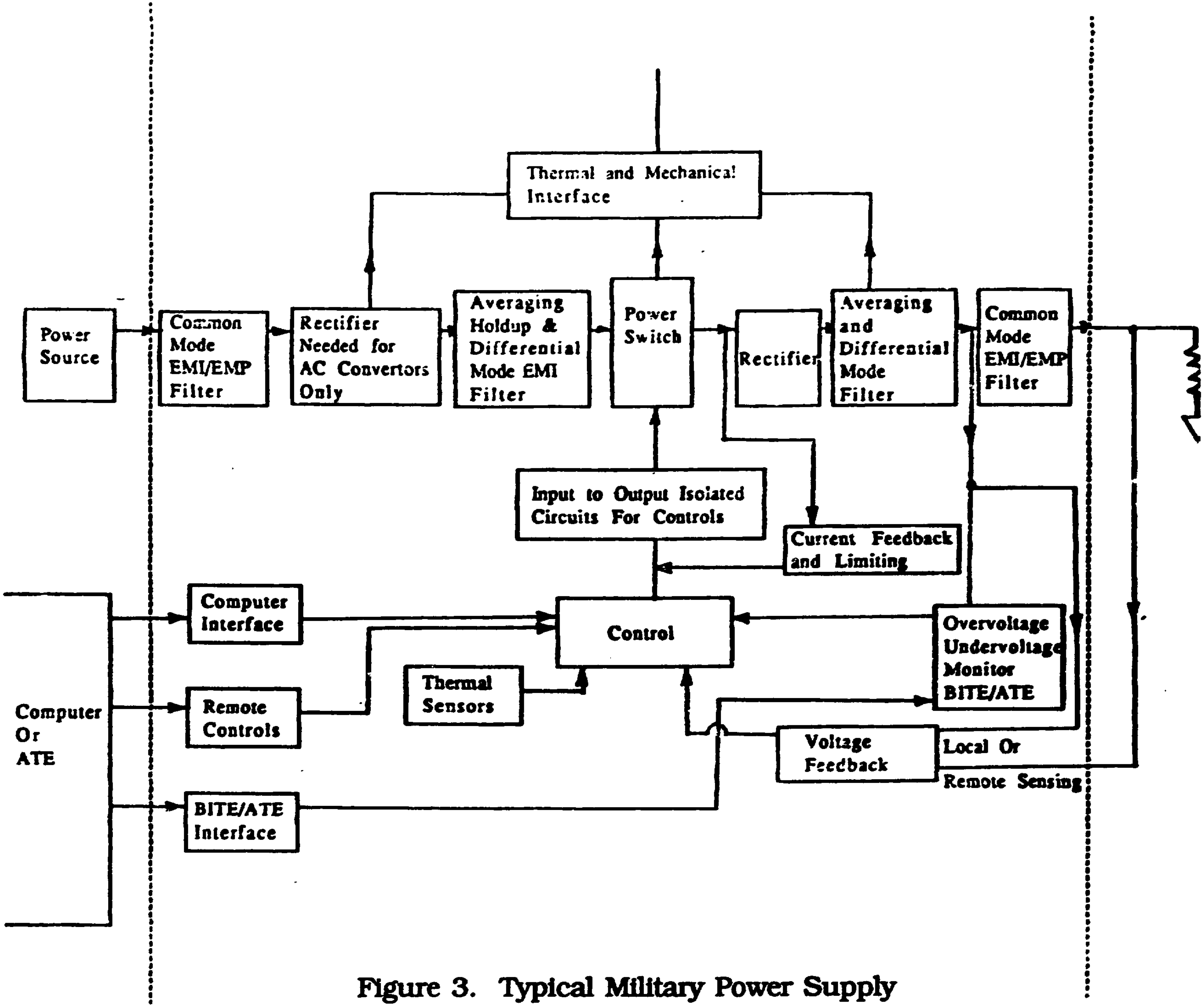

Figure 3. Typical Military Power Supply

5.3.1.1 Life and Reliability

Life and reliability have a significant role in the cost, power density, and design of a power supply. Several surveys have shown that insulation and workmanship have a mean time between failures of 1.0, yet materials and processes, have the highest failure rates in present airplane electronic system power supplies. The results of an early 1980's failure analysis survey are shown in Table 5.

A recent survey, by this author, of airborne power supply failures indicates that approximately 20 percent to 25 percent of the failures are caused by control, BITE, and ATE circuits. The rest of the failures are due to switches (40 percent), capacitors and transformers (5 percent), and other parts and circuits (20 percent to 25 percent). Electrical insulation and workmanship remain the primary reason for the failures of high voltage power supplies.

5.3.1.2 Efficiency

Past power supply designs neglected efficiency as a formidable factor in system weight. The emphasis was placed on component weight and volume. Current airplanes depend on electronic systems for mission success. In some cases, hydraulic systems are being replaced by high-power electrical and electronic systems for better system compatibility. If one of these high-power essential systems malfunctions, a redundant system must take over. A redundant, low-efficiency, lightweight power supply set may be much heavier than a high efficiency power supply, when the weight of the specific fuel consumption, heat removal, are all considered. Two components can be made more efficient by adding a small amount of weight: the magnetics and the switchers. By adding weight to these components, weights for cooling and fuel consumption can be decreased.

Transformers and magnetics can be designed to operate at 97.5 percent to 99 percent efficiency for output power to 100 watts. Larger transformers to 5 kW can be designed to operate at 98.5 percent to over 99 percent efficiency, and very large units of 50 kW or greater to exceed 99 percent efficiency. Some very high frequency, lightweight planar transformers may be thought to require lower efficiency. Designers will be surprised to find they can make

TABLE 5. FAILURE ANALYSIS

Item	Percentage
Design	25
Packaging	24
Materials	15
Processes	36

longer life, cooler operating transformers by adding little magnetic materials. The reason highly efficient transformers and magnetics should be used are as follows:

(a) The materials are larger and heavier but the heat sinks, coolant, and fuel consumption are less total system weight.

(b) The materials will operate cooler with life doubled for every 10°C less temperature.

(c) There is little or no danger of thermal runaway.

(d) The designer does not require waivers to the upper operating temperature limit.

5.3.2 Output Power Density

Power density is the main reason commercial airplanes have been getting 30,000 hours or more for power supplies as compared to a few hundred hours for military airplanes. High power density, life, reliability, temperature and, efficiency are all related. That is, an increase in power density must be accompanied by a decrease in temperature, which increases life, reliability, and efficiency. More significant items that affect increased power density are as follows:

- Parts may not be properly derated
- Insulation overstresses may occur because of compact packaging
- Inadequate heat sinks
- Inadequate heat transfer from a solid-state switcher to the heat sink

- o Thermal runaway caused by poor insulation selection
- o Inadequate EMI and EMP protection, transient shielding, and grounding
- o Waiver for temperature, EMI, and environmental (mechanical) effects
- o Inadequate testing to prove life and reliability

Power density differs for each type power supply, the quantity regulation and control, the addition of BITE and ATE circuits and sensors, the use of VLSI circuits voltage input and output, frequency, and the physical shape and dimension of the power supply. Because many power supplies are not square or rectangular shaped, some wasted space and weight is inevitable.

A number of specification-imposed design factors adversely affect power supply reliability by increasing the output power density beyond what is inherent in the technology being used. These factors may be broadly grouped into mechanical and electrical categories.

5.3.2.1 Mechanical Design Considerations

Allowable volume should be maximized; failure to do so will result in a design that runs hotter, operates with less part stress derating, and use more nonstandard parts. Further, output power density is directly proportional to imposed manufacturing and maintenance costs.

Conduction cooling to a heat exchanger is the preferred method for heat removal because it minimizes the power supply volume that must be devoted to the cooling task. Specification of "natural convection cooling only" should be avoided.

5.3.2.2 Electrical Design Considerations

Although EMI is always important, the allowable level in each case depends on the application and system requirements. Specification of "full MIL-STD-461 compliance" should be designed into the power supply to avoid excessive volume requirements by adding common mode and differential mode rejection after the basic power supply design is complete. By so doing, the result is a higher effective output power density for the remaining circuitry.

Two areas should be considered to increase the output power density due to EMI requirements: (1) the EMI specification should be tailored to actual system requirements; and (2) equipment, or cabinet, or system EMI filtering should be employed whenever possible. This philosophy is particularly advantageous where multiple system power supplies are required.

The designer of the power supply must know the characteristics of the equipment or system level power line filters so that, working with the filters internal to the power supply, equipment and system EMI requirements are met without degradation of power supply characteristics. This requires verification that the combination is satisfactory by both a feedback stability analysis that includes the specified filter and by measurements with the specified filter, in place. The required techniques are described in MIL-HDBK-241.

Proper grounding and bonding is mandatory for low voltage, high-current input and output. The power supply should have less than 2 milliohms as specified for grounding and bending. To avoid ground currents within the power supply, the grounds shown in Figure 4 should be considered. Common mode capacitors should be built into the power supply filter system, input, and output. Pulse forming networks and other very high voltage systems should consider the use of optical sensors and fiber optic lines to transfer signal data to the control, BITE, and ATE circuits.

Some systems, particularly those with computers or memories, require an electrical warning signal in advance of output power failure. This warning signal is usually generated at the time prime power drops below a predetermined level, while the output power continues for a time period dependent on the energy stored within the supply. Energy storage requires volume, so it is advantageous from both power density and reliability standpoints to specify the minimum holdup time required when the requirements are greater than 50 ms as specified in MIL-STD-6051. Another desirable technique that should be considered to minimize stored energy is partitioning system power into critical (required holdup) and noncritical output when more than one output is required and only one output requires extra holdup.

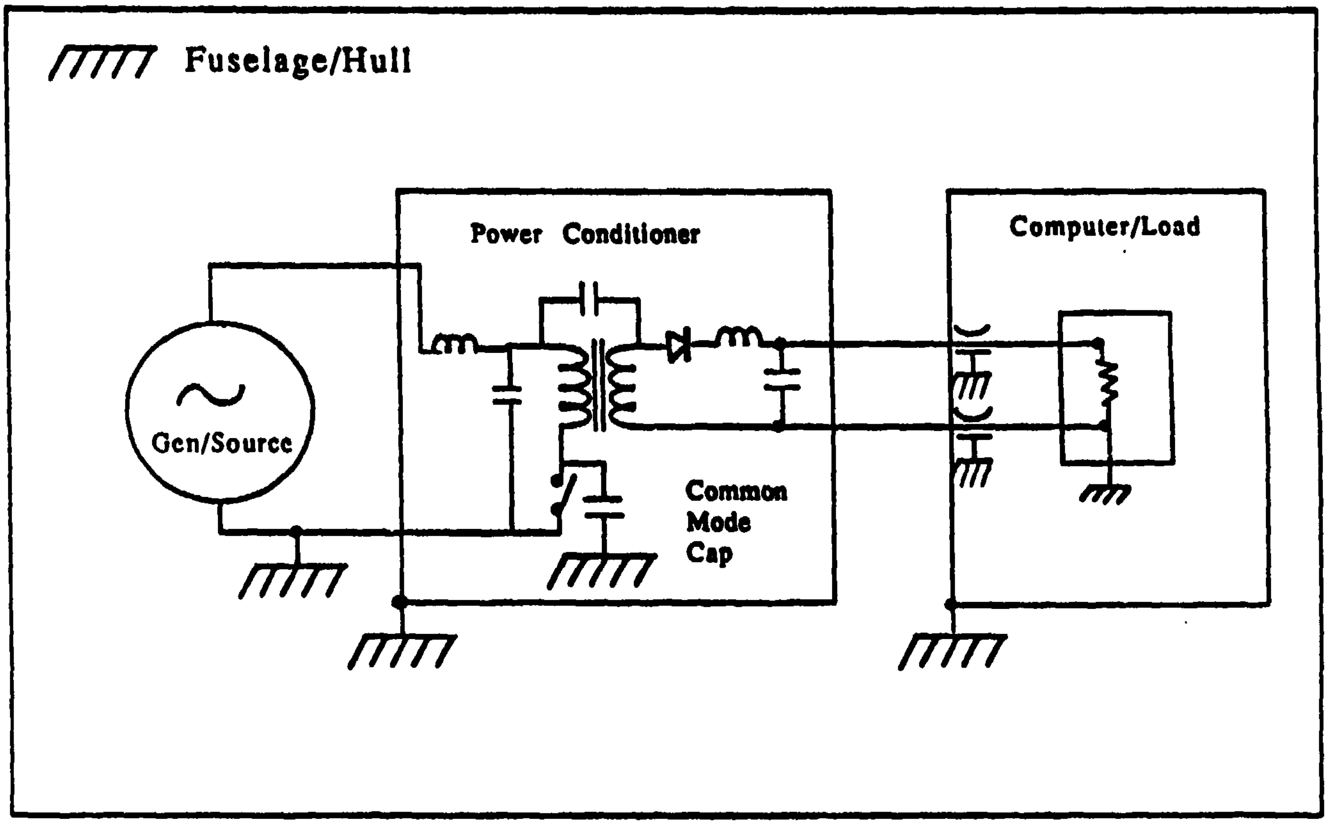

Figure 4. Power Supply Grounds

Performance monitor and fault location (PMFL) should be made a part of the BITE circuitry. The BITE and ATE circuitry can reduce reliability by increasing parts count. When possible, the output monitoring computer should be part of the system to minimize diagnostic circuitry within the power supply.

The following alternatives to requirements that impact output power density should be carefully considered:

(a) Prime power switching and input-output fusing. Provide prime power from the system circuit breaker. Control output power with logic signals and protect output with electronic current limiting inherent in most power supply circuit designs. This eliminates the bulky, sometimes inaccessible, switches, circuit breakers, and fuses from the supply.

(b) Crowbar overvoltage protection. Retain overvoltage protection, but eliminate the crowbar requirement. Positive protection for most switching-mode power supplies may be provided by modifying or terminating the switching action. This eliminates the large, seldom-actuated silicon controlled rectifier (SCR) crowbar devices and their associated circuitry.

(c) Isolated multiple output. Allow all output to be connected to a common point within the power supply. Some systems require isolation to eliminate ground-loop problems, with the output returns ultimately connected at remote points. In these systems, specify the maximum voltage difference between returns. This will minimize the number of internal auxiliary supplies needed for some postregulation methods.

5.3.2.3 Low Voltage

Output power density is most often expressed in terms of "watts per cubic inch" or "watts per pound," where the power is rated output power and the volume or weight is total supply volume or weight, including cooling fins or fan (if so equipped) and integral EMI filters. Because of the large range of output power, prime power, diversity of output power, prime power, and diversity of output configurations and voltages, parameters for the following example are restricted to those in Table 6.

Reliability is a result of many factors, including the ratio of operating to rated stress, temperature, and environment. A specified life and minimum MTBF of 10,000 hours is typical of the mid-1980's design and meets the characteristics of Table 6. The operating time may be increased by a factor of 5 if the environment is restricted to that of a ground support power supply. These MTBF figures should not be used as guides for specifying requirements, but rather as the thresholds above which program management must be especially attentive to the development schedule, cost requirements, and rigorous application of the design and manufacturing guidelines.

Figure 5 displays the range of power densities presently achievable for supplies with characteristics of Table 6, employing standard design and construction techniques. Figure 6 displays the same information in terms of supply weight instead of volume. Both Figures 5 and 6 depict power density versus output power. Actual package density, reflecting standard packaging techniques, remains relatively constant between 0.04 and 0.05 lb/in3. Power density decreases as the number power output increases as shown in Figure 7.

5.3.2.4 High Voltage

High voltage power supplies are often designed in odd shapes to fit into the host design requirements. Also, it has been the practice to pot the whole power supply, inhibiting thermal radiation and conduction paths, which increase heating. High voltage sections of over 1,000 VDC output require total encapsulation to prevent partial discharges, corona, and arcs. Special stress relief design criteria for electric field are also required. For low power, less than 50 watts, high voltage units, of over 1,000 VDC output, the power density is generally in the 0.5 to 2 W/in^3, the same as low voltage switching-mode power supplies.

Power densities for higher power units with more than 1 kW output is generally from 3 to 10 W/in^3 and 50 to 200 W/lb. Converter frequencies for past high voltage applications have been relatively low, seldom exceeding 50 kHz, although recently some effort has been expended to increase the

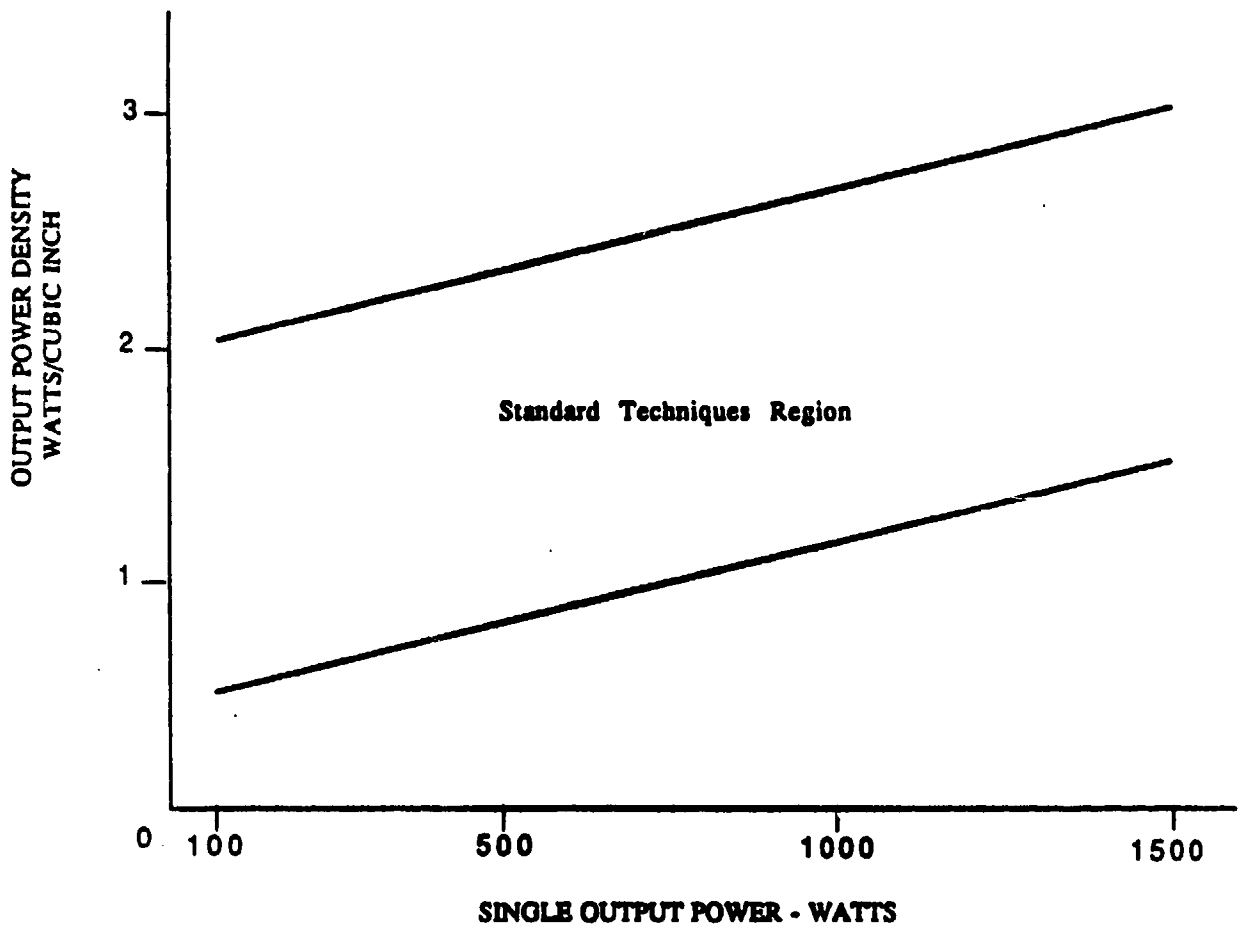

Figure 5. Switching-Mode Power Supply Output Power Density (Watts/Cubic Inch)

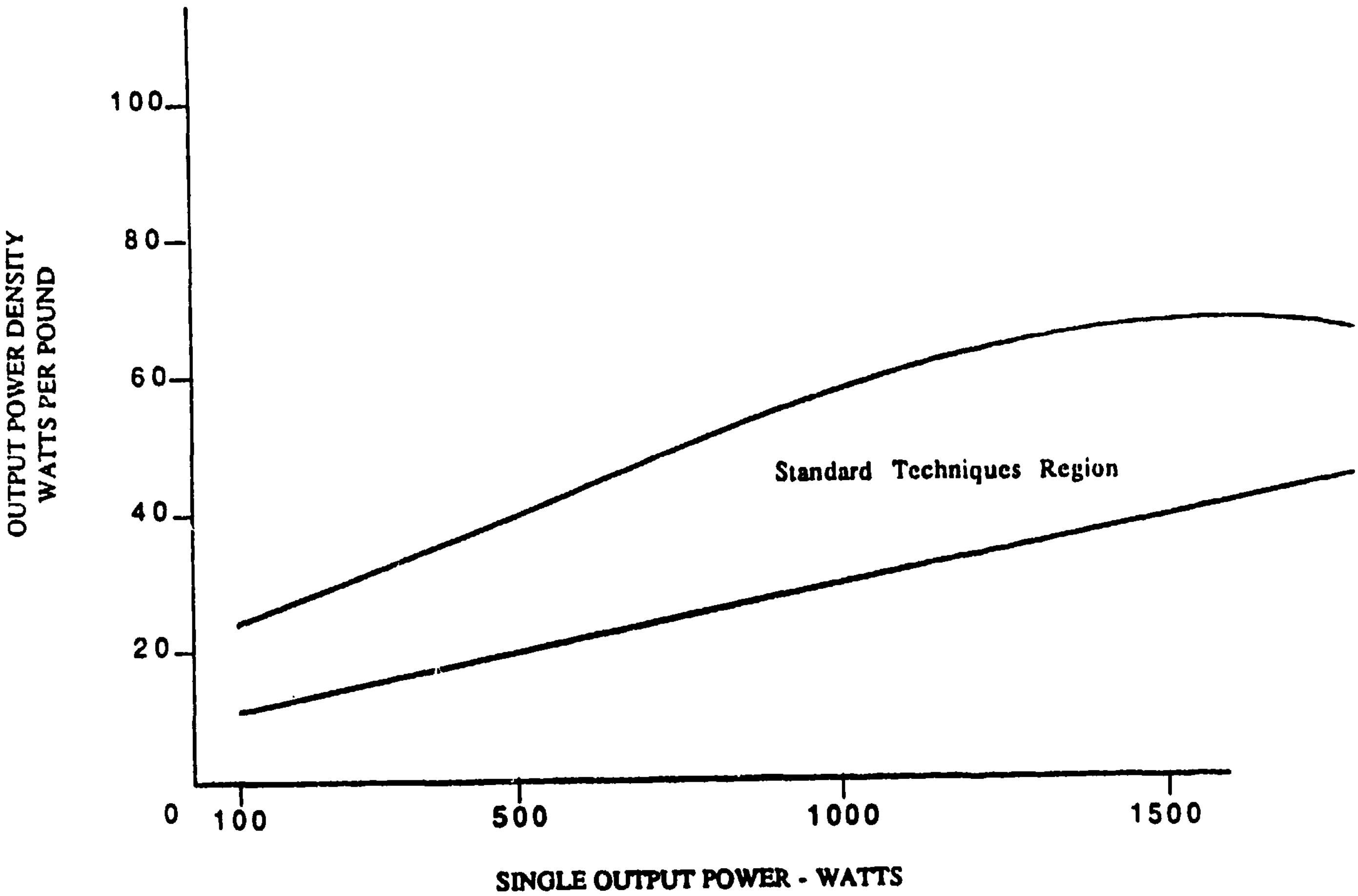

Figure 6. Switching-Mode Power Supply Output Power Density (Watts/Pound)

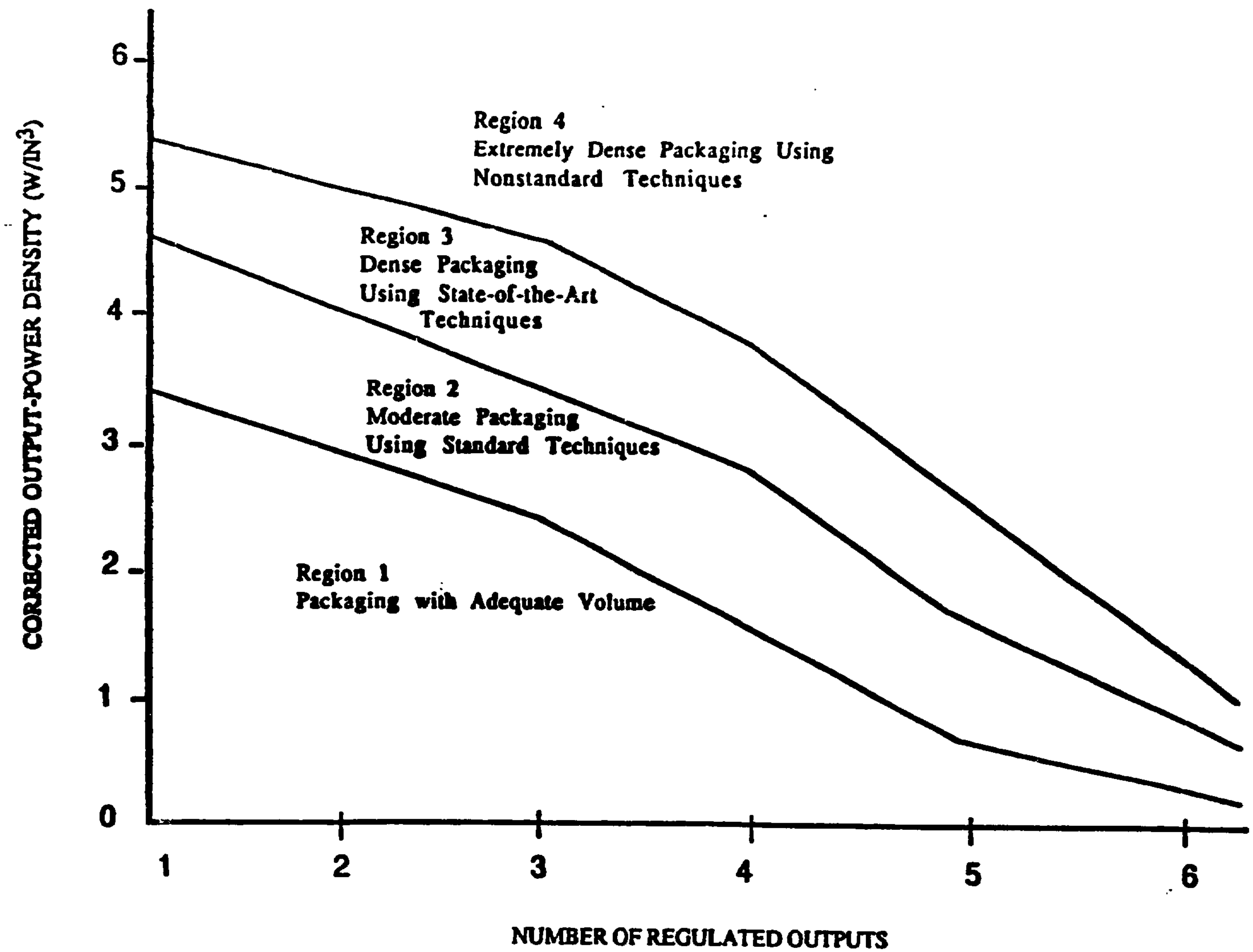

Figure 7. Power-Density Curves for Military Supplies

TABLE 6. POWER SUPPLY CHARACTERISTICS

Switching-mode conversion
Single output (5 VDC < output voltage < 28 VDC)
Holdup period: MIL-STD-6051
Conduction cooled
MTBF: 10,000-hour minimum at 55°C (110° maximum junction temperature, naval sheltered environment)
EMI: MID-STD-461
Prime Power: 270 VDC or 3-phase 400 Hz per MIL-STD-704

frequency to the 50-kHz to the 250-kHz range. A few TWT applications have been started using converter frequencies exceeding 100 kHz. These higher frequency units are more costly and more difficult to reproduce because of large coupling capacitances and inductances.

5.3.2.5 Future Requirements

Rapid technological advances in computer and signal processing electronics packaging that use VLSI circuits and very high speed integrated circuit (VHSIC) chips have resulted in significant reductions in the volume required to implement complex electronic functions. This technology, although used in other electronics, has not generally been applied to power supply designs. Future power supply designs will require some of these weight- and volume-reducing techniques to keep up with the host electronic systems. At the time, the power supply specific density is about 20 percent to 25 percent that of the LRU. At the rate the electronic system circuits are increasing in capacity, the power supply may become larger than the host. Circuits that can become more compact are the control, BITE, ATE, and switching circuits; these can use VLSI or VHSIC technology. Parts such as magnetics, filters, and switches will face more difficult volume and weight reduction. Reliable power supplies with power densities of 1 to 3 W/in^3 will not satisfy the need of sophisticated systems now being designed, much less those of the near future.

System volume required for the power supply is a function of both the system thermal density and the output power density of the power supply. Low voltage low-power switching power supplies can be designed to operate at much greater power density. Development programs underway show that by the year 2000, low voltage power supplies may have the power densities shown in Table 7.

5.3.2.6 Techniques To Obtain Higher Output Power Density

This section highlights some of the techniques currently being used to obtain higher output power densities. While a power supply that meets the specifications of Table 6 and exceeds 3 W/in^3 for low voltage low power switching power supplies does not appear to be available from industry presently, higher power densities are being developed for operation by 1990. Increasing switching frequencies from the 20 to 200 kHz range to the 250 kHz to several megahertz range is one approach to increasing power density. This reduces the size of magnetics, capacitors, and filters. Another method is to use electronic VHSIC and VLSI technology for sensing and control, BITE, and ATE circuits.

Magnetics. As the switching frequency increases, the power transformer becomes the most difficult part to design. If the flux density is restricted to reduce self-heating, most of the common core materials--ferrite, powdered iron, tape core, and others--are suitable at 200 kHz.

While high-frequency magnetic devices can be wound with standard magnet wire, better copper use is gained with either Litz wire, multifilar magnet wire, or copper ribbon. These materials reduce skin effects, which increase above 100 kHz. Many magnetic device coils are designed to use printed circuit boards. These techniques are excellent, except the capacitance and leakage inductance tends to lower the efficiency significantly. The efficiency decrease is acceptable for very low power units of less than 25 watts output, but can cause concern for heat transfer and system efficiency at power output greater than 100 watts. For power outputs greater than 500 watts efficiencies greater than 97 percent is almost mandatory for the magnetics.

EMI shielding is provided by the ferrite cores at frequencies greater than 200 kHz. [illegible]s the foremost problem with high frequency and must be controlled by either ferrite or other shields.

TABLE 7. FUTURE POWER DENSITY

Year	Efficiency Percentage	Power Density (W/in^3)
1990	75 to 80	10 to 15
1995	80 to 90	20 to 30
2000	87 to 95	40 to 60

Semiconductors and microcircuits. A significant reduction in power supply size has been made possible by the introduction of higher-power field effect transistors (FET). Power FETs have several advantages over bipolar devices in offline switching-mode power supplies, including, (1) switching speeds 10 to 100 times faster, (2) reduced drive circuitry due to voltage-controlled high-impedance inputs, and (3) a built-in reverse rectifier.

Low- to medium-power devices can be reduced in size by buying chips and mounting them on ceramic or beryllium oxide (BeO) thick-film substrates. This hybrid technique includes the circuit, plus other parts, yielding a package reduction of at least 40 percent for these subassemblies.

Many monolithic integrated circuits are currently available on the market, which help increase power density. Several manufacturers are developing new standard power supply modules using monolithic devices. Presently available pulse width modulator control circuits for output voltage regulation are moderately complex devices that contain all the necessary analog and digital circuitry, but result in reduced part count, improved reliability, and increased performance over discrete designs.

Before the end of the decade the electronics industry will see further integration of power semiconductors on one chip. The VHSIC program is directed at standardizing 10- to 20-chip assemblies, radiation hardened for signal-level devices, which can be used to customize multichip devices on a single piece of silicon. A customized monolithic circuit could be developed that would incorporate all the low-level and possibly medium-level circuits for a power supply on a single chip. Carried to the extreme, if additional semiconductor circuitry could replace other parts, such circuitry could also be incorporated. This is a possible alternative to hybrids on ceramic substrates.

These techniques alone can improve the power density by a factor of 2 to 4 times over the older printed circuit board technology.

Low Voltage Capacitors. The selection of capacitors is important in keeping the size of the power supply down. Compromises must always be made and the designer may not be fully satisfied with the final selections. Size and cost also have a very large influence on the selection. Capacitor specification is a serious problem in procuring modern switching-mode power supplies. Military specifications are lagging the capacitor state-of-the-art and tend to be very conservative.

Aluminum electrolytic capacitors have improved through the years. They are smaller, and equivalent series resistance (ESR) is improved. Several types are made especially for switching-mode power supplies, but ESR increases by a factor of 10 to 20 at -55°C. Many of these capacitors are limited to 85°C operation. A few will go to 105°C and one type will go to 125°C. They are widely used as input capacitors for switching-mode power supplies, and sometimes as output capacitors.

There are many types of tantalum capacitors. The unreliable wet-slug tantalum silver-cased type (MIL-C-39006/21\0) should not be used due to leakage. Solid tantalum capacitors are very widely used as output filters. Usually several (6 to 12) of these parts are paralleled in output filters for switching-mode power supplies. They have low ESR and this parameter is much more stable across the temperature range (-55° to +125°C). The many advantages of this capacitor over the aluminum electrolytic will keep its use high even though it is more costly. As the switching frequency of switching-mode power supplies increases, the cost and size of capacitors and other filter parts (as percentages of total power supply cost and size) should decrease.

High Voltage Capacitor. Military specifications for high voltage capacitors are very limited, especially at ratings above 1000 volts. Voltage multipliers for low-power cathode ray tubes usually require several ceramic capacitors. Some manufacturers buy the ceramic blanks and then add their own leads. This eliminates materials incompatibility between the supplier material and the manufacturer's potting material. Another important feature is better cleanliness control for the voltage multiplier manufacturer before final encapsulation.

Reconstituted mica capacitors may be used for systems that do not require very low noise. Multitudes of micro spaces exist within the reconstituted mica where partial discharges can be generated. The partial discharges do not harm the mica but they can generate system noise.

Paper and film or combinations are very reliable but require larger volume. Some new development materials added to the market in recent years have much higher dielectric constant than older dielectrics resulting in some size reduction. High dielectric constant materials must be evaluated at high frequencies to resolve polarization characteristics. Polarizations result in heating and short life.

Parts Derating. Operating voltages and power dissipation levels are derated for particular applications to ensure that the parts will operate at required reliability levels under specified environmental conditions. Voltage and power derating are separate, independent procedures. Voltage derating reduces the possibility of electrical breakdown, whereas power derating is done to maintain the component material below a specified maximum temperature.

The first step in the derating process is to establish the operating voltages; and the second step is to adjust the power dissipation level. Voltage derating of passive component parts prevents voltage breakdown, flashover, and corona effects at the atmospheric pressure (altitude) to which the parts are exposed. These effects depend on voltage gradients, configuration of the terminals, and the nature of the dielectric path. Operating voltages of active parts, such as semiconductors, depend on the breakdown characteristics of the semiconductor material.

After the operating voltages are established, the power dissipation level is determined. The degree of heat transfer from a heat-producing part, and the immediate ambient temperature surrounding the part, determines the surface temperature or junction temperature at a particular power level. The junction temperature must not exceed 110°C under worst-case conditions.

Table 8 shows the minimum derating criteria recommended for the design of power supplies. Some power supplies may require more derating because of

TABLE 8. PART DERATING CRITERIA

Part Type	Derating Parameter	Derated to % Rating
RESISTORS		
Carbon composition	Power/voltage	60/80
Film hi stability	Power/voltage	60/80
Wirewound accurate	Power/voltage	60/80
Wirewound power	Power/voltage	60/80
Wirewound chassis mounting	Power/voltage	60/80
Variable wirewound	Power/voltage	60/80
Variable nonwirewound	Power/voltage	60/80
Thermistor	Power/voltage	60/80
Tantalum nitride chip	Power/voltage	60/80
CAPACITORS		
All	Observe ripple voltage rating	60
Ceramic	Voltage	60
Glass	Voltage	60
Mica	Voltage	60 dipped 40 molded
Film dielectric	Voltage	60
Tantalum foil	Voltage/current	60/70
Aluminum electrolytic (85°C hot-spot temperature)	Voltage/current	70/70 (Resin end-seal protected and 99.96% aluminum foil purity required)
RELAYS		
All	Use arc suppression contact current (continuous)	60 Resistive 25 Inductive
	Contact current (surge)	80
	Coil energize voltage	Hold to manufacturer's nominal rating
	Coil dropout voltage vibration	75 (including "Q" of of mounting)
	Contact gap	0.005 minimum opening
SWITCHES	Contact current	50
	Voltage	60
CONNECTORS	Contact current	50
	Voltage (dielectric withstanding)	25

TABLE 8. PART DERATING CRITERIA (continued)

Part Type	Derating Parameter	Derated to % Rating
MAGNETIC DEVICES	Power	50
	Current density	2.0 ma/circular mil
	Current (continuous)	60
	Current (surge)	90
	Voltage (continuous)	60
	Voltage (surge)	90
	Temperature	75
	Hot-spot temperature (operating)	90
	Insulation breakdown voltage	25
RF COILS	Current	60
CRYSTALS	Drive voltage	50
TRANSISTORS		
Bipolar, Power (Note 2 and FET)	Power (see Note 1)	50
	Forward current (continuous)	60
	Voltage	75 across any junction
	Transient peak voltage	75 across any junction
	Reverse junction voltage	65 across any junction
	Junction temperature	(See Note 3)
DIODES		
Switching, General Purpose, Rectifier	Current (surge)	70
	Current (continuous)	60 (5A at 70%)
	Power	50
	Peak inverse voltage	65
Zener	Current (surge)	70
	Current (continuous)	60
	Power	50
SCR	Current (surge)	70
	Current (continuous)	70
	Peak inverse voltage	65
All	Junction temperature	(See Note 3)

TABLE 8. PART DERATING CRITERIA (concluded)

Part Type	Derating Parameter	Derated to % Rating
MICROCIRCUITS		
All	Combination of ac and dc loads	Not recommended
Linear	Current (continuous)	70
	Current (surge)	60
	Voltage (signal)	75
	Voltage (surge)	80
	Voltage reverse junction (signal)	65
	Voltage reverse junction (surge)	85
	Junction temperature	(See Note 3)
Digital	Supply voltage	Hold to manufacturer's nominal rating
	Junction temperature	(See Note 3)
	Fanout	80

Note 1: The maximum rating as determined by the Safe Operating Area (SOA) curves for power switching transistors shall not be exceeded.

Note 2: Power devices exhibiting "punch-through" characteristics should be derated to 50 percent on voltage parameters.

Note 3: Junction temperatures shall not exceed +110°C. Additionally, junction temperature rise above the part ambient temperature shall not exceeding 40°C and 55°C for devices that dissipate <3 watts and >3 watts, respectively.

Note 4: Many families of digital microcircuits exhibit additional characteristics that may require derating (e.g., toggle frequency, hold times). The designer must use good engineering judgment to provide a conservative design (derating of parameters that could drift out of tolerance or cause premature aging or failure).

the ambient temperature environment. Those deratings should be controlled by the detailed specification. Missiles with short life may operate with less derating provided the rules of (1) one-half life for each 10°C rise is followed and (2) one magnitude life reduction for each 10 percent voltage stress increase. Each application should be considered individually whenever design penalties result. The parameters of the values listed under "Derated to Percent Rating" are shown in "Derating Parameter." As a rule, missile and airplane deratings are 60 percent to 70 percent rather than 60 percent for many parts.

Packaging. Good packaging goes a long way in improving power densities. A second or third iteration often produces dramatic improvements in power density, thermal management, maintainability, and reliability. If the program allows sufficient time and funding, substantial improvements are possible.

Shapes of parts can increase power densities. For example, rectangular tantalum capacitors are available from at least one source. The shape factor of the magnetics can also improve power density.

Printed circuit boards and multilayer boards were pioneered by the military. Other techniques with great promise can assist with the interconnections between boards. For example, flexible printed wiring can be laminated to an insulated aluminum substrate. This technique permits greater density of parts than multilayer boards, provides heat sinking with greater rigidity, eliminates all the small heat sinks, replaces connectors and saves space, and is believed to increase reliability. A feasibility study involving repackaging of an already high-density power supply using this technique further increased the power density by 30 percent.

A general packaging design practice is to have all parts and circuit boards built in a planar rectangular form, with interconnecting wires laced together in neat bundles. That is excellent for low-power, low voltage, low-frequency power supplies. High voltage and high-power power supplies must give more attention to magnetic and electric field stresses between parts. Often it is desirable to frogleg many parts, as in a voltage multiplier, to reduce electric field stress. All high voltage filter capacitors should be located to have equalized field stresses between high voltage terminals and ground planes or adjacent parts.

5.3.2.7 Nonstandard Parts for Higher Output Power Density

New designs of switching-mode power supplies with characteristics of higher efficiency, higher density, higher switching speeds, and high reliability require use of some parts that are presently nonstandard. These are described in the following paragraphs. Until these parts are qualified as military standard parts, their use requires the exercise of existing government procedures for nonstandard part approval. The use of nonstandard parts in switching-mode power supplies should not be prohibited, provided there are at least two independent sources.

Many high voltage parts are not controlled by a qualified parts list (QPL). Parts that are out of date are sometimes repackaged into smaller volumes and are not added to the QPL in time for their use. Then the power supply manufacturer must either qualify the parts to MIL-STD-19500, MIL-STD-38510, or MIL-STD-883C. When traceability is required, then MIL-STD-883C should be used for complete control. In reality MIL-19500 and MIL-M-38510 have a tendency to build obsolescence into standard parts because it takes years to fully qualify some parts. In the meantime, new parts have become available. MIL-STD-883C is the preferred specification.

High Voltage Connectors. High voltage connectors require special design. Elimination of voids, tight fitting dielectrics, and long creepage paths are essential design criteria. Creepage paths should not exceed 36 volts/mil along the shortest dielectric surfaces in the connector. All connectors must be qualified for voltage at maximum altitude and temperature.

5.4 **Input Power**

The following paragraph discusses the tradeoffs involved from the viewpoints of the provider of electrical power and the user of electrical power. Airplane multiplatform considerations, and noninterruptible power are discussed. The objective of the discussion is to provide sufficient information about airplane power sources so that the program manager's requirements can be met by specifying required operation from a minimum number of sources, thereby easing the burden on the power supply.

5.4.1 Input Power Standard

MIL-STD-704 establishes requirements for conducted electrical power characteristics on airplanes at the interface between the electrical power system and the input to electrical utilization equipment. A standard ac and dc voltage and an alternate-standard ac and dc voltage are controlled by MIL-STD-704.

5.4.2 Three-Phase Versus Single-Phase Power

Smaller and lighter power supplies can be designed using 3-phase power instead of single-phase power, and 3-phase power is usually preferred from both the airplane power system and user viewpoints.

5.4.3 AC Power

The standard airplane's ac power is a 400 Hz, 115 to 200 VAC, 4-wire, 3-phase, wye-connected system with the neutral of the wye grounded. Loads greater than 0.5 kVA must use 3-phase power. Single-phase loads must be connected line to neutral.

The only alternate standard, when specifically authorized, is 230 to 400 VAC with the amplitude requirements proportional to the 115 to 200 VAC limits established by the standard. Voltages greater than 230 VAC have corona problems at altitudes above 60,000 feet.

5.4.4 DC Power

The standard dc power is 28 VDC. The only alternate standard, when specifically authorized, is 270 VDC. This is the nominal dc voltage obtained when the standard 200 VAC 3-phase line-to-line aircraft voltage is bridge-rectified to dc voltage. Although 270 VDC is an alternate standard voltage that requires specific approval for use, studies have shown major overall weight and efficiency advantages for aircraft using 270 VDC as the primary aircraft power. However there are some disadvantages. Airplanes operating at altitudes exceeding 60,000 feet must have all systems operating at 270 VDC analyzed for corona. Closely spaced conductors will have corona initiation during system transients. If not immediately extinguished this discharge may result in arcs and system failure. In addition, the corona will initiate a large amount of EMI, RFI, and transients into sensitive low voltage circuits which can fail some circuits.

Fortunately, power supplies can be developed for 3-phase 115 to 200 VAC input power, which can be directly used on 270 VDC without modification. If planned for at the start of design, these dual-input power supplies have minimal impact on the size, weight, cost, and other attributes when compared to power supplies designed for 3-phase, 115 to 200 VAC only.

Direct rectification of aircraft 3-phase, 115 to 200 VAC results in approximately 270 VDC. This is the logical dc voltage for aircraft use and, although more limited, circuit and component technology is available for design to this voltage.

5.4.5 20-kHz Power Frequency

Components and parts for a 20-kHz power supply are considerably smaller than for 400-Hz power supplies. This frequency has not become a part of MIL-STD-704, but will probably be added when fully developed for the space station.

5.4.6 Noninterruptible Power

Very short term noninterruptible power is not a requirement set forth by MIL-STD-6051. The time set forth is 50 microseconds. Longer uninterruptible power required by equipment must be specified by the procuring agency.

The two most commonly nonmilitary specification interrupt times imposed by the detailed specification, through which the equipment is required to continue operating, are a short-term interrupt (10 to 300 microseconds) and a long-term interrupt (20 to 150 ms).

Operation for a short-term interrupt of prime power is intended to provide adequate time after recognition of a power interrupt to perform a "putaway" routine to store data, such that an automatic recovery occurs when power is restored. The term is somewhat of a misnomer because it is really not intended to provide performance through a short-term power transient as the name implies.

One method of operating through a bus transfer is to add input capacitance; however, adding capacitor after the rectifiers increases the volume and weight significantly. For long-term interrupt, the weight and volume could be increased 10 percent to 15 percent, greatly reducing the power supply power density. The higher the power density of the power supply with interrupt, the greater the percentage total weight and volume required by the capacitor. An alternative to using capacitors for storage is batteries, with their many disadvantages.

At the present time, this requirement of operating through interrupts may not seem to impact the power supply significantly, particularly for short-term interrupts. However, when it is considered in terms of future electronic line conditioners and higher switching frequencies, both of which have the potential for greatly reducing the amount of input capacitance, it may be of major significance.

5.5 Life and Reliability

Application of new technology to power supply design and production can result in meeting the power density requirements while, in fact, increasing the reliability and life. Since there are several ways to calculate reliability, a fixed reliability number is somewhat unrealistic. Life in hours before removal of a power supply from an LRU or airplane is more acceptable and should be encouraged by adding accelerated life tests as part of the qualification program.

High-reliability parts all have excellent MTBF numbers. The problem with the reliability numbers exists because of manufacturing consistency over a period of years and application of the part to power supply circuits. A misapplied part will obviously be unable to withstand operational stress and have a short life. Accelerated life tests are a method for ferreting out that type of weakness in a power supply.

All modified power supply designs through the U.S. Air Force manufacturing technology programs should require life testing. Then all power supplies designed and manufactured to these and other guidelines that follow the military specification will meet the required life and MTBF. The predicted MTBF numbers can be used to identify internal component reliability problems and alert the designer to lower than normal expected MTBF. These predicted values should not be used to set contract reliability requirements, which should focus on the operational mission and system requirements.

5.6 Standardization

Standardization of ground support power supplies should be encouraged to greatly reduce the inventory of similar or interchangeable power supplies. Airplane power supplies often require specialized form and fit dimensions that are unsuitable for standardization. For instance, a standard rectangular-shaped power supply would be very difficult to fit into some small, round missile applications.

The objectives of power supply standardization include the following:

(a) Partition supplies to allow commonality among a majority of equipment applications.

(b) Provide a rigorous quality program to ensure interchangeability and reliability.

(c) Establish basic requirements compatible with the majority of military electronic system applications and environments.

(d) Reduce recurring development costs and ease the logistics support burden by extensive intersystem commonality of a limited number of power supplies.

(e) Provide established mechanical packaging with flexibility for growth.

(f) Develop functional specifications to preclude dependence on a specific design or technology.

For example, during a recent study at a prime contractor's facility, it was determined that over a 3-year period 161 individual power supplies had been specified. A conservative estimate is that only 50 percent of the 161 supplies required nonrecurring development. To develop the extra identical power supplies cost over 400,000 labor hours. Instead, a few well-designed power supplies could have been designed and manufactured at less than 50 percent of the added labor hours. This would have improved the MTBF and performance, and would have greatly improved airplane system flight readiness. When the additional repair time, logistics, and extra spares required for the many power supply designs are considered, the costs of nonstandardization, when applicable, are high.

A power supply standardization program can provide benefits in each program phase of an electronic system. These benefits are summarized in the following sections.

5.6.1 Development Phase

Reduced Power Supply Development Costs. Engineering efforts are reduced because of fewer new design needs and because manpower resources can be effectively and efficiently applied. Documentation efforts to define and support power supplies are reduced as well. Finally, performance verification testing, hardware costs, and manpower resources to verify and demonstrate performance are reduced.

Reduced Power Supply Development Time. Leadtime is reduced because most power supply requirements could be met with existing and available power supplies. The magnitude depends on how many existing types can be used and how many new types are required to satisfy the requirements of a particular system.

Lower Development Risks. Standard power supplies would represent a mature design; for example, the test analyze and fix (TAAF) reliability development testing concept could be applied to an adequately large sample, an impossibility for small orders of high-reliability custom power supplies.

The tendency for a contractor to "buy in" is reduced because he cannot be assured of winning follow-on production contracts.

5.6.2 Production Phase

Reduced Cost of Production Systems. Production costs for standard power supplies are reduced because of high volume use and volume discounts, multiple source competition, reduced recurring hardware costs due to common electrical and mechanical parts, and a relatively large procurement base. Lower costs are also achieved through high-production-volume learning curves.

Reduce Time. Ready availability of standard power supplies is promoted through development of multiple sources and high-volume use.

5.6.3 Operations Phase

Improved System Reliability. This is achieved by a concentration of scarce resources on a small number of power supplies as opposed to diluted resources dispersed across several unique designs. It is enhanced by increased applicability of the standard power supplies in systems.

Increased Savings. By reducing the number of different supplies between systems, savings occur in maintenance manuals, technician training, and corrective maintenance (due to increased reliability).

Reduced Support Costs. Use of interchangeable power supplies reduces the number of different spare parts, the supply administration costs, the cost of procuring spares, and test facilities.

Program Visibility. Problems with standard power supplies would be more visible; thus, receive adequate attention and resolution.

Standardization can offset any negative factors. Resistance to standardization comes about basically because there is a lack of understanding of its principles and of the program to which it can be applied, or simply because planning for it is too little and too late.

Standardization is the single most effective solution to the problems of reliability, high costs, and logistic support of power supplies. Such an effort not only will aid in the initial acquisition of equipment but also will improve the long-term availability, operability, and supportability of the equipment as well.

5.7 Design Reviews

Design reviews can be powerful tools for the procuring agency to maintain visibility of the status and progress of the power supply vendor in meeting specified requirements and to initiate corrective action if warranted. However, for a design review to be effective, it must be timely, expertly staffed, and have an effective agenda.

The design review must be timed to the completion of major milestones of the power supply development schedule. Rather than establishing firm dates for the design reviews at the onset of the program, it would be advisable to provide a reasonable degree of flexibility in scheduling so that the activities associated with the milestones are indeed completed. This might be accomplished by having the vendor alert the procuring agency 1 month before readiness for any given design review. The procuring agency can then determine if the vendor is adhering to the schedule and either approve the date or take appropriate action if a significant schedule slippage is indicated. In any event, the vendor must be ready for the design review if it is to be effective and constructive. If a design review package is generated with insufficient data and drawings to meet a pre-established date, the design review will probably be less than satisfactory.

The quality and effectiveness of the design review is directly dependent on the technical qualifications of the review team members. Technical incompetence can only lead to misunderstanding, irrelevant questions, and issuance of unnecessary action items.

Design review checklists are useful tools for successful design reviews. They establish an understanding between the procuring agency and the power supply vendor with respect to the items to be covered during the review, and should be provided to the vendor beforehand. During the design review, the checklists allow for an orderly process of reviewing and discussing the items to be covered.

SECTION VI

HIGH VOLTAGE POWER SUPPLIES

6.1 Introduction

A high voltage power supply is a low voltage power supply with some special high voltage subcircuits and parts. This implies that many circuits within a high voltage power supply are similar to those in a low voltage power supply. Similar circuits include the (1) input filter, (2) switcher, (3) control, and (4) BITE and ATE.

The special high voltage circuits include a (1) high voltage transformer rectifier or voltage multiplier, (2) high voltage filter, (3) high voltage control sensors, and (4) output connector.

For past as well as many current designs, the whole power supply is encapsulated. Yet the same companies do not encapsulate low voltage power supplies because of the heat transfer problems involved with encapsulated parts and circuits. Therefore, good high voltage power supply should have only the high voltage circuit modules encapsulated to withstand the altitude environment; all low voltage parts and circuits should be built with open construction, as in the highly reliable, long-life power supplies described in Section V.

A high voltage power supply is defined as any unit having voltage equal to or higher than 300 volts, peak. High voltages, including transients, are subject to corona breakdown and partial discharges. Partial discharges and corona can occur at low voltages; that is, as frequency increases, the corona initiation voltage occurs at low value. At 200 MHz, corona initiation can be as low as 50 volts, peak. Therefore, frequency effects must be considered in the design of all high voltage and low voltage switching power supplies.

Corona and partial discharges initiate more failures in high voltage electrical insulation designs than any other cause. The designer must be aware of this fact and insist that the encapsulating materials are compatible with parts, insulating circuit boards, and the metal structure. All bubbles, cracks, and debris must be eliminated from the encapsulant before it is powered onto the parts, and during its cure. Also, the materials processing engineers must test all parts to ensure they are properly cleaned and that the encapsulant will bond without debonding due to contaminates, incompatibility, or thermal cycling. All these concepts and guidelines are detailed in Volume II of this report, "Design Guide: Designing and Building High Voltage Power Supplies."

6.2 Design Summary

Several subjects were not covered in Volume II, "Design Guide: Designing and Building High Voltage Power Supplies". These were circuit design, component design, and mechanical design.

These items, though very important, are usually done by electronic, electrical and mechanical engineering specialists. Volume II covers the topics that the electronics design engineers have least experience in, that is:

- Corona and partial discharges
- High voltage design techniques
- Field analysis
- Materials selection
- Materials processing
- Manufacturing and quality control
- High voltage testing
- Failure analyses

Most corona and partial discharge problems cannot be fully eliminated in all applications, but they can be kept to an acceptable level. An acceptable level is one where all large voids that grow rapidly and destroy insulation are eliminated. Very small discharges in microvoids will, in time, destroy the insulation, but it may take years of continuous operation. Now, many will say they pot with microvoids, and that microvoids will cause little harm because of partial discharge deterioration. If they have that capability, they should also be willing to test the potted material and circuits to prove only microvoids exist; that is, they should show that partial discharges greater than one 1-pC magnitude will not exist in their circuits when operated at voltages greater than 300 volts, peak.

6.2.1 Circuit Design

Electronic designs and transformer rectifier or multiplier designs are not covered in this paragraph. Several high voltage design details are discussed. First, the high voltage circuit should be designed with respect to the type of insulation involved; that is, solid, space vacuum, vacuum, pressurization, or liquid. Some of the details to consider are listed in Table 9.

An encapsulated high voltage circuit in a high voltage power supply with conformally coated low voltage circuits can be developed with small weight penalty. It will be easily cooled and the potted module or modules can be kept reasonably small in size. The output connector will be larger than that for a low voltage power supply. Low power display and other applications that use a simple high voltage, high-frequency transformer voltage multiplier, filter, and voltage control divider can be potted into one or two modules of very small volume of less than 5 cubic inches in many cases. High voltage units may have the rectifier built into the transformer winding to save weight and volume. The only problem with this technique is rectifier cooling. Often the rectifier and adjacent winding turns become very hot and reduce the insulation life considerably if not designed with heat transfer in mind.

6.2.2 Parts

Encapsulated parts must be selected on the basis of:

- o Stability--time and temperature. The electrical characteristics should not change more than 3 percent to 5 percent. This is crucial for multimegohm voltage dividers.
- o Compatibility--all materials, metal and coatings must be compatible with the insulating materials used in the design.
- o Corona and partial discharges--all parts must be tested to prove they are acceptable by having less than 1 pC, peak discharges per 2 kV applied. All cores must be rounded to form smooth surfaces.

TABLE 9. INSULATION MEDIA

Insulation	Weight	Comparative field stress	Comments
Space vacuum	Least	Average	The power supply must be shielded from space radiation and plasma. Cannot be operated at pressure greater than 10-4 torr. Very difficult to seal.
Vacuum	Medium	Very high	Very difficult to seal.
Pressurized	Medium	Very high	Very difficult to Seal. Leakage can damage other equipment.
Liquid-filled	Highest	Average	Contamination with age.
Potted	High	Average	Partial discharge and arcing problems.

- o Derating--most parts should operate at values less than 60 percent rated value.

Corona or partial discharge detection should take place at either direct current for dc applications or at rated frequency for ac and RF applications. Normal corona detection equipment cannot operate at frequencies above 400 Hz. Special corona detection circuits can be easily designed to operate at higher frequencies. Special circuits should be calibrated with a similar part as the test sample.

Corona testing of transformers is very important. All high voltage transformers should be tested, at operating frequency, in the active state. This tests all insulation between turns, between the turns in adjacent layers of a winding, between windings, and between the windings and core or other ground or metallic surfaces. Transformer cores, after potting, must be thoroughly temperature cycled to determine whether thermal stresses have caused insulation cracking or core cracking. An active corona test at operating frequency is recommended to determine the insulation status. Higher picocoulamb discharges and higher cumulative discharges over a 3-

minute period are an indication the insulation has cracked and will soon fail. All transformers should be tested per MIL-T-27, plus the corona test.

Small encapsulated modules of many parts that make up a voltage multiplier or filter unit should be tested for corona or partial discharges to determine insulation cracking or delamination from parts after the thermal cycling tests. Odd shaped and sized modules often are plagued with mechanical stresses that lead to debonding.

All parts must be thoroughly cleaned before potting. Parts should never be tested in silicone oil before potting.

6.2.3 Materials

Potting materials must be tested for compatibility with all other parts boards and metals to be encapsulated. In addition, the materials should meet or surpass the tests of MIL-STD-454; that is, mechanical, thermal, outgassing, bondability, and electrical tests. Selection of a high voltage potting material should be left to the design and materials organization so they can choose familiar materials that they have confidence in. Some of the selected materials will not meet the -55°C temperature cycling stress test. By supplementing the material with fillers, some suspect materials will meet the -55°C temperature stress test. The user organization must show proof.

6.2.4 Packaging

Several sections of Volume II are devoted to field stresses, mechanical layout of parts, and selection and application of insulation. A summary of these items follows:

(a) The electric fields and magnetic fields must be calculated to determine the electrical stress within an insulation system near the leads and sharp edges of parts cases.

(b) The electric field stress should be less than 150 to 350 volts/mil at the surface of the smallest radii, depending on the potting material, its thickness, and its bondability.

(c) Many parts should be mechanically positioned during potting so they will not move during encapsulation.

(d) High voltage circuits should be isolated or shielded from low voltage circuits to prevent radiated or conducted pulses from damaging low voltage circuit sensitive parts.

(e) Interconnections should be minimized.

(f) Special care must be taken with shielded cabling to ensure excellent bonding without voids at the shield insulation interface.

(g) Do not use multiple potting compounds in one power supply. Two should be a maximum. Never overcoat silicone with epoxy or other materials.

(h) Vacuum impregnation or vacuum pressure extrusion are preferred encapsulating techniques.

(i) Printed circuit boards, when used, must not be porous, must be thoroughly cleaned and have smooth edges.

(j) Delamination between printed circuit boards and encapsulants is common. Keep the surface voltage gradients to less than 16 V/mil between adjacent traces, traces and parts, and parts.

6.3 Prototypes

Developing a prototype is the best method for proving design verification. The purpose of the prototype is to prove the breadboard circuit can be packaged in a high-density volume with the least waste space and minimum volume, while meeting all the electrical input and output characteristics before and after rigorous environmental and mechanical stressing.

The prototype unit or units should be manufactured using shop assembly and test personnel. It should not be a hand-built unit developed using specialized technicians and engineers. Engineering and technical specialists should be called on to solve difficult or modified assembly and test techniques. Those modifications should be reflected as drawing changes to the design. When parts or materials are involved, it must be shown that the modifications will meet or surpass all the original mechanical, environmental, and electrical test characteristics.

6.3.1 Parts and Materials Evaluation

All parts, boards, wire, and materials must be of high quality and proven reliability. Traceability must show that all parts and materials have met performance acceptance qualifications for the applicable environment and power and voltage levels to which they will be subjected. That includes cleanliness before and after visual and quality control inspection. No parts shall be tested in silicone fluid or similar fluid that cannot be easily cleansed from the surfaces. Tests and controls for parts, wires, boards and metals include the following:

- o Bondability
- o Contamination by oils or debris
- o Sharp corners
- o Corona and partial discharges
- o Electrical characteristics
- o Environmental tests
- o Adhesion
- o Dielectric strength
- o Resistivity

6.3.2 Tests

Several in-process tests should take place during the prototype assembly to prove manufacturing and assembly manufacturing processes and procedures. A final assembly test is mandatory to prove flight acceptance. Some tests that should be imposed include:

(a) High voltage corona and partial discharge tests at the design operation frequency for the transformer, voltage multiplier, transformer rectifier, filter (dc and ramp), and high voltage sensors.

(b) Leakage current and arc tolerance.

(c) Overvoltage and undervoltage.

(d) Short circuit.

(e) Electrical characteristics.

(f) Maximum transients at maximum voltage input and output.

(g) Environmental altitude, temperature, shock, and vibration.

(h) EMI tests.

Fortunately, the corona test is simple, nondestructive, and requires little equipment once the technicians have learned how to perform the test. The only problem is performing the test on unpotted, high voltage circuits (that will be potted).

Freon products or gaseous sulfur hexafluoride can be used for the test. Sulfur hexafluoride has limited voltage withstand capability. Some freon products absorb water from the air and have to be filtered regularly. The freons also tend to clean the assembly. Often the cleansed debris and oils recirculate and collect in high voltage stress areas and cause problems.

High voltage tests are often misinterpreted. The first misrepresentation is the dielectric withstanding voltage (DWV) or "high pot" test. The specification reads that the high potential is to be applied at a voltage of two times the operating voltage plus 1000 volts for high voltage parts and circuits. That value is still used by the power industry for voltages where the stress levels will not damage the electrical insulation. For very high voltage, over 115 kV, lesser maximum voltage stress values are used. Because high voltage power supplies are developed with high stress levels, the DWV test should not exceed two times the operating voltage.

Furthermore, the full 2-volt DWV test should not be applied several times. The original specifications in the ASTM state that the initial test at the factory should be at 2 V + 1000 volts. Subsequent tests should be made at 85 percent of the original test. This implies that the subsequent tests should be made at 1.7 times the operating voltage. Because transients of 1.60 times operating voltage are common, the 1.7 times operating voltage is a good number. When it can be shown that the transients within a system are greater than 1.6 times the operating voltage, the DWV voltage should be increased accordingly.

Corona inception voltages and extinction voltage are nondestructive tests that indicate the probability of voids, cracks, and delamination in parts boards and wiring. Corona tests should be performed before temperature cycling and posttemperature cycling. Changes in the magnitude or quantity partial discharges indicate voids or insulation cracking at the surface of parts. Any increase in the partial discharge characteristic is cause to fail the test.

Arc resistance and short-circuit tests should be mandatory high voltage tests. Corona tests of the high voltage lead should precede and follow the short-circuit tests. For some voltage multiplier designs, the arc resistance test can overstress the final capacitor in the circuit or the voltage divider circuit. Any flaws in the insulation will be detected by the corona test.

Environmental tests for high voltage power supplies should be almost the same as for low voltage power supplies. The one basic difference is the high voltage circuits. Safety rules must be rigorously enforced to ensure no hazards to humans are encountered. For instance, the high voltage circuits must be completely grounded and remain grounded throughout the shock and vibration tests unless otherwise directed. Special feedthroughs, connections, and interconnects must be designed for operating at altitude. These designs must all be safety approved. Other environmental tests that must be scrutinized before they are approved are:

- Arc tests in explosive atmosphere
- Pressure vessel explosion
- Case leak tests. Helium leak detection tests are not recommended for a potted power supply. Helium will penetrate into the insulation and greatly lower the corona inception voltage.
- Leak test for pressurized or fluid-filled cases

Electromagnetic interference, radio frequency interference, and electromagnetic pulse may all require test and evaluation. These tests should be made in shield rooms using certified, qualified test evaluation equipment as specified in MIL-STD-462. The low voltage circuits as well as the high voltage circuits must pass all tests and requirements to be fully accepted for flight hardware.

6.4 Manufacturing

High voltage power supplies are plagued by contaminants, debris, improper assembly procedures and processes, and testing. To properly manufacture high-quality, highly reliable, long-life power supplies, the criteria details must be observed:

- Cleanliness
- Excellent inspection and test procedures
- Trained personnel
- Good test equipment and test procedures

6.4.1 Cleanliness

Parts, subassemblies, wiring, and the power supply must be inspected, assembled, and handled using clean room techniques. When the parts are received from the suppliers and inspected, they should be bagged or placed in clean receptacles for storage before distribution to the assemblers.

All assembly personnel should be instructed to wear white cotton, lint-free gloves or equivalent when assembling the parts on the boards, and the boards, parts, and interconnects in the final assembly. Those who assemble low voltage, charge-sensitive parts must be instructed to work at electrostatic discharge workstations. They, too, should wear white cotton, lint-free gloves.

Separate potting rooms should be used for silicones and epoxies; separate extrusion tools should be used for silicones and epoxies. Contamination by silicone rubber products can cause debonding of epoxy products. In addition, when using epoxies for subassemblies and silicones for final assembly, all epoxy parts and subassemblies must be mounted in place before the silicone rubber is applied.

All parts, subassemblies, and wiring should be thoroughly cleaned using as a minimum a freon vapor degreaser, an alcohol-water cleaning method, or another approved technique.

Trichloroethylene vapor degreasing is not recommended for many products, because the cleaning fluid may absorb and cause the coating or other insulation to swell. When the trichloroethylene evaporates, the normal insulation shrinks and debonds from the epoxy or other potting material. Ultrasonic degreasing is a simple, easy method of cleaning many small parts. Other washers or washstands are acceptable for larger subassemblies and final assemblies. After cleaning, parts and assemblies should be placed in humidity-controlled drying ovens to remove unwanted moisture and cleaning fluid residues. Then they should be bagged or placed in clean transfer receptacles.

6.4.2 Inspection and Test

All incoming receiving high voltage parts should be subjected to 100 percent inspection. Parts should be inspected and tested for specification compliance and to eliminate all premature failures before they can be assembled. This saves a lot of rework and early failures. Many solid-state devices, capacitors, transformers, and voltage dividers should have a required burn-in test. This will weed out most early failure parts. Many parts suppliers do their own burn-in tests. When a supplier does the burn-in test, the procedure, time, and characteristics test values should accompany critical parts such as capacitors, transformers, and solid-state devices. Some special tests that should be applied before assembly are as follows:

(a) Capacitors.
- o Corona-dc ramp test is suggested
- o Arc discharge test
- o Characteristics tests
- o Dielectric withstanding voltage (at 85 percent initial value)

(b) Resistors.
- o Stability at rated voltage
- o Temperature rise as a function of area exposed to a cooling plate
- o Characteristics test

(c) Transformers.
- o Active corona test at operating frequency
- o Dielectric withstanding voltage test
- o Shorted term test
- o Characteristics test

(d) Solid-state devices.
- o Characteristics tests

6.4.3 Personnel

Personnel assigned to the high voltage assembly area should be trained to do the special assembly and solder techniques required for high voltage assemblies. On-the-job training may require coaching from engineering as well as shop instructors. Training by engineering is especially important for quality control, inspectors, and test personnel. The purpose is to motivate the assembly personnel to do high-quality, efficient work. The objective always is to develop high-quality, highly reliable, long-life power supplies without rejects.

6.4.4 Encapsulation

There are many ways to encapsulate or pot a high voltage subassembly or assembly. Most result in many failures and rejects. Two methods are used with excellent success: vacuum impregnation with overpressure cure, and vacuum injection molding with cure under pressure. The pressure cure keeps bubbles from forming during cure.

Tests should be performed to ensure that the vacuum pressure times and cure temperature are optimum for the material. When filled encapsulants are used for transformers and inductors, tests should be made to ensure the fillers do not form a dam and cause the material and catalyst to separate. Cases have been cited where the winding material never cured because of catalyst separation.

6.4.5 Tests

Tests bring out three failure modes found in high voltage subassembly and power supply manufacturing. They are (1) cleanliness, (2) poor vacuum impregnation, and (3) workmanship.

Lack of control of workroom cleanliness results in debonding: poor vacuum impregnation results in voids: and poor workmanship results in high field stresses, partial discharges, and failures. The corona test is the best test technique to determine these failure mechanisms.

Much has been said about inspection and test. Three things that show up as overstress are sharp-edged parts, boards, and subassemblies. They are difficult to find because they do not occur in all components. Therefore, the test personnel must be willing to reject suspect items; otherwise, the integrity of the organization is jeopardized.

SECTION VII

HIGH VOLTAGE GUIDELINES TO MINIMIZE FAILURES

High voltage power supply manufacturing and design is greatly influenced by cost, time, and workmanship. Some hurriedly designed and manufactured equipment, developed at low cost, may result in overstressed insulation and low MTBF. This section discusses major causes of overstress and failure during the design and manufacture process. This discussion is followed by remedial guidelines to minimize the probability of overstress and catastrophic failures.

7.1 Technical Exchanges and Reviews

Several design technical exchanges should be held between the contractor and the power supply manufacturer's Engineering, Manufacturing, and Test personnel. The purpose of these technical exchanges is to search for problem areas and find solutions that result in highly reliable, long-life power supplies.

The most important guideline to follow is to anticipate future failure modes and prevent them. For instance, a whole new development program is in progress for high-density power supplies. Power supplies developed for airplanes before 1985 had relatively low efficiency and were plagued with thermal problems. In the near future, power density is expected to double by 1992 and double again by 1995. Unless efficiency is controlled, overheating will be much more serious by 1990. Anticipated power densities and efficiencies are shown in Table 6.

It will be nearly impossible to obtain the expected power densities expected for the 1990s without increasing overall power supply efficiency. Heat generation and removal will be the cause for most power supply failures. New switching devices that operate at higher voltage and high frequency are the most probable way to solve the problem.

EMI will also pose a problem for the 1990s. Capacitors and inductors are inherently large and tend to reduce the power density. This implies that an effort should be made to obtain higher joule capacity capacitors.

When determining the power density of a power supply, all parts must be included. That is the input and output connectors, switchers, rectifiers, filters, controls, BITE and ATE, heat removal, and structure to fit into the mainframe.

7.2 Stress Interactions

Design stress interactions are associated with the electronic design, selection of materials and components, the packaging design, the design of the manufacturing fixtures, and the testing parameters. Manufacturing stresses can be caused by improper mixing, potting, and curing of the materials, component and module assembly, workmanship, and manufacturing facilities and environment. Each major topic is addressed for design and manufacturing stresses that may lead to low MTBF or catastrophic failures.

7.2.1 Material Characteristics

Solid insulation has electrical, mechanical, thermal, and chemical properties. These and other miscellaneous properties are detailed in Table 10. Sometimes materials are specified to be transparent so that the packaging engineer can assess parts stressing and bonding. Weight, water absorption, and outgassing are often specified. Most important for all categories of high voltage insulation is life, which depends on electrical stress and the environment.

Materials characteristics that have contributed to stress include:

- o High viscosity, which prevents complete filling of magnetic devices and densely packaged electronics.

- o Service temperature, which must be compatible with the operating and storage temperature for the application.

- o Brittle and very hard materials that add stress to component structures, solder joints, and printed circuit boards during thermal cycling.

TABLE 10. PROPERTIES OF INTEREST FOR INSULATING MATERIALS

Mechanical Properties	Electrical Properties	Thermal Properties	Chemical Properties	Miscellaneous Properties
Tensile, compressive, shearing, and bending strengths	Electric strength	Thermal conductivity	Resistance to reagents	Specific gravity
Elastic moduli	Surface breakdown strength	Thermal expansion	Effect upon adjacent materials	Refractive index
Hardness	Liability to track	Primary creep	Electro-chemical stability	Transparency
Impact and tearing strengths	Volume and surface resistivities	Plastic flow	Stability against aging and oxidation	Color
Viscosity	Permittivity	Thermal decomposition	Solubility	Porosity
Extensibility	Loss tangent	Spark, arc, and flame resistances	Solvent crazing	Permeability to gases and vapors
Flexibility	Insulation resistance	Temperature coefficients of other properties		Moisture absorption
Machinability	Frequency coefficients of other properties	Melting point		Surface absorption of water
Fatigue		Pour point		Resistance to fungus
Resistance to abrasion		Vapor pressure		Resistance to aging by light
Stress crazing		Glass transition		

- o Very low thermal conductivity, which prevents proper cooling of power circuitry and may cause hot spots within the insulation system.

- o Excessive differential thermal expansion between the potting material and electronic components, which mechanically stress and crack the insulation and components.

- o Low dielectric strength, which leads to catastrophic failure for materials between high voltage small radii conductors and grounded surfaces or small low voltage conductors.

- Dielectric constants greater than 6 and dissipation factors greater than 0.1 which may cause very high stress across microvoids and macrovoids, causing partial discharges and eventual voltage breakdown. High dissipation factor at higher frequencies cause dielectric heating and a rapid decrease in dielectric strength, resulting in short life.

- Low volume and surface resistivities, which tend to increase dielectric heating and probability of surface arcover.

- A high glass transition point adds stress to all electric components within the potted material when subjected to low temperatures. In addition, it enhances the probability of cracking of large volumes at temperatures at or below the glass transition point.

Related undesirable properties in a good potting material for high voltage power supplies and electronic components include:

- High shrinkage during cure
- Gas release during cure causing bubbles (voids) within the potted volume
- Molecular sieving of catalysts and fillers
- Reversion back to the original components
- Sieving of fillers by dense sleevings, tapes, and wrappings

7.2.2 Dielectric Parameters

Dielectric parameters critical to high voltage design are temperature, material thickness, humidity, area, dielectric constant dissipation factor, gradation of dielectrics between surfaces, component electrode configuration, and voids.

Mismatch of dielectrics within an insulation system is caused by placing the low dielectric constant material next to a small radius conductor in a multiple dielectric system. The greatest impact is for gas-filled voids next to a stranded wire conductor. The gas ionizes, heats the dielectric, and causes progressive deterioration of the solid material.

Overheating dielectrics and not derating a dielectric for temperature are other common sources of failure. Both dielectric strength and life at operating voltage decrease as temperature is increased.

Some manufacturing problems associated with the dielectric parameters include:

- o Incomplete outgassing of air from the wiring and parts before application of the potting material
- o Displacing components, modules, or wiring in a way that decreases the insulation thickness between high and low voltage conductors
- o Wrong formulation of encapsulation or filler
- o Debris or foreign matter on the components or in the material
- o Contamination when silicones and epoxies are mixed in the same potting facility
- o Improper use of primers when they are required
- o Variations in manufacturer's formulations

7.2.3 Parts and Component Configurations

Problems associated with parts and components are listed as follows:

- o Coatings--Wax-filled ceramic surfaces are difficult to clean and bond.
- o Surface coating materials that unbond during cleaning.
- o Surface coating materials that are incompatible with the potting compound unbond or form gas voids.
- o Pot Cores--Sealing and filling may crack the seals, making a gap between transformer halves.

- Small, high voltage leads arc to the ferrite core.

- An air void between the outer winding and the ferrite core can result in corona and arcing.

- Ferrite cores are easily cracked during environmental testing.

- Tapes within the transformers and other parts may be a source for voids.

- Connectors--Deep-seated pins with gas-filled wells around the pins are very difficult to pot and are a source of partial discharge and corona.

- Voids or gaps along the insulation interfaces are a source of partial discharges and eventual breakdown.

- Wiring--Use of stranded wire for very high voltage applications have high electrical stress at the conductor.

- Ties--Loose fabric or ties are a source of corona because of dielectric charging.

- Mounting Brackets and Screws--Any sharp-edged or pointed bracket or screw associated with a void or gap will fail on a high voltage system. Plastic and metal screws contribute to failure whenever sharp edges are present.

- Sleeving over components traps air next to the component.

7.2.4 Physical Parameters

Physical parameters associated with components and the completed power supply that cause problems follow:

- Matching materials for stressing in large components such as transformer coils, high voltage solid-state power devices, transformer cores, and base plates.

- Placing low voltage sensitive circuits in a high voltage compartment.

- High voltage and low voltage wire separation.

- Lack of corona shields around nuts, screws, sharp-edged components, and terminations.

- Bonding of multi dielectric systems such as epoxies and silicones.

- Contamination by waxes, greases, and oils after cleaning.

- Mounting parts on circuit boards with exceptionally small gaps, which prevents filling with the encapsulant.

- Circuit board configuration. Potted, densely populated, long, wide circuit boards that crack at low temperature.

The packaging design should contribute to system reliability by:

- Minimizing thermal stress
- Minimizing physical stress
- Minimizing dielectric stress
- Facilitating initial achievement of high dielectric strength
- Maintaining high dielectric strength for the required life

A packaging design that fails to provide for these items is inadequate. Table 11 summarizes typical packaging "inadequacies."

7.2.5 Assembly and Test Methods

The problems associated with assembly and test are caused by the manufacturing procedures developed by engineering, the manufacture and assembly of the components and equipment, and the in-process assembly and acceptance tests.

TABLE 11. AREAS OF CONCERN IN PACKAGING HIGH VOLTAGE SOLID SYSTEMS

POTENTIAL PROBLEM	EFFECT[1]	METHOD OF PREVENTION
Voltage stress across surfaces	Corona creepage	Layout to minimize surface voltage stress. Creepage barriers. Select arc-resistant material.
Voltage stress exceeding material breakdown	Corona arcing	Maintain spacing between routed wires. Increase package size. Select higher strength dielectric. Solder balls. Hardware selection to avoid exposed sharp edges. Use of voltage shields. Large diameter conductors. Insulation dielectric strength compatibility (ac). Insulation resistivity compatibility (dc).
Excessive temperature	Component failure and insulation degradation	Layout to minimize thermal paths within the module. Use of "loaded" insulating materials (higher conductivity). Use of thermal spreaders. Minimize thermal resistance from module to ambient. Increase package size. Select thermally stable material.

TABLE 11. AREAS OF CONCERN IN PACKAGING HIGH VOLTAGE SOLID SYSTEMS (concluded)

POTENTIAL PROBLEM	EFFECT[1]	METHOD OF PREVENTION
Voids in insulation	Corona arcing	Packaging geometry to allow "easy fill" and gas escape. Packaging design to accommodate cure shrinkage. Process control to avoid bubbles.
Cracks and delamination during thermal cycling	Corona arcing	Packaging configuration to accommodate insulation shrinkage and expansion (physical constraints). Coefficient of expansion compatibility. Material compatibility to promote adhesion. Low bulk modules if material is severely constrained.
Part or solder joint failure during thermal cycling	Shorts or opens, corona arcing	Component mounting to provide stress relief. Soft conforming coat of sensitive components.
Particulate contamination	Corona arcing	Packaging design to allow easy cleaning. Process control.

[1] Corona and creepage lead to material degradation, formation of carbon deposits, etc.; thus, produce arcing and circuit failure.

Corona causes EMI, which may affect the operation of sensitive circuits.

Cleanliness. A number of items contribute to the bond worthiness of a potting material; many involve cleaning and personnel handling. Foremost are greases, oils, and residues that contaminate the hardware during assembly when personnel handle them. Secondary items include air pollution such as particulates, flaking of particles from parts, or smoke from hot soldering devices. Last is the handling or lack of cleaning after environmental testing before high voltage testing.

Solvents. Dirty solvents leave residues. In addition, some solvents fill small pores in the surfaces of the cleaned component and outgas for a long time after cleaning. This can result in high voltage surface arcing during testing.

Moisture. Condensates collect on parts and materials during environmental testing and result in lowered surface resistivity.

Soldering. Incomplete solder joints, cold solder joints, or solder flow between conductors.

Parts. Misplaced or misaligned parts. Lack of stress relief on parts terminals.

Spacers. Use of multiple spacers rather than a single spacer, allowing voids to exist in the spacer string. Loose fitting spacers on plastic or metal bolts.

Bolts. Threaded section of bolts extending into the potting material or board. Overstressing bolted components on boards.

Tabs. Use of glued tabs on layered insulation causes voids. The glue may not be compatible with the potting material.

Sleeving. Solid sleeving traps air between the conductor and sleeve, causing partial discharges and breakdown. Some porous sleeves do not fill properly with the encapsulant. Sleeves on small wires should be kept short to avoid voids.

Mold Release Agents. Silicone contamination of epoxies and urethanes.

Materials Aging. Stored improperly or used after recommended storage life.

Batch Variations. Variations in manufacturer's quality control. Variations during mixing, outgassing, and application of catalyst.

Coatings. Part coating materials incompatibility with the potting materials.

Testing. Insufficient quality control test of incoming materials to control viscosity and aging. Inadequate parts burn-in, subassembly continuity test, and module and system acceptance test. Lack of accelerated or aging tests. Overstressing materials by acceleration and temperature tests.

7.2.6 Environmental Constraints

The environmental constraints that contribute to low MTBF are:

- Contaminated cooling gases and liquids
- Thermal shock
- Excessive vibration and mechanical shock at high temperature or low temperature extremes
- High humidity in areas near unsealed high voltage connectors and terminations causing frost and water droplets to form after low-temperature soaks
- Misapplication of solvents or chemicals during cleaning and general maintenance
- Misapplication of contamination of grease seals on high voltage connectors
- Non filtering of incoming cooling or circulating gases
- Admission of engine exhaust fumes or fuel tank fumes to the high voltage equipment compartments

- Admission of loose fibers insulation or metal flakes to the surfaces of high voltage insulated and noninsulated circuitry

- Use of nutrient materials which may promote fungus growth near or on high voltage parts or equipment

Designers, operators, and maintenance personnel must understand these environmental problems to obtain the best performance and long life from equipment.

7.3 Design and Manufacturing Checklists

Design, parts, materials and processes, manufacturing, and testing checklists are available in Section 8.2 and in Sections 7 and 9 of Volume II. These problem areas and repair techniques were assembled after many hours of consultation with engineers and technicians at the U.S. Air Force Air Logistic Centers, and the Army and Naval Development Centers. Manufacturers contributed many problems and solutions. But, as stated in Section 1, higher density packaging is going to result in many thermal problems and voltage overstress problems not inherent in current designs.

SECTION VIII
CONCLUSIONS

Based on the studies and consultations completed and reported in this program, the following summary statements are presented:

(a) The objective of the two volumes is to give the industrial and government management, engineering, and technical personnel a better insight into problems and solutions for low voltage and high voltage power supplies.

(b) These design and manufacturing guidelines are intended for use by low voltage and high voltage power supply designers, technicians, program managers, and manufacturing technologists.

(c) Because a designer has successfully developed an excellent line of power supplies is insufficient for continued success. New, high-density, high-efficiency power supplies must be developed with an entirely new set of problems and solutions.

In conclusion, the author wishes to thank the many engineers and technicians who were consulted and gave freely their time and advice. The ideas and suggestions were written as close to the issuance of the idea as possible. Thanks to all of you.

One recommendation is to let Dr. Bill Dobbs, AFWAL/MLSA, and Ms. Lavera Floyd and Mr. John Price, Aeronautical Systems Division, Wright-Patterson Air Force Base, know of other problems and solutions so that books can be updated in the near future.

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