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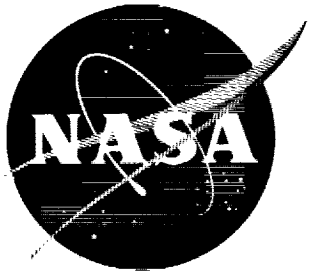
STUDY OF AIRCRAFT ELECTRICAL POWER SYSTEMS

June 1972

Prepared by
Engineering Staff
AIRESEARCH MANUFACTURING COMPANY
Los Angeles, California

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Lewis Research Center
Contract NAS 3-14367

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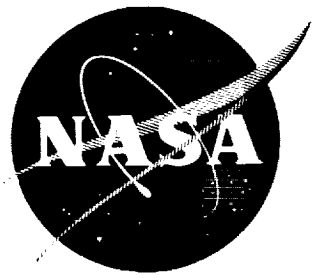
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The work described herein was carried out by AiResearch Manufacturing Company, a division of The Garrett Corporation, from May 1968 to May 1972. Mr. Jack Shank, Lewis Research Center, was NASA Project Manager. Initially, Dr. F.C. Schwarz of the Electronics Research Center, was the NASA Project Manager. Mr. R.E. Vesque was AiResearch Program Manager and Dr. C. H. Lee was the principal investigator.

This final technical report was prepared in compliance with paragraph 15, Exhibit A, of NASA Contract NAS3-14367 entitled "Study of Aircraft Electrical Power Systems." This report incorporates part of the interim report originally issued as AiResearch document 69-5193, under Contract No. NAS 12-659 in August 1969.

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SUMMARY

The study prime objective was the formulation of a philosophy for devising a reliable, efficient, lightweight and cost effective, electrical power system for advanced, large transport aircraft in the 1980-1985 time period. A secondary objective was the determination and recommendation of improvements for subsystems and components.

The scope of the work included studies of all aspects of the aircraft electrical power system including generation, conversion, distribution and utilization equipment. The technology for the projected time period was to be independent of traditional 400 Hz ac systems and methods. In performing the study, information for review was solicited and received from many industrial organizations, airlines and governmental organizations.

Candidate electrical power systems are evaluated and selected, using a method whereby relative weighting is applied to the significant characteristics of reliability, cost, weight, maintainability and performance. It is concluded that a high voltage dc system (300 vdc) is the optimum system for implementation on large transport aircraft in the 1980-1985 era. Furthermore, this system should incorporate software-implemented automatic load management and protection techniques if it is to be truly optimum. The system automatic load management will utilize the most advanced solid-state and hybrid switching techniques in conjunction with multiplexing of control and status signals.

Significant research and technology problem areas associated with achievement of the future selected power system are identified. The needs which are to be resolved are found in:

- High voltage, high current dc switchgear
- High voltage components
- Brushless dc motors of up to 20 hp rating
- An integrated data management subsystem
- An understanding of electrical system static and dynamic interfaces, characteristics and interactions
- Determination of the compatibility of an internal engine generator (IEG) with a high voltage dc system

A design philosophy is presented. This pertains to the selection and utilization of aircraft power systems with emphasis on commercial aircraft usage. Preferences are stated for the design categories of (a) safety-reliability, (b) power type, voltage, frequency, quality and efficiency, (c) power conditioning, control and protection, and (d) selection of utilization subsystems.

The power generation, distribution and utilization subsystems are reviewed and discussed, both as to detailed function and potential improvements. The following principal conclusions are given for the subsystems respectively:

- Where low maintainability cost and weight are most important for the generation system alone either dc generation or wild-frequency generation is recommended.

- Power cable weight can be reduced by 50 percent or more, depending on feeder length, when high voltage (e.g., 300 Vdc) dc transmission is used. Significant weight savings are expected if signal multiplexing is used for systems with large numbers of signals (>150).

- For avionic loads, separate modular interface units are recommended. These will provide the required, closely regulated steady state voltage, and eliminate the need for separate conditioning circuits in each avionics box.

Parametric data for aircraft electrical components is presented and discussed in detail. Components discussed include: electric motors, electric generators, power converters, distribution cabling and transformers, avionics, fans, blowers and hydraulic pumps. A principal conclusion is that, with future (1985) materials technology, using a Samarium-cobalt permanent magnet and high motor speeds, the brushless dc motor could be made weight competitive with induction machines for ratings up to 3 kW.

Included in the section on components are discussions on new promising materials, conductors, insulation, magnetic and structural. Past and future component heat-transfer techniques are presented and discussed. Forced convection methods, liquid and air cooled, are found to be attractive.

Finally, it is concluded that maintainability requirements should be incorporated into the design requirements before development of an aircraft power system is begun. This will eliminate expensive and time consuming changes.

INTRODUCTION

Study Background

This is the final technical report on a study entitled "Study of Aircraft Electrical Power Systems" conducted for NASA Lewis Research Center under Contract No. NAS3-14367.

The work on which this report is based was begun in May 1968 under a contract awarded by the Electronics Research Center of NASA, Cambridge, Mass, Contract No. NAS12-659. The study was for the "Investigation and Development of New Concepts for Improvement of Aircraft Electrical Power". Initially, the program plan called for an effort of about 2 and 1-quarter man years; however, after it became apparent that there was considerable incentive to broaden the scope an additional two man years effort was added. In July 1970, the NASA Electronics Research Center in Cambridge closed down and the contract was transferred to NASA Lewis Research Center. In March, 1971 a further 1 and 1/2 man year effort was added to the program under Contract No. NAS3-14367.

An interim technical report (ref. 1) was issued in August 1969 besides the six quarterly progress reports required by Contract No. NAS12-659. The interim technical report was primarily based on a review of the electrical power systems and equipment in existing commercial aircraft with consideration for improvements. The emphasis of the work since March 1971 has, on the other hand, been on new electrical power systems for large subsonic transport aircraft for the 1980-1985 era.

This resulting final report incorporates review and other pertinent information from the work performed in the earlier phases of the contract, adds the results of system tradeoff and selection, and identifies significant research and technology problems that need to be overcome by the 1980's.

Purpose of Study

Existing aircraft electric power systems were developed approximately 25 years ago and were based on the needs of that time. World War II was barely over and equipment needs and standards were of a carry-over nature. Since that time the size and speed of transport (and other) aircraft has grown, and with it the requirements for an aircraft electrical power system. In the interim, many new components and concepts have been developed for space electrical power and related fields. This study was performed in recognition of the needs for (a) a review of current aircraft electrical systems and equipment, and (b) a formulation of the practical means for devising an optimum electrical power system for the future generations of transport aircraft in the 1980-1985 time period.

Scope of Investigation

The study was conducted primarily with regard to the electrical power systems of conventional, large subsonic transport aircraft. An aircraft electrical power system was defined as including generation, transformation, distribution and utilization of aircraft electric power. For future projections the reference technology level was the 1980-1985 time period. Study areas and tasks were generally covered by main categories with some overlapping. These main task categories were (a) survey and review of state of the art information on aircraft electrical power, (b) examination and definition of areas for subsystem and component improvement, (c) evaluation of candidate systems and selection of a power system for future use and (d) identification of significant research and technology problem areas. The categories are stated in summary below.

Survey, review and analyses.--These are:

- Industry and literature sruvey of current and advanced technology in aircraft electric power systems.
- Survey and review of advanced concepts of reliability, maintainability and operational economy.
- Review and analysis of methods of supplying electric power to the loads. For ac or dc, this includes the various voltage levels, waveforms, frequencies, types of control, regulation and switching.
- Review and analysis of currently applied heat transfer techniques.
- Investigation and analysis of the functional performance of power system components including their static and dynamic characteristics.
- Survey and review of system and component reliability, maintainability and their relationship to aircraft operational status.
- Survey and analysis of present hydraulic and pneumatic powered loads, electric-pneumatic/hydraulic utilization power, servosystems, heaters and lights.
- Review and analysis of the needs of VTOL, V/STOL aircraft and airspace hybrid vehicles.

Subsystem and component improvements.--These areas include presently noted and future improvements:

- Investigation of other than conventional materials for critical system components including exotic magnetic materials; insulation materials, unconventional conductor materials and structural materials.

- Investigation and evaluation of methods of improving electric motor and generator performance, weight and cost.

- Examination of methods of load management, control and protection for improved reliability.

- Investigation, analysis and evaluation of improved power transmission and control techniques.

- Study of the improvement of power supplies for avionic loads.

- Investigation of applicable fault detection, prediction and analysis techniques.

- Examination and evaluation of improved servomotors, electro-hydraulic and pneumatic power actuators, fans, blowers and pumps.

- Investigation of new component heat transfer techniques.

Evaluation and selection of power systems.--The basic tasks included:

- Definition of the significant characteristics applicable to aircraft electrical power systems and their relative weights for system evaluation purposes.

- Determination of a method of applying the significant characteristics, such as to arrive at the maximum cost effective power system for future aircraft.

- Description, analysis and evaluation of power system candidates.

- Selection and description of optimum electric power system for future use.

- Formulation of a design philosophy for electrical power systems including safety-reliability requirements, basic design aspects such as power type, quality, conditioning, control and protection.

Significant research and technology problem areas.--These areas are primarily those identified as associated with achievement of the future selected power system. Included are problem areas for components, subsystems and power conversion equipment whose resolution would improve present and near future aircraft power systems.

Method of Approach

In accomplishing the study, the method of approach was based simply upon (a) approaching industry and government organizations to obtain aircraft technical information, and their points of view on matters such as maintainability,

(b) review of past and current appropriate technical literature, and (c) performance of the general tasks stated previously. Fig. 1 illustrates the methodology used in general conformance with the scope of the investigation. It should be noted that, with the exception of the system synthesis, evaluation and selection process, all of the tasks are shown in parallel. This is a necessary simplification. The actual process, over the years included many tasks such as review of current technical literature prior to, and in series with, analysis of a given component or subsystem. Subsequent industry supplied information was often used to update and revise previous analyses, or to form the basis for new concepts. In general, parametric studies were selected according to their adjudged potential in yielding improvements of significant characteristics.

Improvements in these characteristics was looked for, such as a decrease in physical weight and size, an increase in reliability, a decrease in maintenance time and cost, and better performance.

Finally, it must be understood that the investigation did not seek to add to, or modify the traditional 400 Hz ac aircraft power technology. Rather, it was independent and aimed at the 1980-1985 era. Matters such as the cost of conversion to the new optimized system, were disregarded as being impractical because of the projected time period.

Organization of the Report

The report is organized into eight sections. These are grouped into four subdivisions; (1) the summary and introduction, (2) system aspects, (3) subsystem and component discussions and (4) conclusions.

System aspects are presented and discussed in the sections on 'Power Systems for Conventional Aircraft', 'Power Systems for VTOL, V/STOL Aircraft and Airspace Vehicles' and the 'Design Philosophy for Electrical Power Systems'. In the first of the three sections, the selected power system is presented, followed by the comparison of candidate systems which led to its selection. The second presents and briefly discusses the requirements of VTOL, V/STOL aircraft and airspace vehicles. The section on design philosophy was intended to act as a guide to future system design practice.

Subsystems and component data are presented and discussed in two separate sections. Potential improvements are summarized at the end of each section.

The section on conclusions is made up of numbered itemization of conclusions extracted from the system, subsystem and component sections. It is included for the purpose of review.

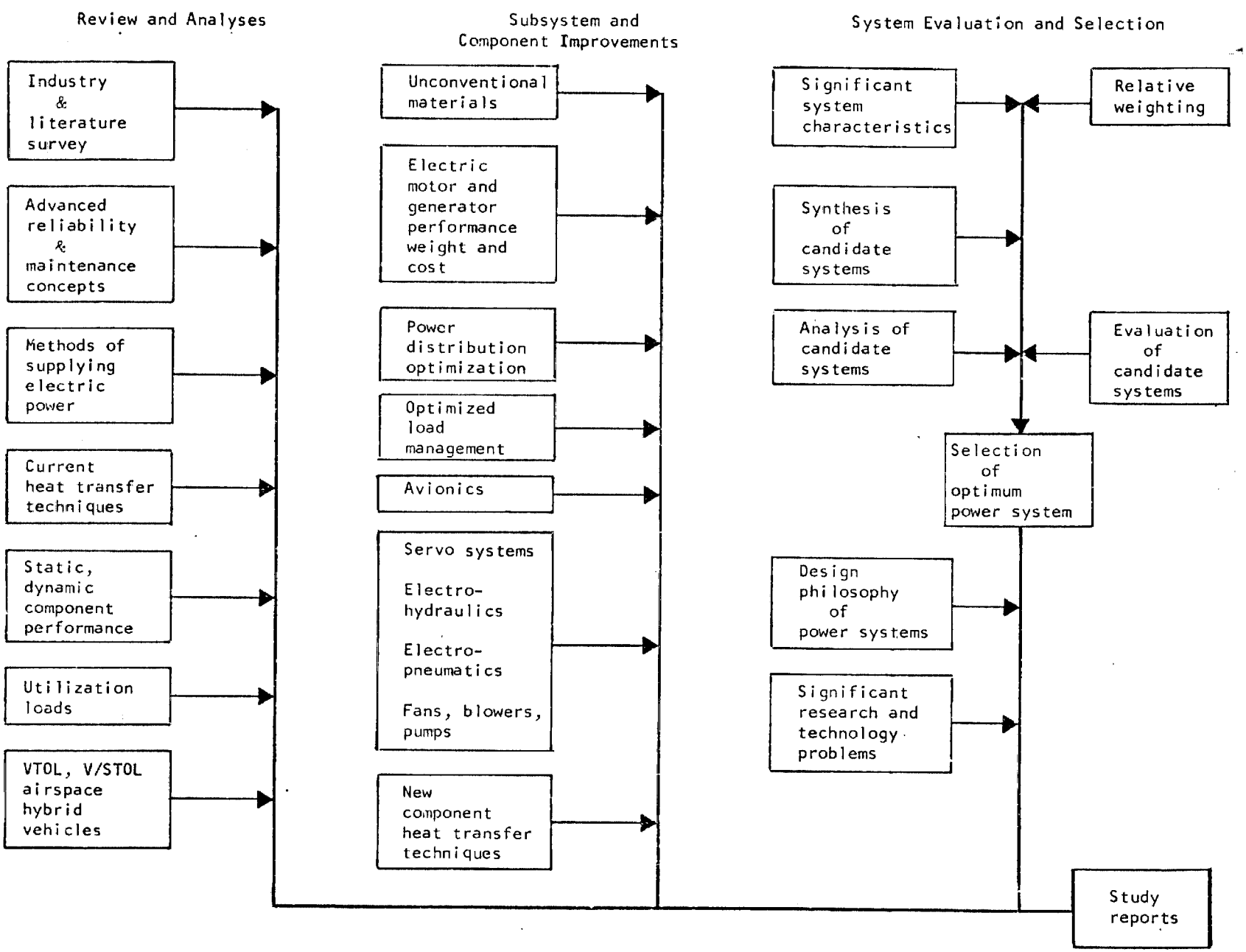


Figure 1. Methodology Flow Diagram

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POWER SYSTEMS FOR CONVENTIONAL AIRCRAFT

Introduction

For the purposes of this report, conventional aircraft have been defined as being large subsonic transports, commercial and military, whose projected technology level is the 1980-1985 time period. In addition, the study was oriented toward a viewpoint independent of present day established practices. This is with regard to maintenance, spare parts and existing ground power facilities.

Present-day, typical electrical energy demand was assumed as a base reference for design tradeoffs. Further, it was assumed that the vehicle in consideration would use three or four propulsion powerplants from which mechanical shaft power could be extracted for electricity generation. Based upon the foregoing assumptions, an electric power system for conventional aircraft was selected and is discussed.

The selected system, which is described in the first part of this section is expected to offer the greatest improvements in the areas of weight, performance, efficiency, reliability, cost and maintainability. Advantages and disadvantages of the selected system are discussed. Following this, an estimate is given of the effort required for acquisition of the selected system. For the most part, qualitative judgments only are made because of the inaccuracies inherent in long-range predictions of cost, etc.

The second part of this section presents a comparison of the candidate power systems. This includes a description of the systems and the method of their evaluation. This evaluation resulted in the selection of a given system which is now described.

Selected Power System

Description.--The selected, recommended aircraft electrical system, which includes generation, distribution and utilization subsystems is a "High Voltage DC System". Incorporating, highly sophisticated load management techniques, it it foreseen as being the optimum for the 1980-1985 era.

The system is adaptable to a three, as well as a four, engine configuration. All source generating channels operate isolated or in split-parallel with provisions for source bus cross-strapping. The optimum system voltage is selected as being 300 vdc with the negative side common with the airframe structure. This voltage is the highest compatible with corona breakdown considerations.

The generating system is the simplest, the lightest and the most reliable, yet foreseen. It eliminates the necessity for a constant speed drive. The power distribution cabling is the lightest and most efficient. It is single wire with no reactance drop. Conversion equipment for the necessary low voltage utilization is lowest in weight due to use of high frequency choppers. The system

provides for the use of brushless dc motors which can be operated at any desired speed and range.

Selection of the high voltage dc system is made with the expectation that (a) suitable high voltage dc switchgear will be available and (b) brushless dc motors will have become competitive with ac induction motors by the 1980's. However, if necessary, 300 Vdc can also be easily inverted to square wave 115 Vac 3 phase 400 Hz for induction motors.

The selected system will incorporate the most advanced methods of solid state and hybrid switching techniques, multiplexing of control and status signals and an efficient data management system. Feasibility of solid-state switching, circuit protection and computer control concepts have been demonstrated recently by development programs. Examples are:

- The Navy "SOSTEL" (Solid State Electrical Logic) program
- Westinghouse "ACES" (Automatically Controlled Electrical System)
- Bendix Airborne Display and Electric Management System.

It is probable that these advanced methods of power distribution, control and management will contribute a major part of the improvement over today's aircraft systems.

A typical transmission configuration and the source bus configuration are shown in Figures 2 and 3 respectively. These are referenced in the following discussion.

Transmission configuration: As illustrated in fig. 2, the main power shield is placed in a convenient location near the power center of gravity, resulting in near minimum transmission cable from all power sources.

An example is given for the length of feeder installation for an airplane similar in size to the Lockheed L-1011. This would be approximately 18 m (60 ft) each for port and starboard engines and 24 m (80 ft) each for aft and APU generators. The weight of the feeders of a conventional system (four channels at 60 kVa) is 67 kg (148 lb).

For the high voltage dc system, it is only 27 kg (60 lb). If 15% of this weight is allowed for additional ground connections, a net savings over the conventional system for the transmission section alone is 36 kg (79 lb). The centrally-located source buses will feed six to eight distributed power centers (DPC) placed at various load centers in the forward, aft, port and starboard sections of the vehicle. Power is converted to lower utilization voltage locally in the distributed power centers, thus assuring maximum utilization of high voltage distribution.

Generating equipment: The generators referred to in fig. 3 incorporate round rotor rotating rectifier alternators. The machines would have six phases,

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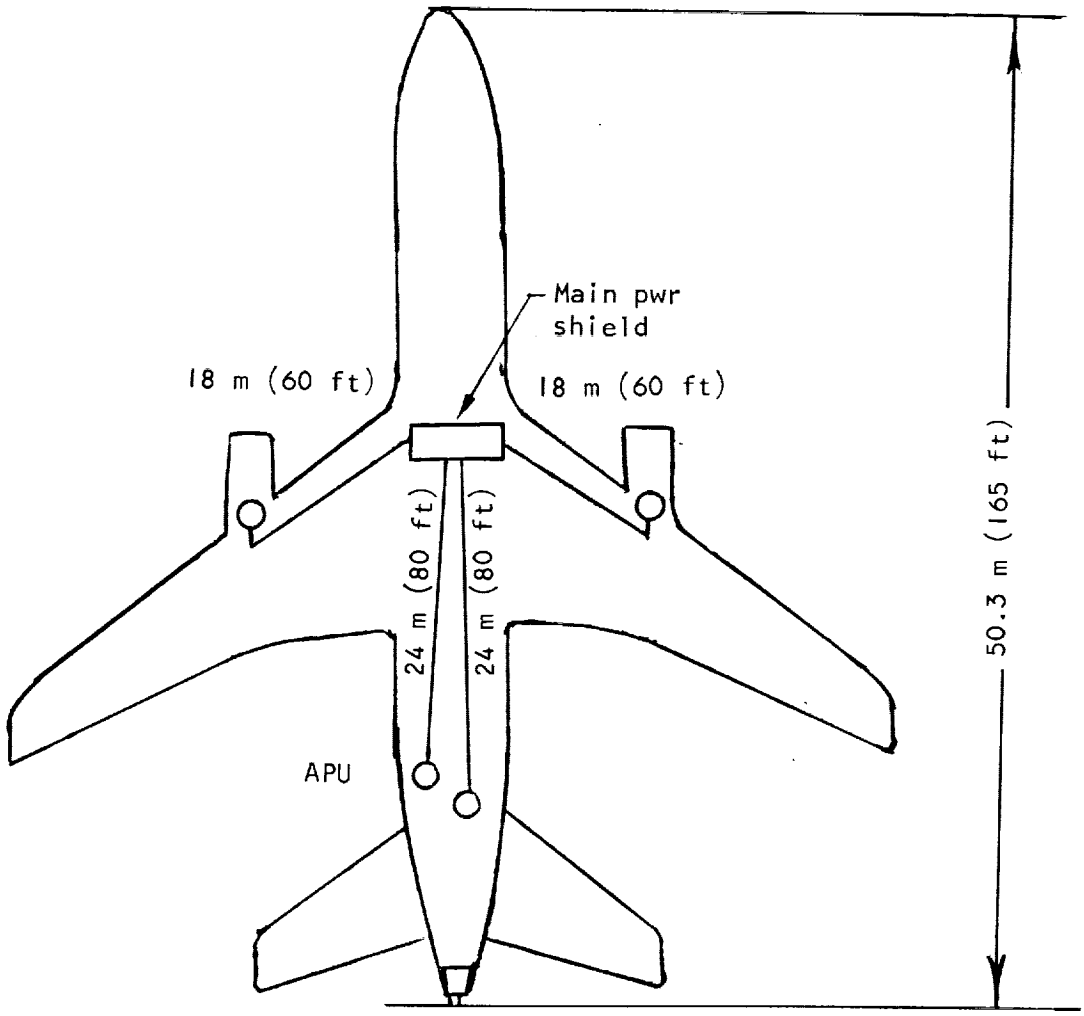


Figure 2. Typical Transmission Feeder Length to Main Power Center on a Large Transport Aircraft

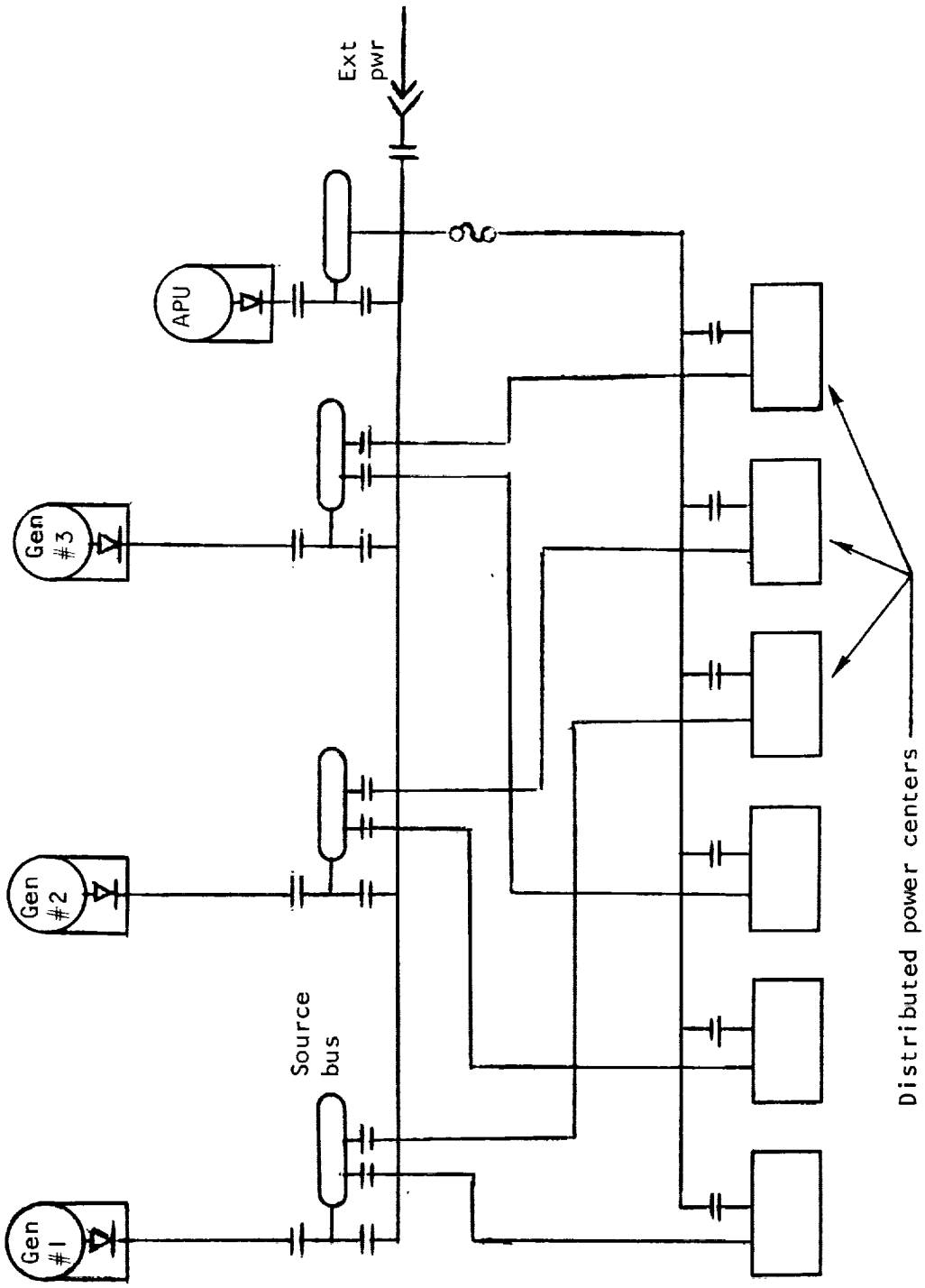


Figure 3. Typical Source Bus Configuration

oil splash cooling and permanent magnet exciter. Projected weight for a 60 KW machine, including power diodes and heat sinks is approximately 23 Kg (50 lb) or less.

Since the output of the ac generator is going to be rectified, it is desirable that for low filter weight, the power frequency should be high. High frequency results inherently from high speed operation of the alternator. Higher alternator speeds reduce the machine in weight and size.

At a first glance, it would seem that the solid rotor type generator, which is capable of operating at extremely high speeds (100 000 rpm or more) would be an ideal candidate for the application. (This is as opposed to the round rotor scheme selected.) However, one important requirement of any alternator when operating into a rectifier load, is that of low internal reactance (subtransient reactance). Due to the rectifier commutation, a certain amount of dc output is lost and this loss increases with frequency and source reactance. The point is quickly reached where practically no dc output may be obtained. All solid rotor generators inherently have high internal reactances due to their long magnetic circuit. As a result, the optimum choice of alternator is a round rotor type. For conventional design, this would be an eight pole machine operating at about 10,000 to 20,000 rpm. For sleeved rotor construction, the operating speed could be higher.

Distribution and power control: Each 60 kW generator at a terminal voltage of 300 Vdc supplies a rated current of 200 A. By using a single feeder line and the airframe structure for the negative return significant weight savings are realized. Many present-day TR unit installations with ratings of 28 Vdc-200 A utilize a structure return. They are within specification of potential drop. An 'electrical reinforcement' of structural provisions may, however, be required for the selected arrangement. This is because the return path would include the nacelle and engine areas. Accordingly, an allowance of 15 percent of transmission cable weight was made for short bypass and structure bonding cables.

(1) High voltage dc switchgear: It is anticipated that Remote Controlled Circuit Breakers (RCCB) or Solid State Power Controllers (SSPC) will be used for source bus switching and protection and also throughout the distribution system. RCCB with 100 A rating and 3600 A rupture capacity (although not for 300 Vdc) are available today from Cutler-Hammer Inc. The RCCB is capable of being remotely set or tripped and provides indication of its state, either via the data Management System or hardwired control by utilization of a low current (1/2 A) pushbutton circuit breaker located at the flight engineer's station.

A typical source bus configuration, with feeders to distributed power centers (DPC's) is shown in fig. 3. Each source bus feeds two (or more) distributed power centers. The in-flight operable APU provides back-up power for all DPCs. Powering of all DPCs is also possible by means of the dc-tie bus. No airplane load is connected directly to a source bus, all loads are supplied via local DPCs and all power processing units are located in the DPC. Switchgears needed in the distribution system are of three basic categories. These are:

(a) Bus Control: Main bus contactors for source switching protection. Load power rating up to 100 kw with max interrupt capacity of 2000 amp. These contactors will probably be of a hybrid construction, i.e. mechanical contactors and solid state control. (See fig. 4a).

(b) Feeder Control: Protection of feeder branches to distributed power centers or substations. Load power rating to 15 kw with interrupt capacity of 1000A (series fuse). These contactors are projected to be all solid state with thyristors as the power switching elements. (See fig. 4b).

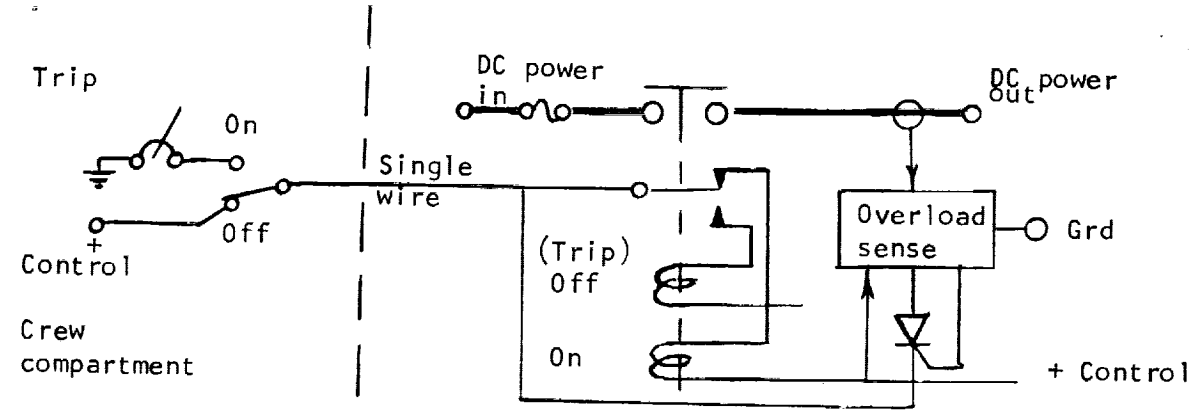
(c) Load Control: Low switching and protection secondary distribution wires to individual loads. Load power rating up to 5 kw with interrupt capacity of 10 P.U. of load current (series fuse) or with current limiting feature. These switches are all solid state control with transistors as switching elements. (See fig. 4c).

The circuit breakers for bus and feeder control which are all located at the main power shield will each have individually hard-wired control switches at the flight engineer's station. Control and surveillance of all the load circuit breakers is to be accomplished by use of a controller/processor (CP) which controls generator to bus power distribution and power distribution to the loads on the buses. Loads will be manipulated or shed according to the flight mission plan and encountered system abnormalities. (This is discussed in more detail later in this section).

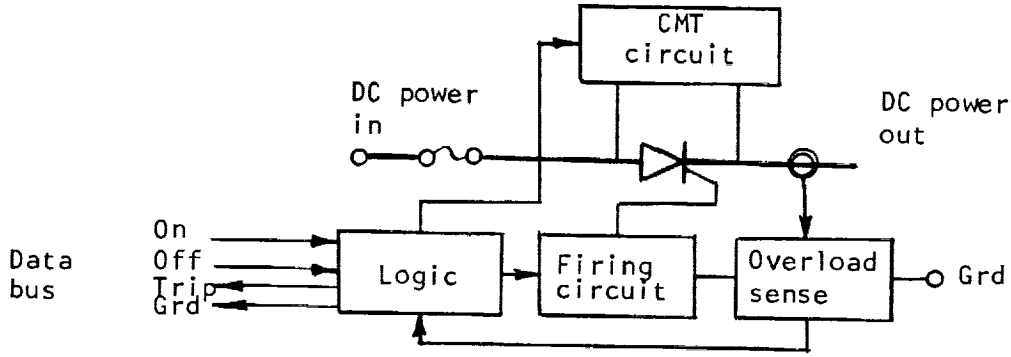
Figure 5 is a block diagram of the load control scheme showing three control substations. Substation interconnections of the Remote Power Controllers (RPCs) with each Data Interface Unit (DIU) are illustrated in fig. 6. A transistor-type RPC is shown. These load circuit breakers will have trip characteristics compatible with the loads and will effectively limit voltage transient overshoots. The RPC senses when a current limiting level is reached, adjusts automatically to a current limiting mode and will trip if the limiting mode persists for a prescribed continuous time. The tripping action is fully automatic, and does not require flight engineer intervention. In this manner, circuit breaker tripping is accomplished in proper sequence and unnecessary load loss avoided. The coordination problems associated with the use of thermal circuit breakers are thus also avoided.

(2) Power conversion: It is assumed that approximately 10% of the total utilization equipment power demand (predominantly avionics and electronics load), will require a lower operating voltage of closer power tolerance than the 300 Vdc generation and distribution potential.

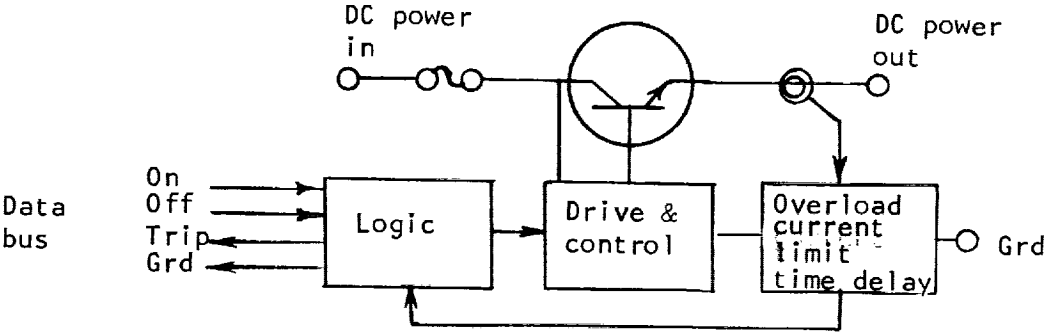
In contemporary power systems a portion of the 115/208 Vac, 400 Hz is converted to 28 Vdc, employing transformer rectifier units. For the high voltage dc system, the low voltage dc power is obtained by use of dc/dc converters. These converters exhibit higher conversion efficiencies and lower weights than the equivalent output T-R units. A small portion of three phase ac power may still be required for instrumentation synchros and resolvers etc., but total demand should not exceed 1 kva. As a result, projected ac load power requirements do not, significantly, influence power conversion philosophy.



(a) Bus control (Hybrid controller)



(b) Feeder control (SCR switch)



(c) Load control (Transistor switch)

Figure 4. Basic Categories of Power Switches

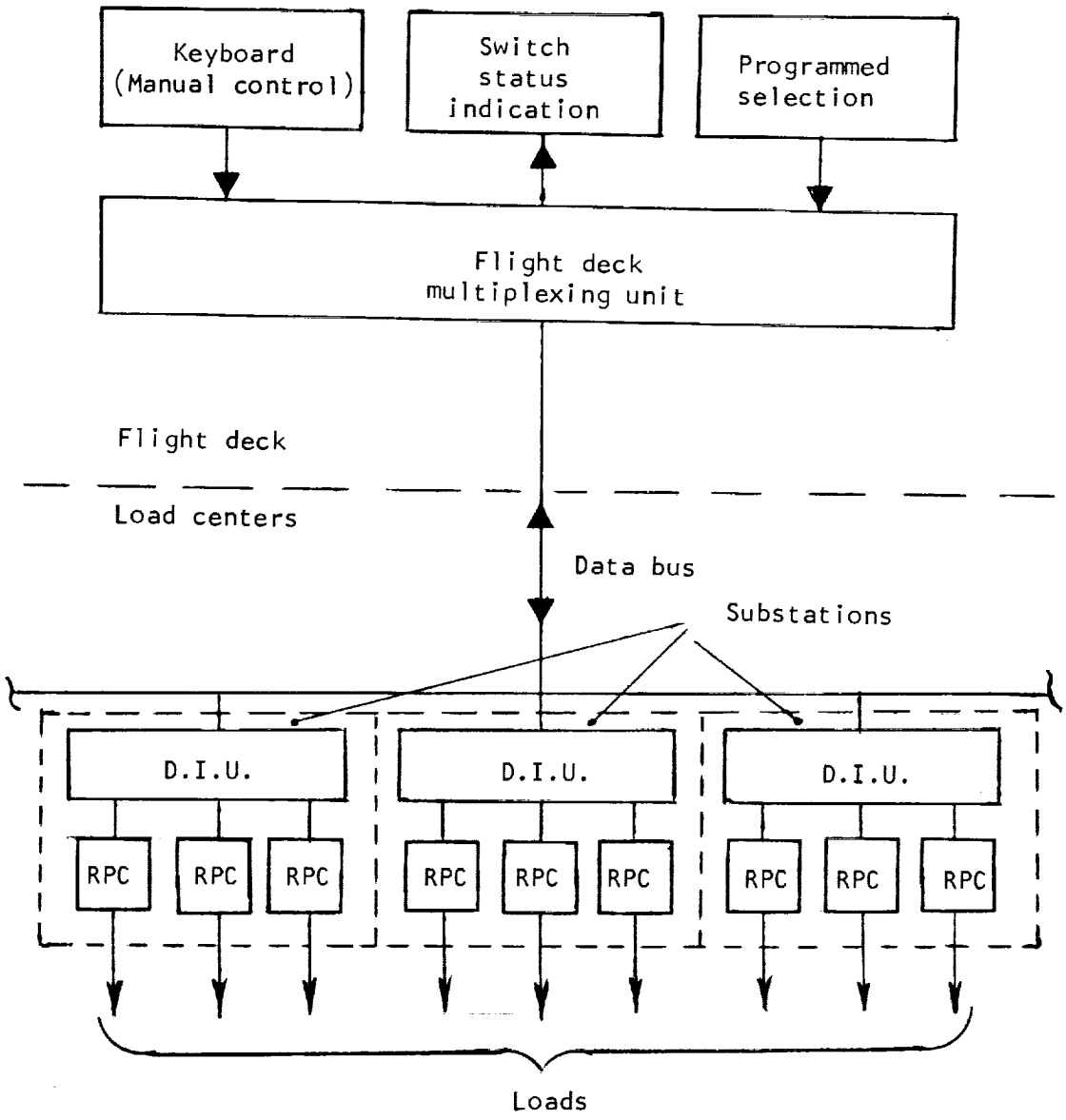


Figure 5. Block Diagram of Load Control Scheme

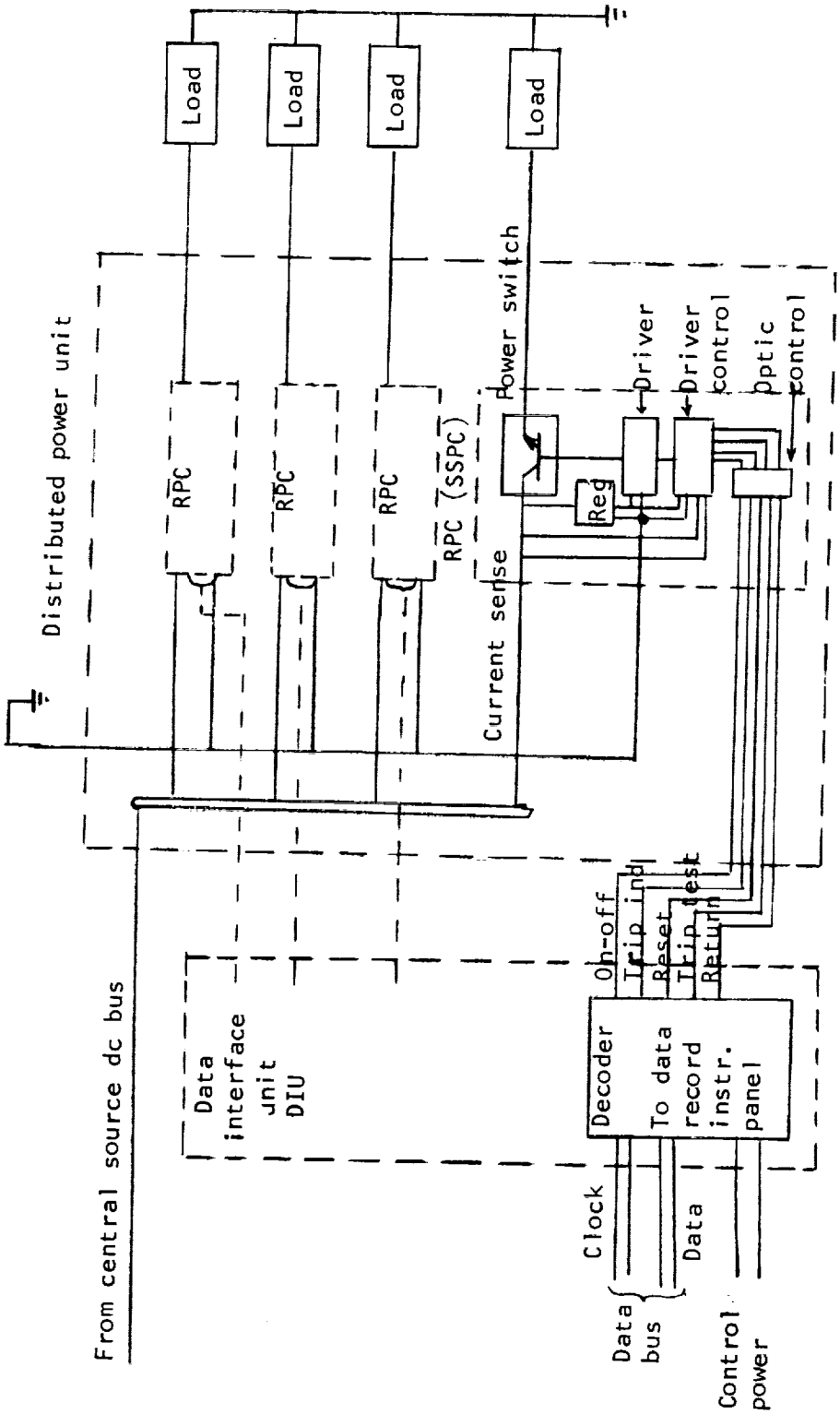


Figure 6. Interface of RPC (Remote Power Controller) with DIV (Data Interface Unit)

All conversion units are located in the various distributed power centers as close to low voltage and ac utilization as possible. If the total connected load is assumed to be 150 kW with 10 percent of this requiring low voltage (assuming 30 Vdc), six to eight dc-choppers with ratings of 80A to 100A and three dc-ac inverters with ratings of approximately 300 to 500 VA each, are required. Figure 7 shows a block diagram of a fixed pulse-width variable-frequency type chopper. These units have been manufactured for several hundred amperes output (28 Vdc) with dc input voltages varying from 500 to 600 Vdc. The output is ripple regulated and additional feedback circuitry is used to provide output current limiting capability. Voltage regulation can be better than 1 percent for the entire load range with input voltage variations to 20 percent. Ripple content better than 1 percent is also achievable. This circuit, of course, is for application where input-output isolation is not required. For special cases where isolation is mandatory, high frequency choppers (up to 20 kHz) with isolation transformers are used. These units, although heavier than straight dc choppers, are still weight competitive with T-R units.

(3) Power control and status signals: Power control and status signals will be multiplexed in order to enhance maintainability and produce a major weight reduction. Maintainability enhancement is a strong function of the specific application since it arises from the fact that the electronics boxes which replace wires can be located such that they are much more accessible than the wires which are replaced. Additionally, it becomes feasible to provide, say 200 percent spares in aircraft wiring since this implies only a few additional wires.

The heart of the control system is located near the flight engineer's station. It consists of a control display panel at the flight engineer's panel and a controller/processor which controls the overall power system configuration.

The flight engineer has the capability of controlling individual remote power controllers (RPCs) as well as of requesting the display of controller status.

The selected system design utilizes integrated RPCs with the following characteristics:

- Switching action is controllable by logic level voltages.
- Switch status (on or off) is identified by a logic level output, the generation of which is independent on the controlling signal.
- Overload conditions (causing an off condition automatically) is indicated by a logic level output to identify the action.
- RPCs are packaged in convenient-sized groups (e.g., 32 or 64) to allow sharing of remote substation electronics.

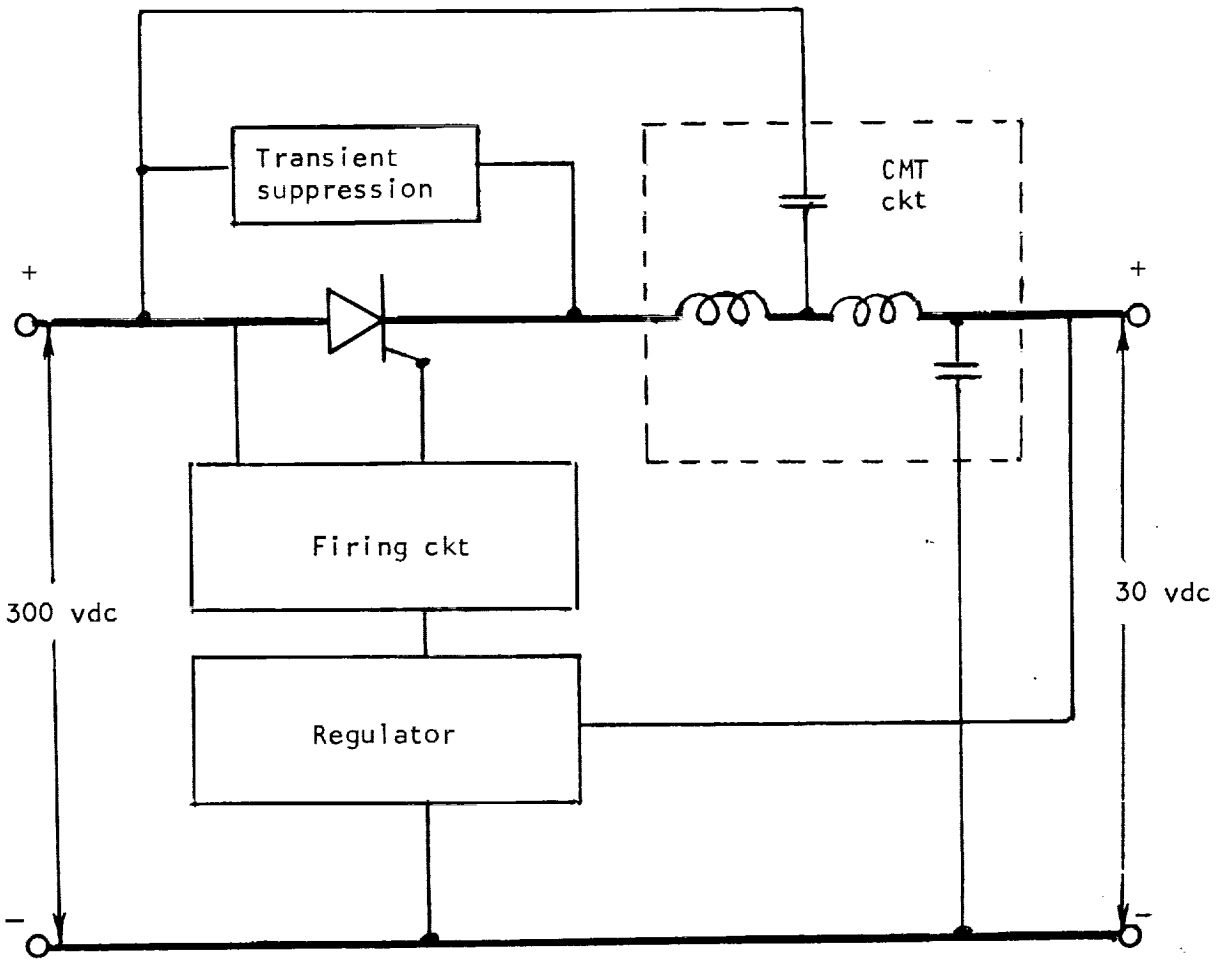


Figure 7. Block Diagram of Typical Chopper

Restricting the stimulus and response signal levels to logic levels promotes commonality in the multiplexing electronics by placing special signal levels and special turn-on, -off devices in the RPCs which require them. Requiring a separate switch sensor, decreases the possibility of a single failure resulting in an erroneous indication to the flight engineer and increases his ability to locate faults. An overload identification signal would be sent to the flight engineer's panel (FEP) display, at the next status request from the controller processor and immediately displayed at the FEP. The flight engineer has the option of taking up further action or attempting to solve the problem by checking pertinent current loads and/or voltages and changing the system configuration or commanding an RPC closure with the hope that a transient caused the switching. All RPCs are grouped in substations or distributed power centers. This will reduce the multiplexing electronics requirement by allowing common power supplies, transmitters, receivers, decoding logic and command storage, in addition to simplifying the load distribution bus configuration.

The system comprises four basic types of boxes.

(1) The control/display panel (CDP)

(2) The controller/processor (CP)

(3) The central bus control (CBC)

(4) Several load distribution substations (LDS)

Individual generator buses are routed to a central location where RPCs in the CBC provide the capability to cross-strap generators to various source buses. This provides reliable power to the power distribution buses. Since these RPCs must be capable of switching very high currents they are hybrid type devices with solid state control. Additionally, the CBC requires the most rapid response in the event of a fault and consequently is the highest priority switching location. Finally, this CBC is unique because it receives several power inputs and distributes several power outputs on feeders which may be deriving their power from a multiplicity of sources.

Priorities for the LDSs are determined by the priorities of the loads they supply. The simplest LDS is one which derives power for itself and all of its loads from one feeder and supplies low priority loads. A loss of the feeder power to this substation would result in a total loss of the station and its loads. Higher priority LDS's will have feeders with the capability of deriving power from more than one source. This ranking continues up to the highest priority LDS which is associated with, and is considered a part of the CP. Redundancy is employed in the power feeding capability in order that the CP recover automatically and rapidly in the event of incipient loss of its own power. This analog power monitor in the CP continuously monitors its input power and generates an interrupt to the CP whenever the supply voltage decreases below a preset level. On receipt of the interrupt, the CP samples all other power source levels and generates commands to the appropriate RPCs to obtain this power. After the automatic action has been taken, a complete status check of power sources is made and logic equations are solved in an attempt to isolate the

problem. If it appears that the problem can be solved by switching, e.g., by dropping a set of low priority loads, the CP will command this action while displaying the faults detected to the flight engineer. Subsequently, the RPC, which opened automatically, can be closed.

Time division multiplexing is used to share a transmission line among all substations. Each substation has an address which is stored in a diode matrix type read only memory (ROM). Thus, the only necessary hardware difference between multiplexing substations is this small ROM which is used to decode all addresses appearing on the line and recognize a request for data or action at the particular substation. Random addressing is used although under normal (non-interrupted) operation the CP will generate the addresses in a particular order for periodic status checks.

The transmission line is triple redundant in order that no single line failure either open or short affects the operation of the system or any substation. Majority voting is employed after the redundant line receivers and decoders in order to obtain the proper data stream at the CP, CBC and LDSs. Since some of the multiplexed signals are derived from analog signal sources, analog to digital converters, ADCs, are used in all LDSs which require an analog measurement to be made. Some LDSs may supply power to very low priority loads, all of which would be shut down in case an overload or partial power loss condition existed.

Analog signals are pulse code modulated and subsequently transmitted as though they were a set of discretes. In order to allow majority voting at the receiver, the binary PCM data from the ADC is converted to a cyclic progressive code prior to transmission. After reception the cyclic progressive code is converted back to binary in the CP by software. Discretes are grouped into data words and transmitted without conversion to a cyclic progressive code.

Manchester encoding of the PCM data for transmission eliminates the need for a separate clock line. Thus, each substation receives self-clocked data from the line. Every station has its own clock for transmitting data ADC clocking, etc. Thus, any substation could communicate with any other substation although this is not recommended at the present time, since an attempt has been made to minimize the decision making capability within individual substations. This places most of the logic within the CP where it can be time shared among the substations.

Although most RPCs have self-circuit breaking capability, most of the decisions regarding the distribution of power will be made within the CP and all command inputs will go through the CP. The basic functions of the CP are the control of source channels and management of the various electrical loads. This is accomplished by remotely controlling all of the RPCs and solving logic equations to determine the optimum control scheme. In normal operation, the CP will send out status requests to the various substations at a frequency which is a function of their priorities, e.g., the status of the CBC is requested much more frequently than that of an LDS which has low priority. The data request word from the CP can be divided into three parts, a substation address (about 5 bits), and OP code (2 bits), and a switch configuration command or analog data request.

The address will identify one substation. The OP code will identify the action to be taken at the substation, i.e., (1) open or close a switch, (2) give a status report, or (3) send back analog data. The remainder of the word will (1) define a switch configuration, (2) be a blank, or (3) identify which analog data is required. Upon receipt of this command data word, the appropriate substation will respond with a word in a similar format. Its address will be repeated as a recognition to close the loop. A one-bit OP code will be added for the purpose of flagging an automatic action that has been done since the last request. Then, the data requested will be given. Using the OP code in the response word allows the CP to request status more than once in order to check the operation of the substation. Several failure types can be detected by comparing the present status word with the previous value whenever no change is indicated by the response OP code. This code will also flag a problem even though the request may be for analog data.

The triple redundant data bus comprises three independent routed essentially lossless transmission lines. Impedance matching terminations are provided at the ends of the lines. The triple redundancy is carried into the substation through the line receivers, receiving clock generators, and temporary data storage registers to the majority voter which loads data into the switch configuration storage registers which provide continuous switch drive signals to the RPCs. The transmitting portion of each substation also uses triple redundancy in those portions which are time shared by more than one signal, with the exception of the logic power supply modules. Since the power supplies can be monitored reliably, they will be dual redundant with automatic switching to the redundant supply on detection of a failure. In the event of a failure in either power, supply the CP will be notified that the redundancy has been lost. Similarly, periodic checks of the incoming data to the CP will detect a loss of the triple redundancy if it should occur. Thus, an attempt is made to assure the highest mission reliability attainable, using the selected redundancy scheme.

Utilization equipment: Table I lists the types of load equipment used in a large transport airplane and typical individual power demand. Heaters use approximately 53 percent of the total power, making them by far the largest single category of user. They are followed by motor loads and lights.

It is recommended that all heavy motor loads (i.e., in excess of 3 Hp) should be powered by other than the electrical system. This applies for any electrical system used, and not for the high voltage dc system alone. The major reason for this recommendation is the characteristically high motor inrush current on starting. As an example, values up to 15 times the nominal rating are not exceptional. This high inrush current penalizes the system since a design allowance has to be allotted. Furthermore, the high inrush current will generally require parallel channel operation for at lest the startup duration. Parallel channel operation is not recommended as a normal operating mode, and should be avoided by removal of the heavy motor loads. Heavy pumps are prime examples of such loads. They should be supplied by the hydraulic system as noted in table I. A secondary reason for prohibiting electrical supply of heavy rating motors is related to the brushless dc motor (BDCM): at heavy ratings, motors will operate in a speed range where BDCMs offer no weight advantage.

TABLE I.--TYPICAL ELECTRICAL LOADS FOR A LARGE TRANSPORT AIRPLANE

Item	Quantity	Watts	kW
Motors			
Heavy Pumps	2	15,000 (hydraulic)	-
Fuel Pumps	8	750	6
Env. Control	4	2,000	8
Fans	50	100	5
Miscellaneous	4	500	2
		Subtotal kW	21
Actuators			
Solenoids	50	30-200	6
Relays	30	10-50	1
		Subtotal kW	7
Heaters			
Galley	5	10,000	50
Env. Control	5	1,200	6
Miscellaneous	60	300	18
		Subtotal kW	74
Lights			
Exterior	10	500-2000	5
Interior	200	10-200	15
		Subtotal kW	20
Electronics			
Analog	80	15-200	8
Digital	80	5-400	6
		Subtotal kW	14
Distribution and Conversion Losses			4
		Subtotal kW	4
		GRAND TOTAL kW =	140

The electronics loads require the highest power quality of all the categories listed in table I. These loads, and also part of the lighting loads (the incandescent lights) require low voltage, closely regulated power. Power conversion will be performed by dc choppers. It is necessary for only 15 percent (approximately 20 kW) of all connected loads. The remaining 85 percent, which includes motors, heaters, actuators and fluorescent lighting will be powered directly from a 300 Vdc supply.

Advantages and disadvantages.--The high voltage dc (HVDC) system was selected because it was found superior to other systems by the criteria for reliability, cost, weight and maintainability. It was considered second best to the VSCF cycloconverter system for performance, and second to the present day (CSCF) system for initial cost. The advantages and disadvantages of the high voltage dc system are now briefly discussed, using the significant evaluation characteristics as a reference.

Reliability: The projected failure rates for the HVDC system are less than half of that for the present system and somewhat less than the other systems considered. The reason for this advantage is found in the elimination of the constant speed drive and the use of solid state switchgear.

Cost: The high voltage dc system has the advantage of having the lowest projected installation cost (after the present system) and the lowest projected maintenance cost. In addition, its lower weight implies a reduction in operating costs as well as in maintenance. On the other hand, the development risk for the HVDC system is high in the important areas of high voltage breakers and brushless dc motors. This undoubted development cost disadvantage is offset by the large gains expected in operating cost reduction.

Weight: The total weight savings accomplished by use of the HVDC system constitutes a great advantage over the present and other systems. This is so, even when a weight penalty for the brushless dc motor is assessed against the HVDC system.

Maintainability: Implementation of the HVDC system is expected to cut maintenance time by approximately 50 percent as compared with the present system. The reason for this advantage is primarily due to the elimination of the constant speed drive which considerably reduces maintenance time. The multiplexing of control and status signals and the use of solid-state switchgear, also allows grouping of black boxes for easy accessibility and, therefore, easier maintenance. At the higher voltage levels selected, (300 Vdc versus 115 Vac) extra caution is required in handling and replacement of live circuits.

Performance: Transmission frequency related problems and restrictions are eliminated. On the other hand, transient voltage excursion is likely to be significantly greater. Overall system efficiency will be improved due to the absence of reactive losses.

Effort And Technology Improvements Required for Acquisition of the Recommended System

Resolution of significant research and technology problems is required for the future advanced electrical system. These are identified in the areas of components, power conversion, load equipment, subsystems and the overall system.

Components.--High voltage, high current dc switchgears are required for future high voltage dc system. The area of investigation and research should include the following:

- Oil filled mechanical circuit breakers for source and bus switching applications
- Sealed circuit breakers with magnetic blowout provision for fault current interruption
- Further research on practical application for the self healing fuse.
- Failsafe solid state switchgear. Present day solid state switches require series fuse for failsafe operation.
- Gate turnoff type switches. These are presently limited to signal level capabilities.
- Improvements necessary for small lightweight commutating capacitors for thyristor turn-off.
- Development of high voltage components such as solenoids, relays, drivers, connectors, indicators.

Power conversion and load equipment.--High power and high voltage dc transmission lead to the following areas of required development:

- High efficiency converters, high voltage to low voltage, both direct chopper type and high frequency transformers for input/output isolation.
- Design criteria for solid state switches, compatible with various load devices such as solenoids, actuators, motors, heating and lighting loads.
- Brushless dc motors with capacity up to 20 hp.
- High voltage (e.g., up to 30 Vdc) digital logic circuits.

Subsystems.--Effort is required to develop the integrated management subsystem, consisting of signal multiplexing and solid-state switching, failure prediction and detection, load management and information display. The effort

should include (a) component interface problems (b) design tradeoffs (c) development of computer software (d) test and evaluation of system performance (e) data analysis and correlation for the failure prediction and detection subsystem, etc. Ground support equipment for 300 Vdc systems also needs to be developed.

Overall electrical system.--To implement the advanced electrical system concept, it is desirable to study the overall system static and dynamic characteristics. The study should investigate the interface problems among the subsystems; the EMI and transient characteristics; the coordination of specification requirements; the cost effectiveness tradeoffs, etc. Two special areas requiring system study effort are:

- Mathematical models of dynamic characteristics of generators, switchgear, power conversion units and load equipment.
- Computer simulation of static and dynamic interactions between subsystems and components.

It is also desirable to study the compatibility of an Internal Engine Generator (IEG) with a high voltage dc system. If compatible, the combined concepts should result in a considerable advance for aircraft electrical systems.

Comparison Of Candidate Power Systems

Introduction.--Several candidate power systems were defined, evaluated and compared for relative merit. The selected power system presented earlier is that system judged to have the highest relative merit. Since all possible factors concerning the aircraft electrical power systems could not be covered in equal depth, it was found necessary to first define the significant characteristics or factors. These only, were in depth. The next step was the assignment of relative merit (or weighting) to the significant characteristics. Finally, the candidate systems were evaluated, composed and a system selected. The methods and results are now discussed in the following subsections.

Significant characteristics and relative merit.--The significant system characteristics were held to be those that imply system worth and effectiveness. This is simply cost effectiveness.

The significant characteristics are:

(a) Reliability

(b) Cost

(c) Weight

(d) Maintainability

(e) Performance

These characteristics were selected from an examination of the system design process, and are illustrated in fig. 8. In addition to the more familiar requirements of performance, reliability, and weight, there are requirements for operability, producibility, and maintainability, all of which contribute to the measure of a systems worth and utilization. These requirements exist within a background of time and cost requirements, which also must be satisfied by the system during the system acquisition period as well as during the system use period.

To achieve the effective design, it is desirable to handle qualitatively and quantitatively all the parameters in the system model. Optimization of the system design will then consist of cost-effective tradeoffs among these parameters.

Reliability: Reliability that an item will perform its intended function for a specified period, under stated conditions. From this definition it can be seen that reliability is closely related to the mean-time-between-failure (MTBF), the reciprocal of which is the failure rate.

Reliability has been receiving increased attention. As the complexity of all kinds of equipment has increased, it has become imperative that reliability be considered a design parameter equal to the importance of functional characteristics. The reliability requirements are usually specified by the customer. In order to meet these specific requirements a reliability program must be employed to include the reliability features in the design and development work.

The reliability of the aircraft electrical power system depends on the reliability of the components. High reliability electrical components are usually accompanied by heavier weight and high cost, which are undesirable for aircraft applications. In order to optimally balance the various requirements, tradeoffs are performed.

Reliability is closely related to the maintainability requirement, as can be seen from the following relation

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

where A_i = inherent availability

MTBF = mean-time-between-failure

MTTR = mean-time-to-repair

From this equation it can be concluded that a highly reliable component, or system, can permit a long downtime and yet attain the availability goal, whereas a component or system with low reliability restricts a minimal downtime. Since the total cost (initial costs and support costs) of a system or component for commercial aircraft application is a very important factor, it would be desirable to know the relationship between reliability and costs. Fig. 9 illustrates a typical curve of total cost vs reliability. It can be seen that

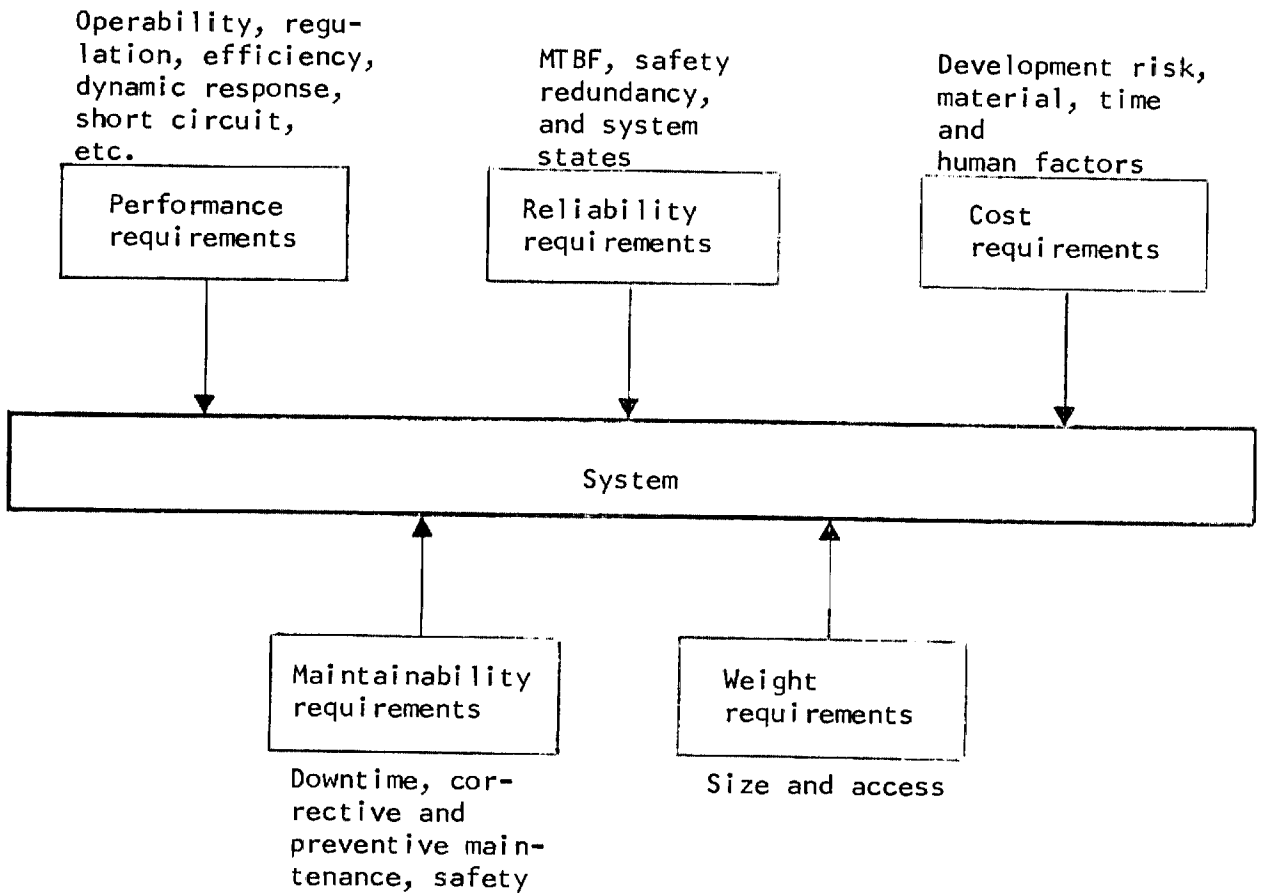


Figure 8. System Significant Characteristics

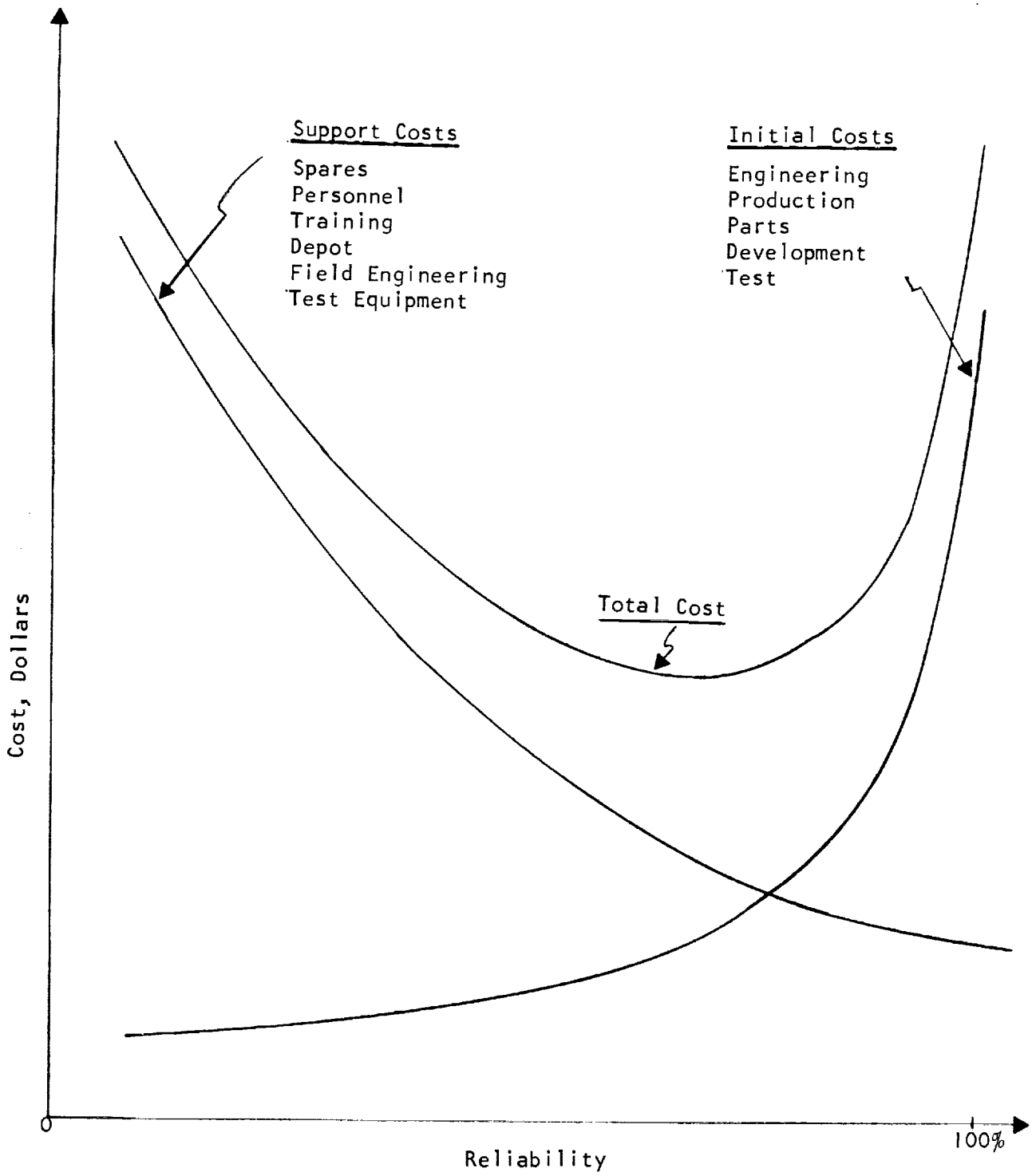


Figure 9. General Trends of Cost Versus Reliability

for relatively low reliability, the support cost is about 5 to 10 times the initial cost. As the design-for-reliability is emphasized, there is reflected a proportional reduction in the support costs. However, there is an optimum point beyond which additional design effort on reliability may not be warranted, since the sharp increase in initial costs will outweigh the reduction in support costs. At this optimum point, the design-for-maintainability becomes an important contributor.

Safety is related to system reliability and is one of the most difficult criteria to indentify and evaluate. There is a general tendency to place an almost infinite value on human life. The proper functioning of the electrical system, which could be thought of as the vital nerve system on an airplane, is therefore of paramount importance. Safety threats caused by the aircraft electrical system from electrical shock, emission of smoke, and actual fire are extremely rare and do not directly jeopardize human life. A number of safety regulations and requirements, however, specify a minimum standard for the prevention of potential hazards which may be caused by the electrical system. These are mainly in connection with maintenance personnel.

A highly reliable system will also be a safer system. Safety also is influenced partly by maintainability and, to a smaller degree, by operability. The number of airplane crashes that have been attributed to component failure (all systems) are approximately 30 percent. There are approximately 2.7 accidents during every one million flight hours. One of the main design requirements, therefore, should be a maximum effort to minimize crash probability. In doing so, even important economic considerations should not be or primary importance in the decision process. For this reason, safety itself should not be subject to a tradeoff evaluation. Safety may reflect its requirements under reliability, maintainability, or operability (performance) categories. It is estimated that the effectiveness could be distributed as follows:

(a)	Reliability	60 percent
(b)	Maintainability	30 percent
(c)	Operability (performance)	10 percent

Cost: Cost is an element of value that is expended to secure a greater benefit. Cost is a negative benefit. Economics give particular attention to money simply because it is the common denominator our society uses to measure the relative value of material things. Included in the cost factor are the elements of acquiring the system and maintaining it. Factors in system acquisition are development risk, material cost and time. A poor maintainability design can easily result in system costs greatly exceeding the acquisition cost.

Weight: One of the most important factors for all airborne application is equipment weight. Experience shows that each additional pound of equipment requires 2.3 to 4.5 kg (5 to 10 lb) additional weight in airplane structure, propulsion engines, and fuel. This varies with type, size, equipment location, and aircraft mission. Economically stated, decreased equipment weight increases payload. Since many methods and approaches for deriving these cost-determining

parameters are in use, no unanimous agreement on the exact weight saving value in equipment has been reached. It appears, however, that an additional 50-dollar investment can be justified for each pound of aircraft weight saved. Thus, each point of equipment weight saved may be worth as much as 500 dollars.

Because of the high value of weights, it is sometimes justifiable to sacrifice equipment life in exchange for weight, as long as safety is not reduced. As with equipment life, other cost affecting factors, such as equipment size, performance, availability, operability, maintainability, etc., may be mutually exchanged with weight to obtain the highest economy or yield maximum profit. The weight factor is made up of three parts. These are: basic equipment weight, installed equipment weight, and system flight weight.

(1) Basic equipment weight: The weight characteristics of electrical equipment are derived from the weights of its constituent parts. The assembly weight may vary for the same amount of power required to operate it, depending on design, type of current, voltage level, frequency range, and environmental conditions. The basic weight of the assembly is obtained by adding the weight of the electrical parts (motors, relays, switches, etc.) and the mechanical parts (drive, reduction gear, actuator, pump, etc.).

(2) Installed equipment weight: This includes the increase in weight due to the following requirements:

(a) Weight of external equipment serving the assembly; these are control equipment, connectors, fuses, circuit breakers, etc.

(b) Weight of conductors to feed the assembly; these are installation accessories, conduits, cable clamps, etc.

(c) Weight of structures to mount the assembly (brackets, etc.)

(d) Weight of the electrical power source; this includes constant speed drive, generator, and all power conversion equipment (TR-units, choppers, batteries, and all cooling equipment necessary for the operation of the power supplies).

(3) System flight weight: The electrical system flight weight includes all additional weights that are brought about by and unavoidably connected with the electrical system installation and operation. This includes all additional weights of the aircraft engine and airframe as well as fuel and lubricant resulting from the bleeding of power from the engine for driving the generators.

The method of computation used for system flight weight is discussed in Appendix A. An example of its use is given.

Maintainability: The definition adopted by the Department of Defense is that "Maintainability is a characteristic of design and installation that is expressed as the probability that an item will conform to specified conditions within a given period of time when maintenance action is performed in accordance with prescribed procedures and resources." This definition indicates that

maintainability is one of the two major design characteristics contributing to system availability. The other characteristics is reliability and the relationship between them has been described before under "Reliability."

In many systems designed without consideration of maintainability characteristics, the maintenance costs over the life span of the system often greatly exceed the original acquisition cost. This ratio can usually be reduced by maintainability design and adequate maintenance planning, the costs of which are more than justified. It can be concluded, therefore, that the design for maintainability serves two major purposes:

(1) When a desired degree of availability (and hence system readiness) for a given system to be developed cannot be achieved by incorporation of reliability in its design, it can be obtained only by increased emphasis on maintainability characteristics.

(2) The maintainability features, when designed into the system with a proper design in reliability, may reduce the total cost (initial cost plus support cost) to a minimum. This is illustrated in fig. 9.

To assure the best design for maintainability the designer should be provided a maintainability guideline prior to the start of the design phase. The guideline identifies the considerations that should be incorporated into the design and reveals the interfaces and tradeoffs that should be considered. The guideline may include:

(1) Minimize the need for support

(2) Minimize downtime

(3) Minimize support cost

(4) Minimize the complexity of support

(5) Minimize support personnel requirements

(6) Minimize maintenance error

(7) Maximize the efficiency and economy of system development.

Performance: Performance requirements of aircraft electrical systems have been specified in a number of military documents (MIL-STD-704, MIL-E-23001, MIL-G-6099, etc.). These requirements stipulate a minimum level of power quality to which the system under evaluation must conform. In practice the capability of most systems will exceed several of the specified minimum requirements. Therefore, the performance characteristics of one system in any particular area can be readily compared to the corresponding characteristic of the other system.

System performance factors which were compared are:

- Steady state voltage variation
- Steady state frequency variation
- Transient voltage and frequency excursions
- Efficiency
- Filtering requirements
- Parallel operation ability

Since frequency-related performance factors are not applicable to a dc system, this would represent an advantage for a dc system. The first four performance factors are self explanatory. Filtering is performed, in ac systems, to improve waveform and reduce conducted EMI. For dc systems, filters are used for suppression of ripple as well as EMI. Parallel operation ability is a performance factor of considerable importance-particularly for ac systems where real and reactive load division occurs.

Relative merit assignment.--The relative merit assigned to each significant characteristic is given in table 2.

TABLE 2.--RELATIVE MERIT ASSIGNED

Characteristic	Merit, Percent
Reliability	30
Cost	24
Weight	20
Maintainability	20
Performance	6
Total	100

The relative merits of Table 2 above were used in computing the merit of the systems for comparison, and presented later in this section (system evaluation). However, the relative merits assigned were arrived at by a mixture of industry reference and judgment based on years of observation. The following indicates highlights of the assignment process:

In Krachmalnick's paper, "Fly-by-Wire Primary Flight Control Systems for Advanced Fighter Aircraft" (ref. 1), the following weighting factors were used:

Handling qualities	20
Flight reliability	18
Mission reliability	12
Weight	10
Survivability	10
Maintenance	9
Volume	8
Cost	7
AGE	6

Reliability is considered the most important factor (handling qualities do not apply in this case) because (1) the reliability of the electrical power system has certain impact on aircraft safety (2) it affects both maintenance and availability and therefore is related to maintenance and operating costs. While cost is relatively unimportant for a military aircraft system, it is more important for a commercial aircraft system where revenue is the main goal. The relative significance of weight and maintainability are approximately equal. Performance of the electrical power system, as long as it meets a certain standard has little impact to the system merit. It is considered to be the least important of the evaluation characteristics.

An airframe manufacturer revealed that one pound of weight for a subsonic transport is equivalent to 160 dollars of initial cost. For the candidate systems selected for comparison, the average total weight and total initial cost (based on the components under considerations) are approximately 1100 kg (2400 lb) and 460,000 dollars, respectively. Since 1100 kg weight is equivalent to 384,000 dollars of the initial cost, it indicates that the weight factor is approximately 0.84 (384/460 = 0.84) times as important as the cost factor.

Maintenance costs over the life of a commercial transport aircraft come to about twice the original purchase price (ref. 3). Assuming a 15-year life for the aircraft, the maintenance cost spent during the life is equivalent to 1.3 times the initial cost. Since the maintenance cost consists of approximately 33 percent of the labor cost and 67 percent of the material cost (ref. 4), the maintainability factor is 0.43 (1.3 x 0.33) times as important as the cost factor. It should be noted, however, that maintainability also reflects a certain amount of operating cost, because it is related to availability. This suggests that the 0.43 factor should be adjusted upward. A reasonable approach is to double the figure.

There is no reasonable and straightforward way to relate reliability and performance to cost. By judgment, it was considered that they should be approximately 1.2 and 0.3 times as important as the cost factor. Using the above rationale as a guide, the relative weighting factors for the various evaluation characteristics were assigned as follows.

Reliability	30
Cost	24
Weight	20
Maintainability	20
Performance	6

Evaluation methods.-- A simplified model of each of the candidate systems was used for evaluation. This was found necessary in order to be able to apply reasonable merit ratings for each system characteristic without encountering a massive statistical task of questionable value.

The simplified models used, while admittedly limited, are nonetheless considered to be a practical basis for comparison at this time.

Simplified model: The model was established on a per channel basis and included the major components in the power generation and distribution subsystems. In the aircraft electrical power system, a number of components are common to all candidate systems. These common components were disregarded in the evaluation process since they cancel when compared one against the other. The utilization devices were not considered for evaluation purposes since they are common to all candidate systems. However, where the candidate system significantly affected the characteristics of the utilization equipment (a variable frequency system, for instance, will impose considerable weight penalty on motor loads), the effect was taken into consideration.

A simplified model which depicts a typical existing system is shown in fig. 10. It should be noted that in a conventional system, no centralized transformer and power converter are used for lighting and electronic loads respectively. In the evaluation process, therefore, the equivalent characteristics were considered. In calculating the system weight, for example, the power converter weight should be the sum of the weight of the power conditioning devices within the individual electronic equipment. When all other candidate systems were selected, functional diagrams similar to the one shown above were used for system evaluation.

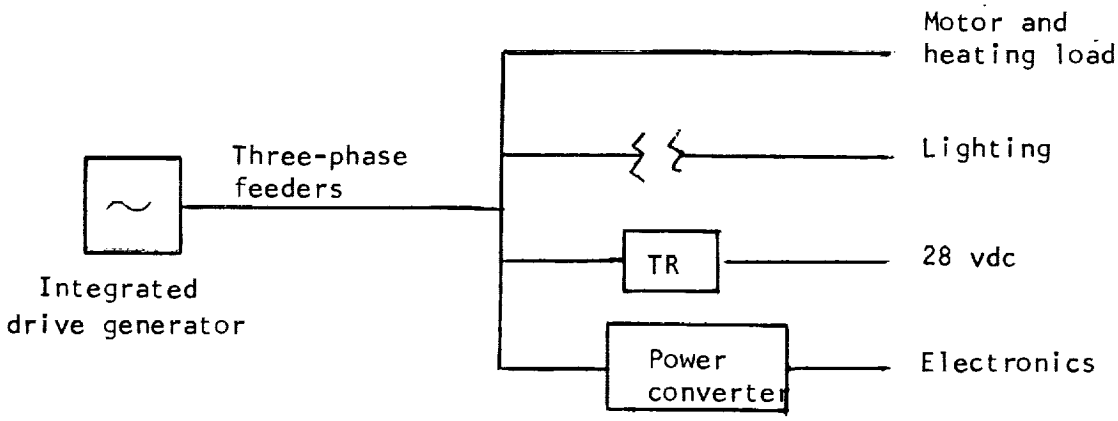


Figure 10. Typical Existing Aircraft Electric Power System

Evaluation factors: As described earlier, the factors used in the evaluation were (1) reliability, (2) cost, (3) weight, (4) maintainability, and (5) performance. The mathematical expressions for all these factors are now presented.

Reliability: Since the function of the aircraft electrical power system is to supply electrical power to the various loads, a reasonable definition is the "probability that the system can successfully supply power to all types of load on a per channel basis." By using the conventional system as an example, the following relation was obtained.

$$P_S = P_G P_T P_{TR} P_C$$

where P_S = probability that the system is operative during the mission

P_G = probability that IDG is operative during the mission

P_T = probability that transformer is operative during mission

P_{TR} = probability that transformer rectifier unit is operative during the mission

P_C = probability that converter is operative during the mission

In general

$$P_S = \prod_{i=1}^{n} P_i = e^{-\left(\sum_{i=1}^{n} \lambda_i\right)t}$$

where P_i = probability that the i-th component in the system is operative during the mission

n = total number of related components in the system

λ_i = failure rate of the i-th component in the system in failures/hour

t = mission time in hours

As described previously, the conventional system does not use a centralized transformer and converter for all lighting and electronic loads respectively. Under this condition, the failure rate values for the transformer and the converter are equivalent values derived from failure rate values of transformers and power conversion devices used in the individual load equipments.

(2) Cost: The system cost as evaluated in this study was taken to be the total acquisition cost plus equivalent total operation cost (operation cost converted to the time when the system is acquired) of the system on a single channel basis.

$$C_T = \sum_{j=1}^{n} \left(C_{aj} + C_{oj}\right) = \sum_{j=1}^{n} \left[C_{aj} + \sum_{k=1}^{m} \frac{C_{ojk}}{(1+i)^k}\right]$$

where C_T = total cost of the system

C_{aj} = total acquisition cost of the j^{th} component in the system

C_{oj} = equivalent total operation cost of the j^{th} compoent in the system

n = number of related components in the system

C_{ojk} = operation cost per year of the j^{th} component in the system for the k^{th} year

i = annual interest rate

m = system life in years

(3) Weight: The total system weight was calculated by using the functional diagram as a guide. Due to the system characteristics, weight savings or penalties in the components which are normally excluded from the weight calculation were taken into account. The following is the mathematical expression used for weight evaluation.

$$W_T = \sum_{i=1}^{n} W_i$$

where W_T = total effective weight of the system

W_i = weight of the i-th component in the system in pounds

n = total number of major components in the system

(3) Maintainability: Maintainability of the system was defined as the total maintenance hours per flight hour of the system on a single channel basis.

$$TMY = \sum_{i=1}^{n} \left(N_i \times MTTR_i\right)$$

where TMH = total maintenance hours of the system per flight hour

N_i = number of maintenance actions/flight hr of the i^{th} component in the system

$MTTR_i$ = mean time to repair in hours of the i^{th} component in the system

n = total number of related components in the system

If MTTR in the equation is replaced by mean maintenance man-hours, the total maintenance man-hours per flight hour can be calculated. This value is directly related to maintenance cost.

(5) Performance: The overall system performance was evaluated according to the factors noted earlier. For review, these are a) Steady state voltage variation, b) steady state frequency variation, c) Transient voltage and frequency excursions, d) Efficiency, e) Filtering requirements, and f) Ability to operate in parallel. It should be noted that the candidate systems include ac, dc and hybrid systems. A quantitative performance evaluation was considered to be out of the question. Except for efficiency - which directly affects overall aircraft weight and cost - performance factors in excess of specification requirements have little direct impact on system merit. The important of each of these factors is, however, a function of user equipment desires. For this reason, relative judgements were made based upon a hypothetical "user equipment" point-of-view.

System figure of merit: Each system figure of merit was determined by use of a weighted factor method as follows:

$$FM = \alpha_1 R + \alpha_2 W + \alpha_3 M + \alpha_4 C + \alpha_5 P$$

where FM = figure of merit

α_1 through α_5 = weighting factors

R = relative value for system reliability

W = relative value for system weight

M = relative value for system maintainability

C = relative value for system cost

P = relative value for system performance

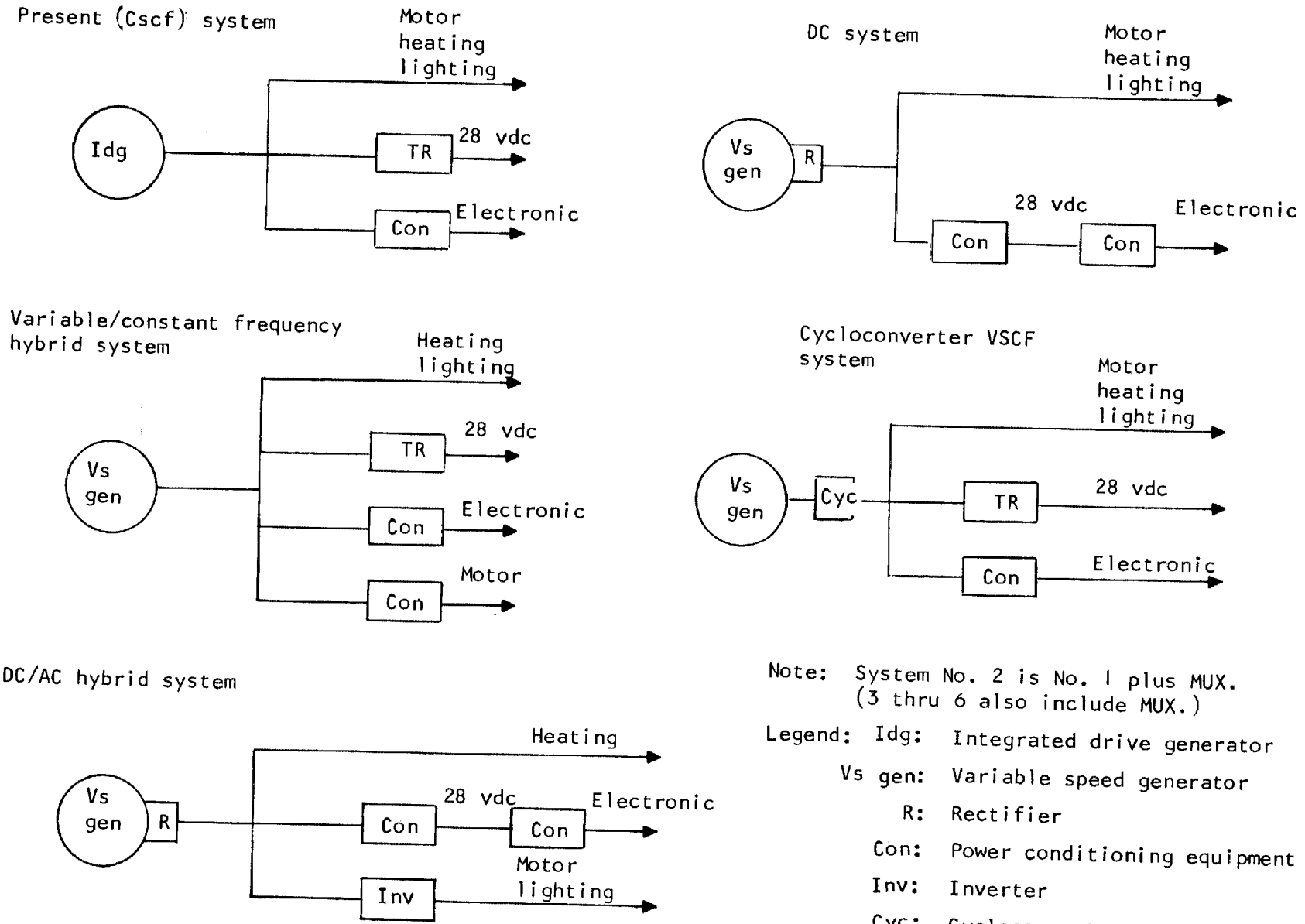
The relative values were obtained by comparing the real values of the characteristic factors of the candidate systems. A value of unity was assigned to the best system for a given characteristic under consideration while the relative values of other systems were calculated proportionally. α_1 through α_5 are all positive. The system which had the largest FM value was considered the best system. A short discussion of system worth and the 'cost basis' method used as an alternate is presented in Appendix B.

Candidate system description.--Using the constraints of acceptable development risk and no inherent safety hazard, five (5) candidate systems were defined. Figure II shows the system configurations.

Except for the conventional system (I), all candidate systems use the remote power control and multiplexing concept. Therefore it is not shown in figure II. Solidstate power controllers are used for load control while remote control circuit breakers are used for bus and feeders. The main power center is located near the electrical center of the aircraft. This is contrasted with the present situation for the conventional system usage where the power control is near the flight deck.

The following is a brief description of the candidate systems with reference to fig. II.

Present (CSCF) system (I): This is the conventional constant speed-constant frequency system. A hydraulic, constant speed drive is placed between the accessory pad and the electrical generator so that constant frequency ac power can be generated. The 400 Hz, 115/200 vac power is transmitted and distributed to the various loads without the need of power conversion. The main ac channels are usually connected for either split parallel or all parallel operations. The power is obtained by using a transformer rectifier unit in each channel.



Note: System No. 2 is No. 1 plus MUX.
(3 thru 6 also include MUX.)

Legend:
- Idg: Integrated drive generator
- Vs gen: Variable speed generator
- R: Rectifier
- Con: Power conditioning equipment
- Inv: Inverter
- Cyc: Cycloconverter
- Cscf: Constant speed const. freq.

Figure II. Candidate System Configurations

A circuit diagram of the present system is shown in fig. 12. When remote power control is added to the present conventional (CSCF) system it becomes another system (2) for evaluation. The circuit diagram is the same as for the present (CSCF) system in fig. 12.

Variable speed, variable frequency/constant frequency hybrid system (3): In this system, variable (i.e., "wild") frequency is supplied to the heating and lighting loads. Constant frequency is supplied to the motor loads. The arrangement is shown schematically in fig. 13.

Although motors can be designed to operate on variable frequency input power, it is estimated that the average weight of the variable frequency motor is 3 times heavier than the constant frequency counterpart. For this reason, 400 Hz ac power is provided for motor loads. This is accomplished by rectifying approximately half of the generated power to dc and then inverting to ac power. The input power of the frequency changer is 115/200 v, 3-Ø , 400 Hz ac which can be paralleled or cross-strapped after failure. 28 vdc power is obtained by using a T/R unit.

Dc/ac hybrid system (4): In the dc/ac hybrid system, power is rectified to dc before it is transmitted to the load center. The rectifier is an integral part of the generator package and power is generated in a manner similar to system (3). Fig. 14 is a schematic of the system. High voltage dc transmission is set at 300 v to optimize wiring and distribution weight. The heating loads, which represent approximately 53 percent of the total can utilize high voltage dc power. The low voltage loads are provided by dc-dc converter.

Constant frequency ac is provided to the motor loads by quasi-square-wave inverters.

Dc system (5): This sytem is identical to the dc/ac hybrid except that there are no inverters used and no ac loads. All loads, including motor loads use dc power. The configuration is shown in fig. 15. In order to realize this configuration brushless dc motors are required.

Cycloconverter VSCF system (6): Variable frequency generated ac power is directly converted to constant frequency power by use of a cycloconverter. Generator frequency varies between 1.2 kHz and 2.4 kHz in order to obtain the 400 Hz power at the cycloconverter output.

From the output of the cycloconverter and looking at the loads, the system looks like the present system plus the MUX with both ac and dc loads. The configuration is shown in fig. 16.

Candidate system evaluation.--The six candidate systems were evaluated using the guidelines stated earlier. The reliability and cost evaluations were both conducted with respect to the systems divided as follows: Constant speed drive (where applicable), generator, power conversion (high and low voltage), motor power conditioning, electronics power conditioning, switchgear.

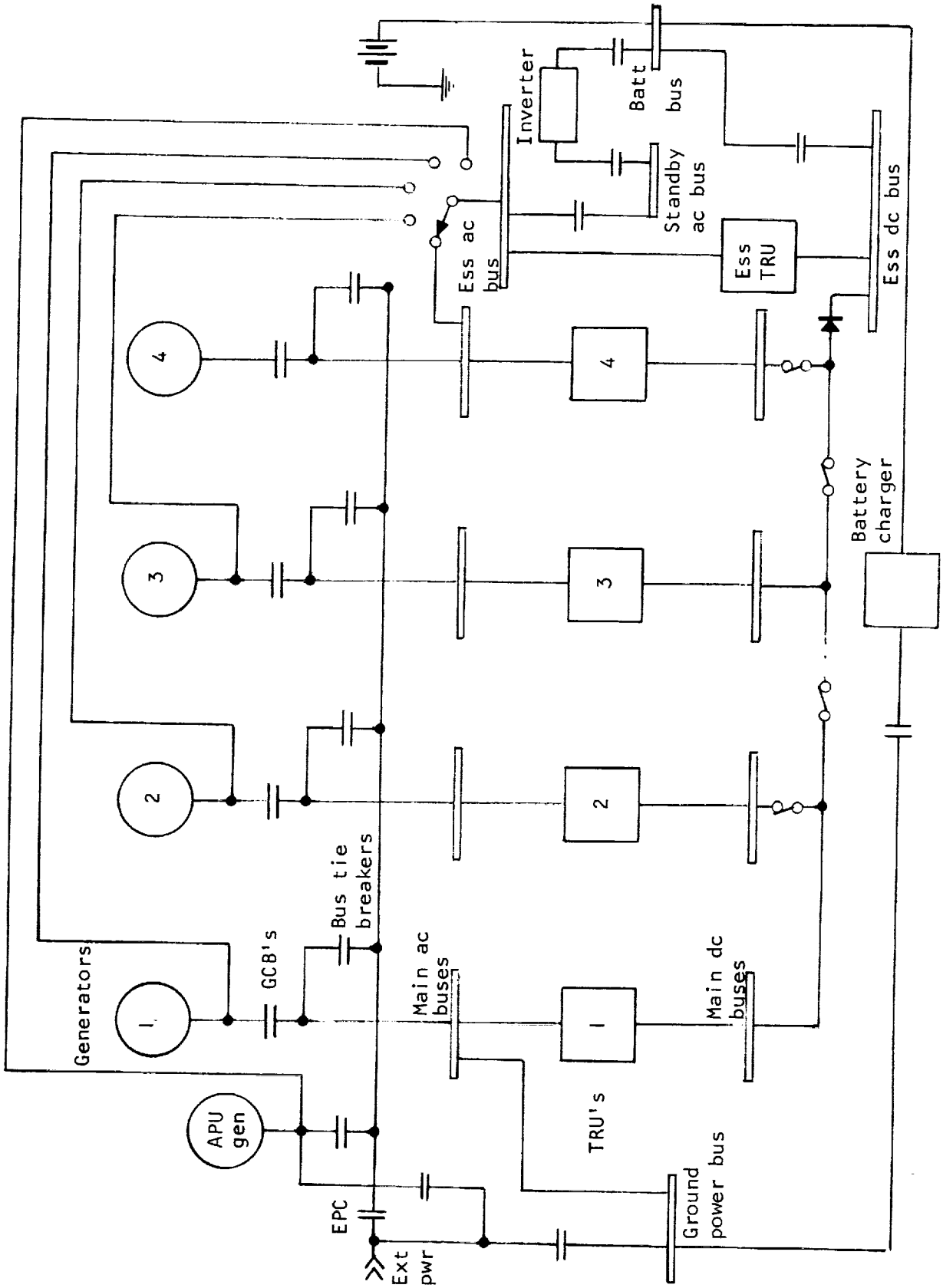


Figure 12. Present (CSCF) System

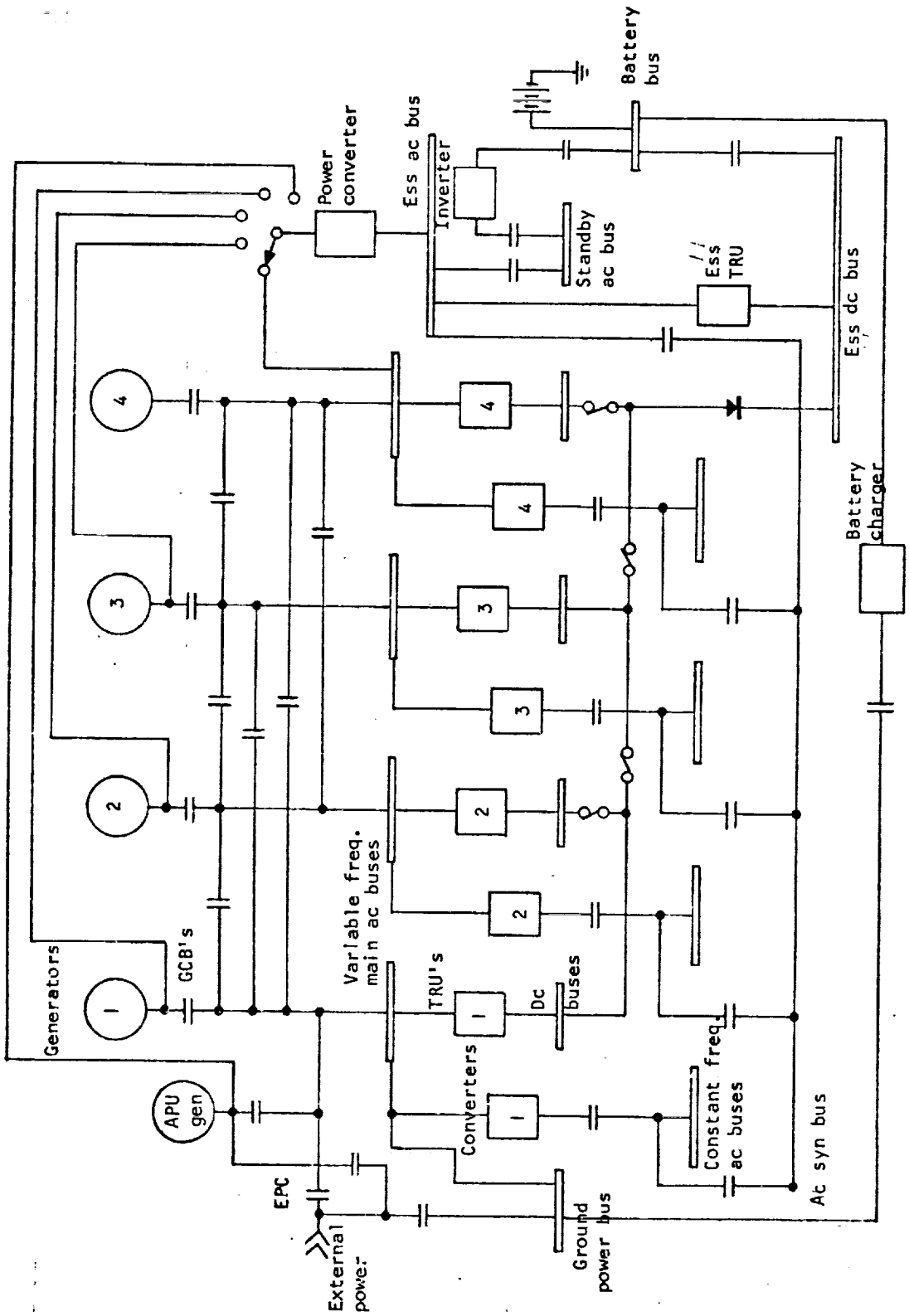


Figure 13. Variable/Constant Frequency Hybrid System

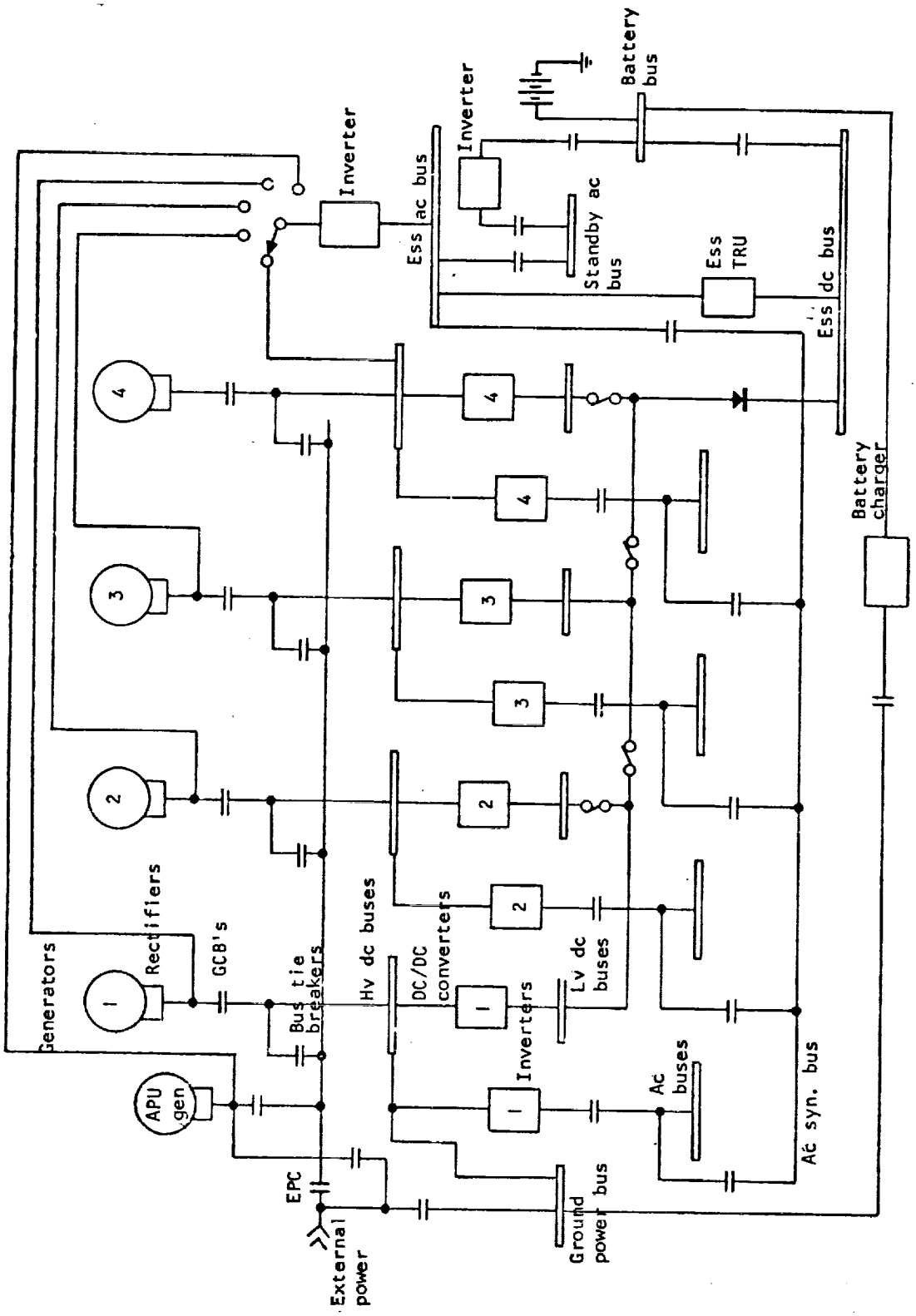


Figure 14. DC/AC Hybrid System

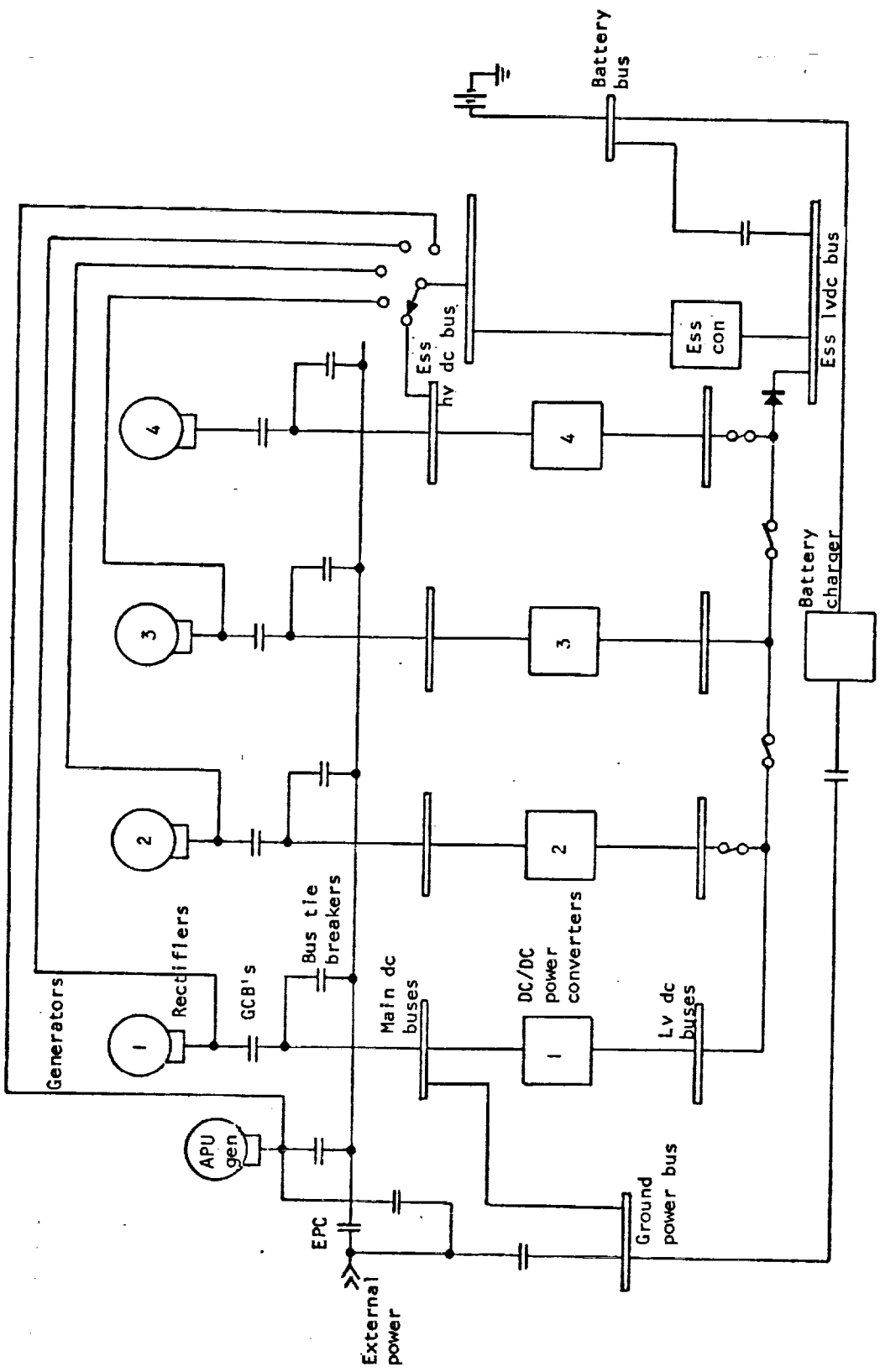


Figure 15. DC System

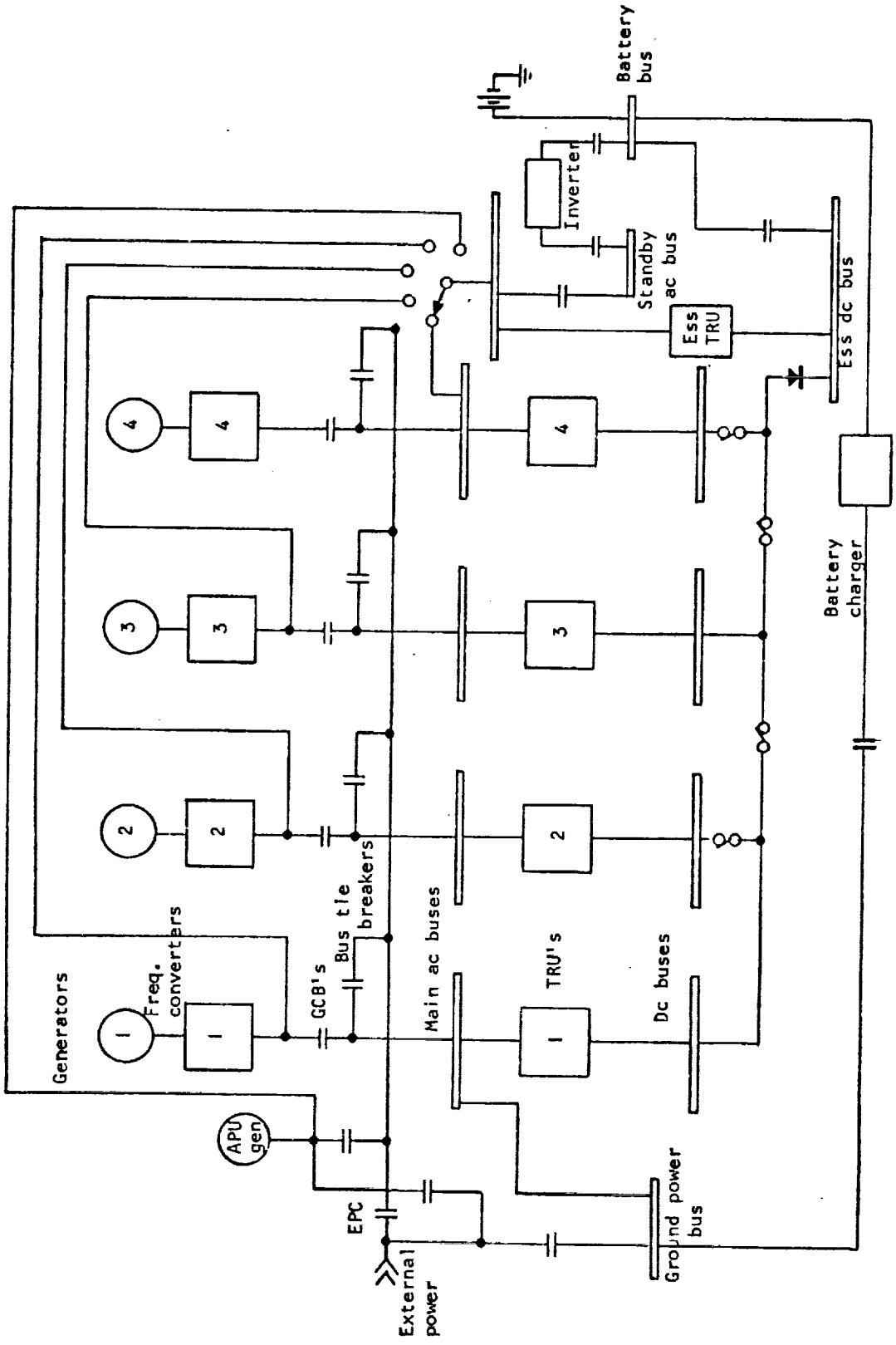


Figure 16. VSCF (Cycloconverter) System

Reliability comparison: Table 3 lists a reliability comparison in terms of failures per 10^6 hr. The failure rate data used are mostly those published by FARADA (Navy Failure Rate Data Center, ref. 5). Reliability data quoted by the manufacturer were generally not used in this study because of the extreme differences in reported data.

In comparison for each evaluation factor, relative numbers representing the merit of each candidate system were established. By using these numbers (relative rating numbers in table 3) in conjunction with the weighting factors, the overall figure of merit was calculated for each candidate system.

Cost comparison: Table 4 presents a cost comparison of the six candidate systems. These are the estimated acquisition costs after development. Operating cost and development costs are separate contributors to system costs and represent different phases. The phases are:

(1) Development

(2) Acquisition

(3) Operation

(1) Development and operation: The present system requires no development. However, the alternative systems all do require development to some extent. These are now discussed one at a time.

(a) Advanced CSCF System: The CSCF system incorporating the advanced load management system requires the development of signal multiplexing and solid state power controllers. LTV has been working on the advanced management system for many years and the system has been implemented for the A-7 aircraft. Development work on the solid state controllers and remote control circuit breakers (RCCB) is also being done in the industry and military services. Since the power generation is of the conventional type and requires no development effort, this system has the least development risk.

(b) VSCF Cycloconverter and Hybrid Systems: The cycloconverter VSCF system and the variable/constant frequency hybrid system each require more development effort than the CSCF system. In addition to the advanced management system, power conversion equipment have to be developed. G.E. has been developing the frequency changer for years and the system has been tested on the aircraft such as the Boeing 707-320 and the Navy S3A. The variable frequency generation has been used in aircraft such as the Canadian DHC-5, Gulfstream II, etc., however, the capacity of the inverters used in the system is relatively low. These systems have not been fully approved by the industry. More development effort is required.

(c) Dc/ac hybrid system: This system is similar to the VSCF dc-link. The difference is that the former inverts only a part of the dc power into

TABLE 3.--RELIABILITY COMPARISON (FAILURES PER 10^6 HOURS)

	Present System	Present Plus MUX	Var/Const Freq Hybrid	Dc/ac Hybrid	Dc	VSCF Cyclo
Constant speed drive	590	590	-	-	-	-
Generator	220	220	220	220	220	220
Power conversion	-	-	-	12	12	100
Power conversion for LV dc	18	18	22	44	44	18
Power conditioning for motor	-	-	75	50	-	-
Power conditioning for electronics	180	180	180	160	160	160
Switchgear	675	295	307	307	295	295
Total	1683	1303	804	793	721	793
Relative rating*	0.43	0.56	0.91	0.92	1	0.92

*For use with merit weighting factor

TABLE 4.--COST COMPARISON ($1000)

	Present	Present Plus MUX	Var/Const Freq Hybrid	Dc/ac Hybrid	Dc	VSCF Cyclo
Constant speed drive	25.0	25.0	-	-	-	-
Generator	2.5	2.5	3.5	4.0	4.0	4.0
Power conversion	-	-	-	1.5	1.5	30.0
Power conversion for LV dc	1.0	1.0	2.5	5.0	5.0	1.0
Power conditioning for motor	-	-	15.0	13.0	-	-
Power conditioning for electronics	50.0	50.0	50.0	45.0	45.0	45.0
Switchgear	10.0	45.0	48.0	53.0	50.0	45.0
Total	88.5	123.5	119.0	121.0	105.5	125.0
Relative rating	1	0.72	0.74	0.73	0.84	0.71

ac power and high voltage dc power is used for certain loads. Westinghouse and other companies have worked on the inverter for a number of years. Due to the lack of available state of the art high voltage/high current dc circuit breakers, little development effort has been devoted to a high voltage distribution system. The Navy has performed studies of a high voltage dc system (refs. 6 and 7), and Martin Marietta Co. is under NASA contract (NAS3-15824) for a feasibility study of 15 A, 300 vdc circuit breakers. The dc/ac hybrid system was judged to have a higher development risk than the previously discussed systems.

(d) Dc system: This system is considered to have the highest development risk. In addition to a power control problem, development of the brushless dc motor is required before the system can be implemented. The development in BDCMS at present is limited to fractional horsepower ratings and the weight and cost of the unit is not competitive with the induction motor. Development of high power BDCMs requires a considerable amount of effort in both permanent magnetic materials, motor design and fabrication. It is however, considered feasible on the basis of projected trends in technology.

Table 5 presents the development ratings. The number 1 is the highest rating which, in this case, applies to the present system which needs no development. Although the results of this table were not used directly in either the cost comparison of table 4, or in the final system comparison of table 9, it represents a background to the system selection and can not be ignored. Development costs, at this point in time, are largely conjectural. Material breakthroughs may greatly decrease any such cost estimates by an order of magnitude. They were therefore not included as such in the cost comparison of table 4.

Aircraft operating cost includes (1) maintenance cost (labors, materials) (2) capital cost (depreciation, interest) and (3) flying cost (crew salaries, landing changes, insurance, fuel) (ref. 4). Except for the maintenance cost and a part of the operating cost related to availability (function of reliability and maintainability) and weight (impact on fuel cost), the remaining operating cost is relatively insensitive to the system type.

Since weight, reliability and maintainability are already included as evaluation characteristics in the system comparison, it is appropriate to exclude the operating cost.

(2) Estimated unit acquisition costs: The estimated costs of table 4 were based on:

- Generator and CSD costs and estimates supplyed by Westinghouse
- Power conversion and conditioning equipment estimates in a current NASA sponsored study (ref. 8)
- Switchgear and conditioning for electronics surveys in trade and technical magazines, and company experience

TABLE 5.--COMPARISON OF DEVELOPMENT EFFORT

Candidate System	Development Effort Required	Rating
Present system	None	1
Advanced CSCF system	Management system 1. Signal multiplexing 2. RCCB and solid state power controllers	2
Variable/constant frequency hybrid system	Management system Variable speed generator Motor drive inverter	3
Cycloconverter VSCF system	Management system Variable speed generator Frequency changer High frequency feeder	3
Dc/ac hybrid system	Management system Variable speed generator High voltage dc breakers Motor drive inverter Dc/dc power converter High voltage feeder	4
Dc system	Management system Variable speed generator High voltage dc breakers Dc/dc power converter Brushless dc motor High voltage feeder	5

The costs are not precise-particularly where projected systems are concerned. This is because of the intangibles inherent in any future system cost projection. They are regarded as today's best estimate.

Weight comparison: Weight data for the major system components are listed in table 6 on a single channel basis. The system is assumed to be 60 kw per channel. For the constant frequency systems approximately 3 kw ac power are rectified to 28 vdc. For the other 3 candidate systems, 6 kw of generated power is conditioned to dc.

Power converters for motor loads used in the hybrid systems are rated at approximately 30 kw. The distance of power transmission line is assumed to be 136 m (120 ft) for the present system, and 18 m (60 ft) for the other systems due to the relocation of the main power center. For the dc system a weight penalty of 18 kg (40 lb) is added to the system weight due to the use of brushless dc motors. This is derived by calculating the weight penalties (or savings) for a typical group of motor loads (the BDCM curve is compared with the 12000 rpm induction motor curves shown later in the section on components). The relative rating of table 6 is referenced to the lowest projected system weight which is the dc system. The dc system is projected as weighing only approximately 2/3 the present system. This is due to the elimination of the constant speed drive (CSD), an order of magnitude drop in transmission line weight and a similar drastic drop in distribution wiring weight. Even when the BDCM penalty weight of 18 kg (40 lb) is added, the projected savings is still a remarkable 107 kg (234 lb).

Maintainability comparison: Maintainability represents the one major area where operating costs are capable of being greatly reduced. The comparison figures of table 7 for Maintenance Man-Hours per Flight-Hour (MMH/Flt-hr) indicate that implementation of either of four alternate systems would reduce maintenance time by approximately 50 percent. Among the major operators, the U.S. Air Force was considered to be the best source for data. For this reason, the AFM 66-1 data were used to estimate the maintenance man-hours for the existing components (ref. 9). For the components used in the new candidate systems, projected data based on the characteristics of the components were calculated.

Performance comparison: In table 8, the major performance characteristics of the subsystems are compared. This does not include signal multiplexing and control, because except for the present system, these characteristics are common to all those discussed. Where a characteristic does not apply (NA), the maximum rating was given (shown in parenthesis).

Some notable features of table 8 are:

- Voltage regulation of systems using variable speed generators is inferior to that of the constant speed generator. (The cycloconverter is an exception)

TABLE 6.--SYSTEM WEIGHT COMPARISON (KG)

	Present System	Present Plus MUX	VAR/Const Freq Hybrid	Dc/ac Hybrid	Dc	VSCF Cyclo
Constant speed	27	27	-	-	-	-
Generator	20	20	28	28	28	36
Transmission line	54	11	13	6	6	13
Power conversion	-	-	-	9	9	41
Power conversion for LV dc	8	8	11	14	14	8
Power conditioning for motor	-	-	35	31	-	-
Power conditioning for electronics	61	61	61	55	55	55
Switchgear	28	28	35	56	55	28
Distribution wiring	113	79	85	50	20	79
Weight penalty	-	-	-	-	18	-
Total	311	234	269	249	205	260
Relative rating	0.66	0.88	0.76	0.83	1	0.79

Note

* For dc systems approximately twice the power is converted to low voltage dc.

TABLE 7.--MAINTAINABILITY COMPARISON (MMH/FLT HOUR)

	Present	Present Plus MUX	Var/Const Hybrid	Hybrid	Dc	VSCF Cyclo
Constant speed drive	0.024	0.024	-	-	-	-
Generator	0.015	0.015	0.015	0.015	0.015	0.015
Power conversion	-	-	-	0.001	0.001	0.005
Power conversion for Lv dc	0.001	0.001	0.001	0.003	0.003	0.001
Power conditioning for motor	-	-	0.004	0.004	-	-
Power conditioning for electronics	0.010	0.010	0.010	0.010	0.010	0.010
Switchgear	0.045	0.020	0.020	0.020	0.020	0.020
Total	0.095	0.070	0.050	0.053	0.049	0.051
Relative rating	0.52	0.7	0.98	0.98	1.0	0.96

TABLE 8.--PERFORMANCE COMPARISON

	Present	Present Plus MUX	Var/Const Freq Hybrid	Dc/ac Hybrid	Dc	VSCF Cyclo
Steady state voltage, percent	±1 (2)*	±1 (2)	±2 (1)	±2 (1)	±2 (1)	±1 (2)
Steady state frequency, percent	±1 (1)	±1 (1)	NA (2)	NA (2)	NA (2)	NA (2)
Transient voltage excursion, percent 1 PU load	+19 -16.5 (2)	+19 -16.5 (2)	+28.5 -25 (1)	+28.5 -25 (1)	+28.5 -25 (1)	+19 -16.5 (2)
Transient frequency excursion, percent 1 PU load	±2.5 (1)	±2.5 (1)	NA (2)	NA (2)	NA (2)	NA (2)
Efficiency, percent	78 (1)	78 (1)	83 (3)	81 (2)	84 (4)	83 (3)
Filtering requirements	None (3)	None (3)	Medium (2)	Medium (1)	Some (2)	Heavy (1)
Parallel operations	Yes (2)	Yes (2)	No (1)	Yes (2)	Yes (2)	Efficient Operation (3)
Total rating	12	12	12	12	14	15
Relative rating	0.80	0.80	0.80	0.80	0.93	1.0

*Numbers in parentheses are rating points

- Relatively heavy filters are required for all systems except the present (CSCF) and the dc system

- Frequency control is better for all systems except the present (CSCF). The dc system, of course, has no problem at all in this respect

- The present system rates better than two of the alternatives because of filtering requirements

A sum of the numbers assigned in parenthesis produced the total performance rating for each system. The highest number is the best performance. On this basis, the VSCF cycloconverter system rated the best. The dc system was a close second.

System comparison: Table 9 shows the results of taking tables 3 through 8 and applying the relatave ratings to the weighting factors assigned. The dc system is indicated as being the best future system followed by the VSCF cycloconverter system and the dc/ac hybrid. The major gains of the future are seen to be in the important cost effective areas of maintainability and reliability rather than performance. Weight can also be clearly improved against the tradeoff of an increase in initial and development costs.

The dc system approaches the optimum in both maintainability and reliability. It is selected for this reason.

New system developments.--A very recent study effort, while being outside the scope of this study, nonetheless has considerable potential impact on aircraft electrical power systems. This is the Internal Engine Generator (IEG) study undertaken by the Boeing Company and supported by NASA-Langley. The IEG concept consists of locating a generator inside a turbojet or turbofan engine, mounting the rotor directly on the engine high speed shaft. This installation would significantly affect the hydraulic and pneumatic subsystems and engine design, as well as the electrical power system.

Potentially, the following advantages are offered by the IEG:

- Operation of the IEG as an engine startup motor, thereby eliminating the high cost pneumatic start system.

- Elimination of the constant speed drive (CSD)

- Elimination of the engine accessory gearbox, permitting nacelle redesign for a smaller frontal area and less aerodynamic drag.

- A larger amount of mechanical to electrical power conversion at the engine eliminates much hydraulic lines and fittings, allows the use of remote electrical/hydraulic pumps and integrated actuator packages for flight control, and improves maintenance and reliability.

IEG development and studies until now have mostly used a VSCF system concept, however, the use of a high voltage dc generator as an IEG coupled with a dc distribution would greatly increase competitiveness. The combination of high voltage dc system and the IEG promise to produce an outstanding advance in aircraft technology.

TABLE 9.--SYSTEM COMPARISON
(Tabulation of Weighting Factor x Relative Rating)

	Weighting Factor	Present System	Present Plus MUX	Var/const Freq Hybrid	Dc/ac Hybrid	Dc	VSCF Cyclo
Reliability	30	12.9	16.8	27.3	27.6	30.0	27.6
Cost	24	24.0	17.3	17.8	17.5	20.2	17.0
Weight	20	13.2	17.6	15.2	16.6	20.0	15.8
Maintainability	20	10.4	14.0	19.6	18.6	20.0	19.0
Performance	6	4.8	4.8	4.8	4.8	5.6	6.0
Total	100	65.3	70.5	84.7	85.1	95.8	85.6

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POWER SYSTEMS FOR VTOL, V/STOL AIRCRAFT AND AIR-SPACE VEHICLES

VTOL and V/STOL Aircraft

Types of VTOL and V/STOL aircraft.--VTOL aircraft (V/STOL is a combination of VTOL and STOL and is considered a specific type of VTOL) can be classified on the basis of the propulsion system and their means of performing the transition from hovering to cruising flight. There are four basic types of propulsion systems: (1) rotor (2) propeller (3) ducted fan and (4) turbojet. Also there are four basic transition types: (1) aircraft tilting (2) thrust tilting (3) thrust deflection and (4) dual propulsion. A total of 16 VTOL types, therefore, is possible. Out of these 16 possible types, all but the dual-propulsion propeller type have been studied with varying degrees of interest during the past years.

Since shaft power is available on VTOL aircraft and propulsion engines used on VTOL are essentially the same as those used on conventional aircraft, the electrical power generation scheme for VTOL is likely to follow the aircraft system. However, certain factors may affect the selection of the power system configuration. These include:

(1) Range and mission duration

(2) Load profile and requirements

(3) Physical size of the aircraft

(4) Requirements unique to the VTOL

For commercial application the future VTOL and V/STOL transport aircraft can be classified according to the operating range of the aircraft involved. Operating range is usually indicated by such terms as local, feeder line, short-range, medium range and long-range. Table 10 defines the various ranges and shows the types of aircraft which may be used for each operating range.

Characteristics of commercial V/STOL aircraft.--The transport type of V/STOL for commercial applications has a few characteristics which are not common to the conventional aircraft. These include:

(1) For the aircraft used for local and feeder line services, self sufficiency is essential.

(2) Except for high speed V/STOL aircraft, the V/STOL aircraft is usually heavier than the conventional counterpart since the engines must be designed to provide vertical lifting capability. Savings in weight becomes relatively more important.

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TABLE 10.--V/STOL AIRCRAFT CHARACTERISTICS

Category	Operating Range, km	Cruising Speed, kmph	Type of Aircraft
Local	Up to 320	240 to 320	Helicopter such as Boeing Vertol 107 and Sikorsky S-61.
Feeder line	320 to 650	320 to 400	Compound helicopter, Unloaded rotor convertiplane
Short range	650 to 1300	560 to 650	Tilt-wing-and-flap, Tilt-duct and fan-in-wing ducted-fan types, Lifting engine turbojet type.
Medium range	1300 to 3200	650 to 900	Tilt-wing-and-flap propeller type.
Long range	3200 to 5500	1000 or more	Large number of small turbojet or turbofan lifting engines.

(3) For V/STOL aircraft operating at relative low altitude, it is feasible to make the APU flight operational thus the APU generator can also be used as an emergency power source.

(4) For the V/STOL aircraft employing cross shafting, the reliability of the power generation system can be improved since the failure of one engine does not mean loss of one channel.

Candidate systems for VTOL and V/STOL.--

Local and feeder line: Two generation system can be used for these type of aircraft depending on whether the system is equipped with an APU.

(1) Ac/Dc hybrid system: If the system is not equipped with an APU, for self sufficient purposes, the dc starter must be used for engine starting (although engine starting can be achieved by using hydraulic or pneumatic methods, electrical starting is still considered the optimum approach). Since the starter can also be used for dc power generation, the logical approach is to utilize its duel function thus the dc starter/generator is used for dc power generation. For aircraft under this category the power demand is usually more than 15 kva per channel. If the starter/generator is sized for the starting requirement alone, its generating capacity is not able to meet all the power demand and therefore alternators must also be provided. The reasons for employing the ac/dc hybrid system over the dc inverter system (size the starter/generator for the power demand and used the inverter for supplying ac power) are as follows: (a) the brush type dc starter/generator has inferior reliability and maintainability characteristics and relatively short life as compared with the ac generator (b) the dc inverter system is heavier than the hybrid system due to the high specific weight of the inverter. Table 10A shows the weight comparison between the dc inverter system and the hybrid system using hydraulic CSD for constant frequency ac power generation. In order to improve the system reliability, TR units should also be used in the system thus the dc power will not be interrupted in the case of starter/generator failure.

The constant frequency ac power can also be generated by using the VSCF approaches. However, the CSD system is preferred for the following reasons: (a) As mentioned previously weight savings for the V/STOL aircraft is relatively more important. The CSD system is lighter than that of the VSCF system. (b) Due to the relatively short mission duration, continuous operating time is short, and long time reliable operation is not required. The need for elimination of the CSD is less attractive. (c) The CSD system has been used for many yeats. Therefore the total cost of the CSD system is much less than that of the VSCF system.

(2) Constant frequency Ac system: If APU is equipped for engine starting the starter/generator can be eliminated. In this case ac generation should be used and dc power can be provided by using the TR unit. For the same reasons stated previously, the CSCF system is considered a better approach.

TABLE 10A.--WEIGHT COMPARISON (KG)

Total Power Per Channel	15 KVA		
Constant Frequency Ac Power KVA/Channel	5	10	15
I. Dc Inverter System			
Dc Starter/Generator	33	36	40
Inverters	30	46	55
Isolation Switches	4	4	3
II. Ac/Dc Hybrid System			
Dc Starter/Generator	25	25	25
CSD	8	10	10
Heat Exchanger	1	1	1
Reservoir, Oil and Filter	2	2	2
Alternator and Control	9	13	17
Isolation Switches	3	3	2
III. Total			
Dc Inverter System	67	86	98
Ac/Dc Hybrid System	48	54	57

It should be noted that the speed variation is dependent on the type of the engine used for the aircraft. For the helicopter for instance, the engine speed, during a typical flight profile, is within ±5 percent for 90 percent of the time and is within ±10 percent for the remaining 10 percent. This indicates that it is feasible to use a wild frequency generation system in which the alternator is directly driven by the engine pad without the use of CSD. The variable frequency imposes a weight penalty on frequency dependent components such as motors, generators and transformers. However, the simplicity and the improved reliability gained in wild frequency generation can offset the weight penalties.

Short range: For this type of aircraft, either turboprop or turbojet engines can be used. Ac power generation is considered the best choice and the selection between the constant frequency system and the wild frequency system is again dependent on the speed variation of the engine. A speed ratio of less than 1.25 to 1 would result in the choice of the wild frequency approach.

Medium and long range: For medium and long range V/STOL aircraft, the related characteristics of the aircraft are essentially the same as those of the conventional aircraft. Although turboprop engines may still be used, the turbojet engines will be found more popular because of the high cruising speed requirement. The candidate systems which are preferred for the conventional transports should also be applicable for the similar size of V/STOL aircraft. One promising system is the variable frequency generation and high voltage dc distribution with secondary quasi-square wave ac for motor loads.

Air-Space Hybrid Vehicles

Basic requirements.--Before any discussion of the electrical power system, it is first necessary to state the basic requirements peculiar to air-space hybrid vehicles. These vehicles operate in an atmospheric (air) and a space (vacuum) environment. Among the known basic requirements there are:

(1) Mission duration

(2) Amount of electrical energy required

(3) Peak energy demand

(4) Type of propulsion

(5) Electrical energy source

(6) Environment

(7) Heat transfer method and media

While typical flight duration of a commercial aircraft is from one up to 12 hours, space booster missions require approximately 2 hours. Orbiter mission time is in the order of 200 hours and the assignment for space stations can last several years.

Table II shows typical energy requirements of the various load categories for an aircraft in comparison with the shuttle orbiter and the space station. As can be seen, the power requirements for aircraft are quite different from those for manned space vehicles. For space application, about half of the generated power is used for a single load category, i.e. electronics and avionics. Also the peak power demand at any given time is considerably smaller. If a representative figure of 140 kva is taken for aircraft, the corresponding peak demand for the booster is 40 kW, for the orbiter it is 15 kW and the maximum power required for the space station is estimated to be 80 kW. In aircraft where mechanical shaft power can be extracted from the propulsion engines for the entire mission phase, the most logical energy source is the engine driven alternator.

Where vehicle propulsion is not required for the entire mission duration (rocket propulsion), different energy sources are sought. Depending on the load profile (peak demand vs time) the optimum source for the booster for instance has been selected as the APU driven alternator and for the orbiter the H_2 O_2 powered fuel cell. Long term power sources (space station) are either solar arrays or various nuclear energy conversion schemes.

A vast difference exists between the methods of heat rejection employed by a vehicle in an atmospheric environment, and a vehicle in a space environment. The weight penalties involved differ as a consequence. In the case of atmospheric operation, the vehicle structure and ram air is used as the heat transfer media. A typical weight penalty is about 0.5 kg/kW of heat removed. The incremental weight for space radiators is, on the other hand, approximately 105 kg/kW of heat removed. From this, it follows that all electrical equipment for space application should have the highest obtainable efficiency.

Power Generation and Transmission.--The selection of the electrical power generation system has been studied by various companies. The study result indicate that the electrical power on the booster should be ac power generated from alternators driven by H_2-O_2 fueled APU's. On the orbiter, fuel cells should be used to provide the main source of power during all phases of the mission. Alternators driven by H_2-O_2 fueled APU's should be used to provide ac power for the main engines during the boost phase. The APU's and alternators are shut down at orbit insertion.

Electrical power can be transmitted either as ac power or dc power regardless of the type of power source. However, to convert power from one type to the other requires the use of power conversion equipment. Due to the high specific weight of the present day solid state power conversion equipment, power conversion before transmission can not be justified. It was concluded

TABLE II.--TYPICAL ENERGY REQUIREMENT

Utilization	Aircraft kWH/Flight	Orbiter kWH/Mission	Space Station kWH/Month
Motors and actuators	150	120	500
Heating	120	15	-
Lighting	60	5	400
Electronics	20	500	4000
Control conversion losses	20	50	600
Total	370	690	5500

that the optimum way to transmit electrical power is to transmit the generated power without conversion. Based on this reasoning, the booster electrical system should use ac power transmission, while the orbiter system should use dc transmission.

Control and protection.--Previous studies indicated that the advanced data bus system offers many advantages over the conventional hard wired circuit. Also the use of solid state switchgears offers a number of improvements over the conventional electromechanical counterpart. For the space shuttle systems, therefore, the advanced configuration using data bus and solid state switchgears should be used. This will result in a significant amount of weight reduction, improved reliability and maintainability and enhanced system capability and flexibility.

Since the solid state power controller has limited current capabilities, hybrid switchgears should be used for bus and feeder controls.

Power conditioning.--A study conducted by Martin Marietta Corporation (McDonnell Douglas Report No. E0391, Space Shuttle Data,) indicates that decentralized power conditioning should be used for space shuttle booster and orbiter vehicles. This is due to the fact that central power conditioning, for this case, increases system complexity without decreasing weight significantly. Moreover, increased thermal losses due to distribution of power at low voltages, result in a weight penalty (increased cooling) that is expected to nullify any power conditioning weight reduction.

The decentralized power conditioning system uses an individual power converter for each electronic LRU. The converter provide the required power at various voltage levels for the various analog and digital circuits. For the shuttle booster 28 vdc power is also required for non-electronic equipment such as valves and solenoids. In this case, therefore, TR units should also be used in the system. In the shuttle orbiter system, on the other hand, ac power is required for the motor loads, substation static inverters hould therefore be employed.

Power losses and weight penalties.--Power losses in the electrical system of the space shuttle impose certain weight penalties. These include:

- Incremental weight of power generation equipment for make up of the losses.
- Weight of the fuel for the APU or fuel cell. This is related to the total energy loss during the mission.
- Incremental weight of the thermal control equipment for removal of heat losses.

Since the total weight penalty is very high for the system of the space vehicle, the components should be designed for high efficiency. To achieve a

minimum weight design, trade off techniques can be applied. One of the trade offs is the transmission cable design. By using large transmission cables under certain conditions, the reduction in weight penalties can more than offset the weight increase in cables.

Weight estimate.--The estimate of component and system weight was made for various system configurations. Table 12 shows the component and system weight for a single channel while tables 13 and 14 show the losses and the weight penalties respectively. It is seen that the 115 Vdc system can save as much as five hundred pounds.

Utilization equipment.--A cross section of the number of individual types of loads and power consumption is given in table 15 for the space station, the orbiter and for a typical large commercial airplane.

For the space station, the number of electronic LRU's (and total electronic load) is an order of magnitude greater than that for either the aircraft or the shuttle-orbiter. The shuttle orbiter and the conventional aircraft are notably close in the number of electronic (avionics) units. On the other hand the conventional aircraft will generally require more motor units and a greater level of motor power than either the shuttle or a space station. Lights and heaters also show outstanding differences reflecting the space environment. The space station is expected to utilize incident solar radiation for heating. This method obviously does not apply to aircraft, although the shuttle orbiter may at times use solar heat inputs. The large number of space station lights is due to the projected size of the space station and the fact that natural (i.e. solar) lighting cannot generally be used. Thus, the space environment is seen to have a considerable effect on all aspects of electric power system design.

TABLE 12.--SPACE SHUTTLE ELECTRIC POWER SYSTEM WEIGHT ESTIMATE (SINGLE CHANNEL)

Configuration	No.	Power KW		kg/KW			Total Weight, kg		
				28 VDC	115 VDC	115 VAC	28 VDC	115 VDC	115 VAC
Transmission	4	10					86.2	19.9	22.0
Switchgear									
Bus control	3	Hybrid	kg/unit	2.2	2.2	2.2	6.1	6.1	6.1
Feeder	4	Hybrid		0.9	0.9	0.9	3.6	3.6	3.6
Motor	8	SS		0.09	0.09	0.09	0.7	0.7	0.7
Heating/lighting	12	SS		0.09	0.09	0.09	1.1	1.1	1.1
Actuator	90	SS		0.09	0.09	0.09	8.2	8.2	8.2
Electronics	40	SS		0.09	0.09	0.09	3.6	3.6	3.6
Power Conditioning									
Analog	25	1		13.6	12.2	14.9	13.6	12.2	14.9
Digital	15	1		42.6	36.2	40.8	42.6	36.2	40.8
Inverter	4	4					24.2	20.1	
TRU	1	2							12.7
Weight Penalties									
Due to losses							399.0	238.0	215.0
Total							588.9	349.7	328.9

TABLE 13.--SPACE SHUTTLE - PPDC LOSS ESTIMATE (SINGLE CHANNEL) (WATT)

	28 VDC	115 VDC	115 VAC
Transmission	702	160	405
Switchgear			
Bus control	72	18	18
Feeder	72	18	18
Load	535	131	131
Power Conditioning			
Analog	266	250	316
Digital	1000	887	1000
Inverter	183	228	
TRU			353
Total	2830	1692	2241

TABLE 14.--SPACE SHUTTLE WEIGHT PENALTIES (SINGLE CHANNEL)

System	Total Loss, KW	Weight Penalties, kg			Total Weight Penalty, kg
		Generation	Fuel	Thermal Control	
28 vdc	2.83	45	89	265	399
115 vdc	1.69	27	53	158	238
115 vac	2.24	1	4	210	215

TABLE 15.--POWER UTILIZATION EQUIPMENT COMPARISON (ref. 8)

	Aircraft		Shuttle Orbiter		Space Station	
Type of Load	No Units	Power Unit	No Units	Power Unit	No Units	Power Unit
Electronic LRU's	113	10-500 W	140	5-450 W	1000	1-500 W
Motors	60	50 W - 12 kW	20	20W -2.5 kW	50	20 - 200 W
Actuators	50	15 - 500 W	350	30 - 250 W	270	10 - 50 W
Lights	40	50 - 100 W	30	15 - 600 W	740	10 - 100 W
Heating	70	100 W - 4 kW	15	40 - 500 W	-	-

DESIGN PHILOSOPHY FOR AIRCRAFT ELECTRICAL POWER SYSTEMS

Introduction

This section presents the philosophy pertaining to the selection and utilization of aircraft and spacecraft electrical power systems in general, with emphasis on commercial aircraft usage. Preferences are stated as a guide for design, the design category being of a somewhat generalized nature. These preferences concern (a) safety-reliability, (b) selection of power type, voltage and frequency, (c) power quality and efficiency, (d) power conditioning, control and protection, and (e) selection of utilization subsystems.

Items b, c, and d are highly interractive basic design areas and are grouped together in the discussion. On the other hand, safety-reliability and utilization system selection are general areas applying equally to any selected power system designs. They should be so viewed.

Safety-Reliability Requirements

A split parallel channel system is recommended for design of generator distribution systems. In general, the split parallel channel system is superior to the isolated channel system for all practical and predictable values of generator and PDU failure. (This excludes the all channel failure case.) The number of generation channels in an aircraft may be taken as being equal to the number of engines. However, supportable deviations from this practice would be acceptable providing the resulting system failure probability is acceptable. A desirable goal is a system failure probability of 10^{-5} or less.

Three or four channel systems.--The definitions of reliability and safety for 3 or 4-channel systems are as follows:

Reliability = probability that 2 or more channels are operative

Safety = probability that 1 or more channels are operative

Depending on the system design, various degrees of redundancy may be incorporated for the essential loads and the associated PDU. In the following analysis, two different cases are considered: (1) one PDU and one set of load equipment for the essential loads and (2) one PDU and one set of load equipment are used for each channel.

Nomenclature:

F_G = failure probability of generator system

F_A = failure probability for one generator

F_P = combined failure probability of PDU and load

Or

$$F_P = F_D + F_L - F_D \times F_L$$

where F_D = PDU failure probability

F_L = Load failure probability

System without PDU and load redundancy: In this type of system, the generation channels can be all parallel, split parallel (for 4-channel system) or cross-strapped after failure. For evaluating the system reliability and safety, the result of the various configurations is the same since the essential load can always receive power from any generation channel. Table 16 shows the equations for reliability and safety while Figure 17 shows the failure probability of the generation system F_G, plotted as a function of F_A.

TABLE 16.--RELIABILITY AND SAFETY FOR SYSTEMS WITHOUT PDU AND LOAD REDUNDANCY

	4-Channel System	3-Channel System
Reliability (R)	$R = (1-F_P)(1-F_G)$ $F_G = 4F_A^3-3F_A^4$	$R = (1-F_P)(1-F_G)$ $F_G = 3F_A^2-2F_A^3$
Safety (S)	$S = (1-F_P)(1-F_G)$ $F_G = F_A^4$	$S = (1-F_P)(1-F_G)$ $F_G = F_A^3$

System with PDU and load redundancy: When one PDU and one set of load equipment are used in each channel for the essential loads, the system configuration can be either all isolated or all parallel (cross-strapping after failure and split parallel system with the capability of closing the bus tie breaker after failure are the same as the all parallel system). The equations for reliability and safety calculation for the two types of systems are shown in tables 17 and 18, respectively.

TABLE 17.--RELIABILITY AND SAFETY FOR ISOLATED SYSTEMS WITH REDUNDANT PDU AND LOAD

	4-Channel System	3-Channel System
Reliability	$R = 1-4F_{CH}^3 + 3F_{CH}^4$	$R = 1-3F_{CH}^2 + 2F_{CH}^3$
Safety	$S = 1-F_{CH}^4 \approx 1-(F_A+F_P)^4$	$S = 1-F_{CH}^3 \approx 1-(F_A+F_P)^3$

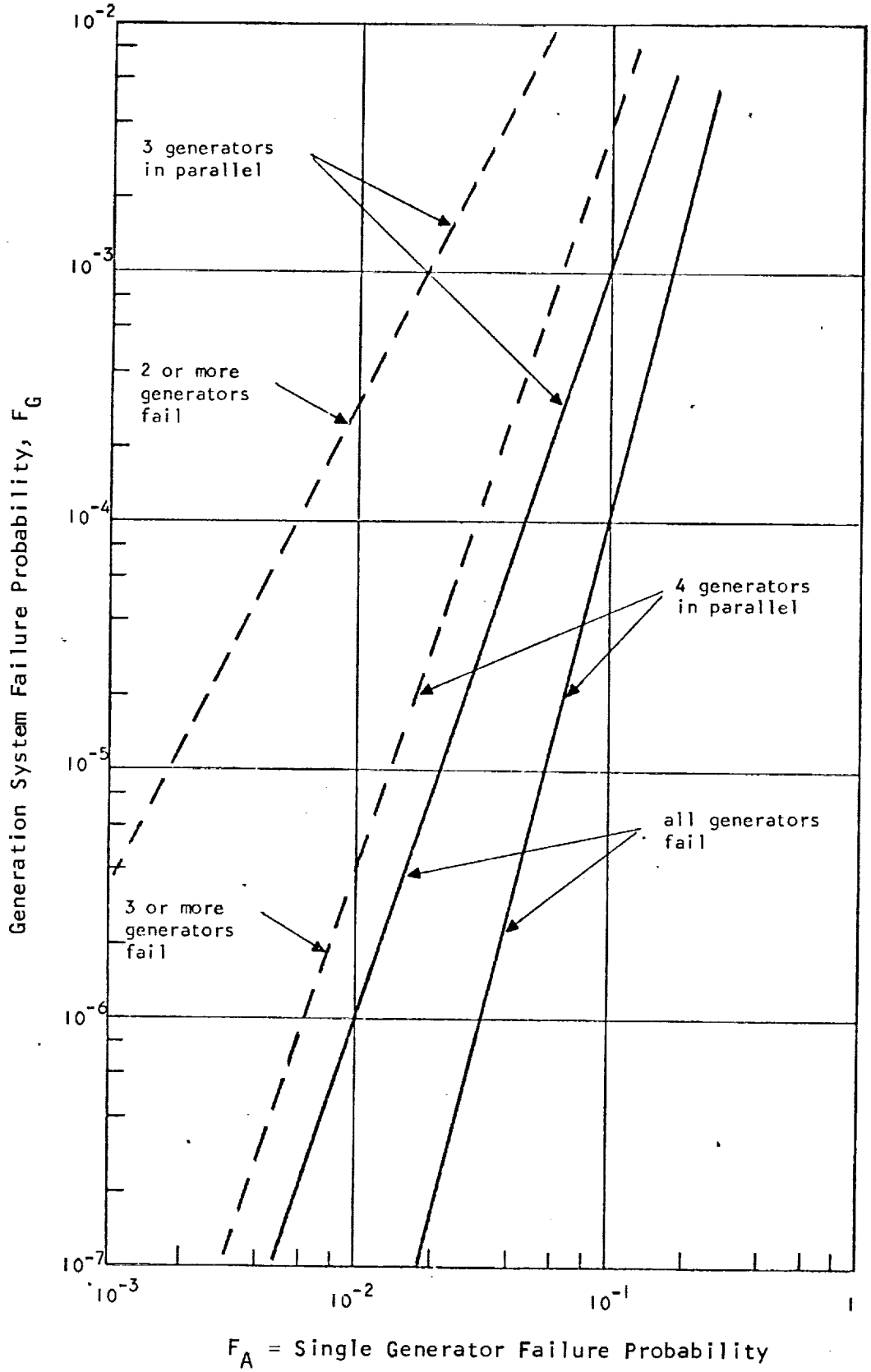


Figure 17. Generation System Failure Relations

F_{CH} = Failure probability of one channel

$= 1-(1-F_A)\ (1-F_P) \approx F_A + F_P$

TABLE 18.--RELIABILITY AND SAFETY FOR ALL PARALLEL SYSTEMS WITH REDUNDANT PDU AND LOAD

	4-Channel System	3-Channel System
Reliability	$R=(1-4F_A^3+3F_A^4)(1-4F_P^3+3F_P^4)$	$R=(1-3F_A^2+2F_A^3)(1-3F_P^2+2F_P^3)$
Safety	$S=(1-F_A^4)(1-F_P^4)$	$S=(1-F_A^3)(1-F_P^3)$

The system failure probabilities (1-R and 1-S) can be plotted as functions of F_A and F_P. These are shown in Figures 18 through 21. It is seen that the all-parallel system is more reliable than the isolated system.

The selection of the system configuration obviously depends on the safety/reliability requirements and the failure probabilities of the pertinent components.

Channel capacity: If the aircraft is equipped with an APU, it is advisable for the APU to be flight-operable and capable of parallel operation with other generators. In a twin-engine airplane, it is almost essential that the APU is flight-operable and has the same rating as the main generators. If this is the case, the APU can be considered as another generation channel. There is no existing specification covering the generating capacity per channel. If an aircraft is dispatched with one generation channel inoperative, it is felt that a second failure should leave a generating capacity of at least 2/3 of the load demand in a reliable system. It is therefore recommended that:

$$\text{Minimum channel capacity} = \frac{2/3 \times \text{load demand}}{\text{No. of channels} - 2}$$

Table 19 shows the comparison of various channel capacities in 2-, 3-, and 4-channel systems.

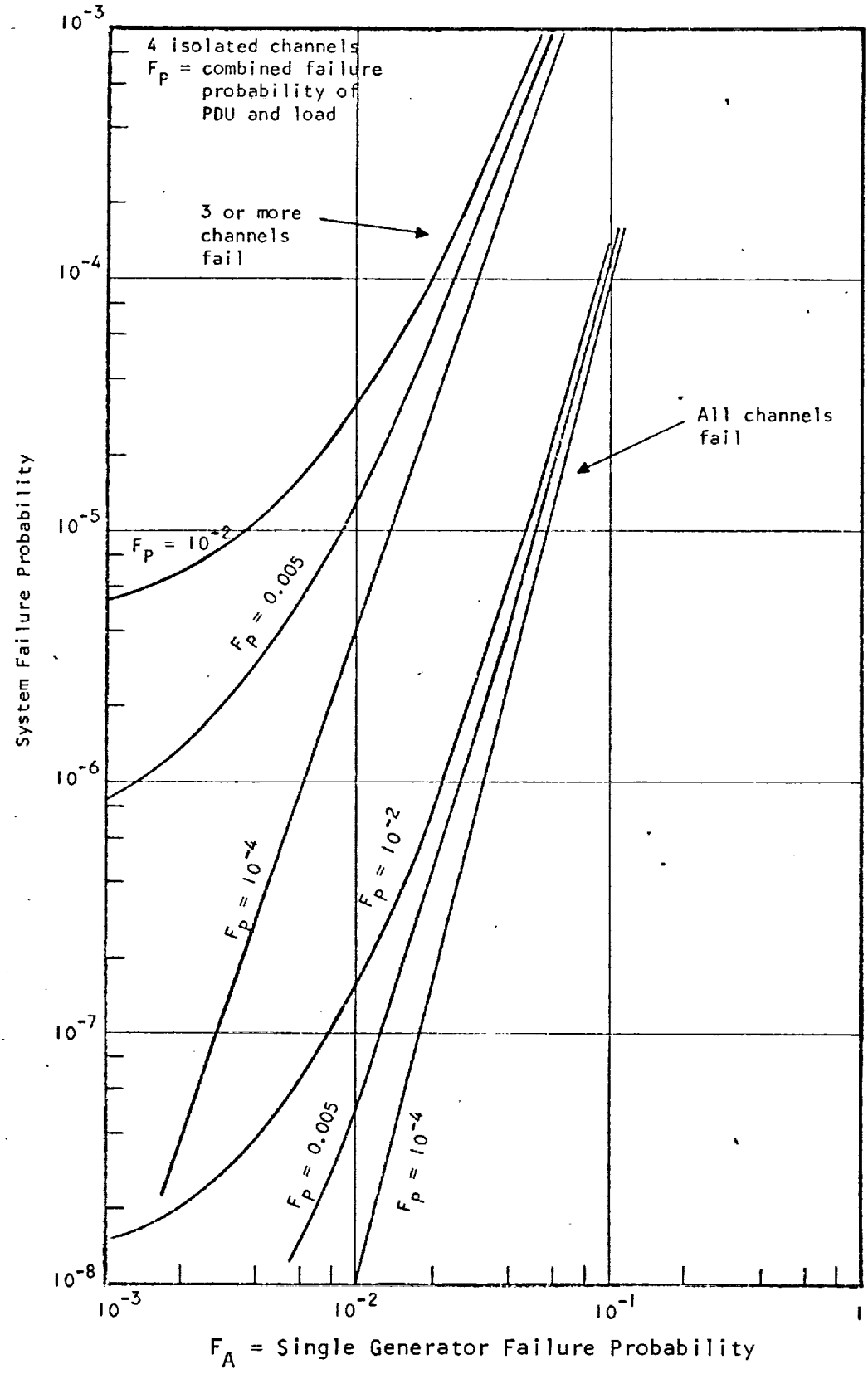


Figure 18. System Failure Probabilities - 4 Isolated Channel System

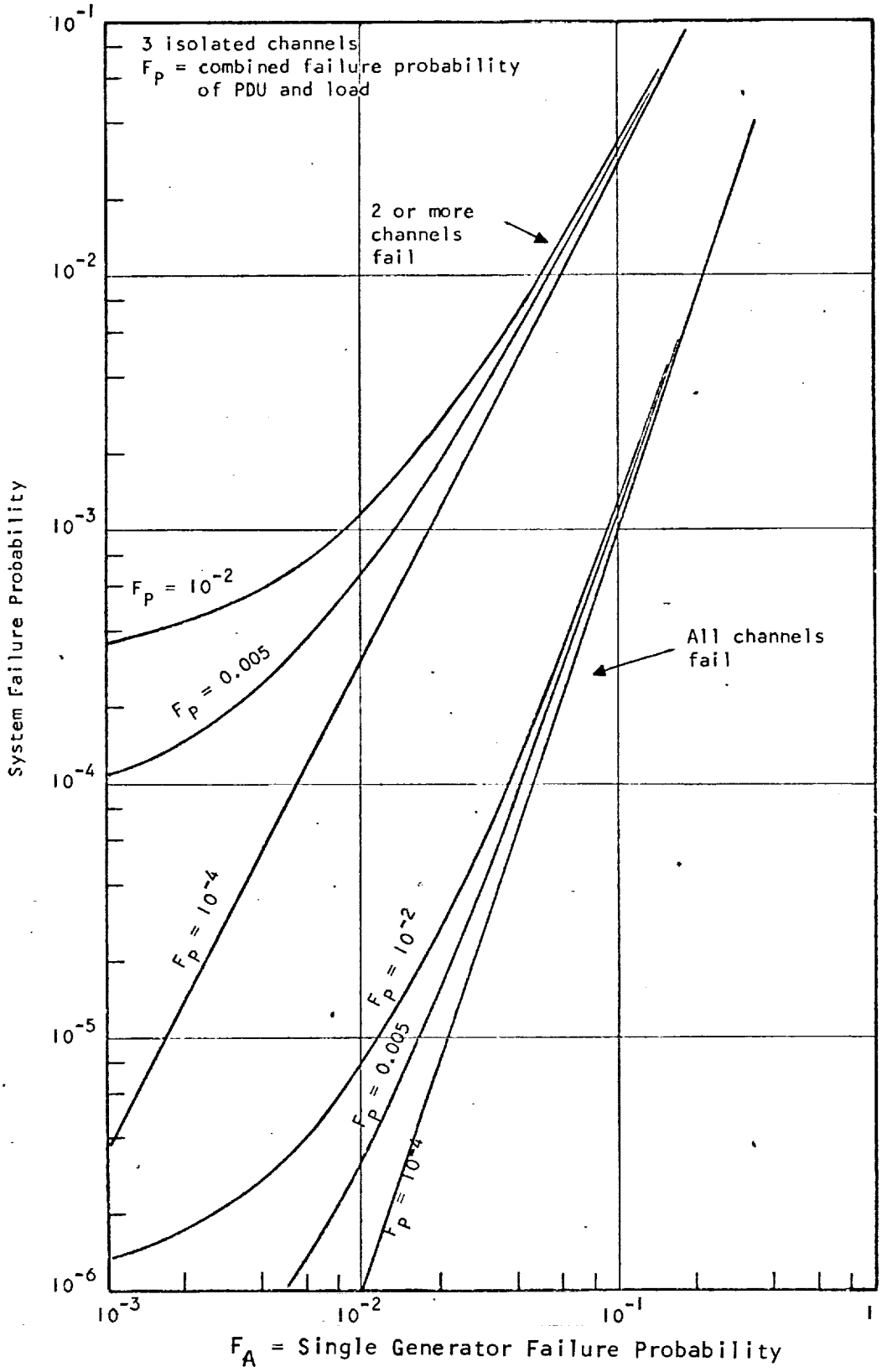


Figure 19. System Failure Probabilities - 3 Isolated Channel System

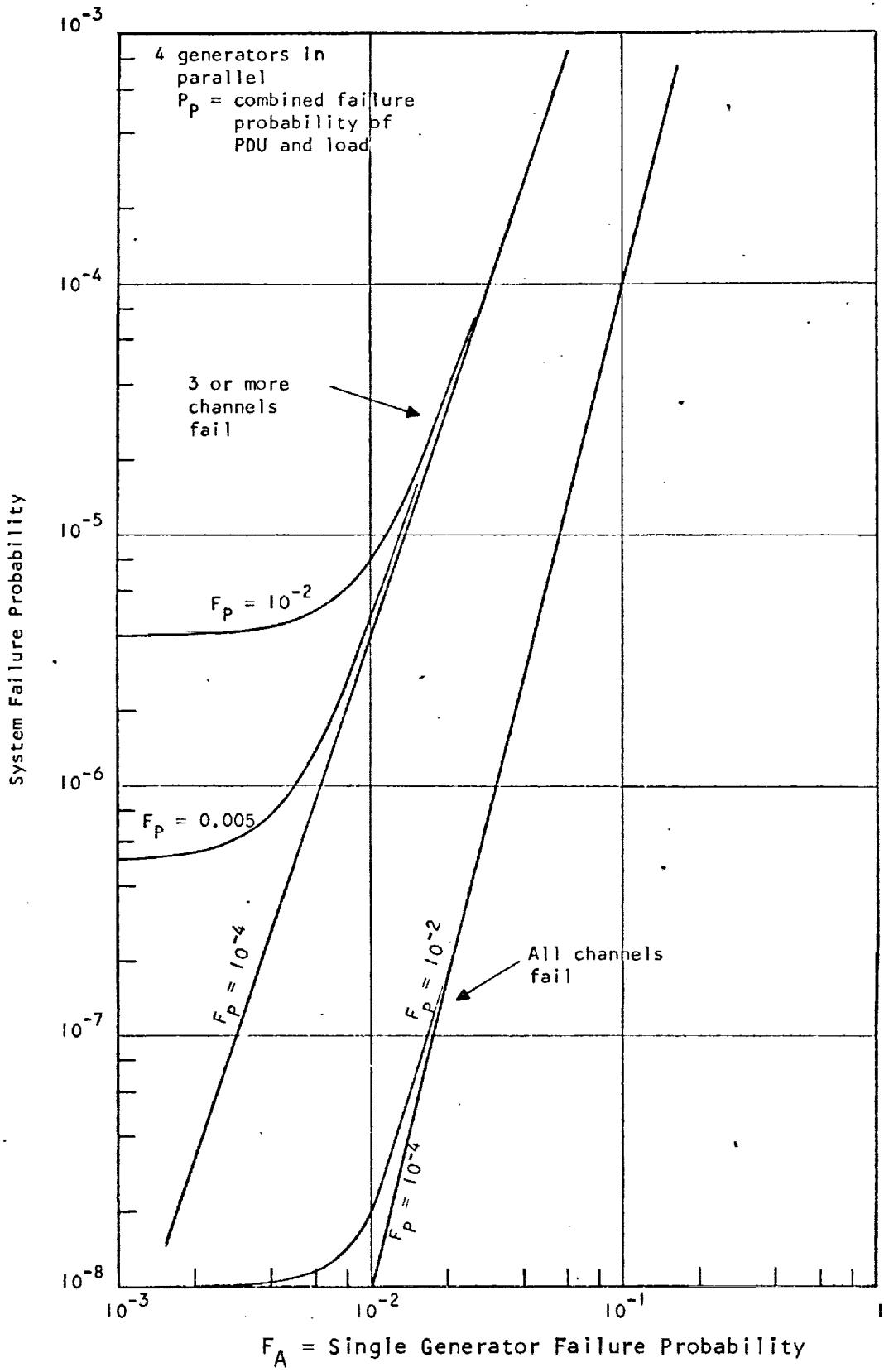


Figure 20. System Failure Probabilities - System with 4 Generators in Parallel

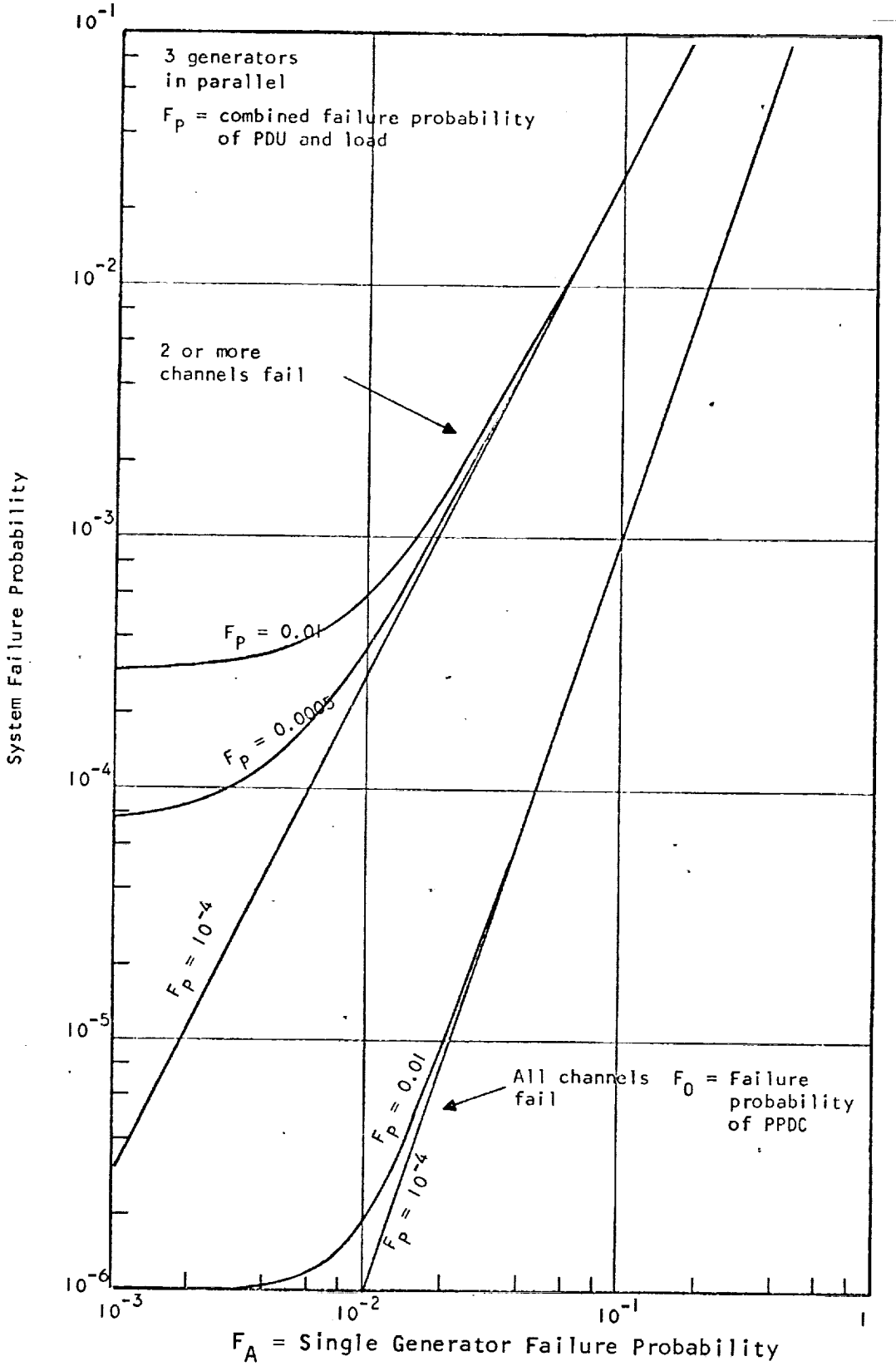


Figure 21. System Failure Probabilities - System with 3 Generators in Parallel

TABLE 19.--CHANNEL CAPACITY COMPARISONS

Number of Channels	Channel Capacity per Unit of Load Demand	Dispatch With One Channel Inoperative	Comments
4	0.25	No	Second failure critical
	0.33	Yes	Minimum contingency factor
	0.50	Yes	Adequate margin for emergencies
3	0.33	No	Second failure critical
	0.50	No	Not sufficient margin
	0.67	Yes	Minimum contingency factor
	*{0.67 Normal 1.0 Emergency	Yes	Margin comfortable
2	0.5	No	Two engine aircraft needs flight operable APU in order to be dispatched with one channel out
	1.0	No	

*1/2-hour emergency rating of 1.5 normal continuous rating.

Recommended improvements for distribution system reliability:

- Solid state power switching, control and protection
- Automatic load management controller
- Redundant T-R units
- A split-parallel system
- Built-in-test equipment (BITE)

Solid state switches, when properly designed, are more reliable than electromechanical switches. Also, solid-state switches react faster and can limit the fault current.

The advanced concept of automatic load management will greatly increase system reliability. Under this concept, any fault or pending failure will be quickly isolated and compensatory action taken to prevent any further damage.

System reliability frequently is increased by use of redundancy, such as redundant T-R units, but feeds through bus tie controllers. Redundant bus wiring will avoid loss of a power bus when a wire break or loose connection occurs. The split-parallel system will also improve system reliability because it prevents the spreading of a fault or large distrubance to the entire power system. Built-in-test equipment (BITE) can be designed to perform inflight

monitoring and control switch-over to redundant channels in case of a failure in the primary circuit and hence improve system reliability. Discrimination is required in applying the above recommendations lest the resulting complexity of the circuitry produce a reduction rather than an increase in overall reliability.

Basic Design Aspects

Power type, system voltage and frequency.--For aircraft application where shaft power is available; the engine driven generator is the logic choice. For a short mission space vehicle, the APU-driven generator and fuel cell are the best candidates.

Generation of dc power is simpler and cheaper than ac generation. Dc generation is particularly attractive if the motor load is a small percentage of the total load. Dc distribution is preferable to ac distribution because:

(1) the transmission cable has no reactance drop and skin effect

(2) the power factor is unity

(3) the corona onset voltage is higher for dc than ac

(4) dc is less dangerous for personnel than power frequency ac at the same voltage level

(5) control of EMI and dynamic interactions is easier

(6) Dc/dc converters are lighter and more efficient than 400 Hz TR units with regulated outputs.

For small VTOL and V/STOL aircraft, self sufficiency is essential. The use of the dc starter/generator for dc supply is therefore preferable.

At present state-of-the-art motor technology, ac power is essential for motor loads since large rating brushless dc motors (BDCM) are not available. However, based on projected trends, a competitive weight BDCM is achievable by 1985. This will eliminate the need for ac input motor power-even at the cost of a slight increase in weight.

A supply voltsge of 300 v to 360 v reduces power loss and wiring weight. The reduction becomes insignificant above 360 v.

The maximum frequency for significant reduction of transformer and motor weight is 1600 Hz. However, high frequency imposes weight penalties in wiring and voltage should be increased concurrently.

Power quality and component efficiency.--Electrical power that meets the requirements of MIL-STD-704A is considered more than adequate for most of the aircraft electric loads. However, it is inferior for the electronic loads and

some control loads which require high quality closely regulated power free from transients.

In most types of aircraft, the electronic loads represent only a small portion of the total electrical load. Since no significant benefits can be obtained by using high quality power for noneelectronic loads, the requirement for high quality power for all aircraft electric loads is generally unwarranted and unnecessary. The philosophy, therefore, is to generate low quality power in the primary system and supply the electronic loads with refined high quality power.

VSCF systems are preferred for applications where large quantities of precise, high quality power are needed, such as for military electronics systems. This capability of VSCF systems, in supplying a better quality power than conventional constant speed systems, has led to an upgrading of specifications. VSCF grade power quality is defined in MIL-E-2300IA dated July I, I968. Table 20 compares the power quality available from the VSCF system with that required by MIL-STD-704A. The areas where the improved power can benefit utilization equipment include:

(I) Reduced steady state voltage range

(2) Reduced voltage unbalance

(3) Increased tolerance of single-phase loading

(4) Reduced overvoltage transients

(5) Precise frequency control.

These improvements can result in significant savings, particularly for aircraft with a large quantity of avionics (e.g., > 910 kg (2000 lb). To obtain quantitative estimates, a study was conducted by Frichtel and Dougherty of G. E. Co. (See Bibliography), in which they analyzed the avionics of 5 selected military aircraft. The result indicated that the following savings could be expected:

Input power	4 to 6 percent
Weight	2 to 6 percent
Volume	I to 3 percent
Cost	I to 2 percent
Reliability	2 to 6 percent

VSCF systems have been under development for years and are now recognized competitive power generation systems.

TABLE 20.--COMPARISON OF VSCF POWER QUALITY WITH MIL-STD-704A

	VSCF	MIL-STD-704A
Steady State Voltage Individual Phase, Cat. B	Normal Abnormal Emergency 110-116 104-122 104-122	Normal Abnormal Emergency 108-118 102-124 104-122
Voltage Unbalance	2-volt spread up to 33% rated current max. difference between phases.	3-volt spread up to 15% rated current max. difference between phases.
Crest Factor	1.41 ±0.07	1.41 ±0.1
Steady State Frequency	400 ±0.001 Hz	400 ±20 Hz
Frequency Drift	Must remain within steady state limits	10 Hz at up to 15 Hz/min with 380-420 Hz band.
Transient Frequency	None	10 Hz excursion 370-430 Hz switching 10%-85%-10% load; 30 Hz excursion 350-450 Hz switching 20%-170%-20% load.
Power Interruption	5 ms	50 ms.

Component efficiency: For aircraft application, component efficiency is relatively unimportant. For example, considering a 60 kW aircraft system with a flight duration of 10 hr, the typical $d W_p/d_\eta$ (where W_p is weight penally) is only 1.8 kg (4 lb)/1 percent of efficiency. However, for space vehicle systems, the weight penalties are much higher and significant. Table 21 shows typical component efficiency while table 22 shows the various weight penalties for aircraft and space vehicle use. It is evident that for aircraft today improvements in efficiency will not generally justify the effort expended.

TABLE 21.--COMPONENT EFFICIENCY

Equipment	Efficiency, %	Remarks
Generation		
IDG System	78	Based on 60 KVA capacity
Variable Frequency	86	
DC Generation	84	
VSCF (NCC)	83	
VSCF (DC Link)	77	
Power Processing		
Analog	75	
Digital	50	
Motor Drive Inverter	93	
TR Unit	90	
Central Inverter	90	
Transmission Cable	>96	Based on 4% max voltage drop
Switch Gear		
SS	97	400 Hz 115VAC
RCCB	99	400 Hz 115VAC

TABLE 22.--WEIGHT PENALTIES DUE TO LOSSES

Equipment	Weight Penalty	
Generation		
Aircraft IDG	0.9	kg/kw
Space Shuttle Fuel Cell	16	kg/kw
Fuel Weight		
Aircraft	0.4	kg/kwh
Fuel Cell (O_2-H_2)	0.4	kg/kwh
Space Shuttle APU (O_2-H_2)	1.8	kg/kwh

TABLE 22.--WEIGHT PENALTIES DUE TO LOSSES (CONTINUED)

Equipment	Weight Penalty	
Cooling Equipment		
Aircraft	0.6	kg/kw
Space Shuttle	93.5	kg/kw (for unpressurized area)
	124	kg/kw (for pressurized area)

Power conditioning, control and protection.--A central PDU is recommended for all unregulated dc or ac loads. These include loads such as lights and heaters and actuators. Typical duty cycles are 5 to 10 min intervals and 200 percent to 500 percent inrush current. The power quality requirements are relatively unrefined as compared with avionic loads.

Motor loads are similarly rough and may use either control PDUs or substation PDUs.

Avionics loads typically require regulated dc power at voltages such as +28 Vdc, and ±15 Vdc for analog and ±5 Vdc for digital use. The duty cycle is continuous, and conducted and radiated interference must be kept low at acceptable limits. This points to the use of local PDUs for the avionics. A single low voltage bus, say at +28 Vdc can be used and local PDUs can then make the required conversion.

According to recently conducted studies (ref. 8), input voltage regulation has a small effect on locan PDU weight, efficiency and failure rate. This applies to systems in general and fig. 22 illustrates the point. However, as noted earlier, for large amounts of avionics even a few percent savings is significant. In that case, relatively close input regulation would be justified.

Table 23 lists control and protective functions required for system operation. As a rule, existing control panels do not provide all the protective functions listed in the table. For maximum safety and reliability all these functions should be provided; even on separate panels if necessary. A typical control and protection logic diagram is shown in fig. 23. (Warning functions are not shown.) All the control and protective functions have been discussed in detail in the Interim Report (ref. 1). In general, the following philosophy applies:

- Mechanical control relays or circuit breakers should be replaced by solid-state switches
- A means of allowing the operator to manually tie the system via the BTB (bus tie breaker) should be provided. This is to allow for autoparallel circuit malfunctions or a specific emergency.
- Automatic control, including resetting of time delay functions and warning circuits is desirable.

$$\frac{E_{in}\,(Max) - E_{in}\,(Min)}{Ein\,(Min)} \times 100\%$$

Figure 22. Effect of Input Voltage Regulation (Ref. 8)

TABLE 23.--POWER SYSTEM CONTROL AND PROTECTION FUNCTIONS

Control functions

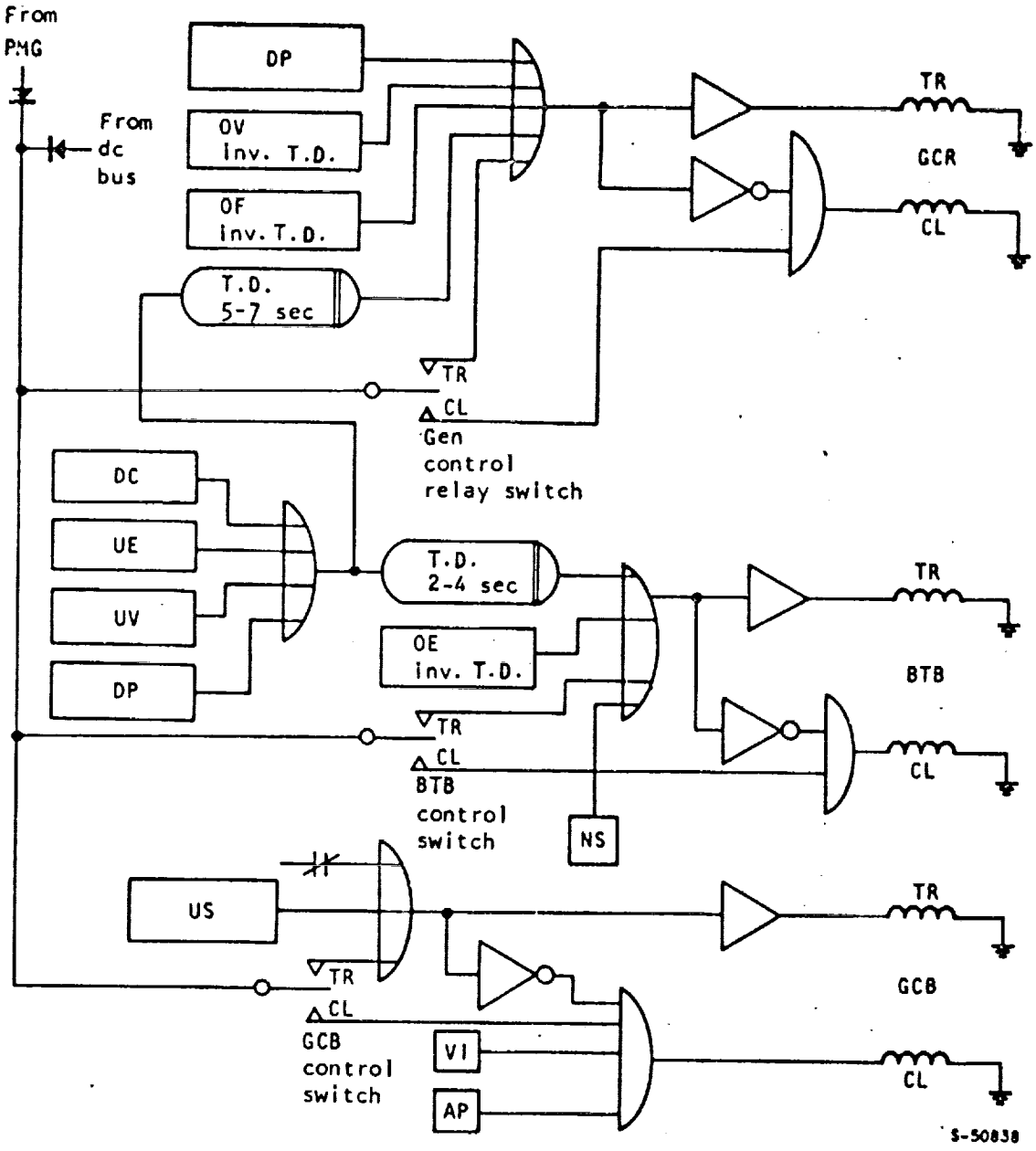
- Generator field control
- Generator circuit breaker control
- Bus breaker control
- Autoparallel
- Time delay functions

Protective functions

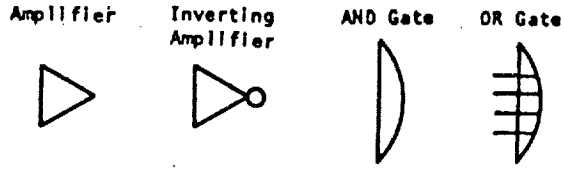
- Overvoltage
- Undervoltage
- Overspeed, over frequency
- Underspeed, under frequency
- Overexcitation, Underexcitation } excessive reactive load division unbalance
- Difference current protection
- Differential protection
- Open-phase protection
- Synchronizing bus protection
- External power out-of-tolerance protection
- CSD protection

Warning and emergency functions

- Generator overtemperature
- Emergency fire switch



Legend:



GCR	Generator control relay	TD	Time delay	OE	Over voltage excitation
BTB	Bus tie breaker	TR	Trip	NS	Negative sequence
GCB	Generator circuit breaker	CL	Close	OP	Open phase
DP	Differential protection	DC	Difference current	US	Under speed
OV	Over voltage	UE	Under excitation	VI	Voltage indication
OF	Over frequency	UV	Under voltage	AP	Auto parallel

Figure 23. Control and Protection Logic Diagram

- The protective circuits which implement the functions of table 8, (p. 55) are concerned primarily with preventing damage to load equipment, the generators and the distribution system. They are not, except by inference, operator safety functions.

- Warning and emergency functions are primarily for the purpose of system and operator safety

- Use of a data bus and computer for control and protection is preferable to the present conventional methods. This should be realizable well before 1985 given the rapid strides being made in minicomputers.

The use of a data bus and computer for control and protection would make the full coverage of all the table functions truly feasible and increase system safety. As compared to hardwire control (ref. 8), for dc, bipolar dc and ac, the number of commands and lines are halved and data retrieval time reduced to 6.05 Msec. FO/FS or FO/FO/FS requirements can easily be accommodated. For large aircraft, crew workload and congestion can be greatly reduced by the use of a data bus and computer together with remote power controllers (RPC's). For small aircraft, where the number of signals is less than 150 and the average distance between signal inputs and outputs is less than 6 m (20 ft), signal multiplexing does not offer significant weight savings. However, it is still preferred for the improvement of system maintainability and reliability.

Selection of Utilization Subsystems: Hydraulic Pneumatic and Electrical

In some aircraft applications, it is preferable to use a power source which is other than electrical in character. These other sources are either pneumatic or hydraulic. The following is a presentation of the philosophy regarding the selection of the utilization method, be it electrical, pneumatic or hydraulic.

General guidelines are given. An example of the application of these guidelines is given in a comparison of utilization methods as applied to actuation systems.

Hydraulic subsystems.--These subsystem are preferred for.

- High power intermittent services such as actuating thrust reversers, retracting landing gear and steering the nosewheel. The hydraulic system offers minimum weight.

- Primary flight control where, in addition to power, good dynamic characteristics (high power amplification, high speed of response, high force to inertial ratio and high stiffness) are required.

- Applications where high pressure systems are possible. Weight savings can be obtained due to reduced volume of hydraulic fluid in the system. For example, the weight of the hydraulic system for the L-1011 airplane could be reduced by 90 kg (830 kg total system weight) for a 0.58 N per sq mi (4000-psi) system as compared with a conventional 0.44 N per aq mi (3000 psi) system.

Pneumatic subsystems.--Pneumatic subsystems should be used fro:

- Applications of extreme environmental conditions where dynamic performance is not critical

- High temperature applications. A high pressure pneumatic system is relatively insensitive to temperature.

- A high radiation environment. Other systems may not be operable.

Electrical subsystems.--Electrical subsystems are used where:

- Moderate loads and moderate response are required. Low stiffness and low torque-to-inertia ratios are characteristics of the load. The result is a reduced envelope and low maintenance and cost.

- Power transmission is a major factor, (e.g. transmission distance is long). The electrical system use should result in higher efficiency and lower weight.

System redundancy.--In order to improve reliability, considerable redundancy should be provided in the form of parallel circuit, duplicate components, or other backup provisions. In some cases, direct mechanical operation serves as a backup or emergency mode. Power source redundancy is also necessary. For large transport aircraft, three or four independent hydraulic circuits, each provided with more than one power source are required. Fly-by-wire concepts should be considered for systems where complex mechanical cable and linkage installation problems exist.

Comparison of actuation systems.--Table 24 compares use of an electrical, pneumatic and hydraulic approach on aircraft actuation systems. Either electrical or hydraulic approaches would be acceptable, with the hydraulic system as the probable choice.

TABLE 24.--COMPARISON OF ACTUATION SYSTEMS

Factors	Electrical	Pneumatic	Hydraulic
Reliability	Good	Fair	Good
Maintainability	Good	Fair	Fair
Growth Potential	Good	Good	Good
Development Risk	Moderate	High	Moderate
Weight	Moderate	Moderate	Low
Volume	Minimum	Moderate	Moderate
Accessibility	Good	Fair	Fair
Temperature	Sensitive	Insensitive	Sensitive
Contamination	Good	Moderate	Sensitive
Low Ambient Pressure	Sensitive	Insensitive	Insensitive
Magnitude	Light to Moderate	Light to Moderate	Full Range
Response	Fair	Fair	High
Accuracy	Fair	Fair	Good
Stiffness	Low	Low	High
Stability	Fair	Fair	Good
Force-to-Inertial Ratio	Moderate	Moderate	High

AIRCRAFT ELECTRICAL SUBSYSTEMS: FUNCTIONS AND POTENTIAL IMPROVEMENTS

Introduction

The aircraft electrical subsystems considered are those which comprise the total electrical power system, viz.:

(1) Generation

(2) Distribution

(3) Utilization

Potential improvements were regarded as resulting from the substitution of either (a) a radically different entire subsystem equipment scheme promising lower weight, higher reliability, etc., or (b) improved means of using existing equipment, including new components if necessary. The components are dealt with exhaustively in the next section.

In general, the discussion on subsystems adheres to the following organization:

(1) Present conventional subsystems are functionally described and summarized.

(2) New subsystems representing improvements are functionally described and summarized.

(3) Direct comparisons are made, where applications and recommendations are made. Where subsystems are to be improved in part (i.e., new components) rather than in total, each improvement is examined and compared as it is introduced.

(4) Disciplines and functions which cross the subsystem boundaries such as controls, signals etc. are discussed separately.

All potential subsystem improvements are regarded as applying directly to future aircraft power system needs.

Generation Subsystems

General.--Unless there is an unexpected breakthrough in the technology of exotic energy sources or dense energy-storage devices, the electromechanical process will continue to be used for aircraft electric power generation in the future. The generation processes discussed in this section are:

(1) Constant-speed, constant-frequency (CSCF, Present System)

(2) Variable-speed, constant-frequency (VSCF)

(a) Cycloconverter

(b) Dc link

(3) Rotating inverter

(a) Synchronous

(b) Line-commutated

(4) Super Auxivar

(5) Wild-frequency (i.e., variable-frequency)

(6) Dc

The present subsystem used on aircraft today is the CSCF subsystem. Fig. 24 shows the family of possible generating subsystems as understood today. An engine accessory gearbox is required for all of the subsystems, and one gearbox is assumed to be installed for each engine. A drive shaft and a power disconnect coupling will connect the gearbox to the engine power takeoff pad. The gearbox provides mounting pads for installation of an air turbine for engine start, a generator (or generator constant-speed drive combination) for the electrical system, one or two hydraulic pumps for the hydraulic system, and an air compressor for the pneumatic system. The gearbox usually incorporates a cooling system that includes a gear-driven air blower and an oil-to-air heat exchanger for cooling the gearbox and the accessories. The engine speed range for all operating conditions usually varies over a ratio two to one.

The subsystems produce power at either constant frequency, dc or at a variable frequency. For the CSCF and the Super Auxivar subsystems, the alternator operates at a fixed speed. For the remaining subsystems, the alternator operates over a varying input speed range.

In the variable-speed constant frequency (VSCF) subsystem, the alternator can be used to provide a variable output frequency which is relatively high. This can then be used for feeding a cycloconverter that converts the input to a low and constant frequency.

Another variation is the dc link VSCF subsystem which rectifies the alternator output to dc power which is then inverted to ac power at a constant frequency.

The rotating inverter subsystems use two rotating machines to provide the ac output power. Synchronous inversion is a dc link process in which dc is obtained by rectification of the engine-driven alternator output. A second rotating machine converts the dc to the desired ac output. This machine exhibits the characteristics of both a synchronous ac and a dc machine. Slip-rings and

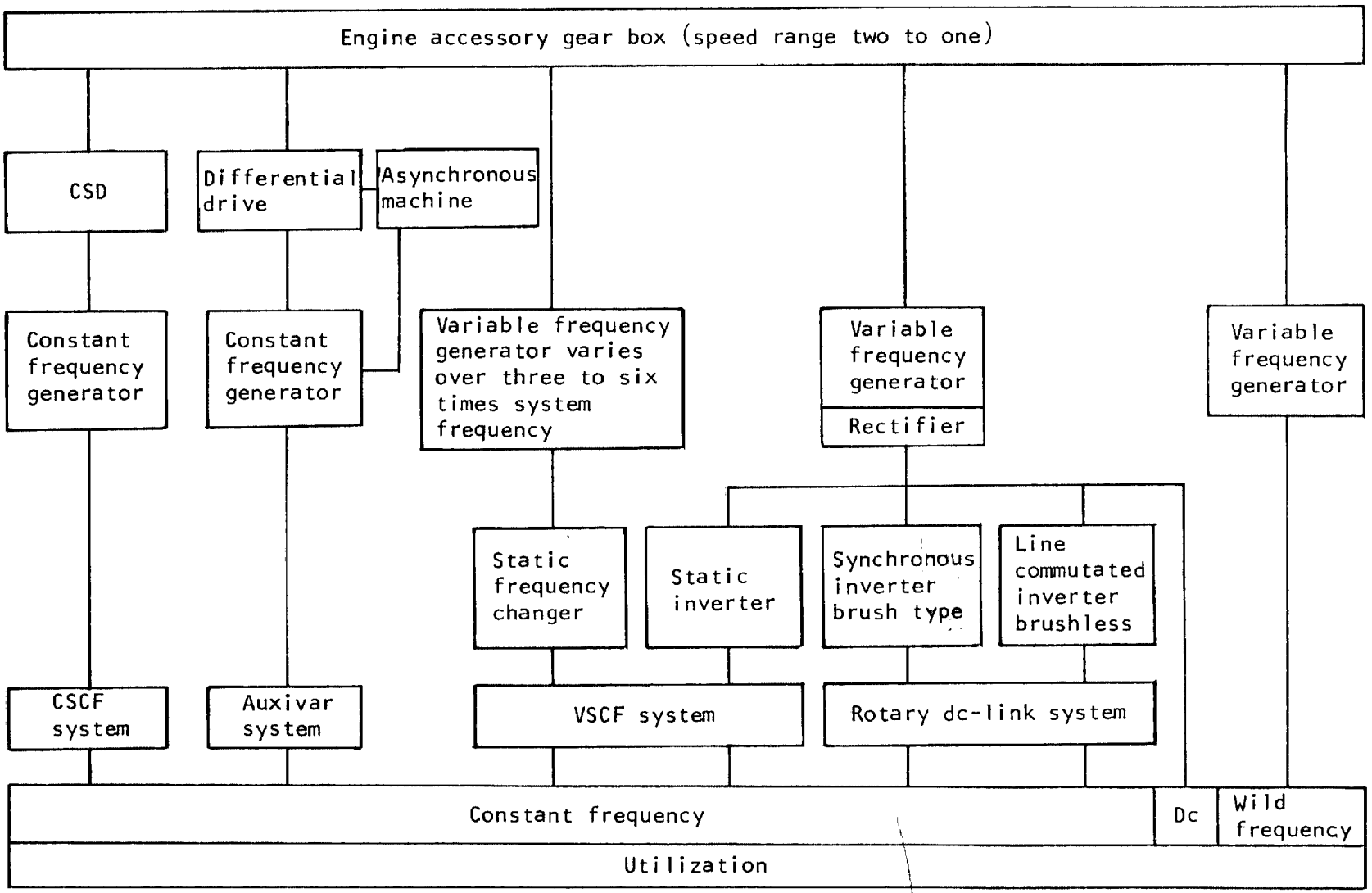


Figure 24. Possible Generating Systems

brushes, however, are required. The line-commutated rotating inverter concept is very similar to the rotating synchronous inverter system except that brushes and slip-rings are eliminated by solid-state commutation.

The Super Auxivar system consists of a mechanical differential interposed between the variable speed engine pad and the constant speed alternator. An induction machine, running from the main ac line, adds or subtracts the engine speed in the differential drive to maintain a constant output speed to the alternator.

A wild frequency system does not modify the alternator output other than to control the voltage. In such a system, most of the utilization equipment will be designed to accommodate the frequency variations. A portion of the loads will be supplied with special rectification inversion packages. The dc system will consist of an alternator and a rectifier bank.

CSCF system.--The CSCF system remains the standard approach for obtaining constant frequency by turning a synchronous alternator at constant speed. In the last 15 years, there have been significant improvements in the development of constant speed drives. The geared differential drive is a recent concept that has increased reliability and reduced weight by one half. The constant output speed delivered by these speed drive units has been increased from a typical 6000 to 12,000 rpm to accommodate lighter alternator designs. The speed limit for the present frequency standard of 400 Hz is set by a two-pole machine that would turn at 24,000 rpm.

Table 25 presents the characteristics of a conventional CSCF system.

VSCF system.--A variable-speed constant-frequency (VSCF) generating system converts variable shaft speed to constant electrical frequency by electrical means, i.e., by using only one full-power-rated rotating electrical machine.

A VSCF system has better performance than a CSCF system. Among the VSCF improvements are:

(1) Precise frequency control

(2) Better voltage regulation and phase balance because of individual phase regulation

(3) Much shorter transient response times

(4) Less transient excursion amplitudes

(5) Better parallel system capabilities

TABLE 25.--SUMMARY OF CONVENTIONAL CSCF SYSTEM

PERFORMANCE

(1) Constant-frequency, good quality power output adaptable for parallel operation with real and reactive load sharing loops.

(2) Improved voltage regulation due to load changes only (no speed change).

(3) Less transients compared to wild-frequency generation.

(4) Lower efficiency than wild-frequency or dc generation.

RELIABILITY

MTBF is less than 50 percent of that of wild-frequency generation system.

MAINTAINABILITY

(1) Expensive to overhaul. (CSD)

(2) Skilled maintenance personnel required.

WEIGHT, SIZE

(1) Weight is about 2/3 higher, and size is about double that of a wild-frequency generation.

(2) High overhung moment.

INITIAL COST

Projected to be about five times that of a wild-frequency generation scheme.

At present, the VSCF system is heavier than a corresponding CSCF system. The VSCF system of the future will have reduced weight and size. This will be accomplished by:

(1) Higher generator rotational speeds

(2) Direct mounting of equipment on engine and accessory pads that deliver optimum generator speeds

(3) Continued improvements in the component designs of the converter and filter unit.

(4) Widespread use of integrated circuit techniques in converter programming and control circuits.

The following material describes the design and performance of both the VSCF cycloconverter and the dc-link systems.

VSCF cycloconverter system: The major components of a VSCF cycloconverter electric power system are: a high frequency variable speed alternator, a static frequency changer, a filter, and associated control and protection circuitry. The minimum input frequency to the frequency changer should be at least three times the required output frequency of the converter to reduce the task of filtering the resultant output waveform. Generator shaft speed must therefore be a high value to obtain low generator weights. The frequency changer consists of a number of switches that are closed and opened in such a manner as to fabricate a low frequency output from a number of high frequency waves. The process of opening and closing the switches produces a jagged low-frequency wave that is smoothed by the filter (fig. 25). The switches are thyristors (SCR's) which in a typical configuration are arranged in six groups with each of three SCR's connected in 3-phase half-wave circuits.

The programming of the firing impulses for the SCR's is derived primarily from two voltage signals: a square wave and a sawtooth wave. The precise, controlled, 400-Hz square wave reference signal is generated by a square wave oscillator. The amplitude of the square wave is clipped in response to a signal from the converter voltage regulator to maintain constant voltage at the converter output under varying load conditions. The clipped square wave is then filtered to give a sine wave which is fed into a phase splitter to produce three equal voltages 120-deg phase displaced. The voltages are amplified to the required power level to supply a modulator.

The sawtooth wave is derived from the generator line to line voltage. A circuit exhibiting a generator impedance analog is fed by current transformers from the generator output. The circuit produces a voltage that is equal to the generator internal voltage drop. This voltage is added to the terminal voltage to produce the air-gap voltage or the "voltage behind commutating reactance" and is clipped and integrated to produce the sawtooth firing wave.

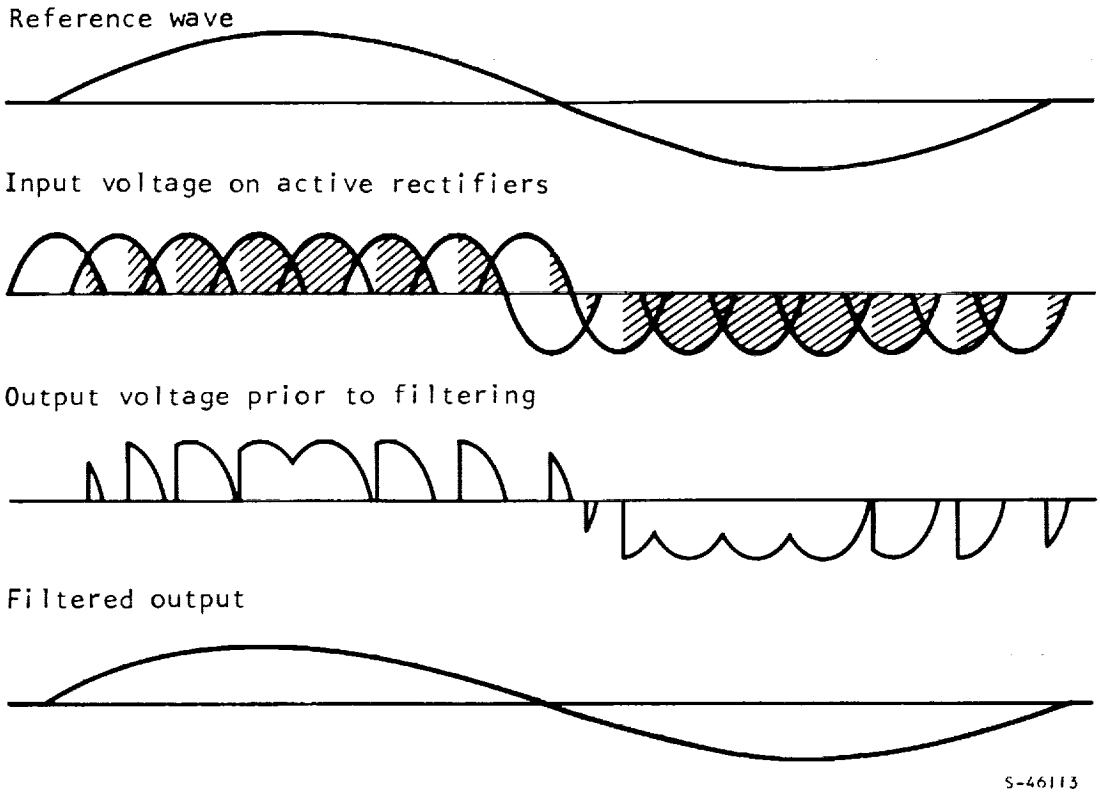


Figure 25. Simplified Description of Sine Wave Firing

The magnitude of the sawtooth wave is regulated by automatically adjusting the rate of charging the integrating capacitor.

Because only the ramp section of the sawtooth wave is active in firing the SCR's, it is necessary to inhibit the region between ramps. This inhibit signal is obtained from the square wave used to gate the integrator. Fig. 26 shows how the modulated sawtooth wave initiates the firing pulses when reaching the threshold. Figure 27 shows a schematic of a typical cycloconverter.

The frequency changer power supply requirement is that the minimum frequency ratio (generator output to system frequency) be at least three to one and that generator subtransient reactance be low (0.1 to 0.3 per unit, maximum). The first requirement is necessary for a practical output filter design; the second is necessary to minimize the commutation effect when switching from one input phase to the other. The converter is a nonlinear load to the generator. Phase retarding, necessary to shape the output voltage wave, results in a low-power factor for the generator that requires a 40 to 60 percent higher generator rating than system rating. Since solid rotor generators exhibit high internal reactance, they are not particularly suited from an efficiency standpoint for the application. To produce a high-frequency output of wound rotor machines at moderate speeds, the number of poles increases considerably. (A recent

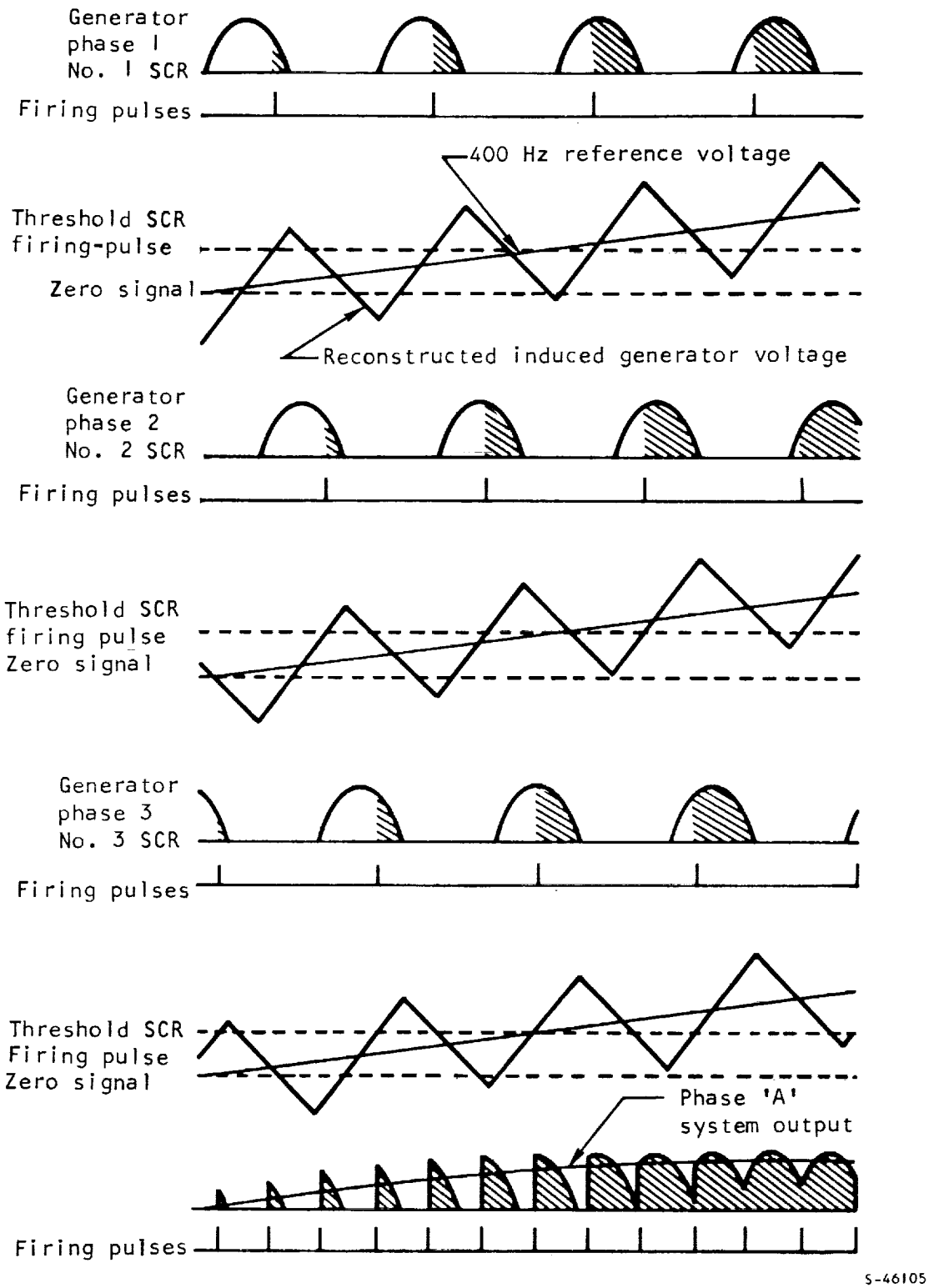


Figure 26. Schematic of High Frequency Wave Firing

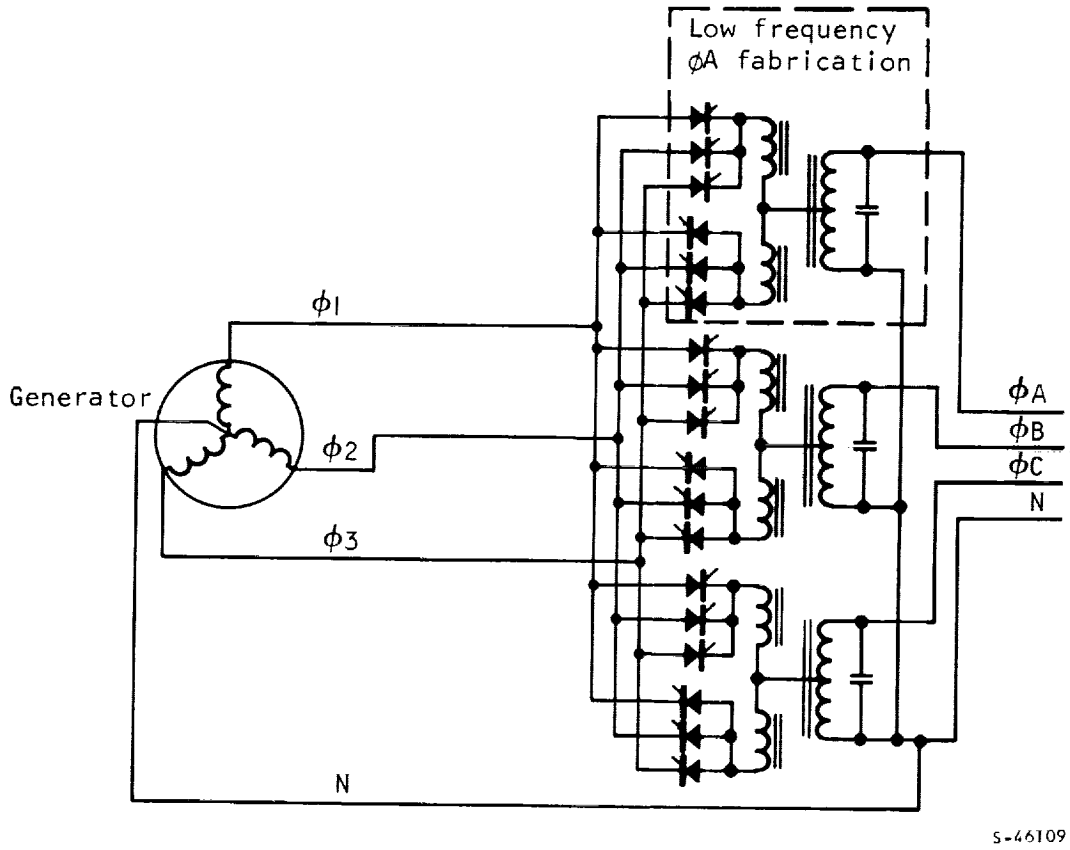


Figure 27. Schematic of Typical Cycloconverter

generator design requires 22 poles for an operating speed range of 6000 to 12,000 rpm.) Further weight increase results from the major design change in the electromagnetics and the provision for a 6-phase generator output (for better utilization factor).

The cycloconverter VSCF generator is estimated to be up to 80 percent heavier than the constant speed generator for the same system rating because of the low power factor operation. The VSCF system can be either naturally commutated or force-commutated. A naturally commutated converter (NCC) has been under development for some time and has been successfully flight-tested. A force-commutated converter (FCC) has not been developed beyond the laboratory stage. Discussions in this report are based on the NCC system only.

Table 26 is a summary of cycloconverter system attributes. In the very important cost areas of maintainability and reliability, the cycloconverter is a considerable improvement over the present system. Although the initial cost is high, 10 percent higher than an Integrated Drive Generator (IDG), the considerable reduction in maintenance and replacement costs is likely to overcome the initial cost impact. The system is recommended for future use.

TABLE 26.--SUMMARY OF CYCLOCONVERTER VSCF SYSTEM

PERFORMANCE

(1) Constant-frequency output, closest frequency tolerance.

(2) Best voltage regulation.

(3) Minimum transients obtainable.

(4) Parallel operation with least real and reactive circulating current.

(5) Requires high-frequency input; generator frequency at least three times that of output frequency.

(6) Special EMI filtering requirement

RELIABILITY

Potentially better than the conventional CSCF system.

MAINTAINABILITY

Better maintainability than the conventional CSCF system; modular construction with automatic ground checkout permits rapid localization of defective components and quick replacement.

WEIGHT, SIZE

(1) Weight is about 25 percent heavier than the Integrated Drive Generator (IDG) system.

(2) Required installation space is approx four times that for the IDG system, but required nacelle space is less.

(3) Converter can be installed at any convenient location.

(4) Low overhung moment for the accessory pad.

INITIAL COST

High initial cost (estimated to be 10 percent higher than that of an IDG).

Fig. 28 shows a dc-link VSCF system; the output waveforms are shown in fig. 29. A simplified dc-link VSCF system is shown in fig. 30; its waveforms are given in fig. 31. Both systems consist of a generator, inverter, and rectifier.

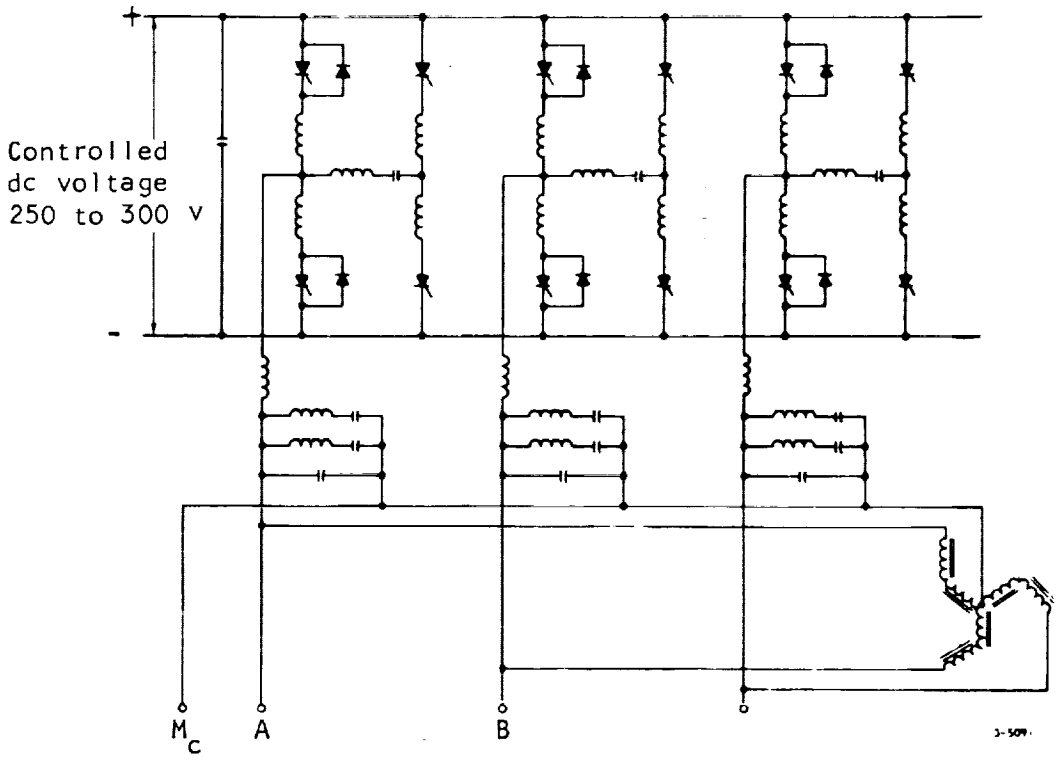


Figure 28. Dc-Link VSCF System

(1) Generator: Since the generator has to furnish rated power, including overload capacity, to the system for all input speed conditions, its size will have to be determined for the low speed. The generator output is rectified and the obtained dc power serves as input to the static inverter. Because the generator feeds a rectifier bank, a low generator reactance is desirable for minimum commutation losses. For this reason, generator ratings are typically about 10 percent higher than the system rating.

Conventional salient pole rotating rectifier generators are presently used for the dc-link application for efficiency and because only limited experience with other types for long-term, high-speed operations has been obtained.

(2) Static inverter: Inverters and filters comprise various combinations of semiconductors, magnetics, capacitors, and heat transfer systems. With presently known materials applied in the latest design of components, the weight relationships presented in the following paragraphs exist. These are expressed

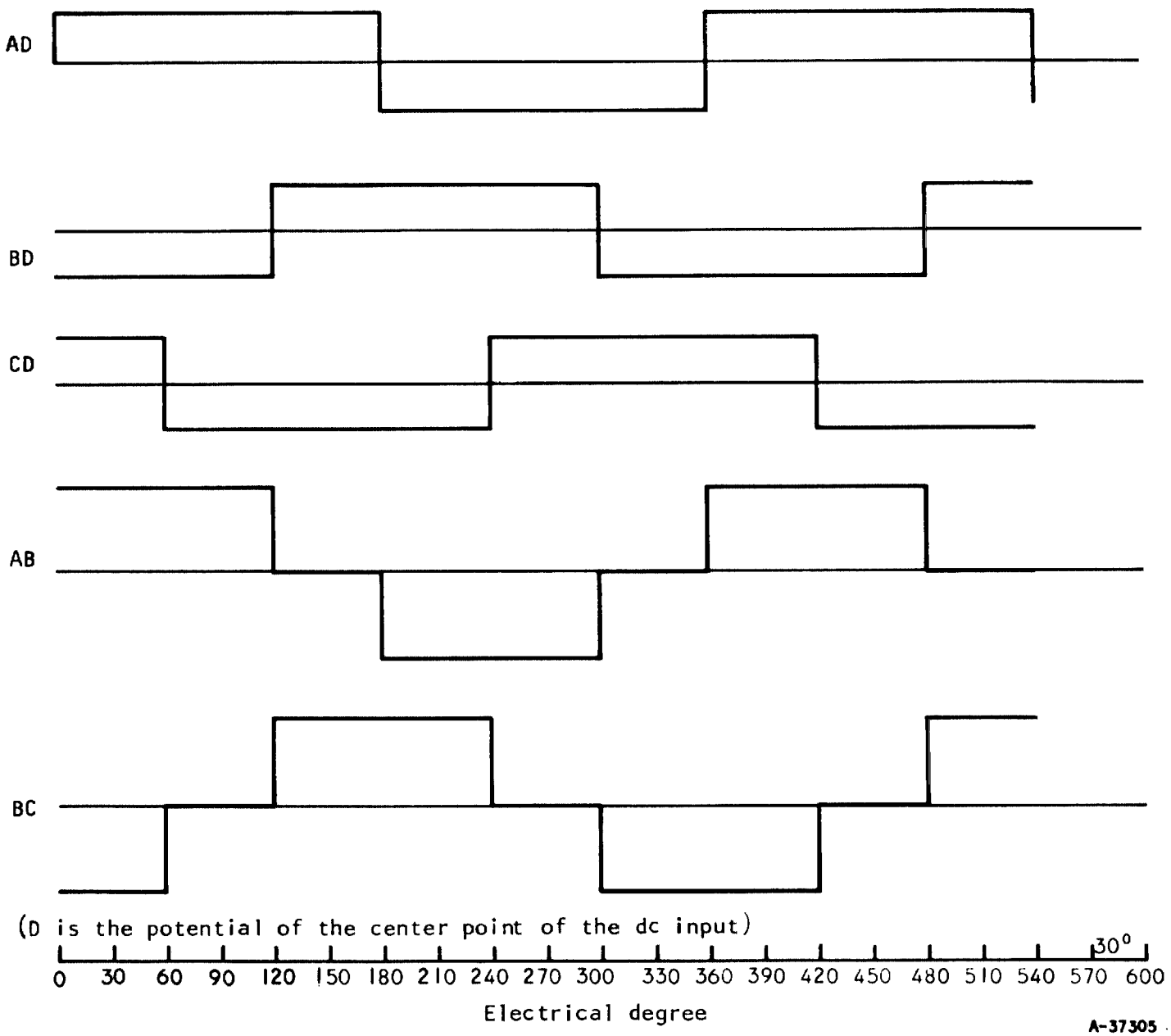


Figure 29. Voltage Waveforms in Three-Phase Bridge Inverter

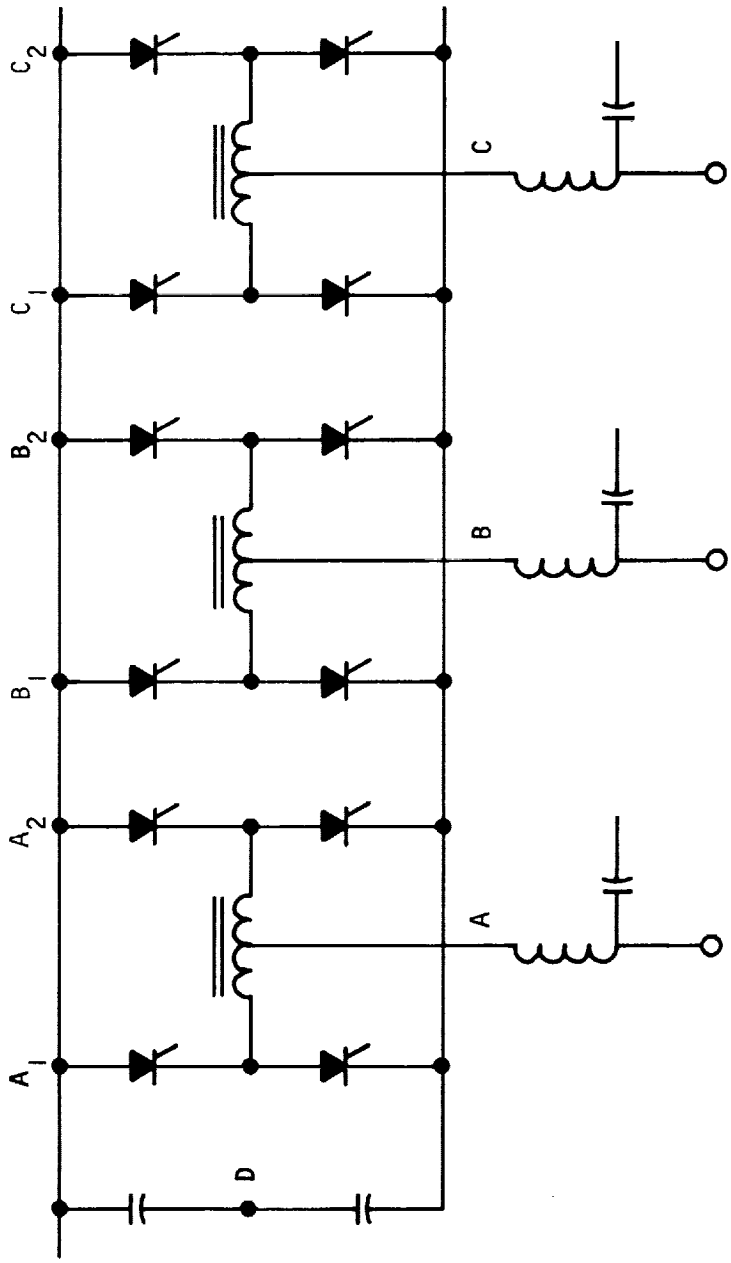
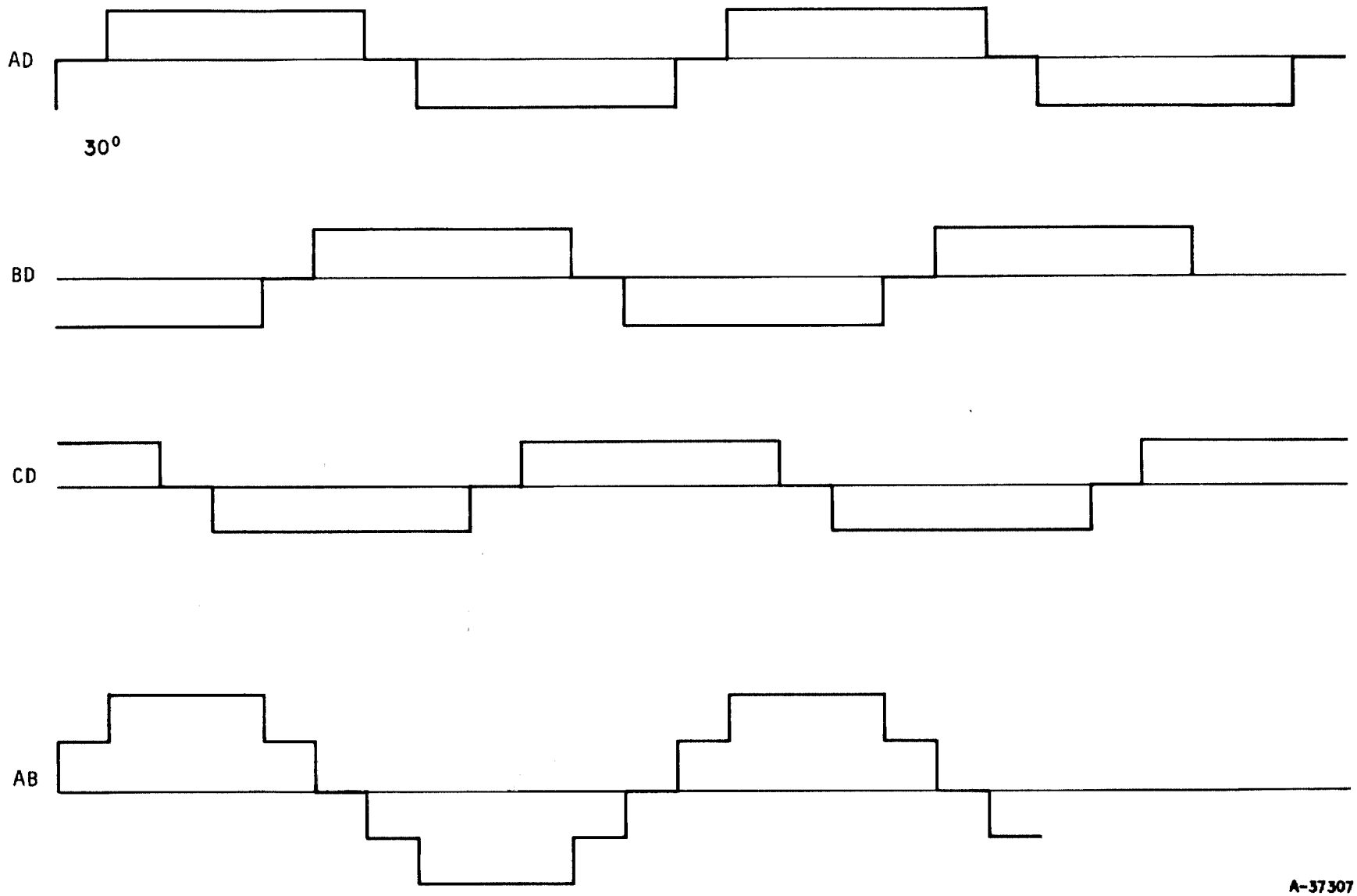


Figure 30. Simplified Dc-Link VSCF System (Double)



(D is potential of center point of Dc input to inverter)

Figure 31. Voltage Waveforms in Double Three-Phase Inverter System

in terms of electrical parameters that are readily calculable in assessing various approaches to the optimum design of the inverter/filter.

(a) Semiconductors: Semiconductors have extremely low weight in terms of kg/kVA. Their method of use does not usually influence the total weight of the system. Viz:

(1) One 235 A SCR with hardware (≈6 kVA) weighs 0.14 kg.

(2) Four 55 A SCR's with hardware (≈6 kVA) weigh 0.37 kg.

(b) Cooling system: With high efficiency heat exchangers and fans weights of cooling system for an ambient of 328°K (55°C) are typically 0.9 to 2.3 kg per kW of heat removed. The following weights are per kW of heat removed:

(1)	SCR's	1.6 to 2.3 kg
(2)	Power diodes	1.1 to 1.6 kg
(3)	Magnetics	0.9 to 1.4 kg
(4)	Capacitors	1.6 to 2.3 kg

These weights are for system employing multiple fans, including one redundant fan. The redundancy is necessary to prevent the MTBF of the whole static system from being degraded. The volume of the cooling system is 1.6×10^{-3} to 6.6×10^{-3} m^3 per kW of heat removed.

(c) Magnetics: Magnetic components are the heaviest components per kVA rating required in any inverter or filter. For a given rating and frequency, the transformer is about 1.4 times heavier than a reactor. Furthermore, magnetic components have higher losses per kVA than SCR's or capacitors, and these losses add loading and weight to the required cooling system. The weight of a well-designed 400-Hz, 3-phase transformer for 60 kVA and 97-percent efficiency is between 32 and 36 kg. The added weight of the cooling system to remove 1.8 kW of heat is from 1.8 to 2.3 kg.

The weight of the inverter/filters should be minimized. Typically good filtering and EMI suppression will result in magnetics weight of 0.9 to 1.8 kg/kVA and a volume of from 50 to 100 cm^3/kVA. Figs. 32, 33, and 34 show the variations of specific weight for magnetics versus rating, frequency and efficiency.

(3) VSCF dc-link summary and recommendations: Table 27 summarizes the characteristics of a VSCF dc-link system. In both reliability and maintainability it is much better than the CSCF present system. Initial cost, while high, is not as high as for the cycloconverter. In cases where the small increase in weight is not objectionable, the system is recommended for future use.

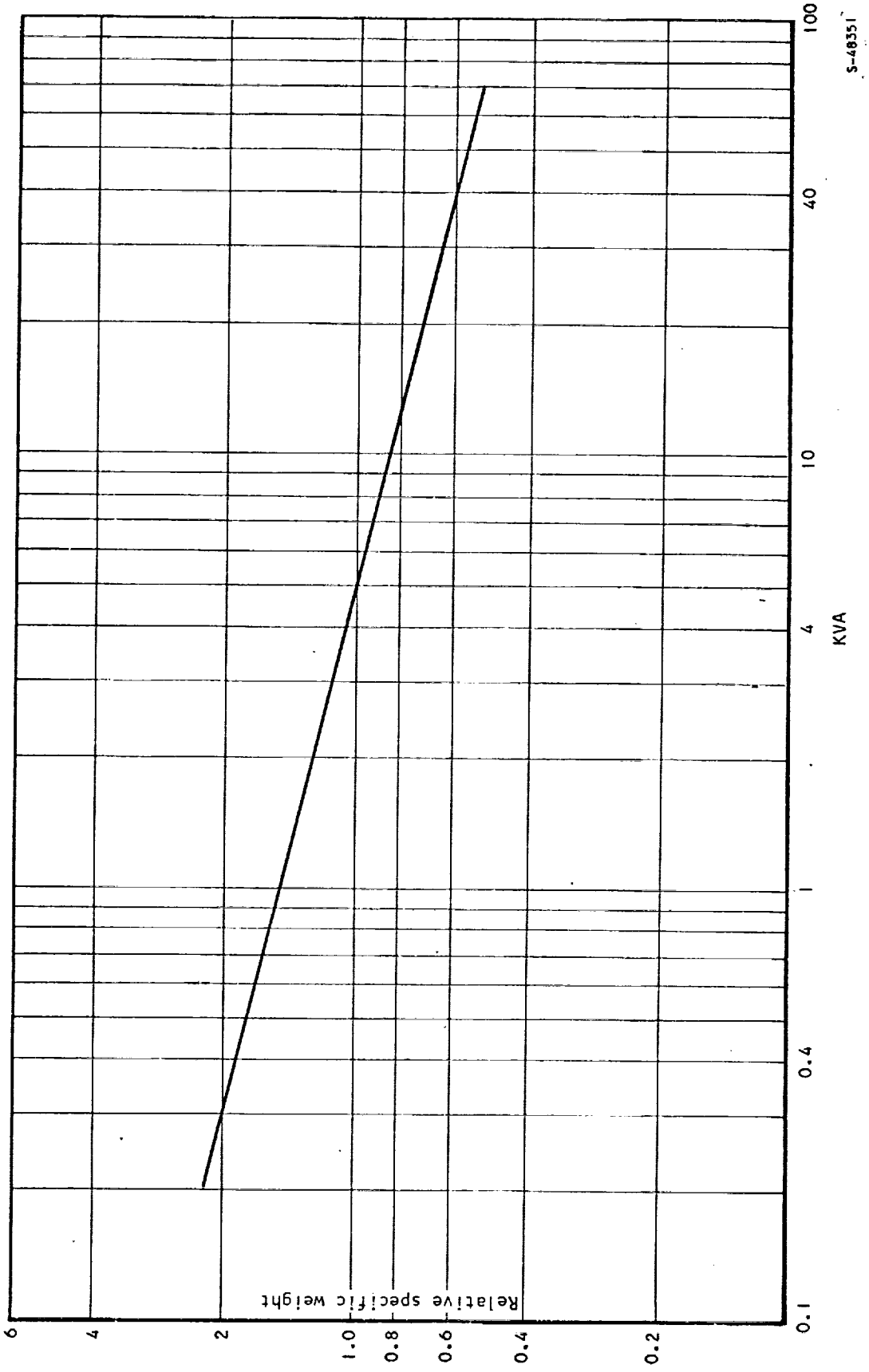


Figure 32. Magnetics Weight/Rating Relation

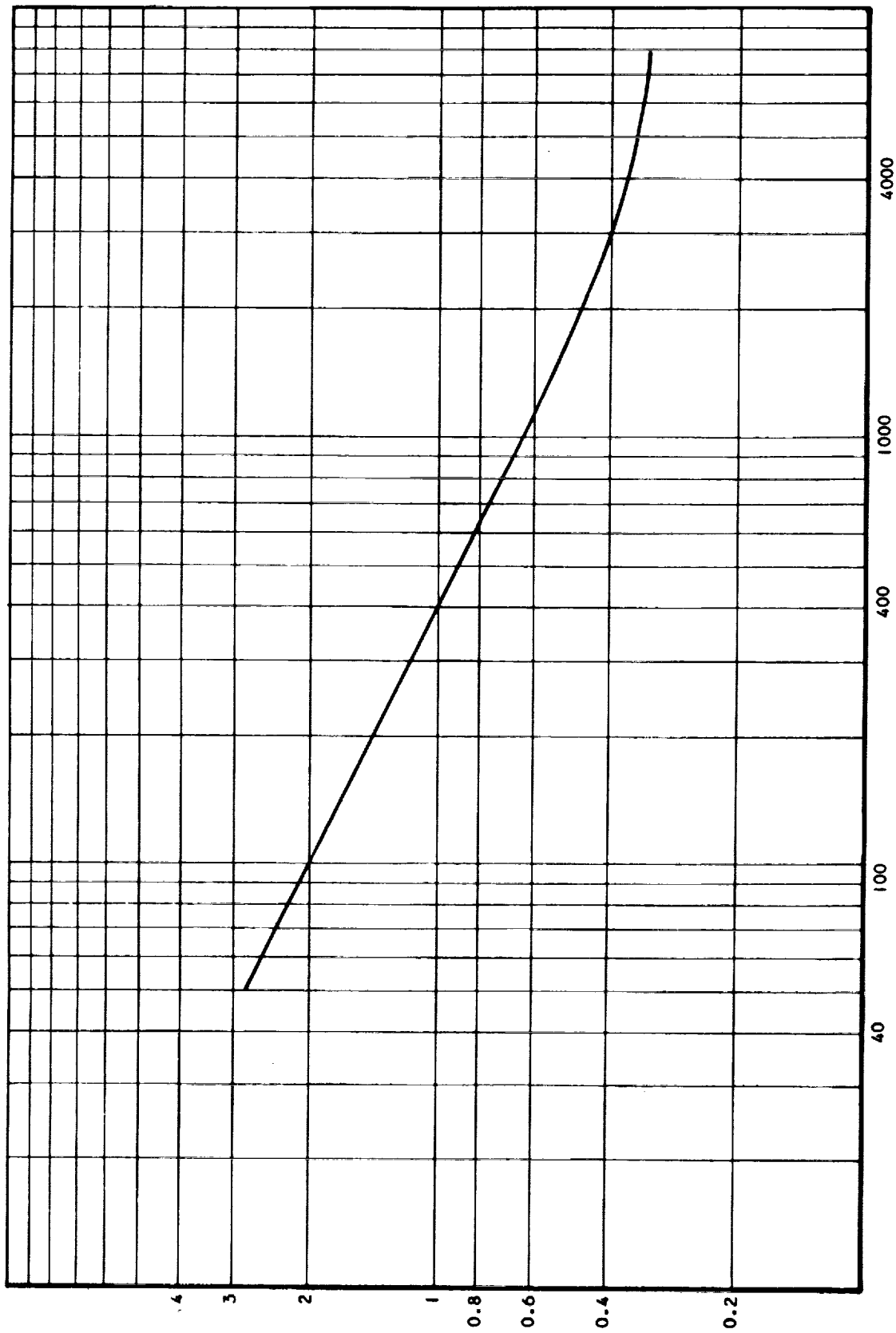


Figure 33. Magnetics Weight/Frequency Relation

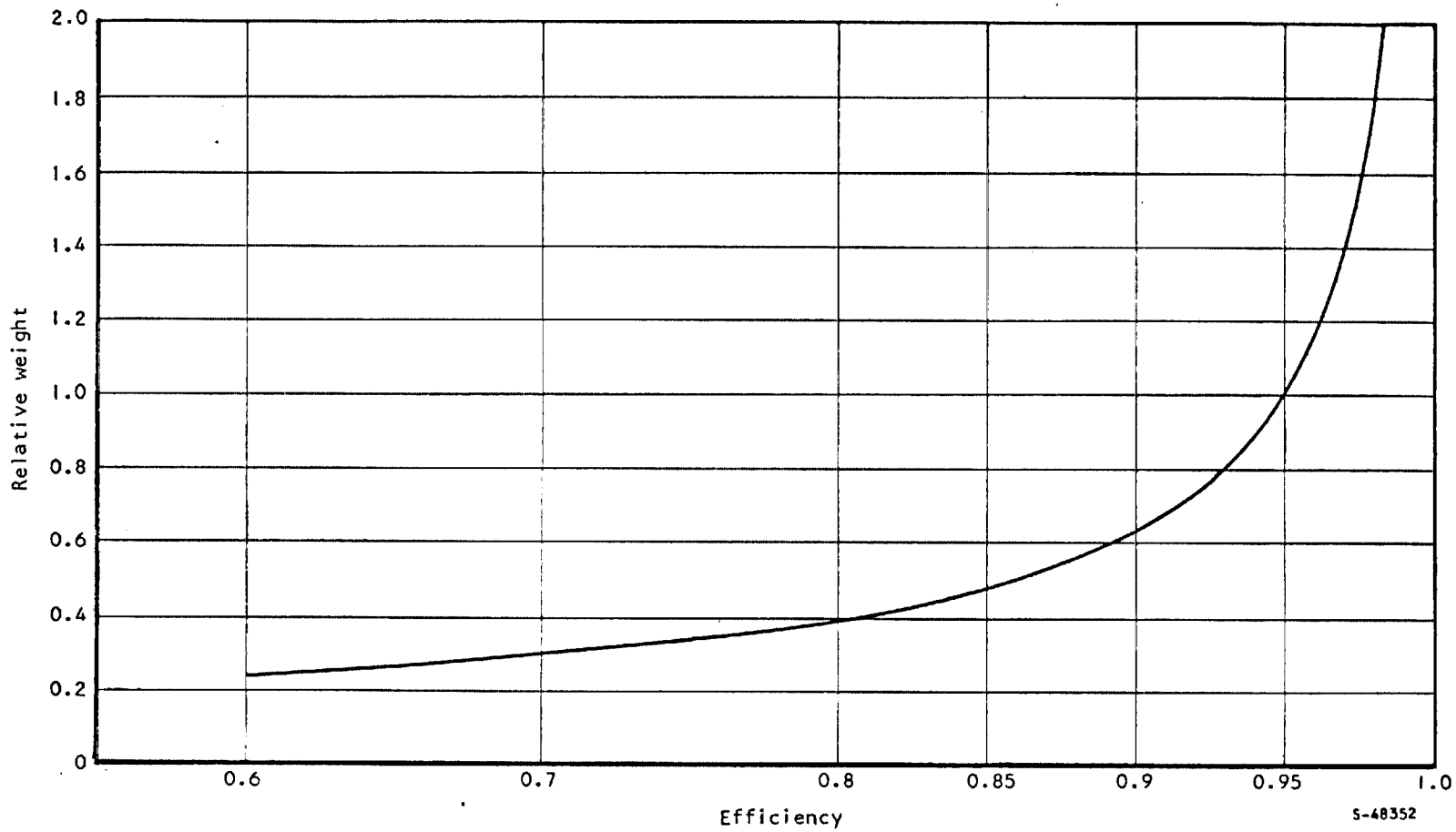


Figure 34. Magnetics Weight/Efficiency Relation

TABLE 27.--SUMMARY OF DC LINK VSCF SYSTEM

PERFORMANCE

(1) Constant-frequency output, close frequency tolerance.

(2) Good voltage regulation.

(3) Parallel operation with least real and reactive circulating current.

(4) No speed or frequency requirement on generator.

(5) Lends itself to hybrid system application.

(6) Inherent disadvantages of all forced-commutation circuitry.

(7) Transient characteristic not as good as cycloconverter system, but comparable with IDG system.

(8) Some filtering required.

RELIABILITY

Not as good as NCC, but potentially better than CSCF system.

MAINTAINABILITY

Good. The same as the cycloconverter VSCF generation system.

WEIGHT, SIZE

(1) About 10 percent higher weight than a cycloconverter VSCF.

(2) Space requirements are approx the same as cycloconverter system.

INITIAL COST

Approximately the same or slightly less than that of a cycloconverter NCC system.

Rotating inverter system.--Two basic types of rotating inverter systems were considered; the synchronous inverter and the line-commutated inverter. Both of these types offer improvements in reliability and maintainability as compared with the present CSCF system.

Synchronous inverter: Fig. 35 shows the basic synchronous inverter system for a single channel. As in the dc-link VSCF system, a variable speed alternator and a rectifier bank are required. The dc power is the input to the synchronous inverter. The major components are a synchronous inverter, a neutral transformer, a voltage regulator, and a frequency regulator. The performance of synchronous converter systems is considered equivalent to that of a conventional CSD system. A disadvantage is that the inverter requires brushes. The weight is about 1.6 kg/kW for a 60 kVA system. The mechanical construction of the synchronous inverter is very similar to that of a dc separately excited generator. In a dc machine the armature winding is connected only to a commutator, while in a synchronous inverter the armature winding is connected to a commutator and also to a set of slip rings by means of taps on the armature winding.

The fundamental character of the synchronous inverter, with regard to speed, is the same as that of any separately excited dc motor. For a given load, an increase in field excitation will cause a decrease in speed, and a decrease in field excitation will cause an increase in speed. The output frequency may be controlled by varying the amount of field excitation.

To maintain a constant system frequency, the speed of the machine is held constant by means of a frequency sensing detector in the control unit, which causes the inverter excitation to be varied according to any deviation above or below the design frequency regardless of the initial cause of such deviation. The output voltage of the system is controlled by the generator excitation, and the output frequency is controlled by the inverter excitation.

(1) Neutral transformer requirement: Because the inverter ac connections are in delta, a neutral transformer is required to establish a system neutral, which is directly grounded to the airframe. In order to prevent saturation of the neutral transformer during line-to-neutral faults and unbalanced loads, it would be designed with double-wound coils in a "zig-zag" connection. Size, weight, and leakage reactance are accordingly reduced. The windings of the neutral transformer are required to conduct only the unbalanced components of the system current.

(2) Voltage regulator functions: The voltage output is maintained constant over the load and power factor range, and throughout the speed range of its associated generator by a static voltage regulator controlling the ac output of the generator and hence the ac output of the synchronous inverter. The regulator operates on a variable pulse width series mode, controlling the average dc current to the exciter field of the ac generator. Voltage sensing on a three-phase basis is located on the synchronous inverter side of the generator circuit breaker (GCB) and at the input to the power rectifier.

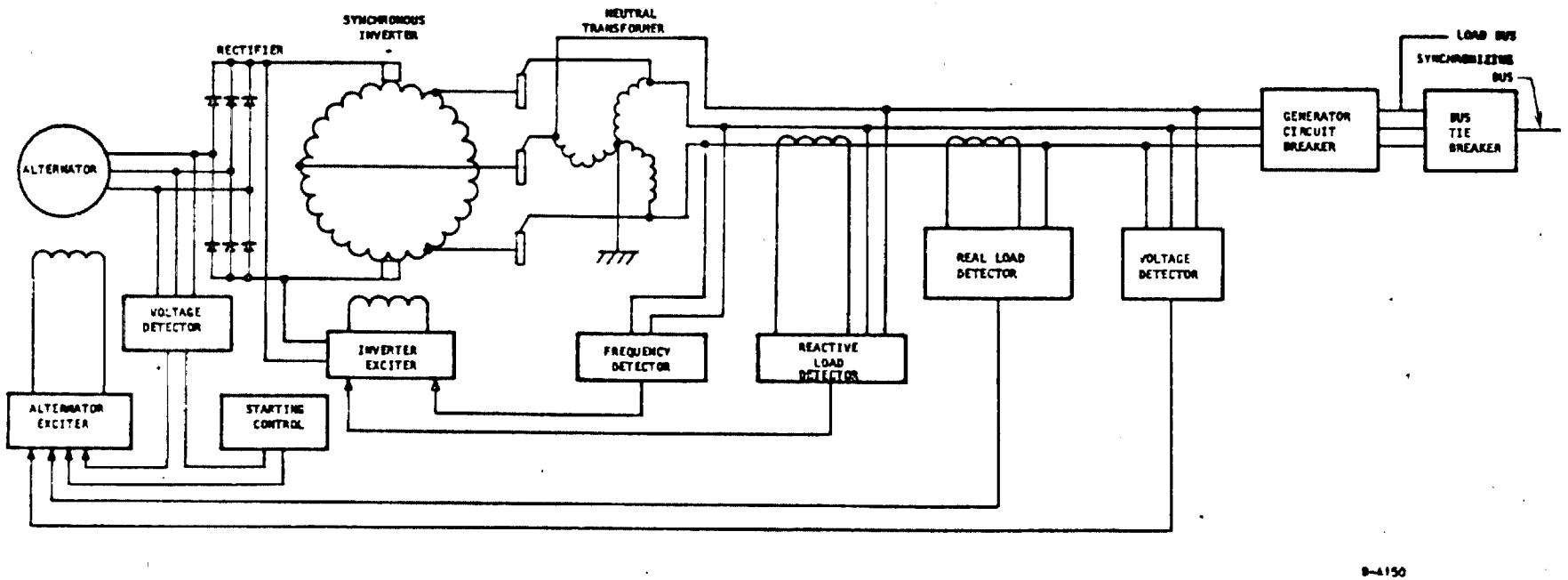


Figure 35. Basic Rotating Synchronous Inverter System

Upon removal of the load, overvoltage transients are minimized by means of suppression circuitry consisting of a momentarily switched dummy load controlled by an error signal from the voltage regulator.

The voltage regulator has the following functions:

(1) Control the output voltage of the synchronous inverter to 115 V rms, line-to-neutral

(2) Enable the synchronous inverters to be paralleled without appreciable unbalance in real load sharing

(3) Limit overcurrent of the generator and synchronous inverter

(4) Accelerate the synchronous inverter (and its connected load) on an approximate constant volts-per-cycle ramp up to synchronous speed

(3) Frequency regulator functions: The frequency output of each synchronous inverter is maintained constant over the voltage range of its associated generator and over the variations in magnitude and power factor of the connected load. This is accomplished through the use of a static frequency regulator controlling the dc excitation of the synchronous inverter field. The regulator operates in the variable pulse width series mode. A frequency feedback signal is obtained at the synchronous inverter output.

The frequency regulator serves to

- Control the frequency output of the synchronous inverter to 400 Hz.
- Enable the systems to be paralleled without appreciable unbalance in reactive load sharing.

There is considerable interaction between the frequency and voltage regulators.

(4) Synchronous inverter summary: Table 28 indicates that although the synchronous inverter represents an improvement over the present generation subsystem in terms of reliability and maintainability it is much heavier. It is not particularly recommended for future aircraft for this reason. An advance in future technology of synchronous inverters resulting in a weight decrease would make this approach much more attractive.

Line-commutated inverter: This system is an alternate approach to the rotating, synchronous inverter system, which eliminates brushes and slip-rings. Preliminary results of investigation suggest that by using the best features of rotating machine technology and the best features of semiconductor technology this approach offers a good combination of a brushless machine and a solid-state inverter. As shown in fig. 36, the system consists of two major packages, a generator package (alternator and rectifier bank) and an inverter package (synchronous condenser and inverter bank). A brushless rotating rectifier

TABLE 28.--SUMMARY OF ROTATING SYNCHRONOUS INVERTER SYSTEM

PERFORMANCE

- Constant frequency output.
- Adaptable for parallel operation.
- Equal or better efficiency than IDG.
- Complicated regulation scheme.
- Slow transient response.

RELIABILITY

- Brush replacement required every 5000 hr with periodic inspection.
- Machine MTBF slightly better than IDG.

MAINTAINABILITY

- Inexpensive overhaul.
- Regular inspection required.

WEIGHT, SIZE

- Approximately twice the weight of the IDG.
- Minimum nacelle space required.
- Minimum overhung moment.

INITIAL COST

Lower cost than other constant-frequency generation systems, but higher than a variable-frequency generation system.

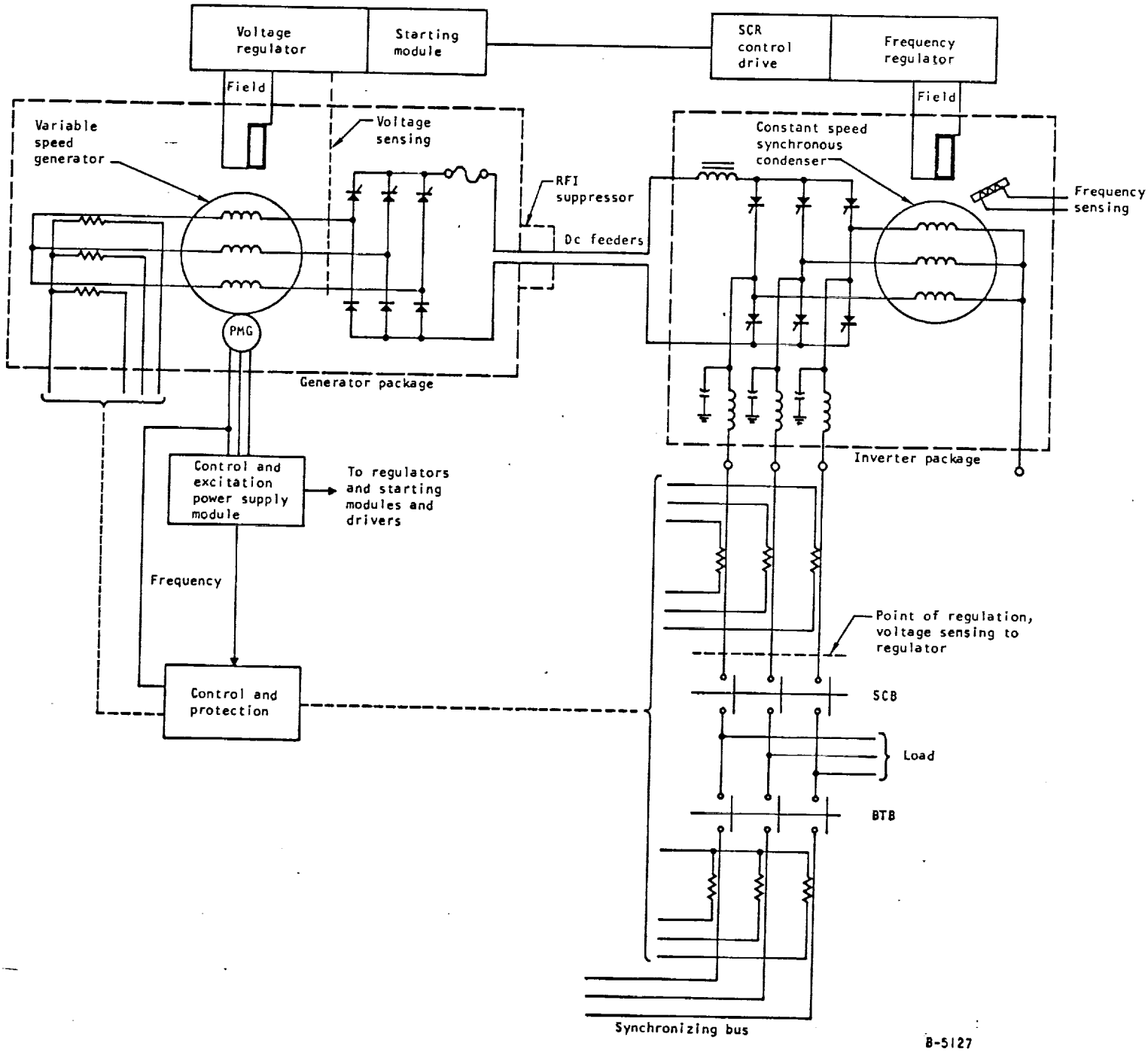


Figure 36. Electrical CSCF System Simplified Schematic

alternator is used; it has optimum weight-to-output ratio for this application and relatively simple design and construction.

A variable-frequency, constant voltage output of the engine-driven alternator is rectified by a full-wave bridge of which one leg is controllable. During normal and overload conditions, the half-wave phase-delayed rectifier is turned on full to provide maximum dc output voltage. Since the dc voltage has a superimposed ac component with a frequency six times that of the engine-driven alternator, a smoothing reactor is employed. This filtered dc power is then input to the line commutated inverter.

If the synchronous condenser turns at nominal speed (12,000 rpm) with field excitation applied to it, the ac side of the inverter sees three-phase 400-Hz voltage provided by the synchronous machine. This output is also sampled and properly conditioned to provide firing pulses to the appropriate thyristors in the converter at the rate determined by the synchronous machine. This enables the inverter to conduct line-to-line rectangular blocks of current which in turn constitute the supply for the synchronous condenser. Because the back EMF of the rotating machine is also seen by the inverter, natural commutation takes place.

The synchronous condenser supplies reactive power to commutate the inverter and reactive power for the load. An ac line-commutated inverter transmits power from the dc bus to the ac output bus. The power circuit is composed of a three-phase full-wave thyristor bridge. The gates of the thyristors are fired within the region of $\alpha = 90^0$ to $\alpha = 150^0$ (fig. 37). The flow of energy is governed by the level of the dc bus and the α angle. The gates of the thyristors are controlled to establish the required ac output voltage. With a phase delay angle of $\alpha = 150$, a maximum output ac voltage is obtained. As the α angle is decreased, the output ac voltage is reduced as shown in fig. 38. The three-phase ac voltages that commutate the converter thyristors come from the synchronous condenser. The initial timing that establishes the thyristor firing pulses is then derived from the synchronous condenser.

System frequency is determined by the synchronous condenser speed, which is controlled directly by its field current. Steady-state frequency regulation can be as accurate as 400 ±1 Hz at the output. System voltage is determined by the engine mounted generator's field current.

The waveform produced by the system is nearly a sinewave requiring little filtering when compared to the straight dc-link VSCF system. This system eliminates the complex and heavy static commutation circuitry and filter elements, replacing them with a brushless, high reliability, cabin-mounted, rotating machine.

The synchronous condenser is by its nature an excellent filter, so that almost pure sine wave output results. Additional filtering, however, is necessary for the system output to suppress the total harmonic content below 5 percent.

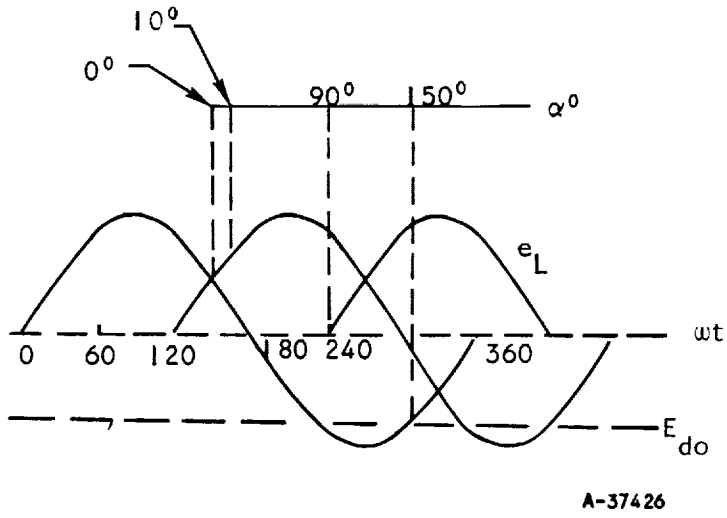


Figure 37. Thyristor Firing Time

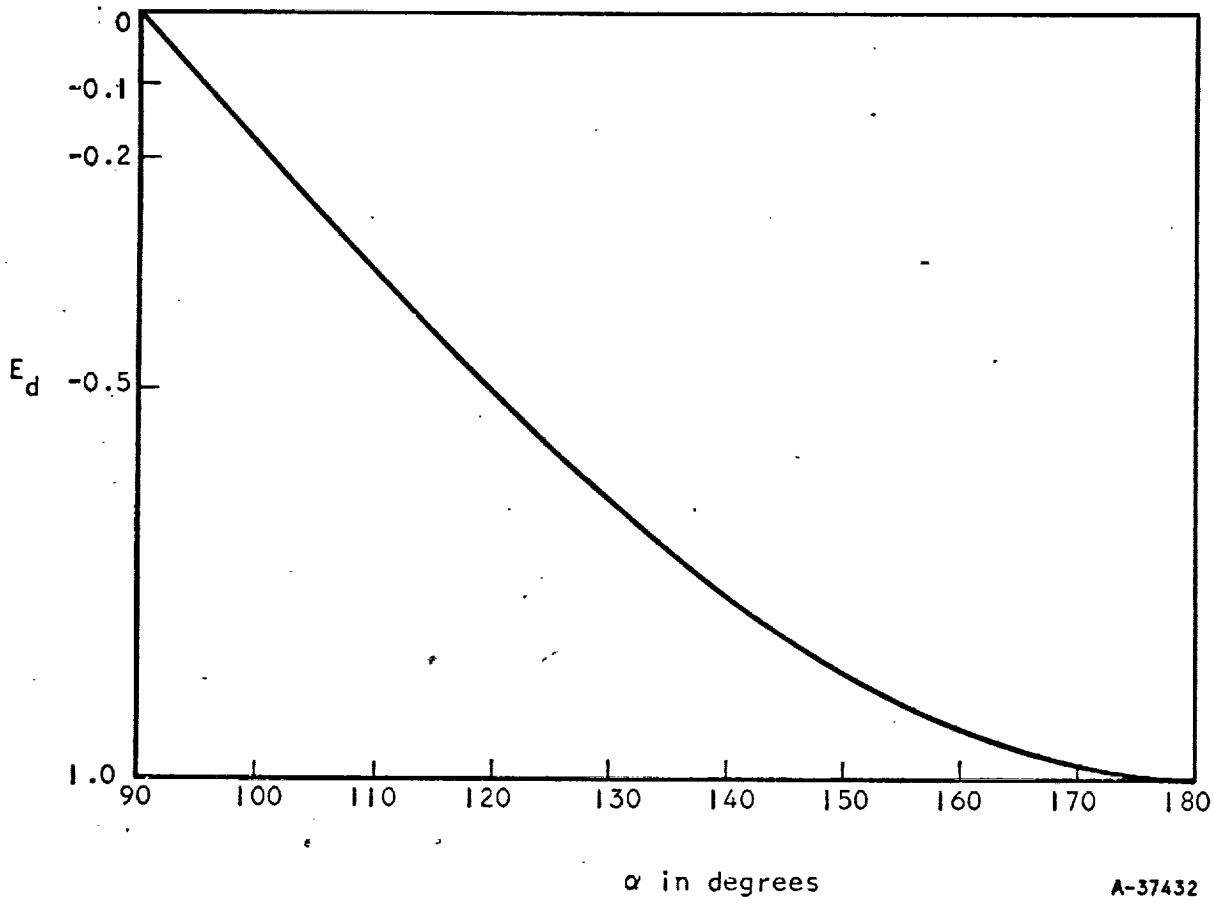


Figure 38. Variation of Output Voltage with Angle α per $E_d = E_{do} \cos \alpha$

Synchronous condenser speed is sensed by a magnetic pickup and compared to a reference. Any deviation from nominal frequency is corrected by increasing or decreasing the field excitation in the required direction. Increasing the field reduces frequency, decreasing the field increases system frequency. In the same way, any decrease in lagging power factor increases frequency, while leading power factor loads decrease system frequency.

If two or more line commutated inverter systems are operated in parallel, control of the field excitation for the generators determines real load power sharing since control of the excitation for the synchronous condensers would affect the reactive load division between systems.

(1) Synchronous condenser reactive requirements: The reactive power requirement of an inverter with suitable regulation on the ac end is approx 0.5 to 0.8 kVA (reactive) per kW active power supplied to the ac bus. This reactive power is supplied by the synchronous condenser.

Converters, in the inverter mode, operate invariably with a leading power factor, the value of which is given approximately by

$$\cos \phi = \frac{\cos \beta + \cos \delta}{2}$$

where β and δ are the SCR trigger angle and the turnoff angle plus margin respectively.

Fig. 39 below shows how the reactive power requirement of the converter varies with the advance angle β, assuming no overlap. In reality, the overlap and the current harmonics' effect on the reactive power of the ac side complicate the relationship.

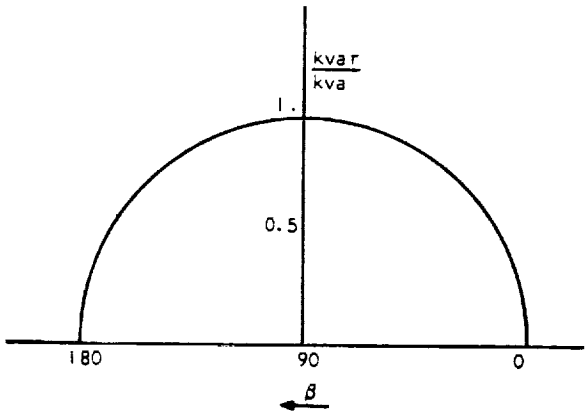


Figure 39. Converter Reactive Requirement vs Advance Angle

If the advance angle, β, is so controlled that the minimum margin of $\delta_0 = 20^0$ is maintained over the entire load range, then the reactive power requirement, and therefore the size of the synchronous condenser becomes minimum. Fig. 40 shows the reactive requirement plotted for a turnoff angle of $\delta = 20^0$. The rating of the synchronous condenser is then the sum of the reactive requirement of the converter and the reactive component of the load.

(2) Short circuit and fault-clearing requirements: Present requirements for short circuit capability of conventional aircraft generating systems are three per unit (P.U.) current output for a minimum of 5 sec to operate trip elements of the distribution circuit breakers for fault clearing. A system, having satisfied this transient excursion, is required to recover with a specified time and is not allowed to discontinue supply to the load bus.

This can be difficult for the system in consideration since, in many cases, the synchronous condenser will be located remotely from the engine-driven generator to take advantage of the ability to use dc feeders and to allow better weight distribution in the airplane and more favorable environment conditions.

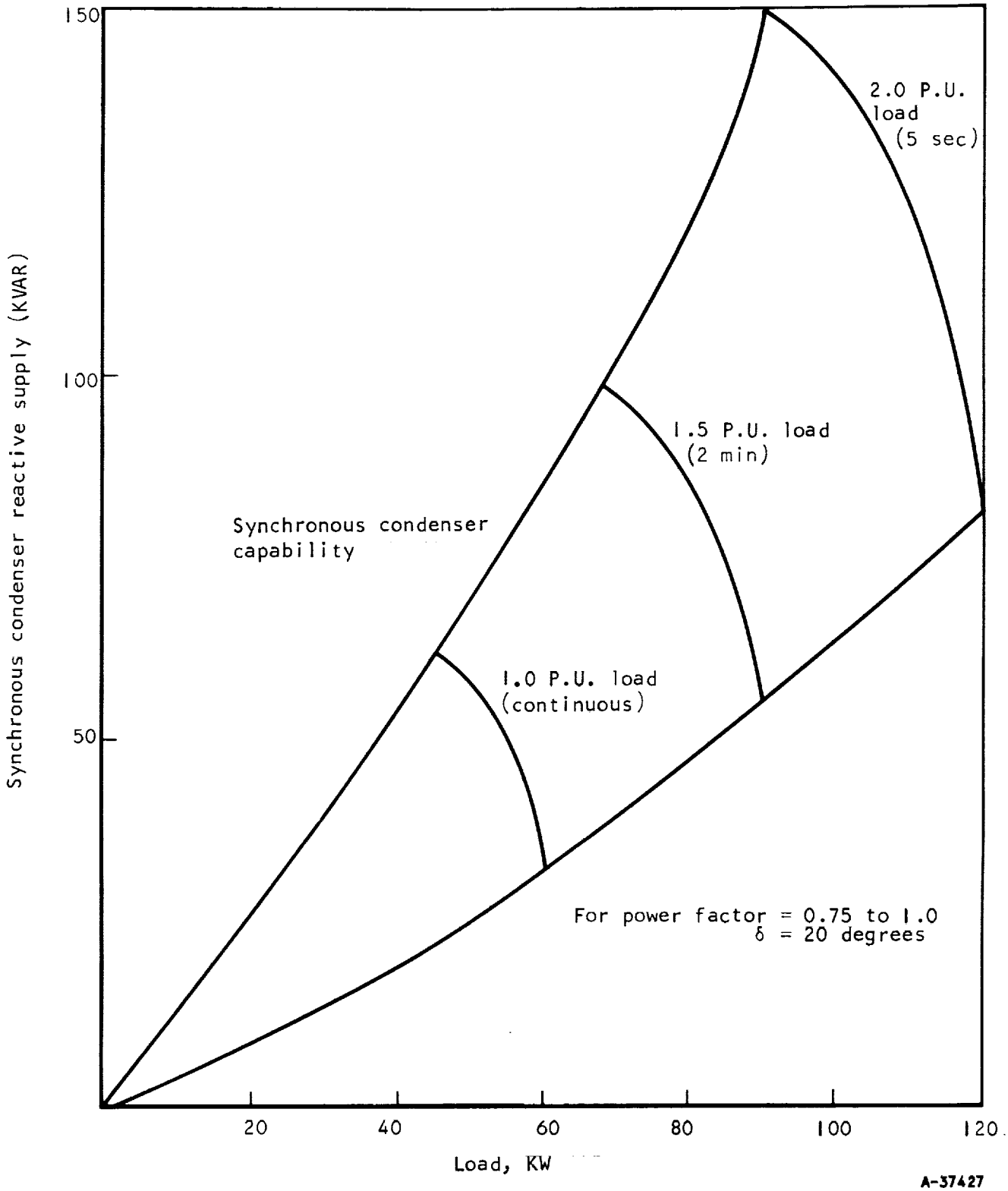


Figure 40. Reactive Requirement of Inverter

Most likely, the installation location of the synchronous condenser will be close to the main power shield or the point of regulation in the system.

Since the synchronous machine is the sole source supplying the fault current, increasing the rotating mass by addition of a flywheel should greatly improve short circuit current capability.

(3) Summary of line-commutated inverter: Table 29 indicates that for maintainability and reliability the line commutated inverter is superior to both the brush type synchronous inverter and the IDG. However, it is much heavier than the IDG (approx twice the weight). Its great drawback is the requirement for a special start-up circuit. Except for the start-up question, the subsystem is one of most adaptable generation schemes and is expected to find much future use in aircraft.

Super Auxivar system.--The Super Auxivar system consists of: (1) an integrated rotating machine where one single case houses the alternator, the induction machine and the differential gear drive and (2) an electronic control unit which consists of the voltage and frequency regulator, various protection and parallel operation and control circuits. A schematic diagram of the system is shown in fig. 41. The relations for speed and torque of the induction machine are indicated. The principle of the constant speed drive is to utilize an induction motor which, through a differential, can add speed to, or subtract speed from, the output speed of the gearbox so that the alternator shaft speed is maintained constant. When the engine pad speed is low, the induction machine acts as a motor supplied by the electric output of the alternator. When the pad speed is high, the induction machine acts as a generator which delivers 400 Hz ac power to the system.

Since the speed range of turbojet engine is typically 2 to 1, the speed of the induction machine has to cover a rather broad range. This is obtained by a combination of pole changing and variation of slip. For example, for an engine speed range of 6 000 to 12 000 rpm, and an alternator speed of 12 000 rpm using a five-step synchronous speed induction machine (with 6 and 12 pole connections) the synchronous speeds would be -8 000, -4 000, 0, 4 000 and 8 000 rpm. The zero synchronous speed is obtained by supplying the stator winding of the induction machine with dc.

The slip of the induction machine is controlled by variation of the magnitude of the ac voltage or the magnitude of the dc current. The variable ac voltage is obtained from the alternator output through a solid state control unit. This control unit consists of back-to-back thyristors which perform both phase switching and regulation functions. Fig. 42 shows the basic design of the regulator and the firing conditions of the SCR's.

The presence of SCR's in parallel on the network necessitates an efficient filter unit. For this purpose a special 3 phase twin winding transformer is used. The first winding carries the network current while the second carries the current going through the SCR's. With appropriate design the distortion of the alternator voltage wave can be compensated. The filter transformer together with the SCR's are integrated into the rotating machine. Thus the electronic

TABLE 29.--SUMMARY OF BRUSHLESS SYNCHRONOUS INVERTER SYSTEM

PERFORMANCE

(1) Special start-up circuit required.

(2) Constant frequency output.

(3) Adaptable for parallel operation.

(4) Equal or better efficiency than IDG.

(5) Complicated regulation scheme.

(6) Slow/medium transient response.

(7) Limited short circuit capacity.

RELIABILITY

(1) System reliability superior to IDG.

(2) Basically two synchronous machines and two semiconductor power converters.

MAINTAINABILITY

(1) Superior to brush-type synchronous inverter (no regular inspection required).

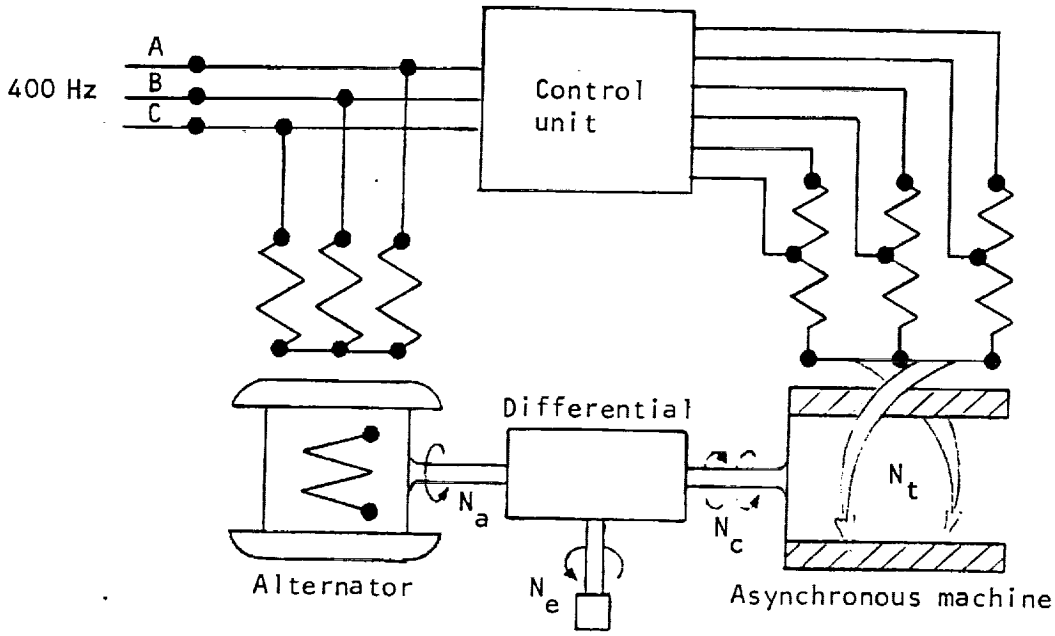
(2) Simple inexpensive overhaul.

WEIGHT, SIZE

- Approx twice the weight of the IDG.
- Minimum nacelle space required.
- Minimum overhung moment.

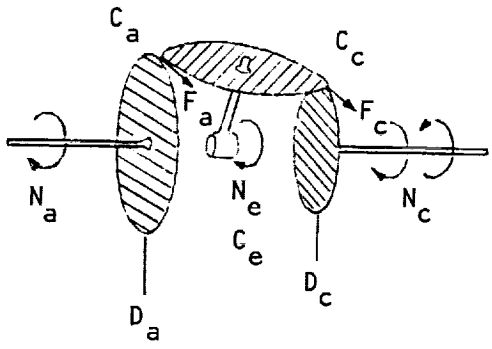
INITIAL COST

- Approximately equal to brush-type synchronous inverter system.



$$\alpha = \frac{D_a}{D_c}$$

$$N_c = (1 + \alpha)\, N_e - \alpha N_a$$

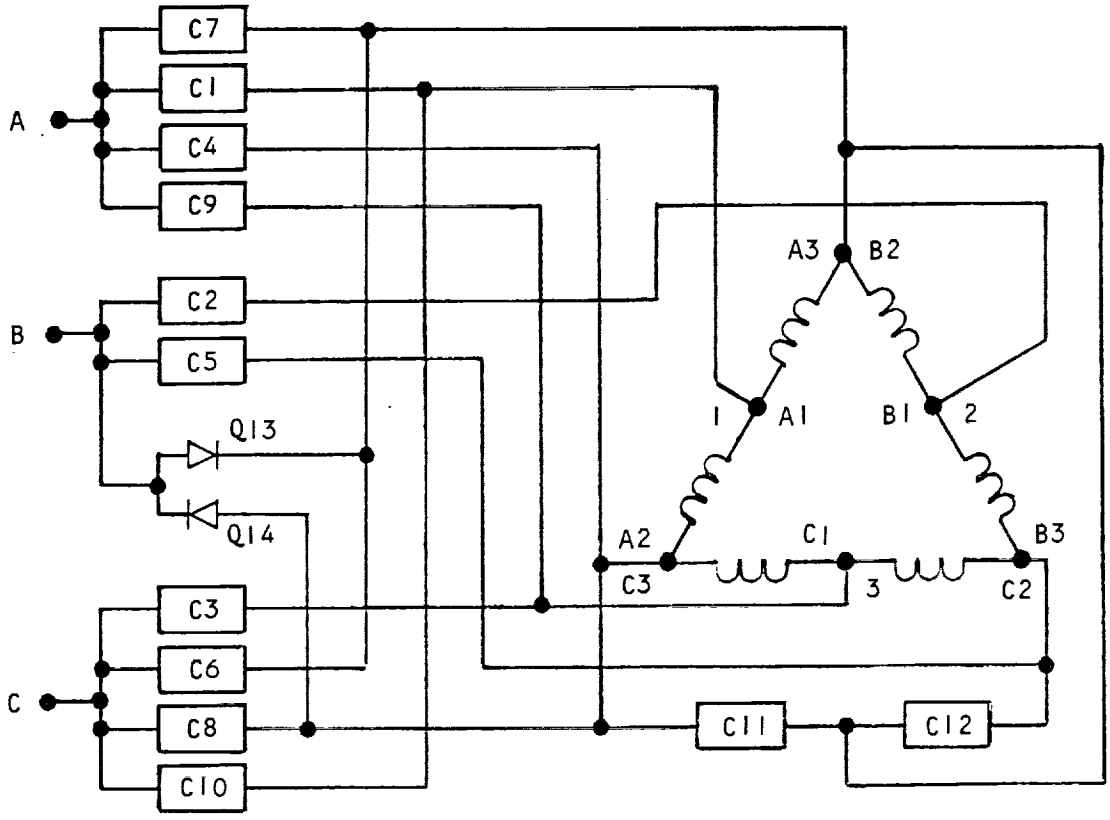


$$F_a = F_c$$

$$C_c = \frac{C_a}{\alpha}$$

$$C_e = C_a + C_c$$

Figure 41. Super Auxivar System Schematic Diagram



Range	Connection	Firing static contactors				
		Phase A	Phase B	Phase C		
I	Y	C1	C2	C3	C11	C12
II	Δ	C4	C5	C6		
III	Δ	Q7 Q4	Q13 Q14	Q6 Q8		
IV	Δ	C7	C5	C8		
V	Y	C9	C2	C10	C11	C12

Figure 42. Induction Machine Control Diagram, Super Auxivar System

control unit consists of only the very low power elements such as logic circuits and measuring and control devices.

The basic equations describe the relationships of speed, torque and power of the components in the Super Auxivar system are:

$$N_c = (1 + \alpha)\, N_e - \alpha N_a$$

$$C_e = C_a + C_c$$

$$C_a = \alpha C_c$$

where N_e = speed of the engine gear pad (variable)

N_a = speed of the generator

N_c = speed of the induction machine

C_c = torque of the induction machine

C_a = torque at the generator shaft

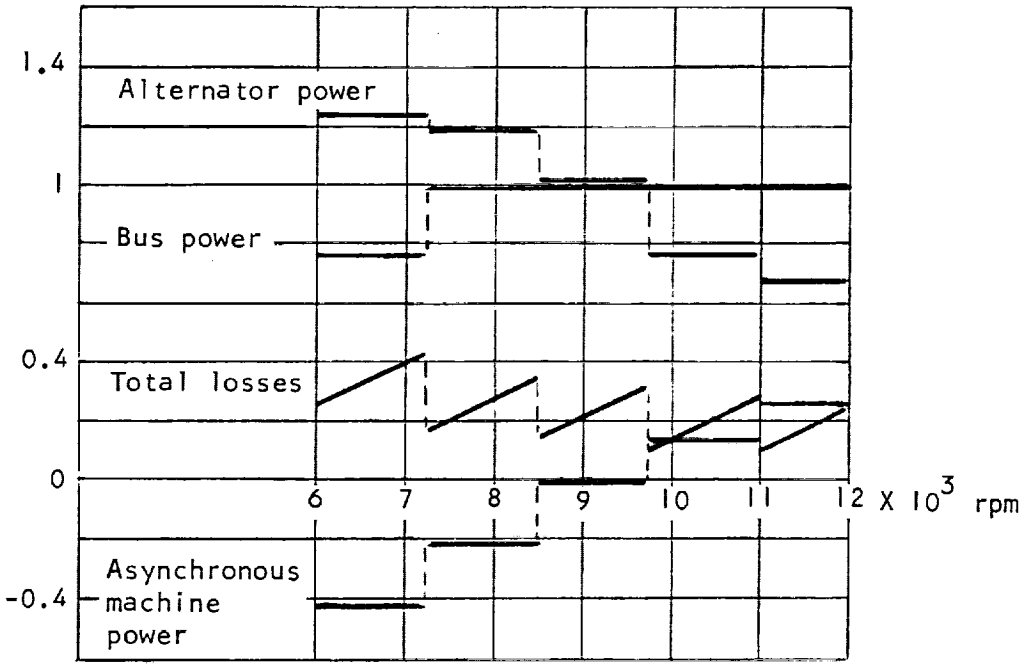
C_e = torque input of the engine gear pad

α = ratio of the diameters of the generator wheel to the induction machine wheel in the differential drive.

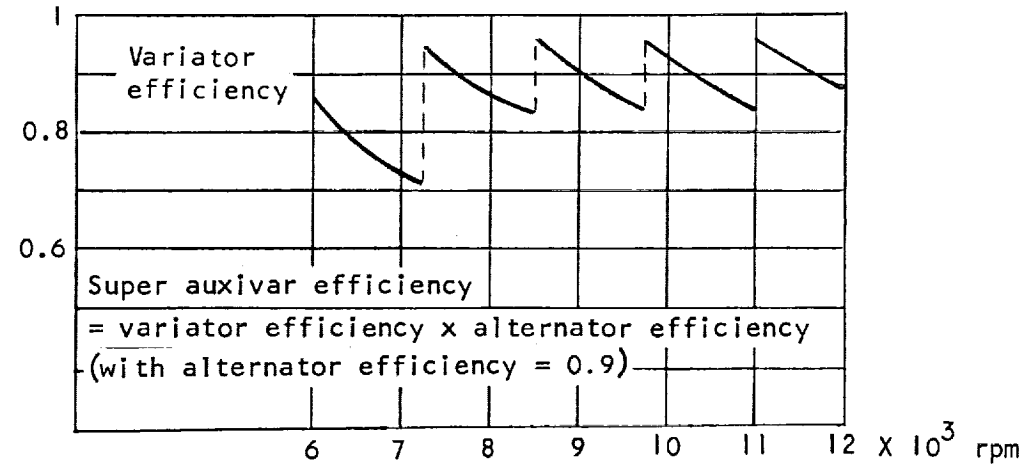
Power balance: The electric power circulating between the alternator and the induction machine is closely related to the input speed. For the example given above, in the first two speed ranges (i.e., 6 000 to 8 200 rpm) power flows from the alternator to the induction machine which is acting as a motor. In the 3rd speed range (8 200 to 9 750 rpm) no power flows between the two machines. The induction machine with its stator excited by dc is acting as a brake. In the last two speed ranges (9 750 to 12 000 rpm) the induction machine, working as a generator, supplies ac power to the system. Fig. 43 shows the real power balance and the efficiency of the system. It is seen that the alternator generates more than 1 pu power in the first two speed ranges and less than 1 pu power in the last two speed ranges. The total bus power is close to 1 pu with input speed above 7 250 rpm, but is reduced to 0.67 pu when input pad speed is below 7 250 rpm. This performance degradation is adopted by Auxilec for the purpose of weight reduction. If full power has to be maintained at lowest speed, the system weight will be heavier.

The induction machine in the Super Auxivar system can be used as the engine starter if ac power is available for engine starting.

Summary of Super Auxivar system: Table 30 summarizes the performance, weight, reliability, maintainability and cost characteristics of the Super Auxivar. Reliability and maintainability are improved at the cost of an



Real power balance



Efficiency

Figure 43. Real Power Balance and Efficiency of Super Auxivar System

increase in weight compared to the conventional CSCF machine. The overall projected improvement is seen as being marginal.

Wild frequency system.--In this case, the alternator is driven directly by the engine accessory pad. The alternator speed varies with engine speed, producing a frequency range of approximately two to one. This generation system is the simplest, most inexpensive, most reliable, lightest weight, smallest volume among the generation schemes. For extreme environmental conditions, the alternator could be of the solid rotor construction, eliminating the need for rotating rectifiers, thus enhancing reliability. One draw-back with this simple, wild frequency supply is that the wild frequency generator cannot be paralleled with other wild frequency generators to provide desirable back-up power. Variable frequency generation appears particularly attractive where the ratio of the engine speed variation is smaller than 2 to 1, as is the case for the turboprop power plant. Here better generator utilization and better compatibility with distribution and utilization is realized.

Wild frequency generation is used in some existing aircraft.

Summary of wild frequency generator: Table 31 indicates that although this generator has some formidable disadvantages it can nonetheless be very attractive for use where variable frequency output is acceptable. The combination of low weight, maintainability and cost versus high reliability make this a highly recommended subsystem.

Dc generation system.--With the exception of wild frequency generation the best approach is a generator whose output is rectified to provide dc power. A full wave power diode bridge supplied by three (or six) generator phases can be made an integral part of the generator. The rectifier elements, mounted to appropriate heat sinks and located in the cooling air stream or cooling oil flow of the generator, may efficiently share a single heat transfer system. With this combination, any desirable voltage level can be produced well within the electrical stress limitations of the semiconductor diode. Considering conventional voltage levels and standard generator ratings, rectification losses of 600 W to 2 kW for machines of 30 kVA to 120 kVA capacity must be accounted for. This lowers the generating efficiency by an average of approximately 2%.

The complete rectification assembly weight is estimated to be within 4.5 to 7 kg, depending on generating capacity. Some radio noise suppression due to diode switching will also be required so that the total additional weight to the variable frequency generator is approximately 7 to 9 kg. Since the displacement power factor caused by diode commutation is imposed on the generator, its sizing has to be somewhat increased. Empirical data for this case shows a generator weight penalty of approximately 17%.

Because of additional components necessary for the power conversion, the reliability is slightly lower than for straight variable frequency generation.

TABLE 31.--SUMMARY OF WILD FREQUENCY GENERATION SYSTEM

PERFORMANCE

Advantage	Highest efficiency obtainable because only one conversion process.
Disadvantages	(1) Output is variable frequency.
	(2) Generator has to be rated for maximum output at lowest speed.
	(3) Not adaptable for parallel operation.
	(4) Possible beat frequency operation with other generation channels.
	(5) Voltage regulation has to accommodate for both load and speed changes.

INITIAL COST

Minimum expenditure.

RELIABILITY

Highest attainable, particularly with solid rotor construction.

WEIGHT AND VOLUME

Lowest weight and volume, least nacelle space required.

MAINTAINABILITY

Simplified--minimum maintenance cost.

PRODUCIBILITY

Straight forward simple design approach well known manufacturing techniques, excellent availability.

Summary of dc generation subsystem: Table 32 indicates that the major disadvantage is the transient response and filtering required. From every other point of view the dc generation subsystem is close to being as favorable as the wild frequency system. It has one major advantage over the wild frequency system, that is, ease of parallel operation. The dc system is recommended for future use.

Comparison of generation subsystems.--The performance of the various subsystems is summarized in Table 33. A specific subsystem weight comparison of some of the generation suhsystems is shown in Table 34. The weight data of the first three subsystems is taken from reference 10. The EMCSD (electromechanical constant speed drive) system is similar to the conventional CSCF system except that the hydraulic CSD unit is replaced by a magnetic particle clutch. The EMCSD system was developed by the Vickers Aerospace Div of Sperry Rand Corp. and due to the lack of data, is not discussed further in this report. The weight figures for the Super Auxivar system are scaled down from the available data of a 60-kVA unit (it has a specified deviation of 0.67 pu power output at minimum speed). For the regular Super Auxivar system, ac ground power is assumed available for engine starting. Table 35 compares the subsystems for reliability, maintainability, weight and estimated initial cost. As can be seen, the wild frequency subsystem appears as the best followed immediately by the dc system.

On the other hand, from Table 33, the line-commutated rotary inverter is probably the overall best choice for performance since it does not have the limitations of either the dc or wild frequency systems. However, where low maintainability cost and weight are most important the dc system or the wild freqiemcy system is recommended.

The Internal Engine Generator (IEG) system concept: As noted earlier in the comparison of candidate power systems, the IEG is the subject of a recent study undertaken by Boeing on behalf of NASA Langley (Contract NAS1-10893). It has the considerable advantages of reduction in engine frontal area drag, improved engine accessibility and allows use of a remote, distributed electrical/hydraulic system for actuation of flight control surfaces. The last advantage arises from the projected use of the IEG as an engine starter. For this the IEG requires a rating of up to 250 kVA. An increase of the rating to 300 kVA would allow supplying the total secondary power system including the hydraulic and pneumatic subsystems. The projected required minimum MTBF is 50,000 hours. Such a high reliability is important because a generator failure would necessitate engine removal. The IEG could be driven by either the low-speed N_1 shaft or the high-speed N_2 shaft of the engine. For the best starter-generator design the N_2 shaft drive would be preferable.

At present, the use of a VSCF cycloconverter, concept (or VSCF dc link) is favored. During engine starting, the cycloconverter would operate in the reverse (or motoring) mode. However, the foregoing applies only to ac generation subsystems. A dc generation subsystem - if practical - would result in simple conversion equipment, i.e., a simplified separate converter for starting and a rectifier. This would certainly increase the attractiveness and competitive position of the IEG. Further work in this area is recommended.

TABLE 32.--SUMMARY OF DC GENERATION SYSTEM

PERFORMANCE

Advantage

(1) High efficiency

(2) Sources may be paralleled easily

Disadvantages

(1) Voltage regulation has to accommodate for both load and speed changes

(2) Transient response, time and magnitude will be a function of generator speed. Voltage overshoot and duration is excessive particularly upon load removal because energy flow is blocked in one direction.

(3) Ripple smoothing chokes may be required.

INITIAL COST

A 16% to 20% higher cost than for wild frequency generation is estimated.

RELIABILITY

Very good, but less than for wild frequency generation.

WEIGHT AND VOLUME

An average weight increase of 40% for standard generator ratings from 30 kVA to 120 kVA is predicted. (Percentual weight increase is lower for heavier capacities.) The generator will occupy approximately 20% to 25% more space than without rectification.

MAINTAINABILITY

Same as for wild frequency.

PRODUCIBILITY

Same as for wild frequency

TABLE 33.--GENERATION SCHEMES PERFORMANCE SUMMARY

Generation scheme	Utility of power type	Parallel operation	Typical efficiency 60 kVA system	Steady state voltage	Steady state frequency	Transient response	Filter
IDG CSCF	Univer-sal	Yes	0.78	Very good	Good	Slow	No filter
NCC VSCF	Univer-sal	Efficient parallel operation	0.83	Very good	Best	Fast	Heavy filter
DC link VSCF	Univer-sal	Efficient parallel operation	0.77	Very good	Best	Fast	Heavy filter
Synchronous inverter dc link	Univer-sal	Yes	0.81	Good	Good	Slow	Some filter
Line commutated rotating inverter	Univer-sal	Yes	0.80	Good	Good	Medium	Some filter
Super Auxivar	Univer-sal	Yes	0.82	Very good	Good	Slow	No filter
Wild frequency	Limited	Not applicable	0.86	Good	Variable	Slow	No filter
DC	Limited	Yes	0.84	Good	Not applicable	Slow	Some filter

TABLE 34.--SUBSYSTEMS WEIGHT COMPARISON (kg)

Total power per channel	10 kVA			15 kVA		
Constant freq. ac power kVA/channel	2.5	5	10	5	10	15
I. Dc-Inverter						
Dc starter/generator	26	28	31.4	33.2	36.3	39.9
Inverters (sine wave)	20	30	46.2	30.4	46.2	55.4
Isolation switches	3.6	3.6	2.7	3.6	3.6	2.7
II. Hydraulic-CSD						
Dc starter/generator	25	25	25	25	25	25
CSD	7.7	7.7	9.8	7.7	9.8	9.8
Heat exchanger	1.4	1.4	1.4	1.4	1.4	1.4
Reservoir, oil, filter	2.3	2.3	2.3	2.3	2.3	2.3
Alternator and controls	6.8	8.8	12.5	8.8	12.5	17
Isolation switches	2.7	2.7	1.8	2.7	2.7	1.8
III. EMCSD						
Dc starter/generator	25	25	25	25	25	25
CSD	7.5	11.1	15.4	11.1	15.4	24.7
Alternator and controls	6.8	8.8	12.7	8.8	12.8	17
Isolation switches	2.7	2.7	1.8	2.7	2.7	1.8
IV. Super Auxivar (induction machine as engine starter)						
TR unit	15.5	10	0	20	10	0
Variator	18	18	17	24	25	23
Heat exchanger	1.4	1.4	1.4	1.4	1.4	1.4
Reservoir, oil, filter	2.3	2.3	2.3	2.3	2.3	2.3
Alternator	13.6	13.4	12.7	18.2	17.7	17.0
Control unit	2.3	2.3	2.3	3.4	3.2	3.2
Isolation switches	3.6	3.6	1.8	3.6	3.6	1.8
V. Super Auxivar (with dc starter)						
Dc starter/generator	25	25	25	25	25	25
Variator	9.7	11.4	4.8	11.6	16.8	22.6
Heat exchanger	1.4	1.4	1.4	1.4	1.4	1.4
Reservoir, oil, filter	2.3	2.3	2.3	2.3	2.3	2.3
Alternator	6.8	8.8	12.7	8.8	12.7	17.0
Control unit	1.4	1.6	2.3	1.6	2.3	3.2
Isolation switches	2.7	2.7	1.8	2.7	2.7	1.8
Total I Inverter	49.6	61.6	80.3	67.2	86.1	98.0
II Hy CSD	45.4	47.9	52.8	47.9	53.7	57.3
III EMCSD	42.0	47.6	54.9	47.6	55.9	68.5
IV S.A. I	56.7	51.0	37.5	73.4	62.8	48.7
V S.A. II	48.7	53.3	62.3	55.4	63.2	73.3

TABLE 35.--GENERATION SUBSYSTEM COMPARISON

Generation scheme	Reliability	Maintainability	Weight	Initial cost
IDG CSCF	Medium	Satisfactory	Moderate	High
NCC VSCF	Good	Medium	High	Highest
DC link VSCF	Good	Medium	Highest	High
Synchronous inverter dc link	Good	Medium	High	Moderate
Line commutated rotary inverter	Good	Medium	High	High
Super Auxivar	Good	Good	High	Moderate high
Wild frequency	Best	Best	Lowest	Lowest
DC	Best	Best	Low	Low

Distribution Subsystem

General trends.--The distribution subsystem includes all the functions needed in order to deliver and control electric power from the generators to the loads. These functions are:

(1) Power and signal transmission

(2) Power switching, control and processing

(3) Provision for secondary (backup) power and protection

Power transmission cables and signal transmission wires are estimated at approximately two-thirds of the total distribution subsystem weight. In existing large transports, the weight is divided equally between power cables and signal transmission wires. Future trends indicate that the share of the signal transmission wires will grow and the power cabling will diminish.

Aircraft power systems have been controlled with the generators typically connected in parallel. The advantages of an all-parallel system are the capability to handle large transient load (for example, starting of a large-induction motor) and minimum load transfer operation under fault condition. The recent trend is toward a split-parallel system. In the split-parallel system, the generators are divided into two groups, one on each side of the aircraft, separated by tie breakers that are open under normal conditions. Thus, the two halves are independent. Since any fault or mismanagement in one half will not affect the other, the probability of losing the whole generating power due to a single fault is reduced. The tie breaker would be closed only during ground operation or in case of a complete failure in one half of the system.

The location of distribution centers is a matter that has received a lot of attention in recent years. In a conventional aircraft distribution system, the distribution center is located in the cabin or flight deck. Heavy power wiring runs fron the generator to the cabin and back to the loads. Power components such as contactors, switches, etc., take up a large amount of space in the cockpit panels. The trend is to place the distribution center in a more convenient place, nearer to the load center of gravity. The total length of power cabling would then be near a minimum. All the bulky power control components would be located at the distribution center and remotely controlled from the cabin using signal multiplexing. Since the control panels in the cockpit have only signal indication and supervisory logic components, the space requirement is also greatly reduced. This is very desirable in modern aircraft with complicated control and display functions.

Considerable attention also has been given recently to the concept of a solid-state aircraft distribution system. In this concept, solid-state components are used to replace electromechanical switches, circuit breakers, and relays. At the same time, power control, protection, data processing, and BITE functions using solid-state circuit logics also are introduced. In essence, the key elements of the system are: power controller, control logic unit, and signal sensors. The power controllers receive command signals from the control logic unit, and are capable of both power on-off switching and current limiting, with trip-out after a specified time.

The control logic unit provides control of the multiplex information and performs all logic control and checkout functions. This unit may be regarded as the information center or the brain of the system, which receives information and converts the data into intelligent command signals for the power controllers. Solid-state sensors have been developed for external stimuli such as mechanical motion, pressure, temperature, etc., and will supply a bilevel (on-off) electrical output, which is free from contact bounce.

The sensitivities and sophistication of modern aircraft avionics equipment are such that a secondary (backup) power source and extraordinary power system protection methods are increasingly required. A battery (plus charger) which feeds an output inverter is expected to provide the future secondary source. The result is uninterruptible power similar to concepts already realized for ground computers.

In addition to the well known fusing and current limiting methods of protection, a considerable need has arisen for fault detection, isolation and compensation techniques. These in great part depend on extended use of onboard minicomputers, recorders, display and monitoring techniques. As aircraft speed and airspace applications increase, this aspect of automatic on-board protection is likely to grow in importance.

All of the foregoing are now discussed in turn in more detail. The subject of fault detection is presented separately because it refers to the generation and utilization subsystem as well as the distribution subsystem.

Power transmission.--The subject of power transmission was studied with a view to minimizing weight and cost while improving safety and dependability. Areas studied--not necessarily in the order stated--were:

(1) Type of electric current, ac or dc

(2) Distribution voltage considerations

(3) Cable weight dependency on voltage

(4) Feeder weights

(5) Temperature considerations

(6) High frequency aspects

The study results are summarized and examples of the analysis approach are presented in the following text and appendices where applicable.

Type of electric current, ac or dc: Dc distribution is preferable to ac distribution for several reasons. These are (a) the power cable has no reactance drop; (b) the power factor for dc is unity; (c) the aircraft frame can be used as a return wire for all cables (this may not be true for a titanium frame, and more research is needed to determine if a titanium frame is a satisfactory current carrying medium); (d) dc has no skin effect; (e) corona onset voltage is higher for dc than for ac; and (f) dc is safer to personnel than power frequency ac at the same voltage level.

Dc distribution also has disadvantages. The first is that direct current is more difficult to interrupt. Conventional circuit breakers for dc are larger than breakers for ac of the same rating. Power transistors for dc switching are limited to ratings of approximately 400 V and 10 amp at the present, although larger units are under development. Silicon gate-controlled switches also are under development, and are expected to be available in the near future. Thyristors, capable of switching high power levels are available. However, the need for external commutation circuitry and energy storage devices detracts from their use for aircraft applications. The second disadvantage is that dc voltages are slightly more difficult to insulate than ac voltages. Depending on progress improvements anticipated in high dc current controlling devices, the advantages of dc distribution will show a clear preference over other ac type systems.

Distribution voltage considerations: In establishing the maximum desirable voltage level, the factors of personnel safety, corona losses, insulation and semiconductor device ratings were considered.

(1) Personnel safety: For practical purposes, the maximum electric current safe for an average man is a little less than that causing him to "freeze" to a circuit. The maximum that a person can tolerate and still be able to release or let-go his grasp of an energized conductor is called the "let-go" current. The let-go ability will decrease rapidly with the duration of contact. Dalziel and Massoglia (ref. 11) investigated the value of let-go current for the human being and have established a mean or average value of 15.87 ma for men and 10.5 ma for women for 60 Hz power. The effect of frequency on the value of let-go current has also been investigated and Dalziel's results are shown in fig. 44.

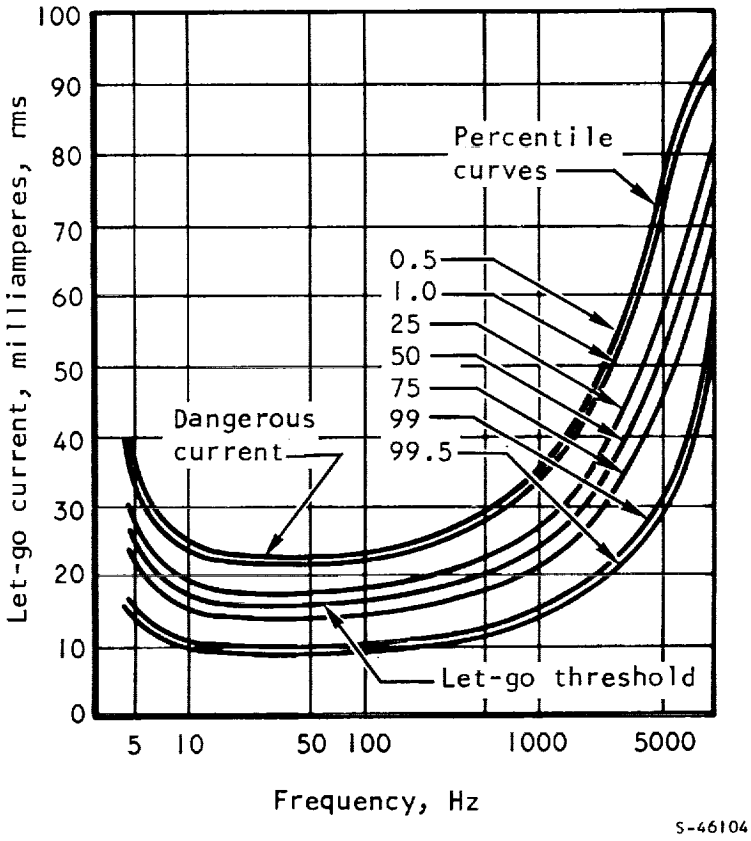


Figure 44. Let-go Current for Man as a Function of Frequency

The let-go value of dc current was also measured and was found to vary from 83 ma (0.5 percentile) to 61 ma (99.5 percentile) with a mean value of 74 ma (50 percentile).

From fig. 44, it is established that dc current is safer than 60 Hz or 400 Hz alternating current. The 400-Hz threshold let-go voltage (50 percentile) and reasonably safe voltage (99.5 percentile) were computed for hand-to-feet and hand-to-hand pathway. A wet contact was used to indicate the worst condition. These values are shown in Table 36 .

TABLE 36.--LET-GO VOLTAGE WITH WET CONTACTS

	Threshold Voltage		Reasonably Safe Voltage	
Pathway	Dc	400-Hz Ac	Dc	400-Hz Ac
Hand-to-hand	128	45	103	25.6
Hand-to-feet	62	22	51	12.5

The hazard of voltages in table 36 would greatly change if contact occurs at locations where the skin contact resistance is deteriorated by laceration or other means.

The minimum current that is likely to produce a serious effect on the heart is known as the fibrillation current. The values of fibrillating current vary according to the shock duration. The 60-Hz fibrillating current vs shock duration curve projected from the values obtained in experiments to animals is also presented in one of Dalziel's papers and is reproduced here as fig. 45.

It must be stressed that, no current, however small, can be considered as absolutely safe. Generally speaking, from the results presented in table 36, a certain 400-Hz voltage has the same degree of danger as a dc voltage 4 times larger. In other words, if a 115/200-volt, 400-Hz system is accepted for aircraft application, then a dc voltage level of 460 or 800 should be considered as acceptable if human safety alone is concerned.

(2) Corona losses: The system voltage should be selected such that corona discharge does not occur. Corona is an audible, luminous electrical discharge due to ionization of the gas surrounding an electrical conductor. Effects of corona include radio frequency interference, insulation breakdown and power loss.

Corona-safe voltage levels (ref. 12) are considered to be (a) 300 volts in unpressurized areas at altitudes up to 30 km (100,000 ft) and (b) a max of 700 volts for a base conductor in pressurized areas.

(3) Insulation: Dc voltage is more difficult to insulate than ac voltage. In dc systems, once a leakage current exists, corrosive action builds up faster since it is not hampered by the continuous change in the polarity. Dc voltage is more likely to cause wire fire than the equivalent ac potential, although dc voltages do not produce the heavy arcing at the fault as does the ac.

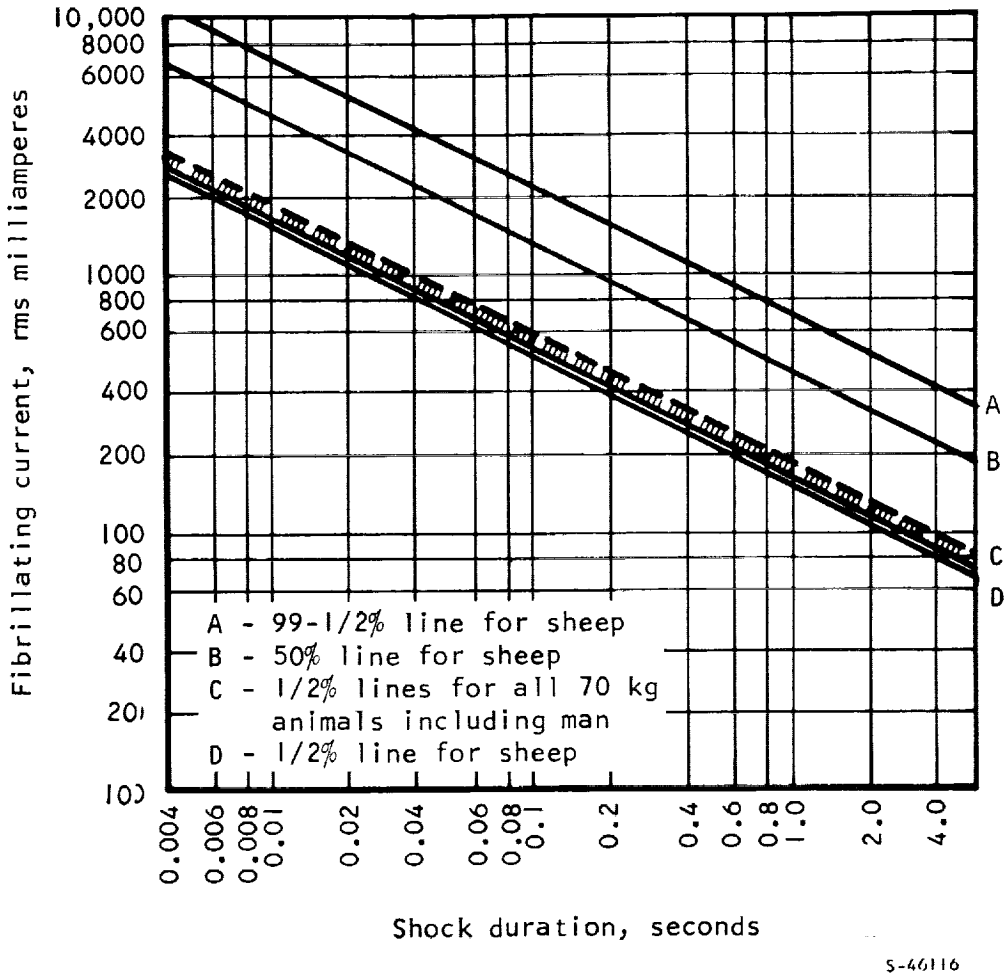


Figure 45. Relation of 60-Hz Sine-Wave Fibrillating Current to Shock Duration

(4) Semiconductor device ratings: The forward drop of solid-state power components is approximately constant regardless of the current. The weight of the component increases with the current rating. Therefore, for better efficiency and lower weight, the system voltage should be as high as practical. The PIV ratings of present day diodes, thyristors, and transistors are higher than the voltage levels considered as safe for aircraft operation.

Cable weight dependency on voltage: For cables carrying continuous loads, the size of the cable is determined by its current carrying capacity and allowable voltage drop. In general, large cables transmitting power over short distances are likely to be limited by their current carrying capacity while small cables of long length are likely to be voltage-drop limited.

When the system voltage is raised a given cable can transmit more power over a longer distance. If the same amount of power is to be transmitted for the same distance, however, the cable can be reduced in size and an appreciable amount of weight reduction can be achieved.

The amount of savings for a particular change in voltage is different for cables operating at different conditions; i.e., the limiting factor of the cable, the ratio of the cable current to the rated current (if the cable is limited by voltage drop), etc.

(1) Assumptions: An analysis is presented for a dc system with the following assumptions:

(a) There are an infinite number of wire sizes. This means when the cable is not limited by voltage drop, there is always a cable size that can carry the current to its maximum allowable current density.

(b) The temperature of the conductor is constant. That is, the fact that the temperature can deviate when the cable is not carrying the rated current (voltage drop limited) is ignored. This means that the resistance is not corrected for temperature variations.

(2) Current capacity limited cable: The case where the cable is limited by its current carrying capacity is considered first. The subscript o denotes the original system and the subscript n denotes the new system in which the voltage is increased. Symbols used in the analysis are as follows:

A = cross sectional area of conductor

I = current in the conductor

J = current density

V = voltage

R = resistance of cable

$P = V_n/V_o$ = ratio of voltages

V_d = allowable voltage drop

W = weight of cable

Since both systems must transmit the same amount of power:

$$I_n = I_o/P$$

and

$$J_o = I_o/A_o$$

$$J_n = \frac{I_o}{PA_n} = \frac{J_o}{P}\frac{A_o}{A_n}$$

or
$$\frac{J_n}{J_o} = \frac{1}{P}\frac{A_o}{A_n} \qquad (1)$$

The maximum current density of aircraft cable versus copper cross-sectional area is shown in fig. 46. This curve can be represented by the following equation:

$$A = K/J^{2.83}$$

where K is a constant

If the cable of the new system is also limited by the current carrying capacity, the following relation can be derived.

$$\frac{A_o}{A_n} = \left(\frac{J_n}{J_o}\right)^{2.83} \qquad (2)$$

substituting eq. (1) into eq. (2) yields

$$\frac{A_n}{A_o} = \frac{1}{P^{1.545}} \qquad (3)$$

Since the weight of the cable is directly proportional to the cross-sectional area (neglecting the insulation weight),

$$W_n = \frac{W_o}{P^{1.545}} \qquad (4)$$

The result shown in eq. (4) is obtained on the basis that the cable size is reduced until it is just enough to carry the current I_n at the full rating. Since the voltage limitation could get involved, it is worthwhile checking the voltage drop of the new system.

The voltage drop of the old system is

$$I_o R_o < V_d$$

$$I_o R_o = g\, V_d$$

where g is a fraction.

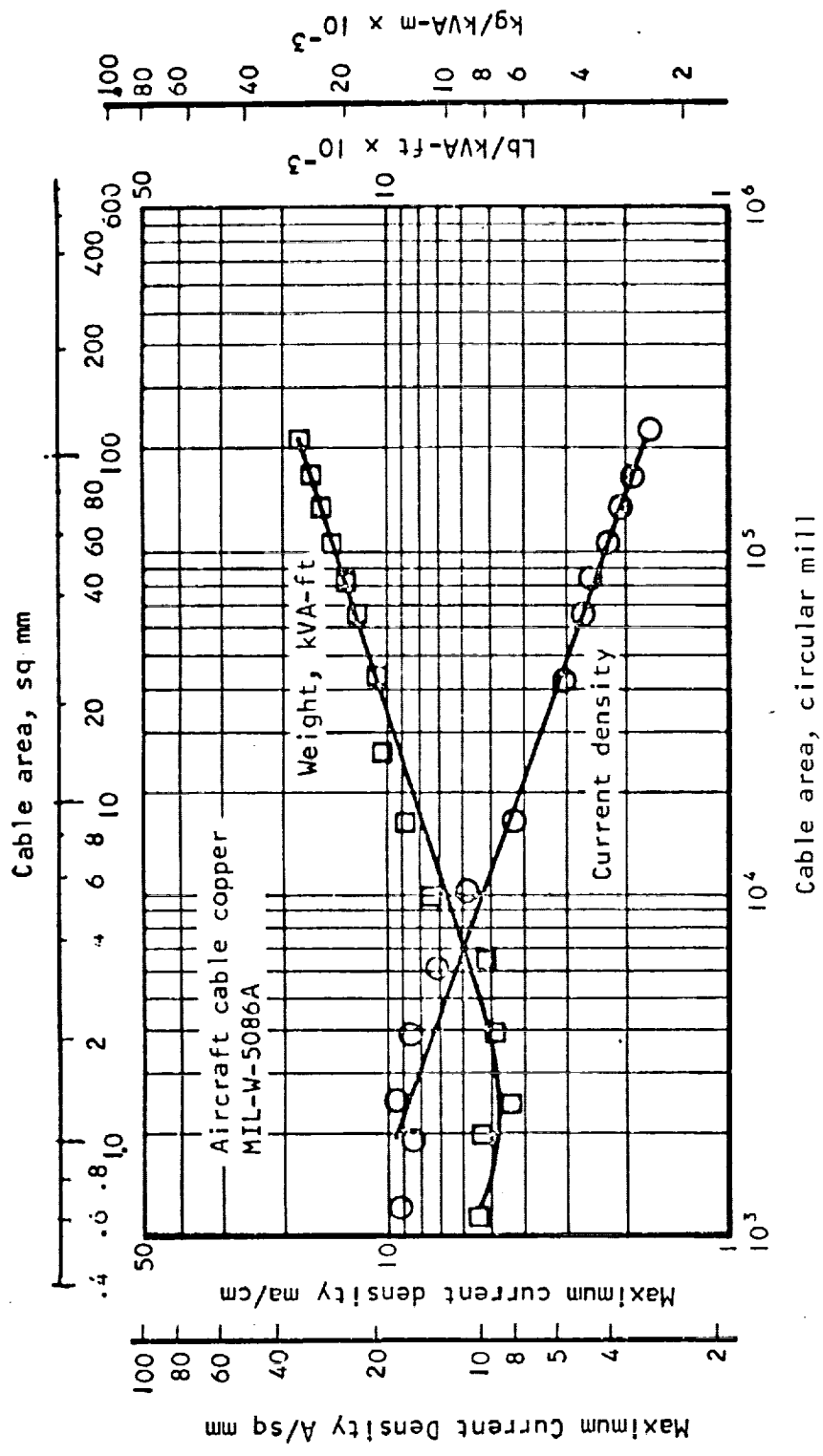


Figure 46. Conductor Maximum Current Density and Weight/kva-ft vs Wire Area

The voltage drop of the new system is

$$I_n R_n = \left(\frac{I_o}{P}\right)\left(R_o \frac{A_o}{A_n}\right) = \left(\frac{I}{P}\, g\, V_d\right)(P^{1.545})$$

$$= g\, V_d P^{0.545}$$

If the same percentage of voltage drop is allowed, the new limit will be PV_d. Since

$$I_n R_n = gP^{0.545}\, V_d < PV_d$$

it can be concluded that the voltage drop limitation will never be the limiting factor when the system voltage is increased if the cable size was originally limited by the current carrying capacity.

(3) Voltage drop limited cable: When the cable is originally limited by the voltage drop, the following analysis applies. If the new cable size is also limited by the voltage drop and the cable cross section is reduced, then

$$I_o R_o = V_d$$

$$I_n R_n = PV_d$$

$$\frac{R_n}{R_o} = P\,\frac{I_o}{I_n} = P^2$$

hence

$$\frac{W_n}{W_o} = \frac{A_n}{A_o} = \frac{R_o}{R_n} = \frac{1}{P^2} \qquad (5)$$

The new cable might become limited by current carrying capacity before the limit of voltage drop is reached, depending on the percentage of rated current the original cable is carrying. The controlling factor can be determined as shown below. Since the current and current density values in the cable are not necessarily the maximum (or rated) value, the subscript "max" is used to denote values limited by maximum permissible current density due to heating.

$$\frac{I_o}{I_{o\,max}} = \frac{J_o}{J_{o\,max}} = \gamma \qquad (6)$$

$$J_n = \frac{I_o}{PA_n} = P\,\frac{I_o}{A_o} = PJ_o \qquad (7)$$

From eq. (2)

$$\frac{A_o}{A_n} = \left[\frac{J_{n\ max}}{J_{o\ max}}\right]^{2.83} \tag{8}$$

substituting eqs. (5), (6), and (7) into eq. (8) yields

$$J_n = \gamma\ P^{0.294}\ J_{n\ max}$$

If the factor $\gamma P^{0.294}$ is less than one (which means the current density of the new cable does not exceed the allowable current density of the cable), the voltage drop will be the limiting factor, and eq. (5) is applicable. If $\gamma P^{0.294}$ is greater than one, the area A_n in eq. (5) is not correct and must be recalculated, which can be done by replacing J_n in eq. (7) by $J_{n\ max}$. Hence,

$$J_{n\ max} = \frac{I_o}{PA_n} = \frac{\gamma\ I_{o\ max}}{P\ A_o}\frac{A_o}{A_n} = J_{o\ max}\frac{\gamma}{P}\frac{A_o}{A_n}$$

or

$$\frac{J_{n\ max}}{J_{o\ max}} = \frac{\gamma}{P}\frac{A_o}{A_n} \tag{10}$$

substituting eq. (10) into eq. (8) yields

$$\frac{A_o}{A_n} = \left(\frac{\gamma}{P}\right)^{2.83}\left(\frac{A_o}{A_n}\right)^{2.83}$$

or

$$A_n = A_n\left(\frac{\gamma}{P}\right)^{1.545} \tag{11}$$

$$W_n = W_o\left(\frac{\gamma}{P}\right)^{1.545}$$

(4) Conclusions: Table 37 is a summary of the analysis of cable weight depending on voltage level in a dc system.

When the voltage of the system is doubled, for example, the maximum reduction will be a factor of $4(2^2)$, while the minimum weight reduction will be a factor of $2.92(2^{1.545})$, depending on the condition of the cable.

The analysis shows that in a dc system, increasing the system voltage will reduce the weight of feeder cables and transmission wires in the distribution system. The weight reduction is principally due to the current reduction obtained from the voltage increase, but is also due to the increase in both the allowable current density and the allowable voltage drop obtained from the voltage increase.

TABLE 37.--CABLE WEIGHT DEPENDENCY ON VOLTAGE LEVEL, DC SYSTEM

Original limiting factor	New limiting factor	Criterion	New cable weight
Current	Current		$W_n = \frac{W_o}{P^{1.545}}$
Voltage	Voltage	$\gamma P^{0.294} < 1$	$W_n = \frac{W_o}{P^2}$
Voltage	Current	$\gamma P^{0.294} > 1$	$W_n = W_o\left(\frac{\gamma}{P}\right)^{1.545}$

Nevertheless, because of mechanical strength considerations, there is a minimum size of cable for aircraft application. Therefore, it is desirable to change the system voltage such that a maximum percentage of load is transmitted at or near the current rating of the minimum size wire. Thus, for any distribution system, there is a certain voltage which results in maximum average current density in the system.

Increased system voltage would also cause increased insulation weight, increased danger of arc-over, corona phenomena, increased personnel hazard, etc. In view of these problems, an optimum system voltage cannot be determined without considering the entire electrical system.

Feeder weights: A study of feeder weights was made for both ac and dc distributions. Ac voltage levels examined were: 115/200 vac, 230/400 vac and 345/600 vac. Dc voltage levels were 200 vdc and 400 vdc. Each voltage level was analyzed for 40 kVA, 60 kVA and 90 kVA power levels and 400 Hz was taken as the base frequency for the ac analysis. Table 38 compares channel currents and allowable transmission line impedances of ac vs dc systems at different voltage levels. Appendix C illustrates the method of ac cable weight calculation.

For practical consideration, the number of conductors in parallel per phase was assumed not to exceed three. In the case of three in parallel, a triangular equilateral group arrangement with one inch elevation from the airplane structure is assumed.

From available wire impedance tables, the single phase impedance at 400 Hz for general purpose wire at 293°K (20°C) ambient is given in ohms per km in table 39. (Equilateral group configuration with one inch spacing.)

It is realized that the transmission system also utilizes sections of high temperature wire due to altitude and elevated temperature conditions and also aluminum feeders. However, for the purpose of this study, the comparison with one wire type (copper conductor) at one temperature condition only was investigated.

TABLE 38.--CURRENTS AND ALLOWABLE IMPEDANCES, AC AND DC SYSTEMS

		40 kVA		60 kVA		90 kVA	
		I Amp	Z Ohm	I Amp	Z Ohm	I Amp	Z Ohm
3 ϕ	115/200 Vac 400 Hz	111	0.045	166	0.030	250	0.020
	200 Vdc	200	0.0415	300	0.0277	450	0.0184
3 ϕ	230/400 Vac 400 Hz	55	0.180	83	0.120	125	0.080
	400 Vdc	100	0.166	150	0.1106	225	0.7378

TABLE 39.--CHARACTERISTICS OF AIRCRAFT CABLES

AN size	Current carrying capacity single conductor in free air	R	X_L (ohm/km)	Z / °	Weight finished cable g/m
0	245	0.1738	1.54	0.4913 /69°	600
1	211	0.2008	1.55	0.5140 /67°	454
2	181	0.2324	1.63	0.5497 /64°	370
4	135	0.3296	1.76	0.6304 /58°	245
6	101	0.4870	1.86	0.7479 /49°	165
8	73	0.7147	1.97	0.9329 /39°	100
10	55	1.0886	2.10	1.2345 /30°	65
12	41	1.5833	2.22	1.7220 /23°	39
14	32	2.5797	2.37	2.6794 /15°	27.2
16	22	4.4433	2.53	4.5095 /9°	17.7
18	16	5.6141	2.60	5.6699 /8°	14.1
20	11	6.9267	2.77	6.9771 /6°	10.2

For elevated transmission line voltage it was assumed that the allowable voltage drop may be increased proportionally. Therefore, when doubling the system voltage, the feeder impedance may be increased by a factor of four. For triple system voltage, feeder impedances may be multiplied by a factor of nine. Figs. 47, 48, and 49 show minimum weight feeder configurations for 40 kVa, 60 kVA and 90 kVA respectively. The stepped increase in feeder weight is due to the stepped change in wire size. As shown in table 39, only even numbered wire sizes (except No. 1) are used. If odd number wires are also used, there will be twice as many steps with smaller increments. For the case of three times standard voltage (345/600 V) possible corona limitations at higher altitudes were ignored. Also, a weight penalty of approximately 10 percent of the cable weight might become necessary to provide ample margin for increased insulation stresses.

Cable resistance for the dc transmission has been chosen to produce the same energy loss as for the ac system. The resistances for cables at 293°K (20°C) from MIL-W-5086 were taken, rather than the resistive component from the complex notation in table 39. There are some ac effects also reflected into the real term so that the "Dc Resistance" when used on ac is slightly altered. The data from which figs. 47, 48, and 49 were plotted is given in Appendix D. From these curves, a comparison of the dc with the ac transmission weight can be made. For the 40 kW and 60 kW sources, a weight advantage using the 200 Vdc line is evident when installations in excess of 25 m are considered. The 400 Vdc line offers slight by insignificant weight savings. With the 90 kW source, the weight advantages are more evident. From this general comparison, it can be derived that a high voltage dc transmission line would be the lightest energy transfer method available. This is because of:

(1) Inductive reactance which is predominantly influencing feeder impedance for the heavier size cables is absent for dc

(2) Utilization of structure return (the assumption of utilizing a structure return is explained in the following paragraph.)

In contemporary aircraft electrical systems, the primary 3 Phase 400 Hz ac power has its neutral grounded to the airplane structure. The low voltage (28 V) dc system which is obtained through transformer rectifier units from the primary ac system has its negative potential also tied to the structure, common with the ac fourth wire. The capacity of the dc system typically is from 4 each 50 A units to 4 each 100 A units. This results in a sum totalling up to 400 A dc carried by the airplane structure. This suggests that a high voltage dc primary system utilizing the structure as return conductor is also feasible. Assuming four 40 kW systems with a voltage equal to the line voltage in a double standard voltage ac system (230/400 V rms), this source would also cause 100 A return current or 400 A total current in the structure. The current carrying capability of the airplane skin and structure may be far in excess of that which is considered here.

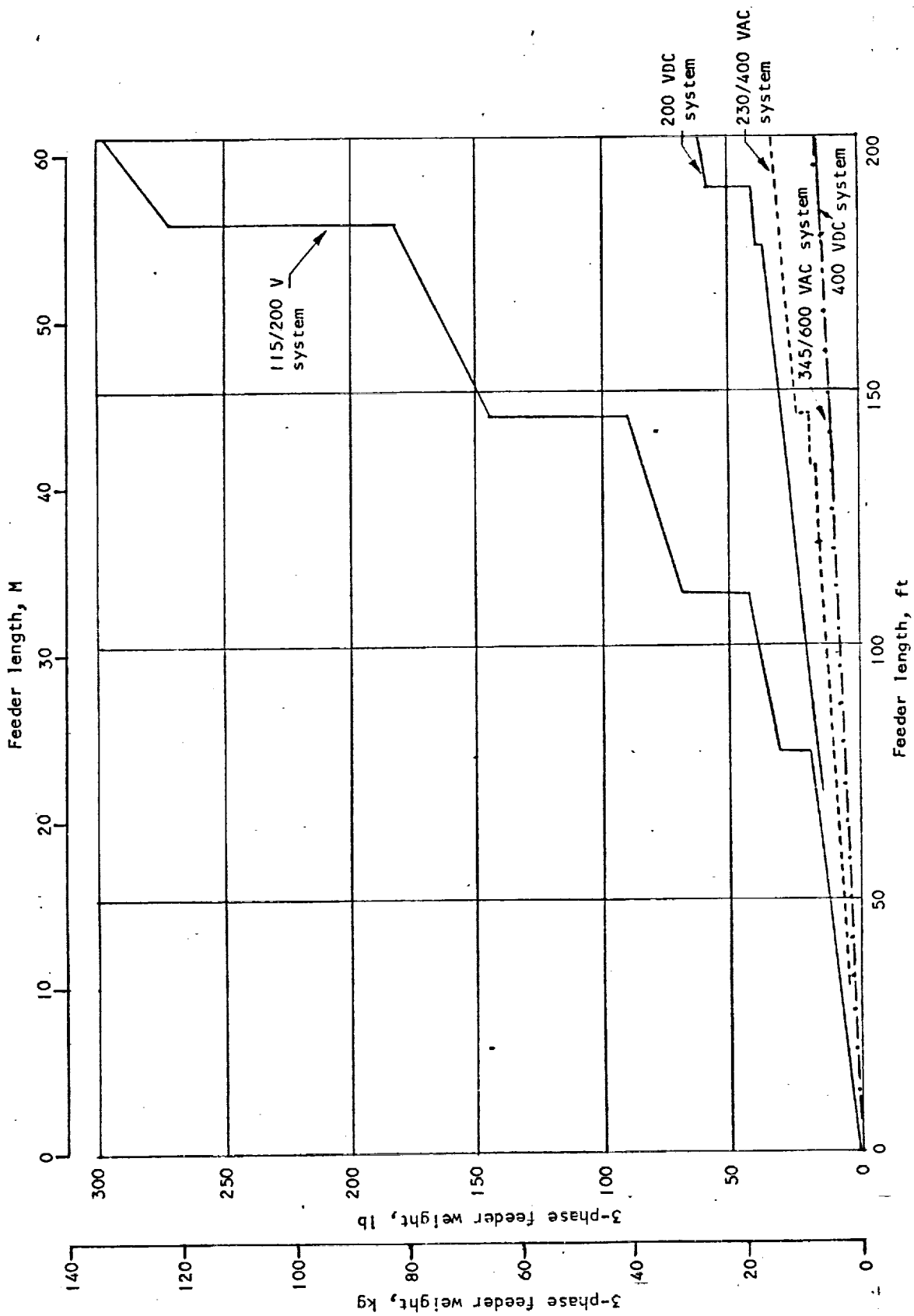


Figure 47. 3-Phase Feeder Weight, 40 kVa System

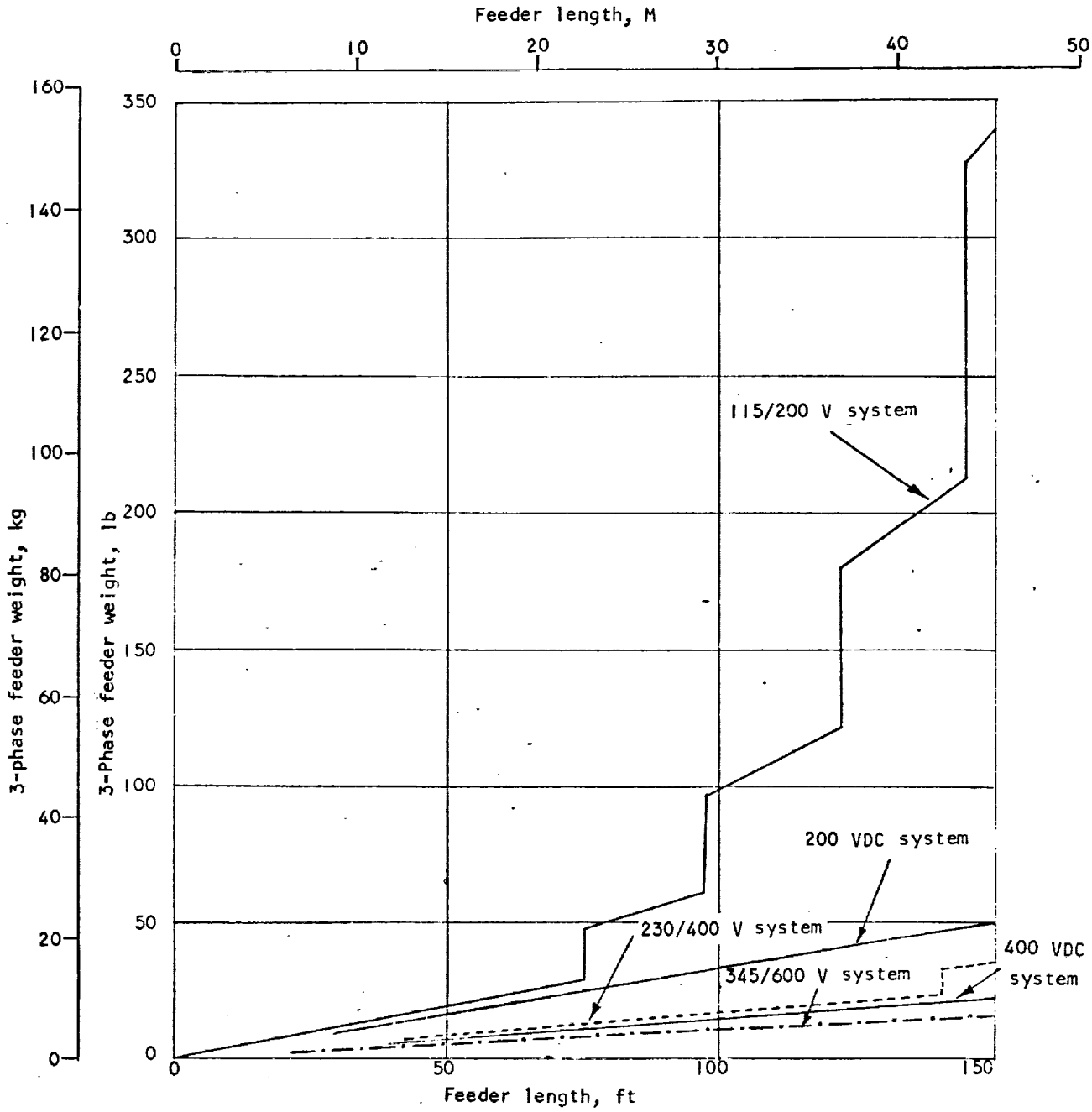


Figure 48. 3-Phase Feeder Weight, 60 kVa System

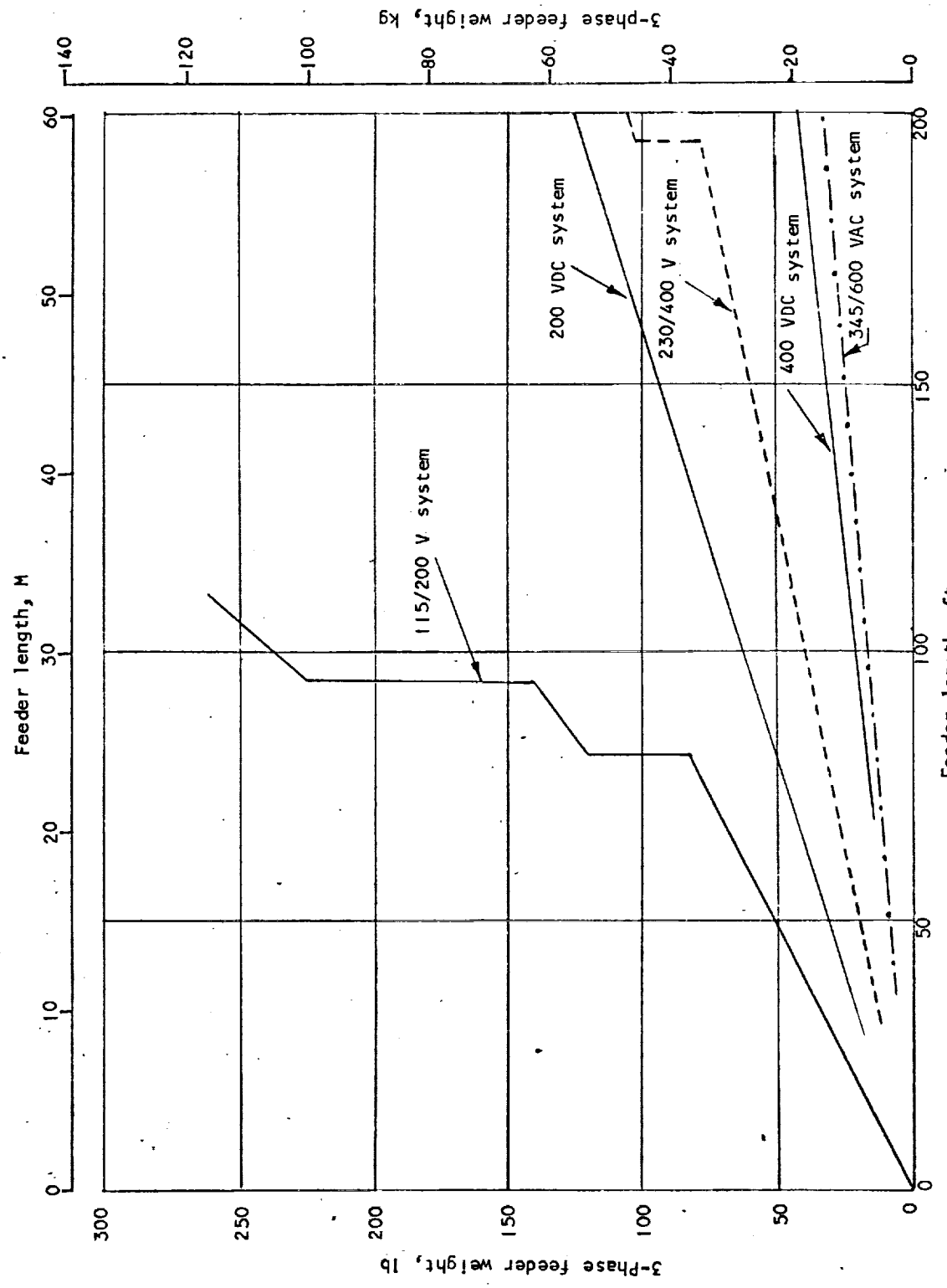


Figure 49. 3-Phase Feeder Weight, 90 kVa System

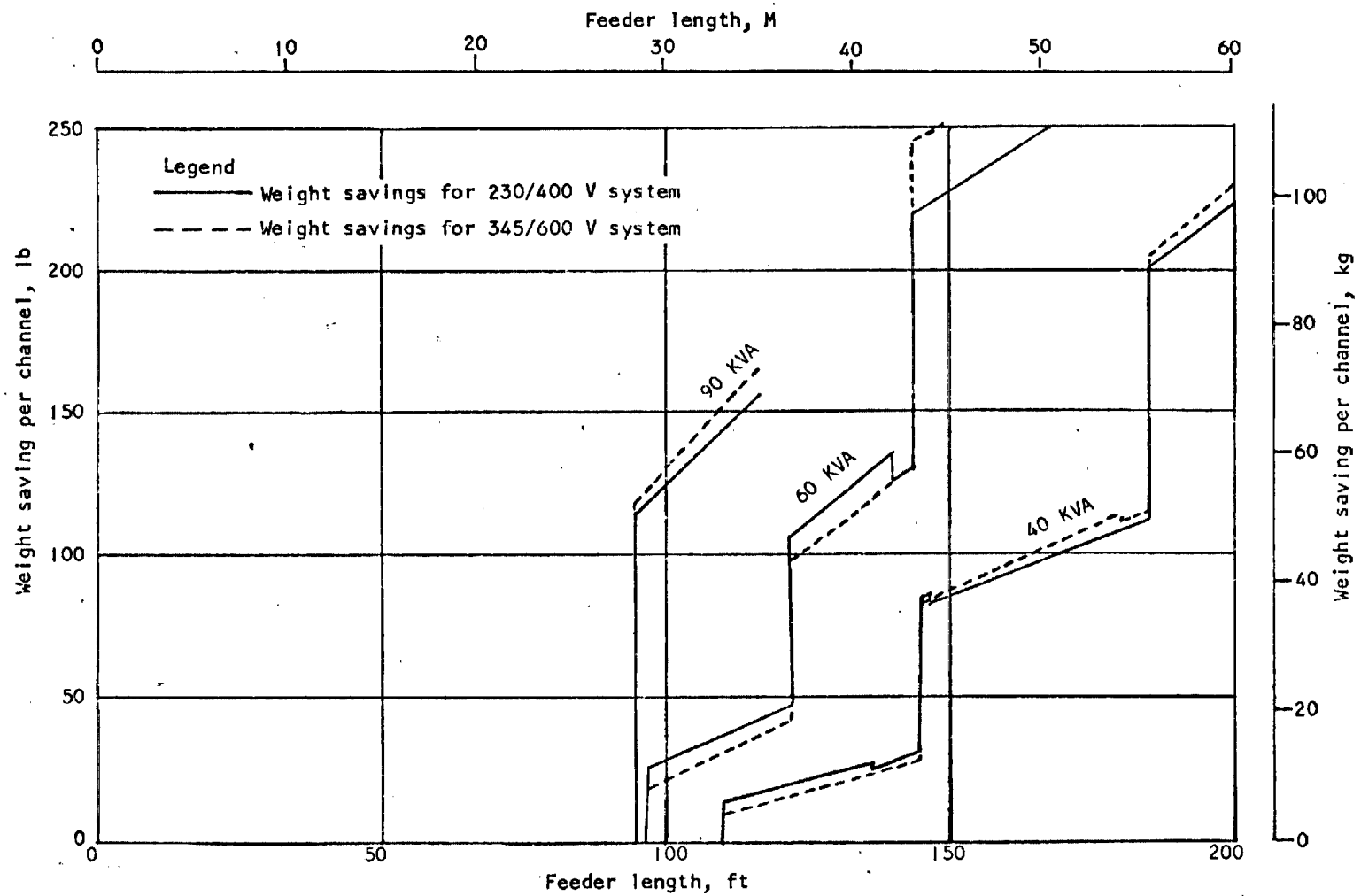


Figure 50. Weight Savings per Channel with High Voltage Transmission (Voltage Step Down to 115/200 at Main Power Shield)

cable installations exceed 50 M (150 ft) for the 40 kVA case, 40 M (120 ft) for 60 kVA and 30 M (100 ft) for 90 kVA. These are the critical installation distances where net savings of 90 to 100 lb per channel may be obtained. As can be seen from the curves, the 345/600 V transmission does not offer substantially greater weight savings than the double voltage system. Transmission at triple standard voltage may become attractive for 90 kVA or 120 kVA systems with long feeder runs (i.e., in excess of 40 M (125 ft)).

For still higher transmission line voltages (i.e., higher than triple standard voltage), two winding transformers with isolation between input and output should be used for step down operation. This is for safety reason; also, there is no weight advantage for autotransformer at high voltage ratio of transformation. In this case, some weight savings could be realized by using the airplane frame as one conductor, as depicted in fig. 51. This configuration, however, may have the undesirable effects of coupling of power circuits and acceptability would have to be determined by test.

High temperature effects: Higher ambient temperature reduces the current carrying capacity of aircraft cable in two ways. First, it reduces the permissible temperature rise. Second, it increases the wire resistance and, therefore, the losses. The resistance of a copper conductor at 617°K (650°F) is 2.25 times that at 294°K (70°F). Based on the resistance drop, it would take 2.25 times as much conductor (copper) to carry the same current as at room temperature. At high altitude, besides the high ambient temperature, the reduced air density also impairs the conductor current carrying capacity.

The operating temperature of the aircraft cable is determined by the insulation material. For continuous loads, the wire temperature must remain within certain limits to avoid excessive aging and deterioration of the insulation. For overloads of short duration, the temperature must remain below that which will cause smoking or the emission of noxious fumes. Higher allowable operation temperature of aircraft cable is desirable since it permits transmission of more power for a given size of wire.

High frequency aspects: The previous discussion of feeder weights used a 400 Hz frequency as the base assumption. If transmission frequency is treated as a parameter and varied upwards in steps to 4 kHz the effects on projected weight can be calculated. This is now discussed.

(1) Impedance: In order to analyze the wiring weight as a function of voltage and frequency the impedance of various sizes of wires at frequencies from 400 to 4 000 Hz was calculated. In calculating the ac resistance, the skin effect was included while the proximity effect was not considered. The equation relating the skin effect, the wire size and the frequency was taken from "Standard Handbook for Electrical Engineers" by Knowlton and is shown as follows:

$$\chi = 2\pi a\sqrt{\frac{2\mu f}{\rho}}$$

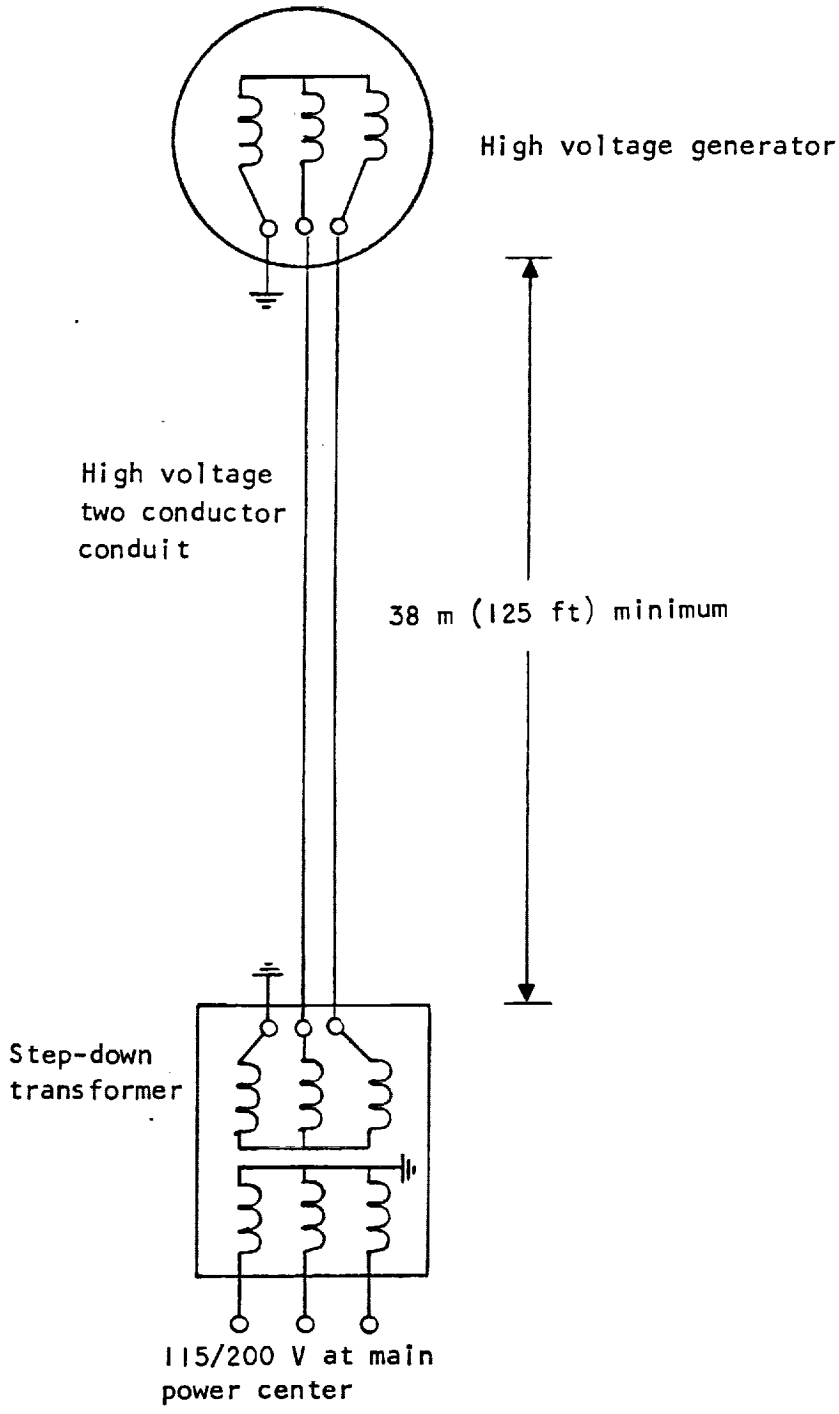


Figure 51. High Voltage Transmission System

where a = wire radius in cm

μ = permeability of conductor

f = frequency in Hz

ρ = resistivity of conductor in ab ohm-cm

X is related to the skin effect ratio k as shown in fig. 52 and the ac resistance was determined by using the following equation

$$R_{AC} = k\, R_{DC}$$

R_{DC} values shown in table 40 were used in the calculation.

The reactance calculation was based on the measured values at 400 Hz for an equilateral group of conductors with one inch elevation from the structure. Values at higher frequencies were calculated proportionally. Curves relating the cable impedance and the frequency are shown in fig. 53.

Due to the increased impedance at higher power frequencies, the transmission and distribution subsystems will introduce added line drop and losses. To keep this within tolerable limits the size of the feeder wires and distribution cables have to be increased, resulting in an overall heavier distribution weight. This, however, can be avoided by increasing the system voltage. A linear increase in voltage not only allows the impedance to increase by the square of the voltage ratio but also, due to the proportionally reduced current, smaller conductors can be used which exhibit better power factors than the heavier cables. The characteristic of conductor size vs power factor for an equilateral group of conductors with one inch elevation from the structure is shown in fig. 54.

(2) Generator feeder weights at high frequency: Previous to this discussion all generator feeder calculations were based on a 5 V allowable potential drop between generator terminals (generator rating 120/208 V) and the point of regulation (system voltage 115/200 V). This was according to specifications MIL-G-6099A para. 3.3.4.8 and MIL-G-21075 para. 4.3.2.6. In the case of higher than conventional system voltage, the allowable voltage drop was increased proportionally.

Assuming a channel of 60 kVA and 4/0 cable, the feeder length is 32 M (100 ft). Table 41 below shows calculated feeder weight for a transmission voltage of 115/200 Vac.

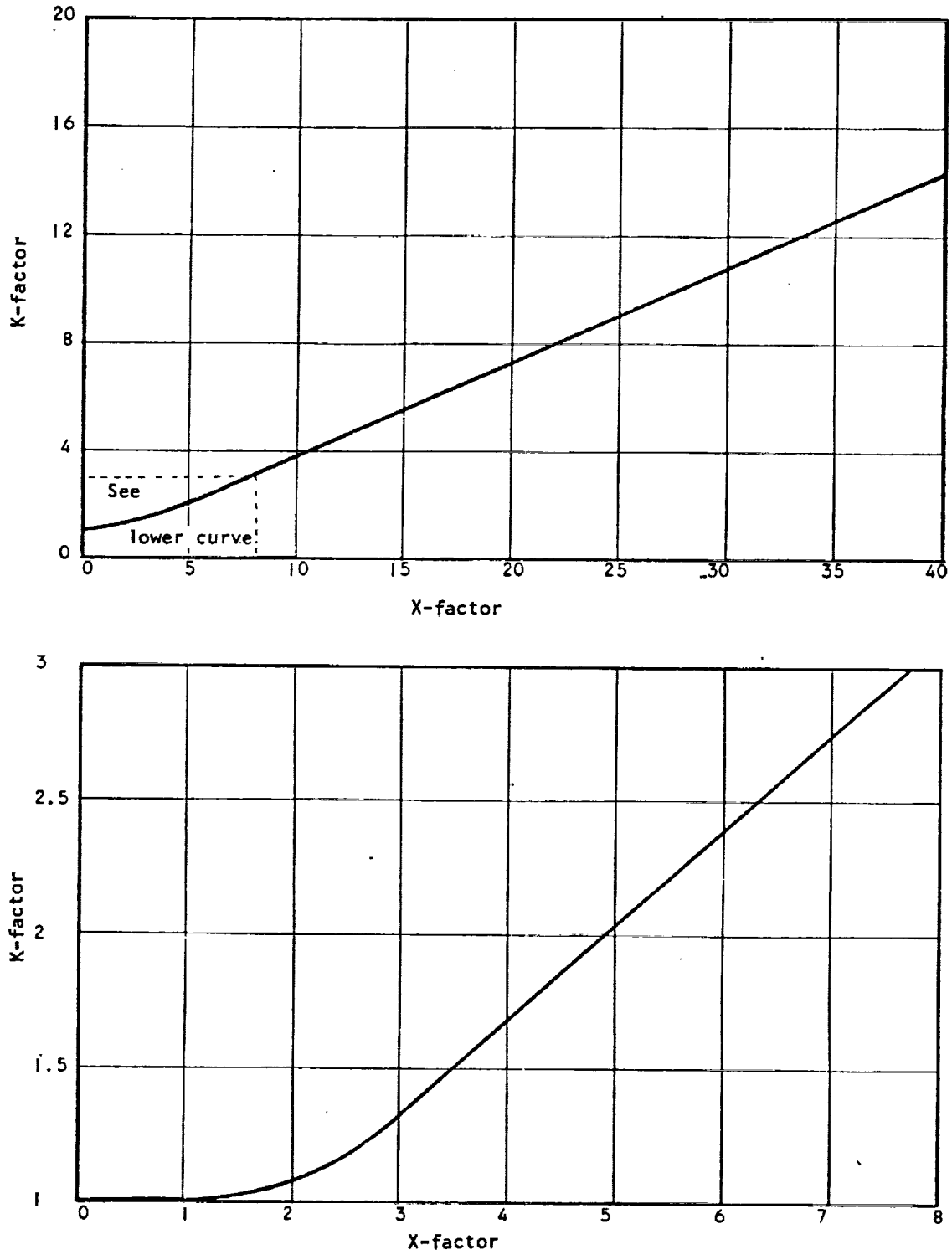


Figure 52. Skin Effect Ratio, K-Factor versus X-Factor

F

TABLE 40.--PROPERTIES OF AIRCRAFT CABLE (COPPER)
(MIL-W-5086)

AN size	293°K (20°C) ohms	Max amp 333°K (60°C) ambient		Mm^2 area	Max dia cable (mm)	Max dia conductor (mm)	Weight Finished Cable (kg/km)
		Bundled	Single condition in free air				
22	15.52	5	-	0.383	1.9 ±0.13	0.84	7.0
20	9.7	7.5	11	0.609	2.2 ±0.13	1.04	10
18	6.08	10	16	0.968	2.4 ±0.13	1.32	14
16	4.76	13	22	1.22	2.7 ±0.13	1.55	17.7
14	2.99	17	32	1.94	3.2 ±0.18	1.93	27.2
12	1.88	23	41	3.08	3.7 ±0.18	2.44	38.7
10	1.16	33	55	5.01	4.8 ±0.18	3.25	65.4
8	0.70	46	73	13.6	6.1 ±0.18	4.47	103
6	0.436	60	101	13.6	7.4 ±0.18	5.54	164
4	0.274	80	135	21.6	9.0 ±0.25	6.91	246
2	0.179	100	181	33.9	10.8 ±0.25	8.76	372
1	0.144	125	211	41.6	11.9 ±0.25	9.75	454
0	0.114	150	245	53.2	13.3 ±0.38	11.0	595
00	0.090	175	283	67.8	15.0 ±0.38	12.4	744
000	0.072	200	328	84.9	16.5 ±0.38	13.9	922
0000	0.057	225	380	107.5	18.3 ±0.38	15.6	1 170

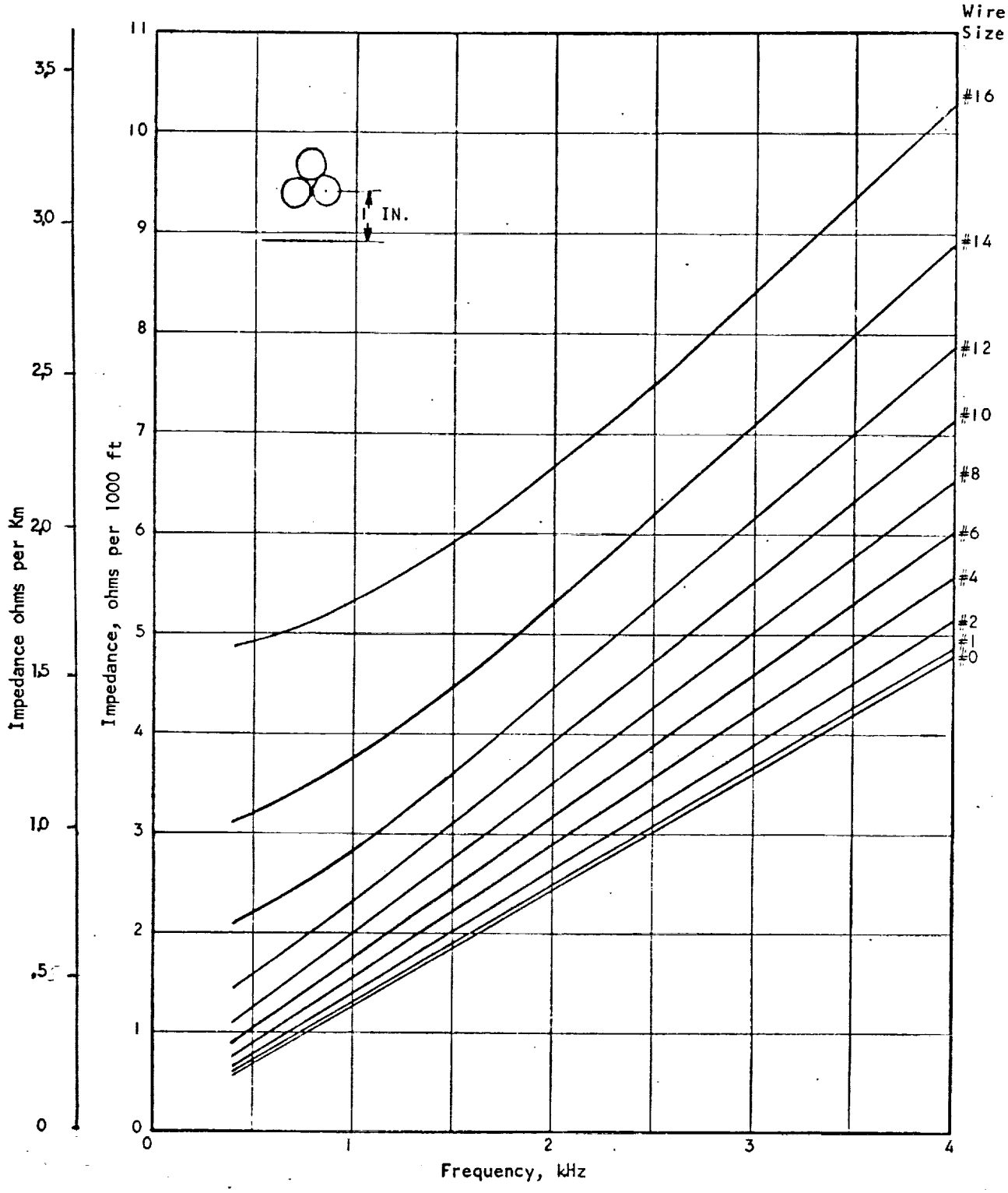


Figure 53. Impedance versus Frequency

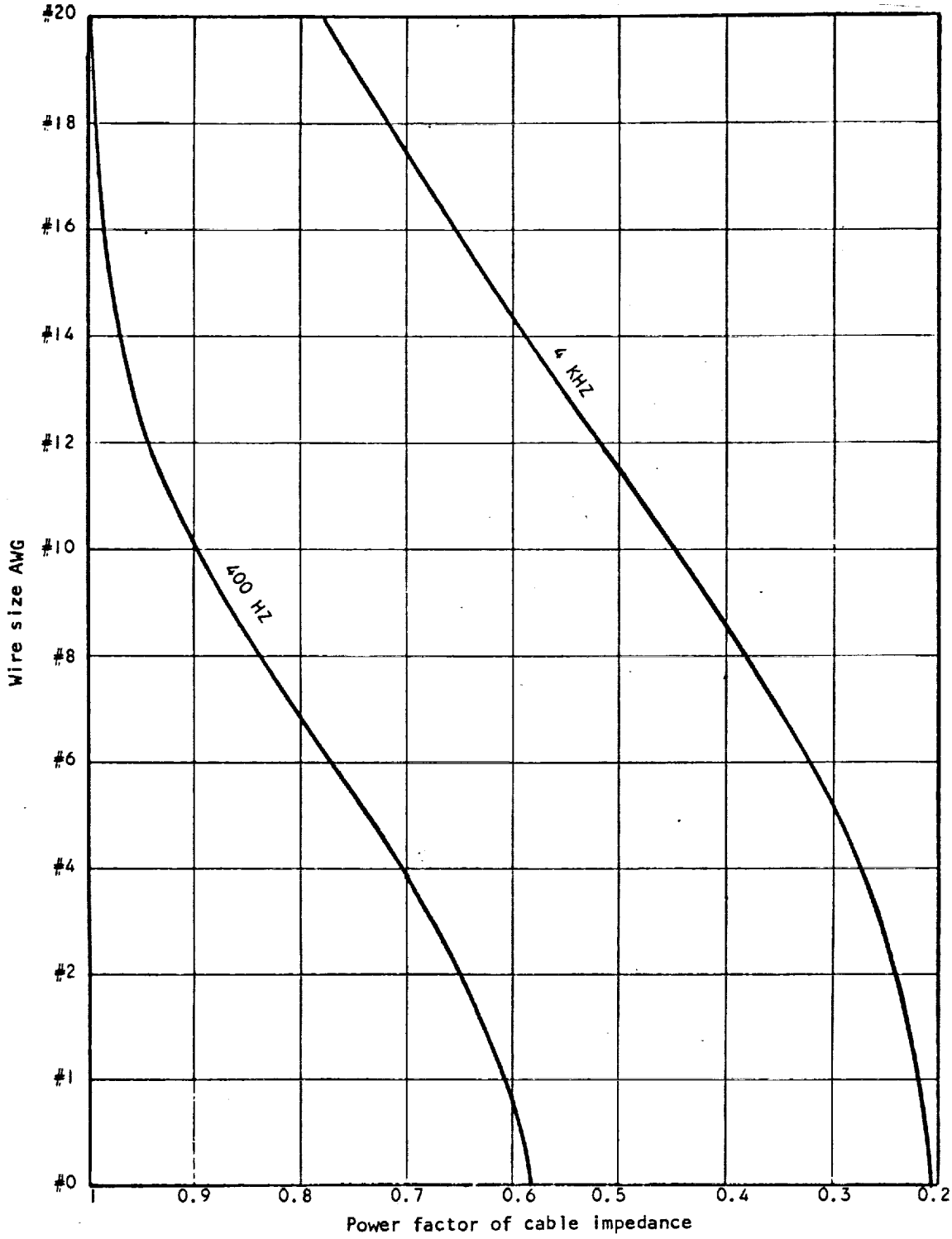


Figure 54. Cable Impedance Power Factor at 400 Hz and 4 KHz for Various Cable Sizes

TABLE 41.--FEEDER WEIGHT VS FREQUENCY AT 115/200 VAC

Frequency Hz	No. of cables in parallel per phase	Total weight (kg)
400	3 No. 10	181
800	3 4/0	1 280
1.2k	5 4/0	2 140
2.0k	8 4/0	3 420
4.0k	15 4/0	6 140

Since the weights shown in table 41 above are obviously not desirable, the alternatives were considered. These are:

(1) Adopting higher system voltages

(2) Allow higher line voltage-drops

When the system voltage is increased to 230/400 Vac the resulting weight is as shown in table 42.

TABLE 42.--FEEDER WEIGHT VS FREQUENCY AT 230/400 VAC

Frequency Hz	No. of cables in parallel per phase	Total weight (kg)
400	2 No. 14	28.3
800	2 No. 14	28.3
1.2k	3 No. 12	42.4
2.0k	3 No. 8	114
4.0k	4 No. 0	1 710

If it is decided to power all loads at conventional voltage levels the weight of four full rated 60 kVA autotransformers have to be added. The results are shown in fig. 55 for two transmission voltages 230/400 and 345/600 stepped down to 115/200. Clearly, for this case, a frequency of 2 kHz and a voltage of 345/600 Vac produce minimum weight.

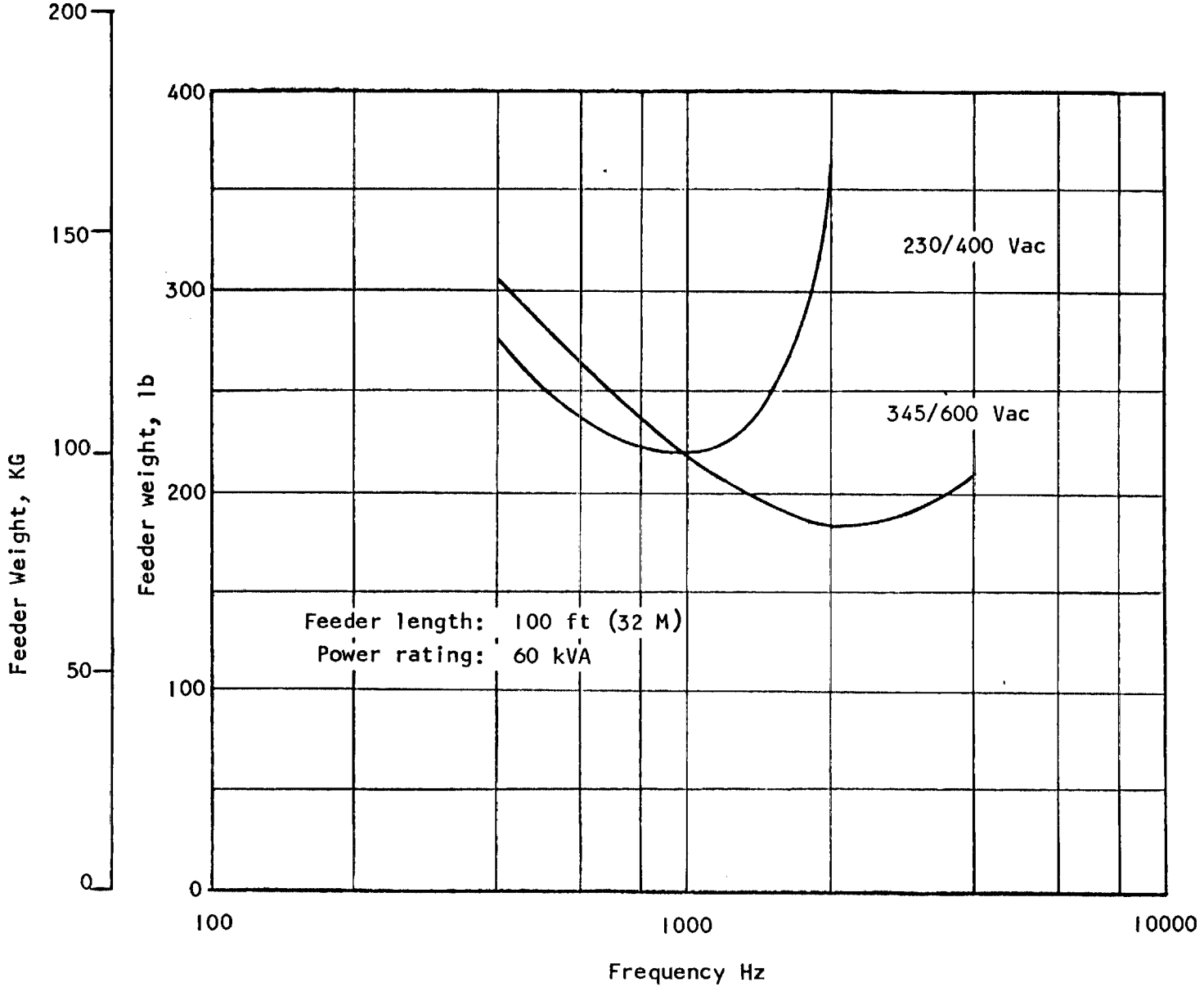


Figure 55. Feeder Weight Plus 4 Autotransformers Stepped Down to 115/200 Vac as Function of Frequency

When a higher line-voltage drop is allowable, a significant feeder weight reduction can be made. The increase in generator weight however, can be made negligible for a relatively small increase in line-voltage drop. For example, at a 10 V drop, the kVA rating of a 60 kVA machine needs to be increased by only 4.15 percent of 2.5 kVA. At 0.454 kg/kVA (1 lb/kVA) the result is an increase of only 1.1 kg (2.5 lb). Likewise, a 15 V drop results in a 2.3 kg (5 lb) increase and a 20 V drop increases generator weight by 4.5 kg (10 lb). It is realized that the higher permissible feeder impedance will adversely affect system dynamic regulation. However, the effects of this may be acceptable. Table 43 below shows the total feeder weight (4 channels) for a 50 kVA 115/200 V system, at a distance of 30.5 M (100 ft). For correct weight evaluation the generator weight penalty is to be added.

TABLE 43.--PROJECTED FEEDER WEIGHT (KG) FOR VARIOUS FREQUENCIES

Volt Drop \ Frequency	400 Hz	800 Hz	1200 Hz	2000 Hz	4000 Hz
10 V add 4.5 Kg gen. weight	71.8 3 No. 10	114 3 No. 8	407 3 No. 2	1710 4 4/0	3410 8 4/0
15 V add 9 Kg gen. weight	71.8 3 No. 10	71.8 3 No. 10	71.8 3 No. 10	407 3 No. 2	2140 5 4/0
20 V add 18.1 Kg gen. weight	71.8 3 No. 10	71.8 3 No. 10	71.8 3 No. 10	114 3 No. 8	1710 4 4/0

Three conductors per phase were used, except for the cases where the usage of 4/0 cables was indicated. As can be seen, this same size cable configuration of 3 x No. 10 conductors was chosen for the 10 V 400 Hz case through the 20 V 1200 Hz case because cable size was defined by the current, rather than the voltage drop limitation. A summary of transmission weight for the specific case of 4 x 60 kVA capacity and an average distance of 30.5 M (100 ft) to the main power center is given in table 44 for the frequency levels indicated. In all cases (except for the dc voltages); it is assumed that utilization equipment will operate at 115/200 Vac. The ac values in Table 44 are taken from Fig. 55 with extra allowances noted.

In conclusion, for long feeder runs, high voltage transmission will be unavoidable to keep feeder weights within tolerable limits. A configuration of all factors which influence transmission weight will have to be considered. These are:

(1) Configuring special low reactance feeders

(2) Utilizing high voltage transmission

(3) Allowing higher line drops

TABLE 44.--MINIMUM TRANSMISSION WEIGHT (KG)
FOR VARIOUS POWER FREQUENCIES

	Dc		Ac				
	400 Vdc	200 Vdc	400 Hz	800 Hz	1.2 kHz	2 kHz	4 kHz
Reference	-	-	180	-	-	-	-
First choice	25		76.1	80.9	80.9	88.5	101
Second choice		59.8	126 Note A	102 Note A	99.3 Note B	132 Note E	Excessive
Third choice			139 Note B	114 Note B	107 Note A	165 Note A	Excessive

NOTE A: Generator at twice standard voltage with step down autotransformers at end of feeders.

NOTE B: Generator at three times standard voltage with step down autotransformers at end of feeder 5 percent of generator weight and 10 percent for heavier insulation of feeders included.

NOTE C: Generator at standard voltage, 10 V line drop allowed. 4.5 kg additional generator weight for upgraded rating included.

NOTE D: Generator at standard voltage, 15 V line drop allowed. 9.0 kg additional generator weight for upgraded rating included.

NOTE E: Generator at standard voltage, 20 V line drop allowed. 18 kg additional generator weight for upgraded rating included.

Generator feeder impedance for the high frequency cycloconverter system: The impedance of the generator feeder which inputs to a VSCF cycloconverter (NCC) cannot be treated in a manner similar to other systems. This is due to the harmonics in the input wave form producing a significantly higher reactance. The reasons for this are explained in the following discussion:

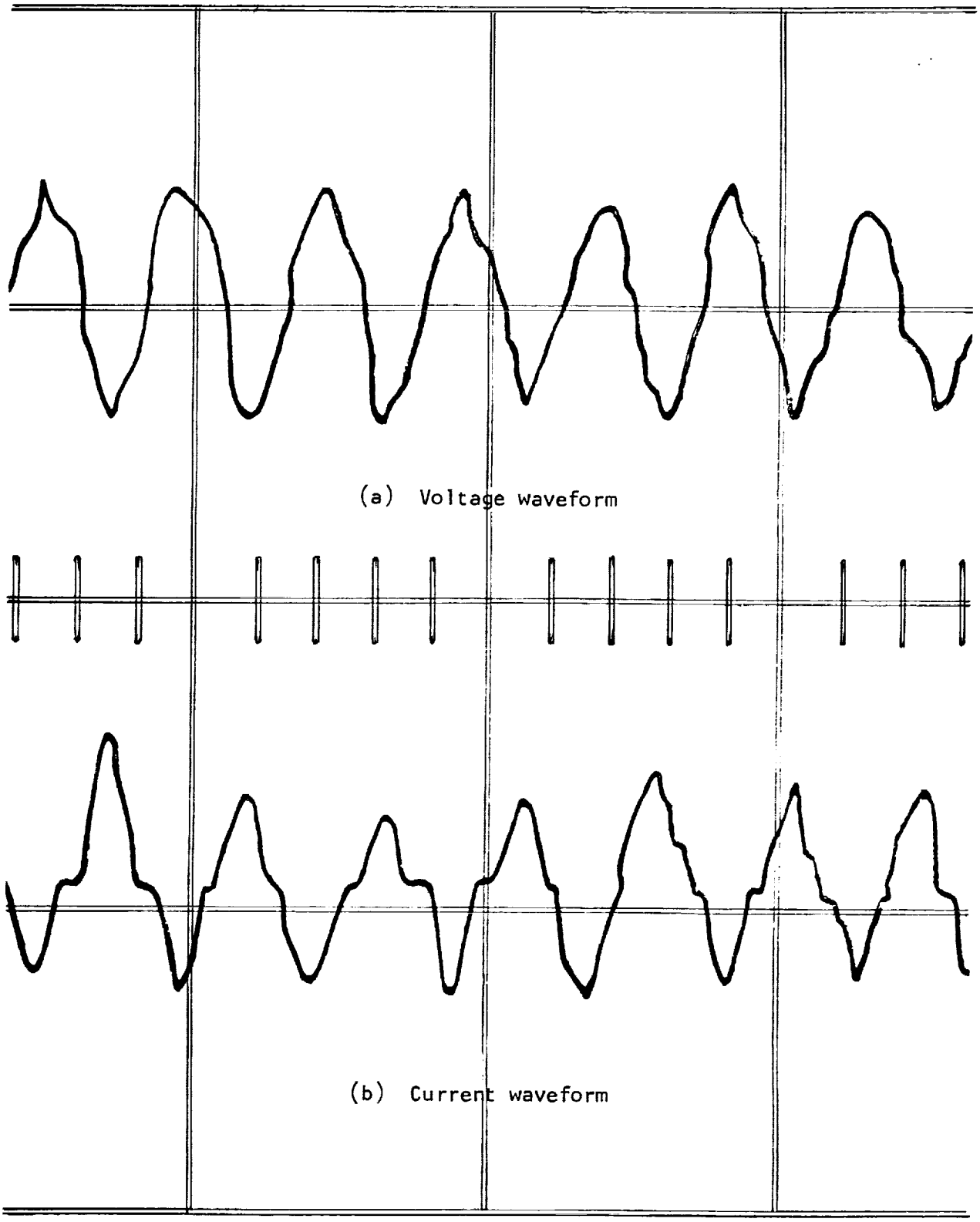
For a conventional utilization frequency output of 400 Hz, the cycloconverter requires a minimum input frequency of 1.2 kHz. This allows for an adequate, low-weight filter design. For an engine speed raise of 2:1 the upper frequency level will be 2.4 kHz. Since the cycloconverter is switching the high frequency wave form under conditions of continuously varying conduction angles, an irregular, highly distorted chopped sine wave results. Because of the power displacement factor introduced by the inverter load, voltage and current are not only apart in time, but exhibit wave forms of little resemblance to each other. For these reasons, the frequency range of 1.2 kHz to 2.4 kHz can not be considered as the true frequency band for impedance calculations. A Fourier series harmonic analysis shows that the equivalent frequency band (for impedance) is actually much broader.

Fig. 56 shows an enlarged oscilloscope trace of the high frequency generator voltage and current waveforms produced when feeding a cycloconverter.

Computed data of five individual consecutive cycles of the current are collected in table 45. As can be seen, the third harmonic wave reaches a level of 32 percent of the fundamental. Also, high dI/dt ratios of the fast switching semiconductors (as much as this is desired from the standpoint of efficient converter operation) introduce considerable EMI problems, both conducted and radiated. Shielding of the transmission line therefore becomes necessary. These facts will all result in increased transmission weight.

TABLE 45.--HARMONIC CONTENT (CURRENT WAVEFORM)

Percent of Fundamental						
1st wave	2nd wave	3rd wave	4th wave	5th wave	Average of five waves	
100.0	100.0	100.0	100.0	100.0	100.0	
9.6	18.6	26.6	10.9	20.5	2nd	17.2
8.1	32.3	12.1	14.7	18.5	3rd	17.1
6.8	3.7	6.1	10.9	3.8	4th	6.3
8.0	10.2	2.4	1.2	5.7	5th	5.5
8.4	3.2	5.8	4.6	6.5	6th	5.7
2.3	2.5	5.5	4.3	3.4	7th	3.6
4.0	2.9	3.8	1.3	2.1	8th	2.8
2.2	5.1	4.3	2.5	1.5	9th	3.1
0.5	0.7	1.7	2.6	0.8	10th	1.3
1.4	1.7	3.0	0.7	0.8	11th	1.5
2.5	2.2	1.1	0.5	0.8	12th	1.4
0.4	1.7	2.0	0.1	1.1	13th	1.1
1.1	1.0	1.4	0.4	0.4	14th	0.9
0.1	1.9	1.2	0.2	0.8	15th	0.8
					Total hamonic content	27.1%



(a) Voltage waveform

(b) Current waveform

Figure 56. VSCF Generator Waveforms

The increase in line impedance drop due to the harmonics can be illustrated by the following tabulation

Harmonic	I	IX	$(IX)^2$
Fundamental	1.00	1.00	1.000
2nd	.173	.346	.120
3rd	.172	.516	.266
4th	.063	.252	.064
5th	.056	.280	.079
6th	.057	.342	.117
7th	.036	.252	.064
8th	.029	.232	.054
9th	.032	.288	.083
10th	.013	.130	.017
11th	.015	.165	.027
12th	.015	.180	.032
13th	.011	.143	.021
14th	.0092	.129	.017
15th	.0088	.132	.017

$$\Sigma(IX)^2 = 1.978$$

$$\text{RMS value} = \sqrt{\Sigma IX)^2} = 1.406$$

Considering only the first 14 harmonics, the feeder reactance drop is 41 percent higher due to the distorted waveform. Since the harmonic content does not converge rapidly, the total increase in reactance is estimated at being more than 50 percent.

In recognition of the inherent impedance, special shielded, low reactance feeders for VSCF application have been designed carrying six phases and a centrally located neutral. It has been claimed by the manufacturer that these cables weigh only 20 percent more than conventional feeders. This of course depends on the specific application and length of installation, allowable potential drop, etc.

Solid state power switching and control.--Future aircraft power distribution systems will utilize solid state switching elements capable of being computer controlled. When integrated in a multiplexed remote power control and management system, solid state power switching is possibly the most promising improvement. The relationship of the power controls to other elements of the electric power system are shown in the block diagram of fig. 57. As illustrated in the diagram, the power controllers receive command signals from the master control logic unit via the multiplexing and remote output terminals. The control unit combines the input of multiple signal sources, thereby eliminating redundant signal wire installations which were necessary to "collect" appropriate logic conditions as input for each individual subsystem. The role of the master control unit as the central 'brain' has been previously discussed in the description given of the selected system.

Many advantages are offered over systems using conventional electromechanical switching devices. Among the major advantages are better reliability, longer life, inherent compatibility to load equipment and insensitivity to hostile environment. Because of the increasing demand for electrical power in aircraft, a corresponding increase is occurring in the number of distribution paths and power switching functions. This is complicating the distribution system. The application of solid state switchgears will greatly reduce, and simplify the complexity of the distribution system.

This simplification would not otherwise be possible. In addition, better distribution system performance is expected because of the regulating capability of the solid state device, which may be adjusted to operate in a current limiting mode. As a result, switching transients will be virtually eliminated. The main functions of a solid state power controller (SSPC) are:

- Switch power on and off to load equipment on command.
- Remote control capability.
- Provision for circuit overload protection
- Adjust to a current limiting mode during overload conditions.

These functions, with the exception of current limiting, are, or can be, provided in conventional systems which employ combinations of toggle switches, circuit breakers, relays, fuses, etc. The SSPC, as a single switching element, replaces several types of these devices, and has the added advantage of reducing the total number of switching elements required. Each load circuit of a conventional system normally employs a circuit breaker (or fuse), and one or more of the other switching elements in order to provide functional capability. The solid state switching and power control concept was initiated about 10 years ago by LTV Vought Aeronautical Division. This effort has progressed to the design and fabrication of a simulator of the electrical distribution system of the A-7 aircraft. Similar development programs were also carried on later by Westinghouse, Grumman, Bendix companies, etc. A series of 28 Vdc and 115 Vac controllers have been developed for a limited current range. The dc type

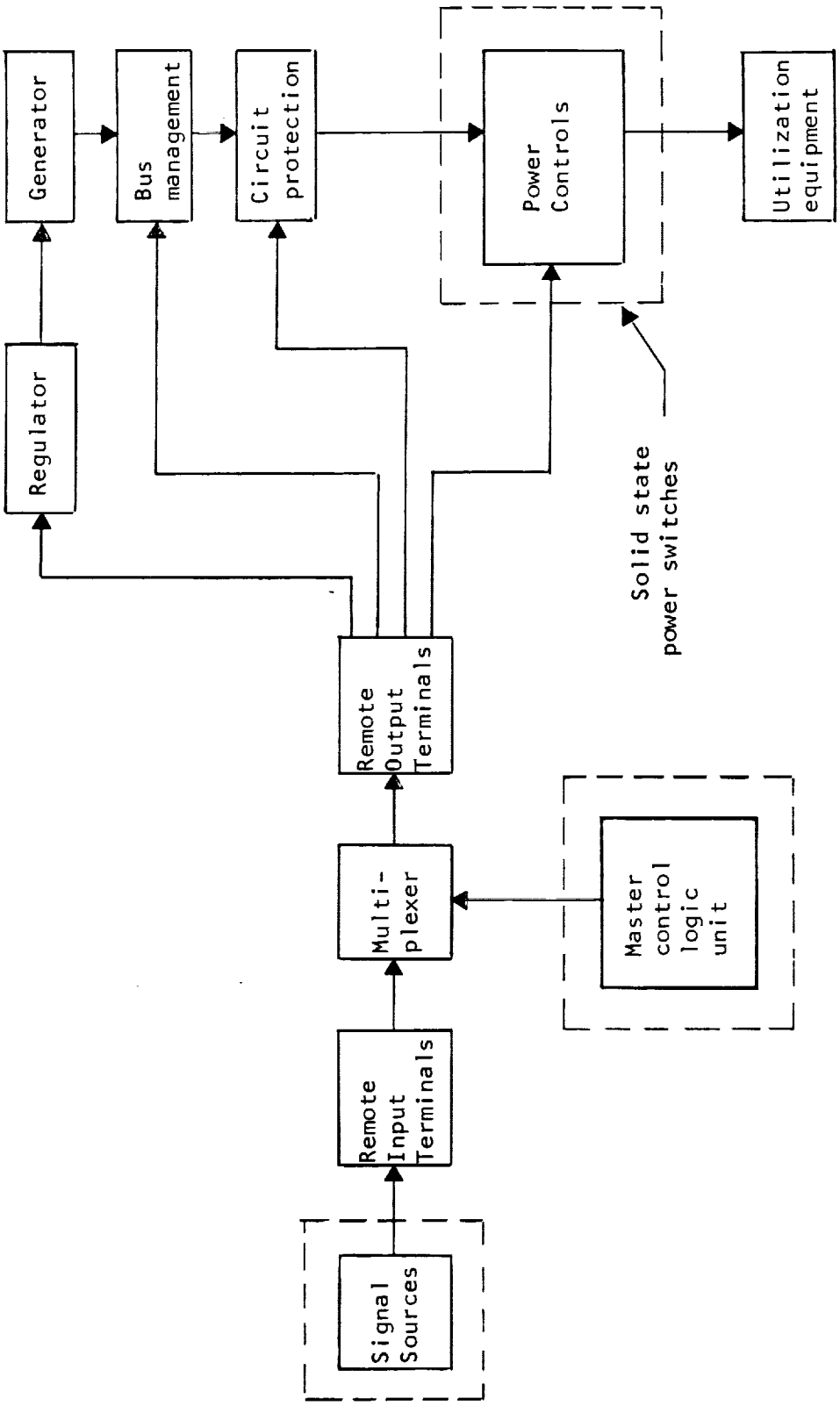


Figure 57. Aircraft Electric Power System Control Block Diagram

controllers use high-power switching transistors, while the ac type uses back-to-back connected thyristors.

SSPC basic design considerations: The static switch is not merely a simple component like its mechanical counterpart, the relay, or circuit breaker. Solid state power controllers are quite complex multi-technology semiconductor devices. They not only employ power semiconductors, but also a host of integrated circuit technology in various forms. For the design of an SSPC, there are several important criteria which must be considered. These are: (1) high current capability, (2) low voltage drop, (3) isolation between power and control, (4) low leakage current, (5) current limiting capability. These a re now discussed separately.

(1) High current capability: The maximum current rating obtainable with state-of-the-art semiconductors, particularly transistors, is very limited. Power dissipated within the device has a direct relationship to its current handling capability. A further reduction of power dissipated during the "on" state will decisively influence the degree of success expected for high current application.

(2) Low voltage drop: A low voltage drop across the device is important because it affects the dissipation, and thereby the thermal stress and efficiency. Since the voltage drop increases only slightly with increased current for a saturated semiconductor, better efficiency is obtained for higher system voltages.

(3) Power/control isolation: Isolation, between the control input circuit and the power output, is important because of the adverse influence exerted by the power circuit on data bus control operation. Solid state switches unlike their electromechanical counterparts, do not inherently offer isolation; special attention must be given to this requirement. Present techniques commonly used to provide isolation are, solid state (LED) optically coupled devices, and transformer coupling between the control input and the drive stage.

(4) Low leakage current: The characteristic of low leakage current in the "off" state is important because of its effect on the overall efficiency of the distribution system. This generally restricts the selection to the use of silicon, rather than Germanium power semiconductors.

(5) Current limiting capability: The capability of current limiting by the solid state device, without using external circuit elements, pertains mainly to the transistor and is therefore, applicable primarily in dc circuits. Ac type current limiting may be accommodated by phase control of thyristors, with consequent deterioration of the sinusoidal waveform supplied to the load. A current limiting capability by the switching device, is very desirable because of its effect in minimizing transients in the power distribution circuit due to overloads and faults. Parameters, such as individual load characteristics, system voltage, power semiconductor ratings, magnitude of current limiting and time duration, affect the extent of current limiting available with any particular SSPC design.

Advantages and disadvantages: The advantages of solid state switching and control arise from the capability of solid state components in remote control, fast response and lack of moving parts. Some of the advantages are discussed below:

(1) Compatibility with automatic load management: Automatic load shedding and load sequencing require a large increase in switches, wires, control signals. There is also the need for digital computer and fast acting power controllers. These requirements cannot be met by the conventional electromechanical switches. Solid-state switches on the other hand, show every promise of meeting these requirements. Solid state devices require only low level control. These control signals can be multiplexed to save wiring complexity. System protection and control can be managed by a data bus control system.

(2) Reliability and maintainability: Electric power system reliability and maintainability will be enhanced by the use of solid state switching and control method. Static switches are potentially more reliable than mechanical switches. The problems of mechanical contact bouncing and pitting during switching are well known to power system engineers. With built-in test (BITE) equipment, the system maintainability should be substantially improved.

(3) Weight: Solid state switches are lighter and smaller than the remotely controlled electromechanical circuit breakers. Since the switches are remotely controlled, there will also be weight saving in power cabling. Accordingto LTV, the distribution system weight for an A-7 aircraft can be reduced from 262 kg (576 lb) to 143 kg (315 lb) by converting from the conventional to solid state switching, or a reduction of 45 percent. A comparison of switchgear weight for a typical large transport is shown in table 46. Three types of switches are compared, remotely controlled electromechanical circuit breakers, 115V, 400 Hz ac, and 120vdc. Higher voltage dc switches are not listed because of the difficulty in securing data. High voltage and high power dc solid state switches are future development areas which should be pursued because of their application to future aircraft high voltage dc systems.

(4) Performance: Semiconductor switches respond to control signals rapidly. Power transistors with proper circuitry can limit the fault current. These features can minimize transients on the power bus due to overloads and faults, thus improve the power quality and decrease fault capacity requirement of generators. Fast response also increases the accuracy of protection.

Contact bounce is a major source of EMI. Solid state switches have less EMI problem when compared with electromachanical switches. Using remote control concept, there will be more compact and workable flight deck arrangement, resulting in significant structural payoffs. Another advantage of solid state switching and control is the separation of signal and power switching requirements.

Disadvantages of solid state switches are a large forward voltage drop (typically 1 to 1.5 volts) and incomplete isolation of the control and power circuits. For a high voltage dc system, say 300 volts, the voltage drop significance is reduced.

TABLE 46.--SWITCHGEAR WEIGHT COMPARISON*

	No. of units	Watt/unit	Weight kg		
			RCCB	Solid state dc (120 v)	Solid state ac (115 v)
MOTOR	19	<150	6.0	1.3	1.1
	15	150-500	4.8	1.4	1.0
	13	500-1000	4.4	1.8	1.2
	1	1000-2000	0.4	0.2	0.1
HEATING	15	<150	4.8	1.0	0.9
	28	150-500	8.9	2.5	1.9
	30	500-1000	10.2	2.7	1.8
LIGHTING	26	<150	8.3	1.8	1.5
	37	500-1000	12.6	3.7	3.4
	4	1000-2000	1.4	0.7	0.5
ELECTRONICS	72	<150	22.8	4.9	4.1
	4	500-1000	1.4	0.5	0.4
CONTROL, ETC.	137	<150	43.4	9.4	7.8
TOTAL			129.4	31.9	25.7

*Switchgears with capacity in excess of 2KW are excluded due to present limitations of solid state switchgears.

LTV has made a comparison (ref. 13) between the conventional and solid state distribution system for an A-7 aircraft, and found that the solid state distribution system has substantial improvement over the conventional system. The result is shown in table 47.

TABLE 47.--COMPARISON OF ELECTRIC SYSTEMS (A-7 AIRCRAFT)

	System		
	Convention	Solid state	Reduction
Weight, kg	262	143	45
Volume 1000 cubic cm	45.3	24.6	45
Reliability (failures/10^6 hr)	498	116	77
Maintainability (man hr per flight hr)	0.014	0.0028	80

System implementation: The electronics involved with the solid state distribution system, such as control logic unit, sensors, and multiplexing equipment are in state of the art. However, high voltage, high current power switches are under development. Ordinarily, aircraft power control circuits require several relay contacts in series. The use of solid state switches in such circuits is not practical because of excessive voltage drops. For immediate and near-future high power circuit applications using a remotely controlled circuit breaker (RCCB), a hybrid remote power controller is recommended. Both the RCCB and the hybrid RPC have been described in earlier discussion. A further comparison of these switches is presented in the section on "components." Since a great number of published literature is available on solid state power switching and control (ref. 14 through 24), detailed discussion on this subject is not presented in this report.

Signal multiplexing.--The first aircraft applications of multiplexing were to systems whose failures did not impair flight safety. Now the state-of-the-art has advanced to the point where flight-critical systems such as the power distribution system can and should employ multiplexing to enhance maintainability and reliability and to save weight. The power system, with its reasonably well localized power control centers, lends itself particularly well to multiplexing techniques. Basic concepts are not new, however, advances in miniaturization, as well as solid-state power switching devices, make their implementation more attractive as time progresses. The maximum benefit is derived when the signal multiplexing is coupled with integrated remote power controllers.

A description of the functions and operation of multiplexed power control and status signals was given earlier in this report in the section on power systems for conventional aircraft. The incorporation of this system into an aircraft would itself be a major improvement. Its implementation depends largely on the success of solid state power switch development. In this section,

a discussion is presented on the signal multiplexing schemes which were considered and the tradeoffs which were made. The selected scheme, a time division multiplexing (TDM) approach, is the signal multiplexing method most favored.

Control signal multiplexing is based upon the following assumed remote power controller (RPC) characteristics:

- Switching action is controllable by logic level voltages.
- Switch status (on or off) is identified by a logic level output. This output is independent of the controlling function.
- Voltage and/or current information is in analog form.
- An overload condition is indicated by a logic level output to identify the action.

After the discussion on the possible multiplexing schemes, the weight of a signal multiplex system is compared parametrically with a hardwired system. The result supports the contention that the weight savings are significant when a system with a large number of signals (>150) uses a multiplexing scheme.

Candidate multiplexing schemes: Two multiplexing schemes were considered, frequency division multiplexing (FDM) and time division multiplexing (TDM). The former is a carrier approach where analog information may be put on the carrier, using a frequency modulation, amplitude modulation or phase modulation. Similarly, digital information may be modulated, using frequency shift keying, amplitude shift keying (e.g., turning the frequency on or off to represent 1 or 0) or phase shift keying. If the analog information is to be digitized, a code must be selected and then one of the digital modulation techniques may be used. In cases where two channels or stations must transmit and/or receive information simultaneously, FDM must be used rather than TDM. This would allow full duplex capability on a transmission line which carries more than one stream of information simultaneously. The system complexity will, in general, exceed that of a TDM system.

Analog information can be modulated in a TDM system, using Pulse Duration Modulation, Pulse Position Modulation, or Pulse Amplitude Modulation. Analog data, which has been converted to digital or digital information (e.g., the RPC status and control signals are inherently digital) can be modulated in the digital counterparts of the analog pulse modulation schemes. However, in general, the digital modulation techniques are termed pulse code modulation PCM in cases where some analog data is involved; then the selection process involves code and digital format selection.

In the power generation and distribution system, most of the signals to be multiplexed are inherently digital and do not require high individual data rates. These discrete signals should be grouped into "data words" for transmission in order that the data be transmitted in a relatively fixed format for synchronization purposes. Thus, analog data can be converted to digital at remote

locations, improving the signal to noise ratio of the transmitted data and discretes can be grouped and treated essentially as the analog data is for transmission purposes. This approach is compatible with the state-of-the-art in microcircuitry and leads to time-sharing of hardware and commonality. If, for example, discretes can be arranged in groups of 32, over 1000 switch positions could be transmitted in 32 data words; since this word length would be much more than is required for analog signal resolution, 1 32-bit word length could represent 4 eight-bit analog words.

Two basic categories of codes exist for the encoding of analog data, PCM and Differential. The latter codes (e.g., "delta modulation" and "delta squared modulation,") utilize a data stream wherein the transmitted data indicates the change from the previous value rather than the present value of the analog signal. These codes are not suitable for data which comprises groups of discretes. In PCM, many codes exist, e.g., "pure" binary, binary coded decimal, the Gray codes, etc. Similarly, several digital formats can be used such as non-return to zero and bi-phase. The selected encoding scheme, cyclic progressive code, is a result of redundancy considerations.

Since the power distribution control system is a critical aircraft system, redundancy must be used to enhance mission reliability. In present power systems this is done through the arrangement of multiple power sources and rather complex switching schemes. This type of redundancy should be maintained. Additionally, since in a multiplexed control system, the potential hazard of single failures resulting in the loss of several signals exist, it is recommended that redundancy in the shared hardware be employed. In the case of the transmission line, two popular alternatives exist; 1) the use of a "lossy" line connected in a loop, 2) the use of redundant lossless lines. In the former case, intentional line loss is introduced at intervals along the line--locating them at the substations is a convenient solution. Thus, an open or short at any position along the line does not destroy the line. However, if the failure occurs in a connector at a substation, that substation would be lost. Consequently, a redundant line should be used to avoid this problem. In the interest of simplicity of the decision-making hardware, a triple redundant line with majority voting was considered. It is anticipated that triple redundancy will give adequate mission reliability without resorting to three looped data busses which would provide something on the order of sixfold redundancy as far as the line, as a whole, is concerned. Thus, to optimize the signal-to-noise ratio, a lossless line was chosen. This also eliminates the possible requirement for automatic gain control at individual receivers to compensate for a disparity of voltage levels due to variable line losses, using lossy lines.

To minimize the hardware at individual substations, time-shared analog-to-digital converters (ADC's) were selected. The prevention of a single ADC failure resulting in the loss of more than one signal, means that the ADC's should be redundant. If stations exist where three or less analog signals need to be converted, this design would be subject to review. However, in other locations, notably the generator bus control substation, triple redundant ADC's are warranted in terms of hardware minimization.

The use of majority voting on the discretes poses no special problems since the individual bits are independent. However, with the use of triple redundant ADC's, converting analog signals to digital, the bits in each data word are related and could result in voting problems if the coding scheme is not selected with care. As an example of this, assume that a successive approximation ADC is used which results in a pure binary code. The smallest voltage increment which can be added to or subtracted from the converter approximation determines the accuracy to within which the converter can approximate the analog parameter. However, it is possible for three converters to approximate, simultaneously, an analog parameter and make different dicisions regarding the smallest increment, and yet be converting to within the same accuracy. This condition can arise when the analog parameter is very close to the nominal voltage level at which the smallest increment is decided. In this case, the decision depends on whether the difference between the converter approximation and the analog parameter is greater than the resolution of the converter. Theoretically, converters with infinitely small differences in resolution can produce different decisions, and hence still have an accuracy of plus or minus the smallest increment.

At first sight, it would appear that this need not present a voting problem, since the smallest increment, or least significant bit (LSB), could be ignored in a majority logic dicision. However, further investigation shows that all the digits, or bits, of a pure binary number change completely when the number changes from (2^n-1) to 2^n, or vice-versa, see fig. 58 below:

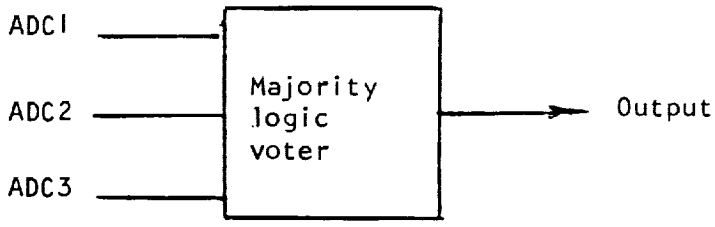


Figure 58. Example of majority logic voter for ADC output

In this case, the numbers, in terms of four bits, which differ by one count are:

Case I	ADC1	0110 ≡ 6	
	ADC2	0110 ≡ 6	
	ADC3	0111 ≡ 7	
and the	Majority Voter	0110 - 6	and is valid

This means, therefore, that two of the binary outputs of the three ADCs could be similar, differing in only the LSB position, and the third be quite different, differing in each bit position. All three numbers could still be within one increment (one least significant bit) of each other in magnitude. A majority logic voter makes decisions by providing an output which is representative of the majority input, as in the case just illustrated. In this case only one decision was made on the least significant bits. When one of the digits is different, in each bit position as in the case shown below (Case II), the voter can still make a valid majority decision.

Case II

ADC1	0111 ≡	7
ADC2	0111 ≡	7
ADC3	1000 ≡	8
Majority Voter	0111 -	7 and is valid.

The complication which still remains is, that if a failure occurs in one of three ADC's, the voter can no longer make a valid decision since it is now possible for all three numbers to be different. This case is illustrated in Case III, and the voter output is invalid since a majority decision does not represent either of the correct ADC outputs.

Case III

Introducing an error into ADC1 procedures:

ADC1	XXXX ≡ ?	X : '1' or '0'
ADC2	0111 ≡ 7	
ADC3	1000 ≡ 8	
Majority Voter	XXXX - ?	and is invalid.

In each of the voter inputs is preceded by a binary-to-cyclic-progressive-code converter, this will ensure that even when the binary numbers change around $2^n \pm 1$ the bit pattern of each cyclic progressive number changes in only one bit position. If the ADC outputs are correct (within one increment, or "count") the three numbers will only differ in one bit position, and the voter output is valid. This is illustrated in Case IV. If a failure occurs in one ADC the voter can still produce a valid majority vote decision.

Case IV

	Binary		Decimal		CPC		Binary		Decimal
ADC1	XXXX	≡	?	→	XXXX				
ADC2	0111	≡	7	→	0100				
ADC3	1000	≡	8	→	1100				
			Majority Voter		X100	→	0111 or 1000	≡	7 or 8

Fig. 59 below shows the new scheme:

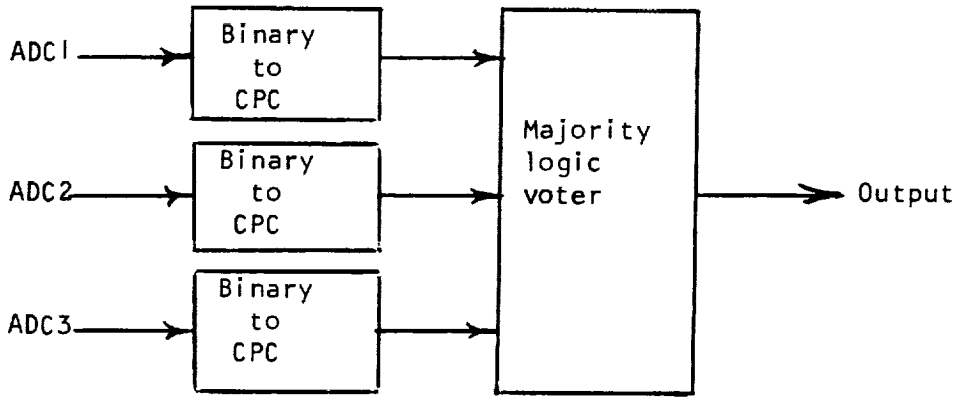


Figure 59. Majority logic voter with binary to CPC pre-conversion

The requirement for binary to CPC converters could be avoided by using an ADC of the counting type where the counter counts in CPC. However, the clock rate at each substation would have to be significantly higher, e.g. for an eight-bit work length, the clock rate for a counting approach is on the order of 16 times that required for a successive approximation approach in order to convert at similar speed.

Random substation addressing was selected in order that the controller processor, CP, can address individual substations easily as a function of the status in the event of one or more failures. This facilitates handling the priority interrupts and requesting data from some substations more frequently than others. It also provides a great deal more system flexibility in the event of requirement modifications.

A Manchester biphase code was selected in order to eliminate the requirement for a separate clock line (which has to be redundant) in addition to the fact that the transmission line design is simpler than for many other codes. The latter is true since there is a transition every clock time and a total frequency deviation on the line of a factor of two to one, unlike a pure binary code which could, for example, remain high for many data bit times. This feature of the Manchester code also allows transformer coupling into the transmission line and decreases the possibility of a transmitter failing hard and disabling the line. Since triple redundancy is used, hard transmitter failures which cause the generation of a continuous stream of data would only result in the loss of a redundant path. This type of failure would be detected at the CP in order that the faulty transmitter could be repaired postflight.

Weight comparison of signal multiplex system versus hardwired system: a comparison between a multiplexed and hardwired system is presented, using the number of signals as a parameter. The assumptions are:

Hardwired system

Wiring weight = 0.00444 kg/m (3.2 lb/1000 ft) (No. 26 AWG)

Relay logic weight = [0.018 kg (0.04 lb)/signal]

Multiplexed system

Remote terminal weight = 0.0175 kg (0.0384 lb)/signal
(0.56 kg for 32 signals)

Central unit weight = 2.28 kg +10.00146 kg/signal

Connecting signal wiring = 0.0073 kg (0.016 lb)/signal
(1.53m/signal)

Transmission line = 0.455 kg + 0.0023 kg/signal

Based on the above assumptions, the total weight of the two systems can be expressed as follows:

$$W_H = N\,(0.0182 + 0.0044L)$$

$$W_M = 2.72 + 0.0284\,N$$

where W_H = total weight of the hardwired system, kg

W_M = total weight of the multiplexed system, kg

N = Number of signals in the system

L = Average distance between input and output, m

By using the equations, the total weight of this two systems are plotted in fig. 60. Fig. 61 shows the weight savings achievable by using the multiplexed system.

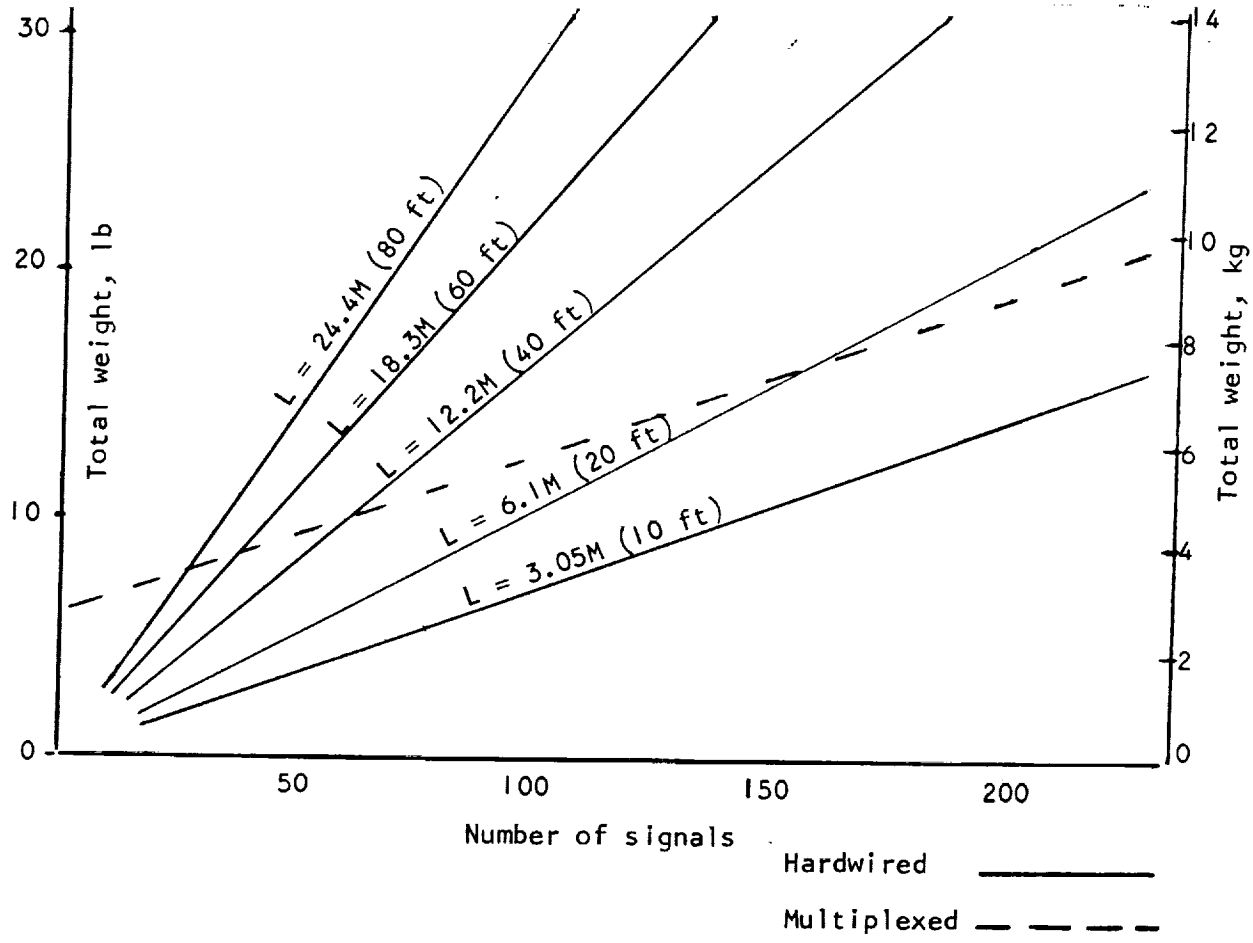


Figure 60. Total System Weight vs Number of Signals

It can be seen that for a system with a large number of signals and a large average distance between input and output, the weight savings are significant.

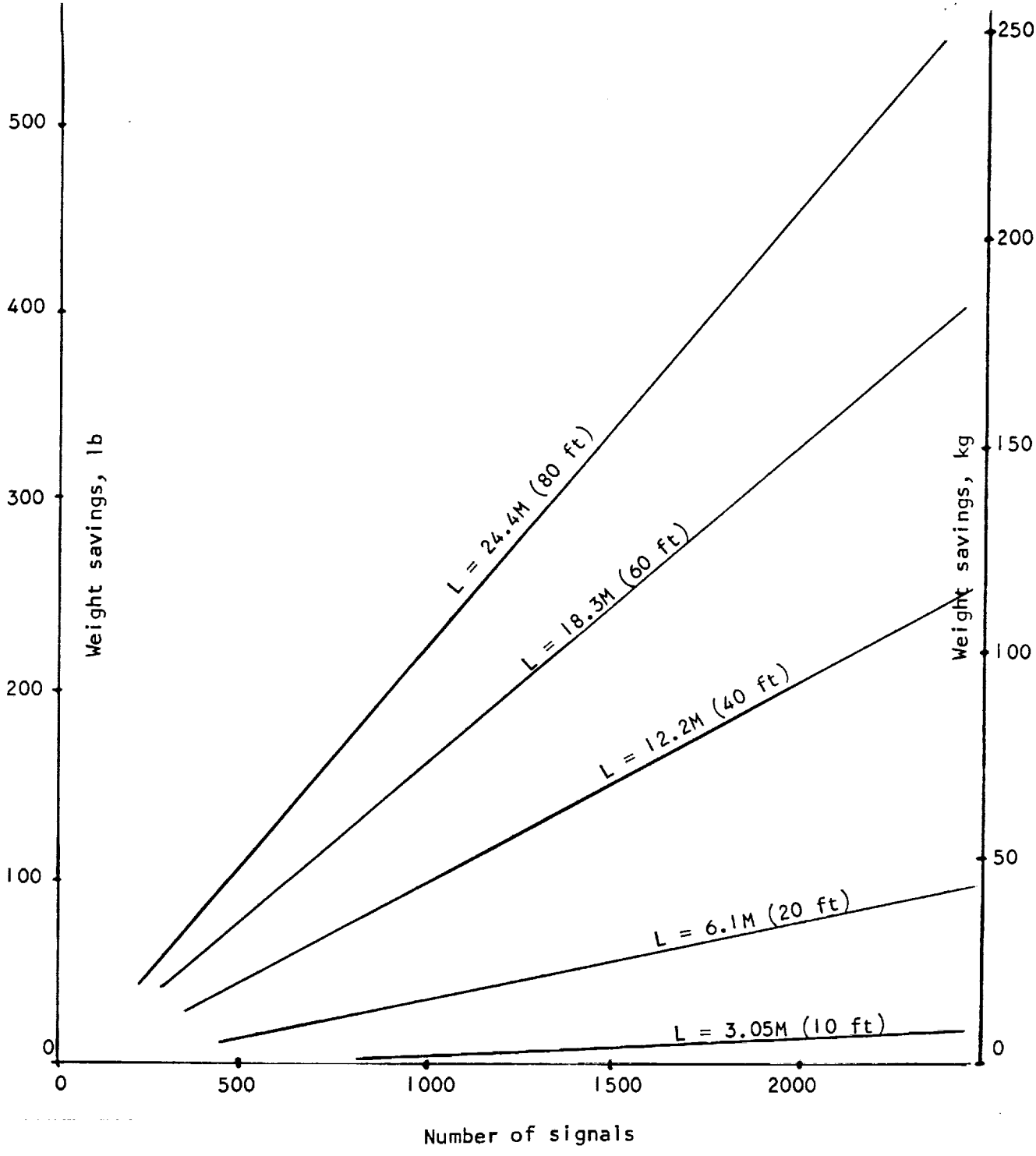


Figure 61. Weight Savings vs Number of Signals

Uninterruptible power.--Modern aircraft have varieties of digital equipment such as an autopilot, inertial navigation, data computer and automatic landing devices. This type of equipment is notably sensitive to line voltage transients. A short duration, power discontinuity could have a serious effect when the aircraft automatic landing subsystem is operating in a critical flight phase. This, and similar disruptions, can be avoided by the installation of an uninterruptible power subsystem. It would be an improvement of unquestionable benefit.

The concept of uninterruptible power has been already realized for ground computer operation. The approach there is to convert 3-phase utility power to dc. A battery bank is connected across the dc link which is always charged, and the dc link feeds an inverter which changes the power back to 3-phase ac. In case of failure of the ac input, the battery takes over at any part in the cycle, thereby replacing the failed source instantaneously.

Fortunately, the amount of power required on aircraft for uninterruptible service is relatively small. It is estimated at being in the order of 1 percent of the total installed generating capacity. Some of the electronic loads in present day aircraft use a scheme similar to that shown in fig. 62. For energy gaps which are low in magnitude and up to 1 msec duration, capacitor storage is frequently employed.

One scheme for ultimate reliable ac power is shown in fig. 63. An inverter floats in parallel with the regular normal supply to the equipment. Upon loss of the regular supply source, the inverter takes over instantly. Power is prevented from flowing in the direction towards the normal supply source by semiconductor switches or magnetic decoupling. The primary supply to the inverter(s) may be constituted by all generators via individual TR units and by the airplane battery. Blocking diodes prevent power interchanges between sources.

Uninterruptible power system arrangements such as are shown in fig. 64 is recommended for future aircraft. The special low amp-hour battery may be connected to the inverter in any of a number of ways. A few of the most frequently used (in ground power) schemes are shown in fig. 64.

Fig. 64a illustrates a method which proved satisfactorily for smaller inverter ratings. This system requires the inverter to operate from the complete battery range from charge to discharge. It also requires a relatively large rating in the regulated battery charger because it not only has to supply the load but also charge the battery.

Fig. 64b illustrates a system which permits the use of a small battery charger. It has however a disadvantage because the inverters must operate over a wide range of input voltage which includes regulation of the input transformer-rectifier and the battery charger voltage for the charge and discharge condition.

Fig. 64c illustrates a system which is economical for higher power ratings. Here the battery may be floated at a voltage considerably higher than the input to the static inverters from the transformer-rectifier. This voltage is blocked by an SCR switch until such time when the voltage difference between

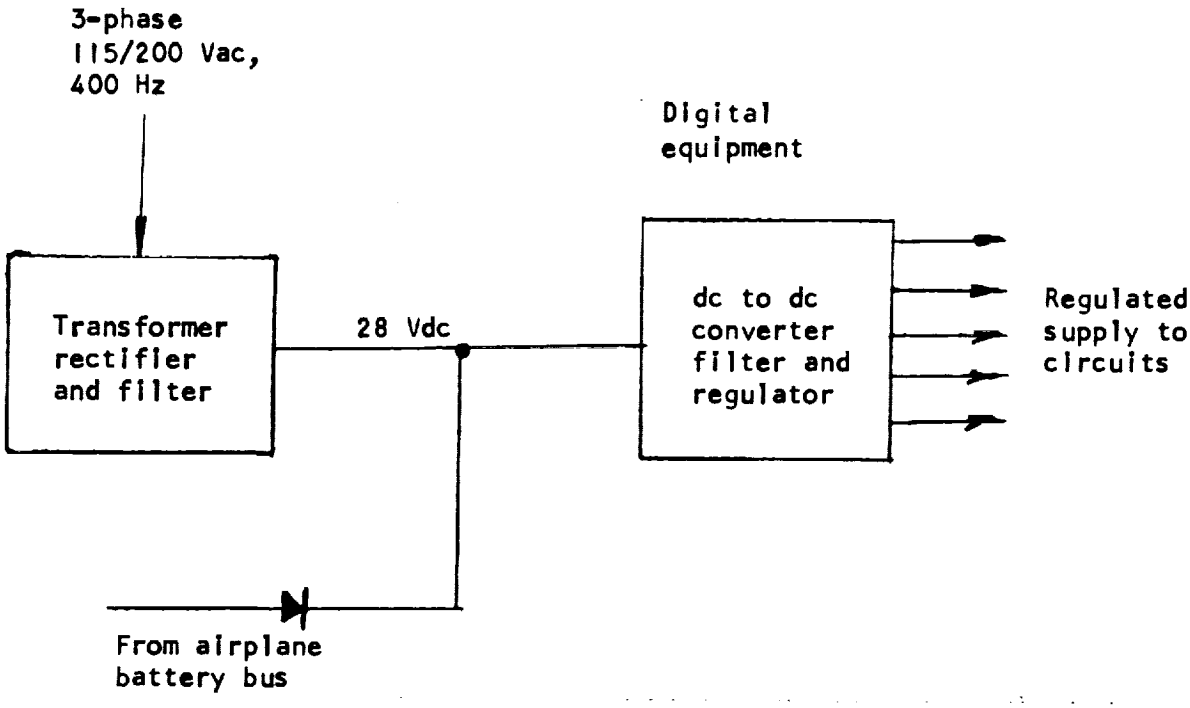


Figure 62. Present Day Uninterruptable Power

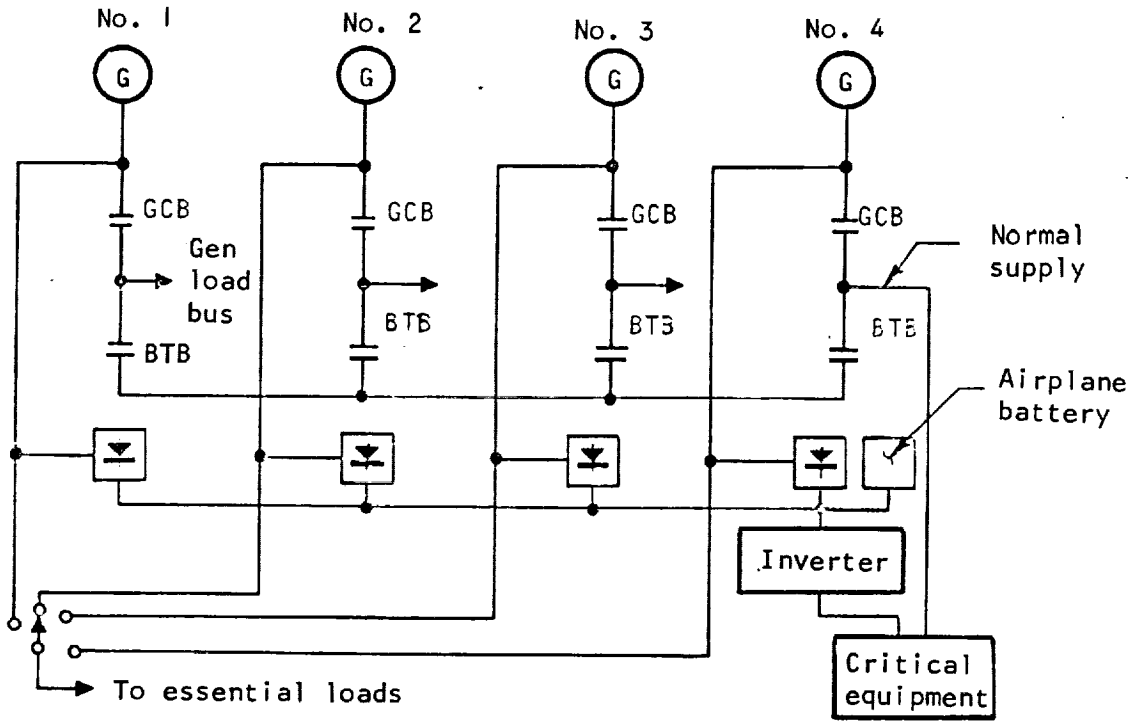


Figure 66. Ultimate Reliable Source for Critical Equipment

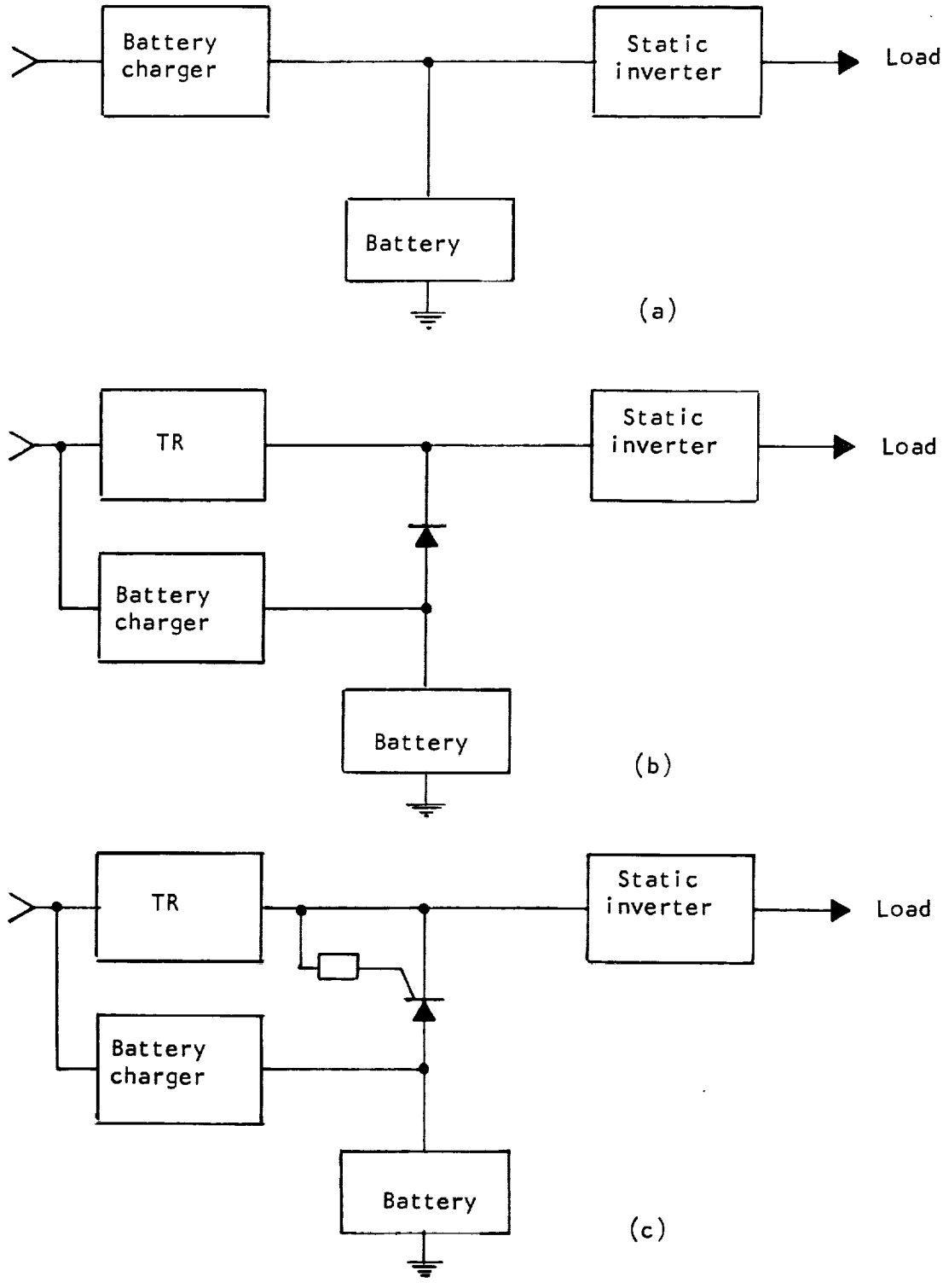


Figure 64. Various Schemes of Uninterruptible Power

the battery and inverter input exceeds a predetermined value. The SCR switch operates in about 10 μsec to connect the float-charged battery to the inverters and the battery terminal voltage drops as current is drawn from the battery by the inverters. A normally closed contact with an operating coil energized by the intput line is normally connected in parallel with the SCR in order to handle these currents and turn off the SCR when the input voltage is restored, the contact opens and the switch is reset. Systems using the above approach have been designed in ratings of several hundreds of KW for ground applications. For the dc to ac inversion process in the ratings considered (up to 2 kVA) the use of power switching transistors rather than thyristors will become practical.

Utilization Subsystems

Load functions.--Basically, there are five different load functions to be performed in an aircraft. These are:

(1) Mechanical motion

(2) Heating and cooling

(3) Lighting

(4) Controls and instrumentation

(5) Electronics

Mechanical motion loads are pumps, fans and blowers and a wide variety of actuators (both linear and rotary). These actuators range from miniature sizes producing a few inch-pounds to contrivances exerting forces of several tens of tons. All these mechanical motion load functions may be either electrically, mechanically, hydraulically, or pneumatically powered. Many of these loads are most economically powered by hydraulic or pneumatic power. This is discussed later under the 'hydraulic and pneumatic power actuation' heading.

Heating and cooling loads include anti-icing, windshield heat, pilot heater, cabin and cargo compartment heat and air conditioning, galley, water heaters, equipment heaters, etc. As with the mechanical load function, some heating loads are more economically performed when not powered electrically. Anti-icing, for instance, is a large heating load that is better obtained by extracting hot engine bleed air.

While it is possible to perform and power the first two load functions by a means other than electrical energy, the last three load functions (Lights, controls and electronics) almost exclusively require an electrical source. There are some minor fluidic or pneumatic control applications. These are not discussed here. The following discussion is divided into two areas: a) electrically powered loads and b) power actuation by hydraulic or pneumatic means. The hydraulic/pneumatic discussion is presented as pointing up the preferable means of powering large motors when a choice is available.

Electrically powered loads.--Table 48 summarizes the general characteristics of aircraft electric loads.

TABLE 48.--CHARACTERISITCS OF AIRCRAFT LOADS

Load Group	Type of Power Best Suited
Motor	Fixed frequency ac or dc, coarsely regulated, insensitive to waveform and transients.
Heating	Constant voltage ac, constant or variable frequency, or dc. Tolerate low quality, coarsely regulated power.
Lighting	Incandescent lamps prefer low voltage ac or dc. Tolerate transients and poor waveform. Fluorescent lamps prefer high frequency ac with square waveform.
Electronics	Closely regulated, clean dc or ac. Input power ultimately transformed to low voltage dc for utilization.
Control	Part of this load requires closely regulated power, ac and dc. The rest can tolerate low quality supply.

Motor loads: These usually present one of the larger portions of the electrical load. Motor loads can tolerate power of poor quality, and motor poerformance is not significantly affected by poor voltage waveform. However, the motor is the most critical component directly affecting any scheme involving electromechanical power conversion. For ac motors, it was assumed that the input power would be constant frequency, 3-phase at 400 Hz and a voltage of 115/208 v. Two phase ac motors were also studied as were dc motors. Dc motors included the brushless type, conventional brush type, and high performance servomotors for servosystem applications requiring high torque-to-inertia ratios. Special design techniques are utilized and unconventional configurations are adopted for the purpose of reducing electrical and mechanical time constants. These high performance motors included the printed dc servomotor, the Minertia motor and the Hyper-Servomotor. They are discussed in detail in Appendix E.

Motor drive summary: Dominant motor type for aircraft applications at present is the ac squirrel-cage induction motor. For this motor type, constant-frequency ac power is preferable. Although the motors can be designed for use with variable-frequency supply, a weight penalty results. Newly developed high performance servomotors such as the Minertia and the Hyper-Servomotor produce high torque-to-inertia ratios. For control purposes, this represents a significant improvement in motor response. Efficiency is however, relatively low at 10 to 20 percent. In the future, a thyristor-controlled brushless dc motor will compete with the ac induction motor for airborne applications. The brushless dc motor has better torque/speed characteristics and better efficiency, and it is an adjustable speed device. This means that aircraft designers will be given greater lattitude in their motor applications involving variable speed range. While induction motors draw a large current during starting, the brushless dc motor can easily be designed with a current limiting feature. Where the load calls for low-speed drive, a high speed motor with reduction gears is recommended as being lighter than a corresponding low-speed motor.

Heating loads: The heating load is insensitive to power type and quality; both dc and constant or variable-frequency ac are acceptable. In general, the heating loads represent the most flexible area and can be relegated to the lowest level in any future design decisions. Where there is a question of ac versus dc, the recommendation is for ac because it is slightly easier to control.

Lighting loads: For aircraft lighting, incandescent, fluorescent, and electroluminescent light sources are all used for different requirements. The majority of lighting power in an aircraft presently is consumed by incandescent lamps. Aircraft incandescent lights are operated at low voltage so that the heavy rugged lamp element will withstand shock and vibration during flight. Present practice of 5 V for small incandescent lights and 28 V for large incandescent lamps seems to be satisfactory.

The effects of input power frequency, wave form and voltage on the efficiency and weight of fluorescent lamps have been extensively studied. Fig. 65 shows efficiency versus input power frequency for two fluorescent lamps (ref. 25). Fig. 66 shows the effect of type of ballast and frequency on fluorescent lamp efficiency (ref. 25). The effect of input voltage wave form on light output with the same rms lamp current is shown in fig. 67 (ref. 26). These curves indicate that fluorescent lamps are better operated on high-frequency, square-wave form ac power. Fluorescent lights can also be operated on dc. The useful life of fluorescent lamps using dc for burning is reduced by approximately 8 percent of that for ac burning.

Another consideration for selecting frequency for fluorescent lights is electromagnetic radiation. An experimental study by Cooke Engineering of Chicago (ref. 27). found that the operating frequency should be between 400 and 1000 Hz to reduce the electric field spectrum radiated by fluorescent lamps.

The overall circuit efficiency of fluorescent lamps is better when operated at higher voltage levels. Some of the fluorescent lights in existing aircraft are operated on 800 Vac.

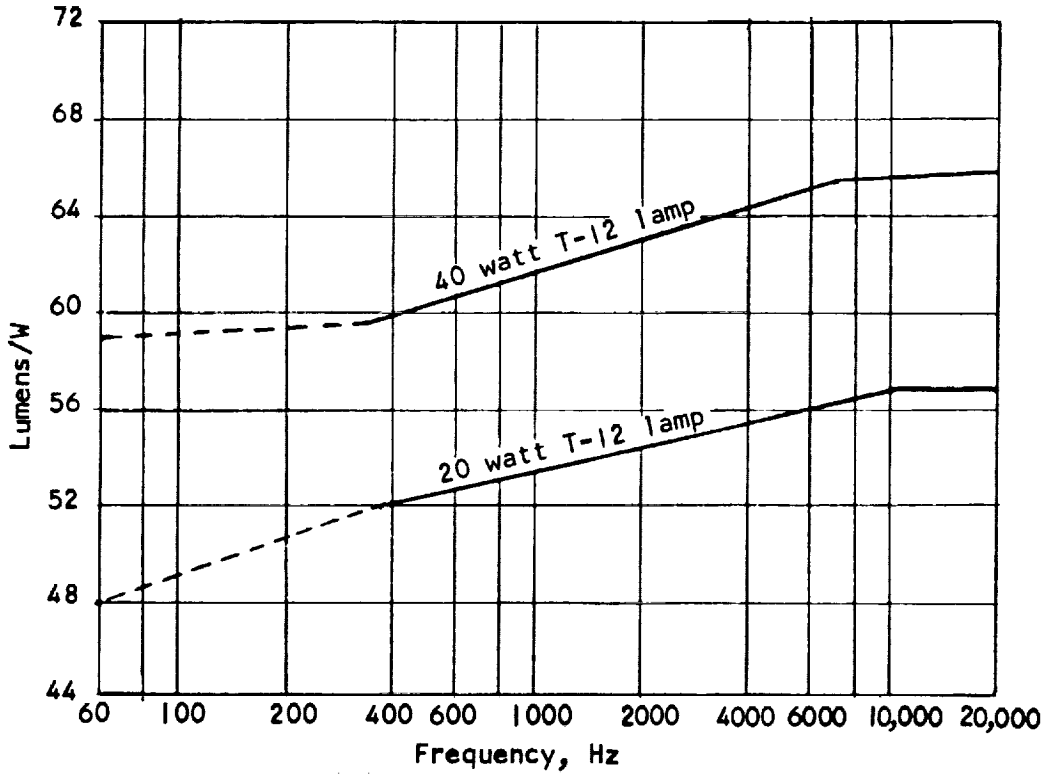


Figure 65. Lamp Efficiency vs Frequency (T-12 lamp) (Ref. 25)

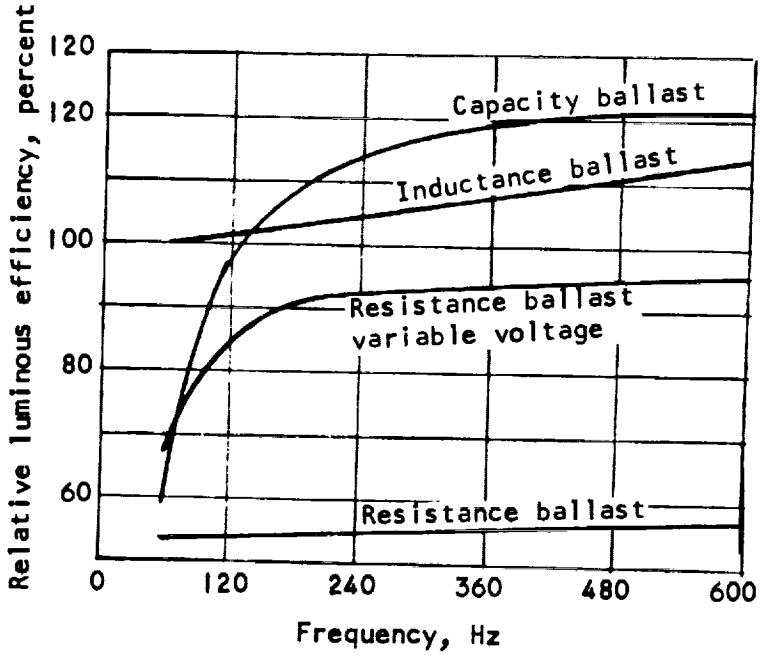


Figure 66. Relative Over-all Luminous Efficiency with Various Ballasts (Ref. 25)

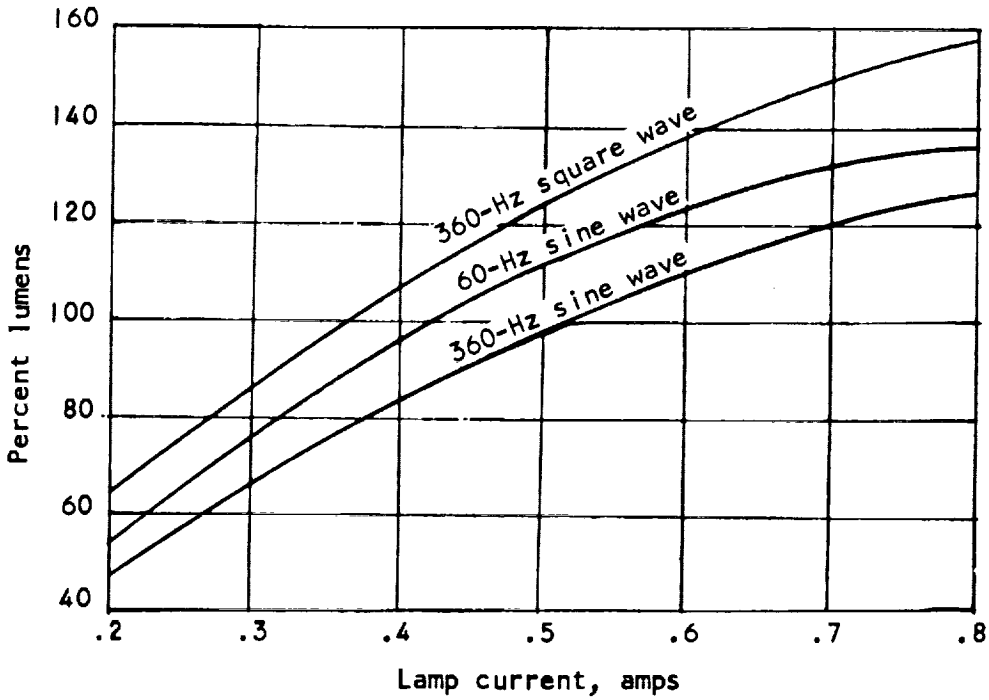


Figure 67. Relative Lumen Output vs Lamp Current for T-12 Lamp, Comparison of Square and Sine Wave Current Input (Ref. 26)

Electroluminescence has a lower efficiency than other light sources (electroluminescent lights, 3 to 5 lumens/W; incandescent lights, 16 lumens/W; and fluorescent lights, 75 lumens/W). However, it does offer the advantages of high reliability and uniform large-area lighting. The light output of the electroluminescent source increases almost linearly with the applied frequency until a saturation is reached at about a 100,000-Hz frequency. The electroluminescent lights are better to run at a 120-V level. The active layer in a lamp operating at that voltage level is about 1 mil in thickness. For lamps operating at 20 V, the film thickness has to be 1 micron in thickness. The cost of the 120-V lamp would be cheaper than that of the 20-V lamp.

Control loads: Included in this category are relays, small actuators and indicators. The latter includes indicator light and low level electronic drives. The requirements of control electronics is included in the discussion on electronic loads. As indicated in table 48 (p. 185), part of the control loads require closely regulated power, both ac and dc. The regulation voltage may be as close as ±1 percent. The requirement, however, has little impact on design selection because the control loads are expected to represent less than five percent of the total. Further, perhaps a quarter of that, or 1.25 percent, may need close regulation.

Electronics loads: Electronic equipment utilizes mainly low-voltage dc power. If ac is the input to the equipment, it is converted to dc internally. Generally speaking, electronic loads are critical to:

- Steady state voltage changes
- Frequency deviations
- Amplitude modulation
- Transient surges
- Ripple current in dc
- EMI susception
- Short supply interruptions

The specification governing power characteristics for load utilization is MIL-STD-704A. This has been in existence since April 1952 and was revised in February 1968. However, the revised MIL-STD-704A is now inadequate for many of the more stringent demands imposed by present day sophisticated avionics. Due to the inadequate power quality (meeting MIL-STD-704A) which is supplied to the terminals of avionics equipment, internal filtering and regulation are necessary for proper operation. As a consequence, weight, space, maintenance and cost penalties result. This suggests, the implementation of a special, precise power quality source for avionics use.

A separate source is impractical and out of the question. However, an alternate and feasible solution is available. This would consist of an interfacing filtering link between the bulk power supply - ac or dc - and the sensitive utilization electronics. Only a few, large modular interface units would serve as the links. This would be more economical than the multiplicity of separate conditioning devices now existing in the many individual electronics boxes.

The modular interface units will have to supply:

(1) Close steady-state voltage and frequency tolerances.

(2) Clean dynamic characteristics, no noise, modulation, and virtually free from both overshoot and dipping voltage excursions.

(3) Ultimate reliability of continuous supply.

(4) Distribution system characteristic with low surge impedance and a means of effectively attenuating disturbances and their propagation.

An example of the minimum change in present day configurations to meet the requirement is illustrated in Figure 68. For a high voltage dc distribution system, the modular interface units would be either dc-ac or dc-dc converters. The high voltage dc power is chopped, inverted and transformed to a low voltage, filtered ac for the avionics. A low voltage dc output may be in preference.

In essence, the power conditioning module configuration is a duplication of the main ac power distribution system. Each module is supplied by its own generator bus. The high frequency conditioned output can supply the loads in single source or parallel source configuration.

All avionics loads are usually confined to one location only (electronics equipment bay). Therefore, a centralized distribution system with minimum branches of shorter length is suggested so that distribution losses due to the higher frequency can be kept within tolerable limits.

Summary of preferred electrical power: Table 49 summarizes the preferred power types for aircraft electrical loads.

TABLE 49.--PREFERRED POWER TYPE FOR ELECTRICAL LOADS

Order of Preference	Utilization				
	Motor	Heating	Lighting	Electronics	Control
1	Constant frequency ac	Any	Constant frequency ac	Dc	Dc or constant frequency ac
2	Dc		Dc	Constant frequency ac	Variable frequency ac
3	Variable frequency ac		Variable frequency ac	Variable frequency ac	

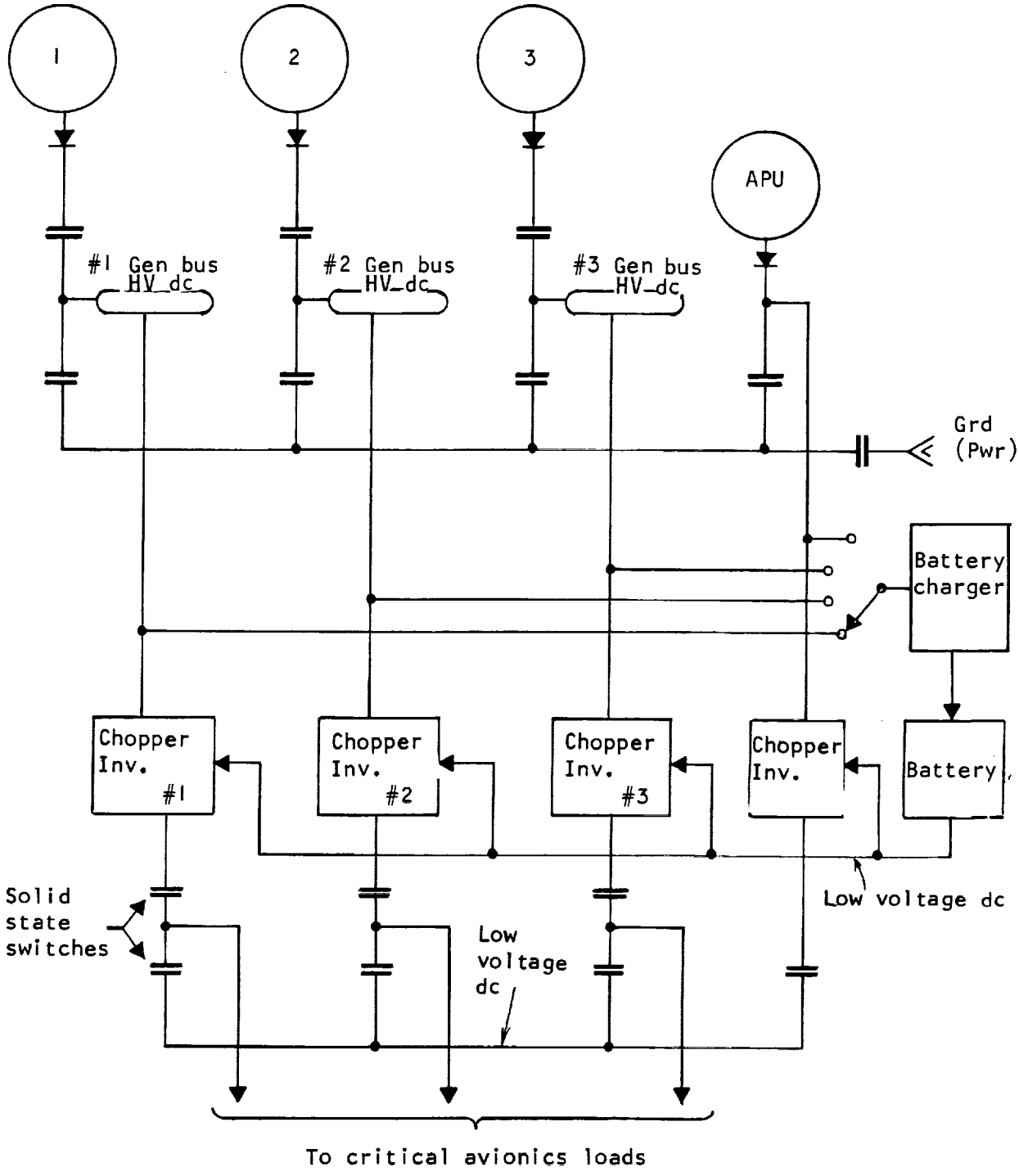


Figure 68. Power Conditioning Module, Arrangement for Critical Avionics Load

Hydraulic and pneumatic power actuation.--In present day aircraft, hydraulic and pneumatic power are primarily used for controlling the position of an output member. These loads include the primary flight controls, the secondary flight controls, landing gear, brakes, thrust reversers, nose wheel, steering, and doors. The power consumption of the load devices range from 1 or 2 horsepower, for a secondary flight control device, to several hundred horsepower for extension and retraction of the landing gear. In addition to the static power requirements, most of these loads require certain dynamic characteristics such as (1) high power amplifications, (2) high resolution coupled with high speed of response, (3) high force to inertia ratios, and (4) high stiffness to satisfy the dynamic requirement. The hydraulic system is preferred, and in some cases, it is the only system that can accomplish the load requirements for state-of-the-art designs. The characteristics, advantages, and disadvantages for various systems are compared below.

Hydraulic actuation: A hydraulic actuation system uses an incompressible fluid to transmit power to the load. The hydraulic system consists primarily of hydraulic pumps, transmission lines, reservoirs, servovalves, and actuators. The hydraulic power source is usually provided by pressure compensated variable displacement axial piston pumps driven from the accessory pads of the aircraft's propulsion engines. Emergency hydraulic power can be supplied by similar pumps driven by electric motors. This type of pump usually has high efficiency and low specific weight (lb/hp). It can be operated at pressures up to (5000 psi) with flow response from approximately 2 to 5 msec. Hydraulic power output devices include motors, power actuators and the electrohydraulic servovalves that control the power actuator pistons.

(1) Electro-hydraulic servovalves: By using good design techniques, the servovalves can be made compact and reliable with precise position control characteristics and high-power amplification. Servovalves can be classified as three way or four way, open center or closed center, single stage or two stage. The four-way, close-center, two-stage servovalve is most commonly used for aircraft applications. The three-way servovalve is more linear over a large range and is less affected by supply variations than the four way. It also provides greater force output. The closed-center type is superior to the open-center type since it provides minimum dead zone and maximum dynamic response. Almost all mechanical input servovalves are single-stage, spool type that require relatively high power to overcome inertia friction Bernoulli forces.

The two-stage valves, however, have a hydraulic amplification stage that provides higher response. Any source of power can be used to actuate the servovalve though electrical or mechanical inputs are the most common. A large selection of servovalves suitable for aircraft applications have been made available by various valve manufacturers, some of which have incorporated combinations of various concepts to meet specific design requirements. Some of the more severe problems associated with electro-hydraulic servovalves are listed below:

(1) Null shift - a serious problem in nozzle flapper valves

(2) Contamination and erosion

(3) Weight compactness, construction ease, and reliability are not as good as other designs.

(4) Torque motor design for maximum response with minimum external disturbance susceptibility.

(5) Endurance and constant performance for large environmental temperature changes not good because thermal expansion can change valve characteristics considerably if not accounted for.

In view of the foregoing, mechanical inputs might be preferable to electrical inputs.

(2) Power actuators: The studied actuator types are a) linear, b) rotary, c) digital and d) dual tandem. These are briefly discussed below.

(a) Linear actuators: The linear actuator is the most common type of hydraulic actuator used in flight control applications. It provides high force-to-inertia-ratios and can be built lighter and simpler than other types of hydraulic motors with equivalent power ratings. Design considerations include the seals and critical stress areas, such as piston rod and cylinder barrel.

(b) Rotary actuators: The types of rotary actuators include single-vane, multi-vane, gear, and piston motors. They are generally used when the angular motion of the linear actuator and crank arm incorporates unacceptable non-linearities. The gear motors usually have serious crossover leakage problems and have been largely confined in operating range to relatively low pressures (under 1500 psi). Vane-type units have difficult sealing problems. They are subject to much the same limitations as the gear types, but with proper pressure balancing, higher pressure ranges have been achieved (1500 to 2500 psi). The piston-type motors, radial or axial, are being used in most high-pressure applications (3000 psi and above). The axial-piston motors are most commonly used in applications where speed control is desired.

(c) Digital actuators: Prototype digital actuators have been designed and built. The digital actuator accepts a parallel 8-bit, straight-binary-coded electrical input signal that controls the output shaft position linearly. The advantages of this type of actuator are (1) it provides a high degree of resolution and accurate repeatability, and (2) it can be used in digital systems without digital-to-analog converters, servo amplifiers, and proportioning servovalves. The Servodyne actuator concept incorporated in the French-built Caravell aircraft uses two hydraulically independent pistons in one common body with rods extending from both ends. Two servovalves are mounted on the body. Constant pressure is supplied to the piston rod ends, and actuator control is accomplished by controlling the supply and return pressure to the blank ends.

(d) Dual tandem actuators: The dual tandem linear actuators are widely used to improve reliability. This type of actuator has two pistons located on a single rod. Each piston is controlled by a separate servovalve and is supplied by an independent hydraulic power source. This configuration provides dual redundant characteristics. When a failure occurs in one of the systems, the

actuator is still operative but with reduced performance capability. Development programs are in progress for designing actuators that can account for single and double failure correcting performance.

Advantages and disadvantages of hydraulic actuation:

Advantages are:

(1) Actuators controlled by precision servovalves can provide very high power amplification.

(2) By using multi-stage servovalves, a high degree of controllability can be achieved.

(3) Due to the high bulk modulus of the fluids, very high force-to-inertia ratios and stiffness factors can be reached.

(4) Good frequency response characteristics are obtained because of the fluid characteristics.

(5) Redundance techniques (such as dual-power supply driving dual-tandem actuators) can be easily incorporated in the hydraulic system to meet the increased demands of system reliability.

(6) Pumps and motors used in the system are compact and efficient devices (efficiencies around 90 percent). The specific weight of the pumps is between 0.12 and 0.24 kg/kw.

Disadvantages are:

(1) The system requires more installed power.

(2) Although hydraulic power transmission is reasonably competitive with other power transmission systems, the efficiency drops off rapidly with increasing distance.

(3) The hydraulic fluid is subject to contamination and radiation.

(4) Seals and leakage problems are inherent.

Pneumatic actuation: Pneumatic actuation systems use a compressed gas as a power transfer medium. In general, under moderate environmental conditions, the pneumatic actuation system is not competitive with the hydraulic system for various applications. However, since the compressible gases are capable of operating over extreme temperature ranges, the pneumatic actuation system becomes promising for future aerospace applications where environmental conditions are more severe. Furthermore, pneumatic power is readily available in missile applications. Therefore, development of pneumatic actuation systems has been stimulated in recent years, and work with high-pressure pneumatic systems has demonstrated that pneumatic controls can be designed to meet some of the high-speed requirements.

Although the basic components of the pneumatic subsystem are similar to those of the hydraulic subsystem, the power source of the pneumatic system is significantly different. Unlike the hydraulic system, in which pumps are used for supplying power, the pneumatic system can employ many different approaches, some of which are as follows:

(1) Air compressors

(2) Stored gas

(3) Engine bleed air

(4) Ram air

(5) Gas generators

The choice of approach requires knowledge of the application. In general, it depends on (1) duration of operation, (2) continuous or intermittent power requirements, (3) size, weight and environmental considerations, and (4) vehicle type. The stored gas system is practical only for missions of very short duration because of weight and volume requirements. The use of ram-air systems depends on the mach number of the vehicle and the duty cycle. For aircraft application, because of response and duty cycle requirements for flight controls, high pressure compressed air is the most preferable. Engine bleed air offers potential for some aircraft applications; however, the pressure must be increased in order to provide high performance for flight controls. The gaseous products of the various gas generators contain solid particles of larger than micronic size. Some of the solid propellants produce very hard and high erosive particles. When these types of pneumatic power source are used, special considerations in the design of the control and utilization devices are required.

(1) Servovalves: The pneumatic servovalves are relatively complex if design techniques are used to make the performance competive with other servo-actuation systems. There are several types of servovalves used in the pneumatic system. The flapper nozzle type is the simplest single-stage valve and is often used as the first stage of two-stage valves. It requires a comparatively large operating force and is suitable for relatively low-power applications. The jet-pipe type has a power level approximately equal to the flapper-nozzle valve; however, it requires a relatively small operating force. Since the jet-pipe type is relatively insensitive to dirt particles and high-temperature effects, it is suitable for applications when the environment is more severe. The spool-type servovalve is often used as the power stage in a two-stage valve; however, it is not well suited for pneumatic applications because of tolerances. The poppet type is a seating-type valve which is fabricated in various forms. It does not require close-fitting, sliding parts and is relatively insensitive to contaminants. The sliding-plate type valve has no metal-to-metal contact between plate and body. It is attractive for pneumatic applications where lubrication is a serious problem.

(2) Actuators: Because it affects dynamic performance, the actuator is one of the critical components in a servosystem. Although the pneumatic motors are not, in general, competitive with the hydraulic or electric motors, they are more tolerant of high-temperature and high-radiation environments; they are therefore attractive for such applications. The pneumatic actuators for servosystems are constant-displacement types with configurations the same as those for hydraulic motors. Several types of pneumatic actuators are discussed below.

(a) Nutating-disc motor: The nutating-disc motor provides good frequency response characteristics and high-stall torque. It has low moment of inertia with few moving parts. No seals are required between the disc and the annular displacement chamber.

(b) Gear motor: The gear motor is a high-speed, low-torque device. Due to its simplicity, good reliability can be predicted. Several high-temperature units for 1200° to 1400°F are being developed.

(c) Cam-piston motor: This type of motor is suitable for low-speed, high-load, and high-temperature application. It exhibits fast acceleration time and is relatively compact for the linear type. Because of the low speed operation, problems such as wear, lubrication, rotational stress, balancing, and vibration are reduced.

(d) Rotary vane motor: This is a high-rotational-speed, low-stall torque device. The sliding vanes create wear leakage and friction problems.

(e) Linear actuator: The linear actuator has a relatively simple design that offers good reliability. The dynamic characteristics are limited due to the large volume under compression. For this type of actuator, the friction of ram must be held to a minimum. In addition, dynamic sealing problems are usually encountered.

When pneumatic devices are used to position a load, gearing is generally used to increase the stiffness. Although the loop gain can be increased to make the servosystem less sensitive to load, system stability becomes a problem. It is possible to overcome stability problems by using various stabilizing devices. However, the system becomes more complicated and reliability decreases.

Advantages and disadvantages of pneumatic actuation: The pneumatic actuation system is primarily used for low-leak, low-inertia applications. It has been used for thrust reversers, landing gears, nose-wheel steering, doors, and brakes; it has not been used for primary flight controls for manned aircraft. The pneumatic actuation system has the following advantages:

(1) The gases used for power conversion usually have good thermal stability. They have invariant properties over wide temperature ranges.

(2) It offers good potential for operating in high-temperature and high-radiation environments.

(3) Due to the properties of the gaseous media, some weight savings may be achieved for certain applications.

(4) It is less susceptible to contamination when compared to hydraulics.

Disadvantages are:

(1) The gases generally have poor lubrication properties.

(2) For flight control applications, complicated designs are required to improve frequency response.

(3) In comparison to hydraulic systems, the pneumatic system has low stiffness factor and slow response for high-load inertia.

(4) For high-power applications, the overall weight is relatively large compared with hydraulics.

(5) The system has leakage problems.

Failure Prediction, Detection and Compensation

There have existed, for some time, various equipment and subsystems whose function is that of fault detection and failure compensation. Further, by use of data collected on a regular basis, long term failure prediction can be achieved. Much of the equipment is well known, but has had little or no direct application to an aircraft electrical power system. The equipment referred to include (1) automatic test equipment (ATE), (2) built-in test equipment (BITE), and (3) aircraft integrated data systems (AIDS).

Failure prediction.--For each generator and voltage regulator the following should be monitored for fault prediction:

(1) Signals that should be monitored and displayed during flight for indicating potential trouble are bearing temperature of each generator, (and perhaps electrical insulation due to oil film between the journal and bearing) and stator winding temperature of each generator.

(2) Signals that should be monitored and recorded to aid in analyzing faults and general system condition are generator phase voltages, generator frequencies (this signal appears to be the only economical means of detecting spline and coupling problems or potential failure), and dc excitation voltages (this signal will indicate faults or malfunctioning of the dc excitation systems).

(3) Regulator temperature

Where a hydraulic constant speed drive (CSD) is used a number of parameters should be measured. For example, failure can be predicted by noting hydraulic unit wear which is best shown by measurement of volumetric efficiency or case drain leakage. Other CSD parameters are output speed, oil temperature and trim head current.

For power distribution, the only practical fault prediction measurement to date is the direct current outputs of transformer rectifier units. These should provide indication of TRU condition.

Failure detection and compensation.--Failure detection techniques require the installation of sensors at critical sense points; the interpretation of output signals by electronic logic means, and output action signals. Where electronic equipment itself is being monitored, built-in self-test circuits are often required.

Appendix F discusses all of the foregoing in detail with particular reference to AIDS. The discussion includes aspects of fault detection and sensor development.

Summary of Subsystem Improvements

A summary of the subsystem improvements discussed in the foregoing section is now presented. The order of presentation is the same as the order of subsystem discussion. This is:

(1) Generation

(2) Distribution

(3) Utilization

(4) Fault prediction, detection and compensation

Generation.--In the areas of reliability and maintainability any of seven different generation schemes constitute a significant improvement over the present day IDG CSCF generation scheme. The best is the dc generator which also has the next to the lowest weight and initial cost.

Elimination of the constant speed drive is seen as the biggest single improvement, reducing maintenance time.

In the area of performance, the alternative generating schemes exhibited generally improved characteristics. Major improvements are in:

- Much shorter transient response times possible
- Precise frequency control
- Better voltage regulation.

These significant improvements were found when the VSCF and rotating inverter generators were considered. They do not apply to the dc or wild frequency generation schemes.

Distribution.--Major improvements are foreseen in weight reduction, reliability and maintainability. These are expected to result from the use of a) 300 vdc power transmission with a structural return, b) the incorporation of solid state remote power control, c) the use of control signal multiplexing techniques and d) design for truly uninterruptible power.

By using high voltage (e.g., 300 v) dc power transmission the following cable improvements result:

- Cable weight is reduced by 50 percent or more for feeder lengths in excess of 25 m (80 ft).
- The number of cables required is reduced by use of single wire transmission
- Cable reactance losses are essentially eliminated.

By use of solid state remote power control these improvements result:

- Minimizing of voltage transients due to overloads or faults.
- Improved power quality and decreased required generator fault capacity
- Simplification and uncluttering of flight deck by use of remote power controllers.
- Ease of maintenance and replacement by placing of power controllers in centralized accessible locations.
- Reduction of EMI produced by switches. There is no 'contact bounce' in solid state switches.
- Automatic fault detection, failure isolation, and current limiting is made practical.

Control signal multiplexing schemes have the following effects as compared with hardwired schemes:

- Remote control for numbers of remote power controllers in a large aircraft is made practical.
- Signal wire weight is significantly reduced. This applies to average input-output distances of >6 m (20 ft).
- The complexity and number of signal wires is greatly reduced.

Uninterruptible power provisions will improve safety and ensure the availability of power to critical avionics equipment at all times.

Utilization.--For electrical motor loads noted improvements are:

- High torque-to-inertia ratios giving better response as a result of using high performance ac motors such as the Minertia and the Hyper-servomotor.

- Wide speed range resulting from future use of thyristor-controlled brushless dc motors.

For lighting loads, no particular improvements are foreseen except in the increased future use of electroluminescent lighting. This form of lighting offers high reliability and uniform large-area lighting. Fluorescent lights will produce greater illumination per watt input and less electromagnetic radiation when operated on a square wave ac power input at a frequency between 400 and 1000 Hz.

For electronics loads the use of a few centralized, precisely regulated power conditioning centers should reduce maintenance and cost while providing good quality power. This should eliminate the need for each avionics equipment to provide its own filtering and regulation.

Hydraulic and pneumatic power actuation systems are presently able to meet requirements ranging from 1 horsepower to several hundred horsepower, through a variety of devices. Improvements are looked for in high temperature and high radiation application design by use of pneumatics.

Future improvement is also expected in overcoming present day hydraulic system seals and leakage problems.

Failure prediction, detection and compensation.--As a consequence of using integrated remote power control multiplexed signal control and the advent of mini-computers, the automation of failure prediction, detection and compensation techniques is expected to become practical for large aircraft power systems. A large reduction in maintenance time and cost is expected to result together with increased safety and reliability.

Electric Motors

Introduction.--Within the near future the constant-frequency ac squirrel cage induction motor will probably remain the best choice for motor drive. In the more distant future, however, the use of brushless dc motors may become more advantageous than the use of ac motors. A brushless dc motor, together with its electronic control (including electromagnetic interference (EMI) equipment) is heavier than an equivalent squirrel cage motor. However, the brushless dc motor provides an adjustable speed drive, draws no large starting current, and has better overall performance than an equivalent squirrel cage motor.

Weight reduction of electric motors may be accomplished by: (1) application of high-permeability magnetic materials such as Hyperco alloys, supermendur, etc., and (2) going to a higher frequency system (ac) or using higher speed motors (dc). Speed reduction gears may be used if the load required low-speed drive. A wild-frequency system improves the reliability of the generation subsystem, but will place a weight penalty on ac motors.

The weight and performance characteristics of various types of electric motors are given below. The effect of new magnetic materials on electric motors is discussed later in this section.

Constant frequency induction motor.--The average specific weight (kg/hp) vs horsepower relationship as well as the average efficiency and power factor of constant-frequency induction motors were presented in the interim technical report, ref. 1. Fig. 69 gives the relative weights of induction motors of a given horsepower with the same number of poles for different operation frequencies. Fig. 70 gives the relative weights of induction motors at constant operation frequency and various speeds resulting from different numbers of poles. These curves were obtained from weight information of electric motors built by AiResearch and other manufacturers. The relative slopes of the curves in figs. 69 and 70 represent an approximate 10-percent reduction in working flux density in the motor as the frequency doubles, which corresponds to common design practice. These curves are for typical ac induction motors with silicon steel laminations and present specifications for aircraft application. The weight of a motor with a certain horsepower, speed, and frequency can vary considerably depending on the motor's efficiency, power factor, starting requirement, overload capability, ambient conditions, class of insulation, and other factors.

For a specific motor drive, weight saving can be obtained by increasing the motor speed even if additional gears are required to maintain the same output speed. Using the information from ref. 28, the gearbox weight w_{gear} in kilograms is given by:

$$W_{gear} = 87\left(\frac{Hp}{R_o}\right)^{0.807}\left[\frac{(N+1)^3}{N^2}\right]^{0.807}$$

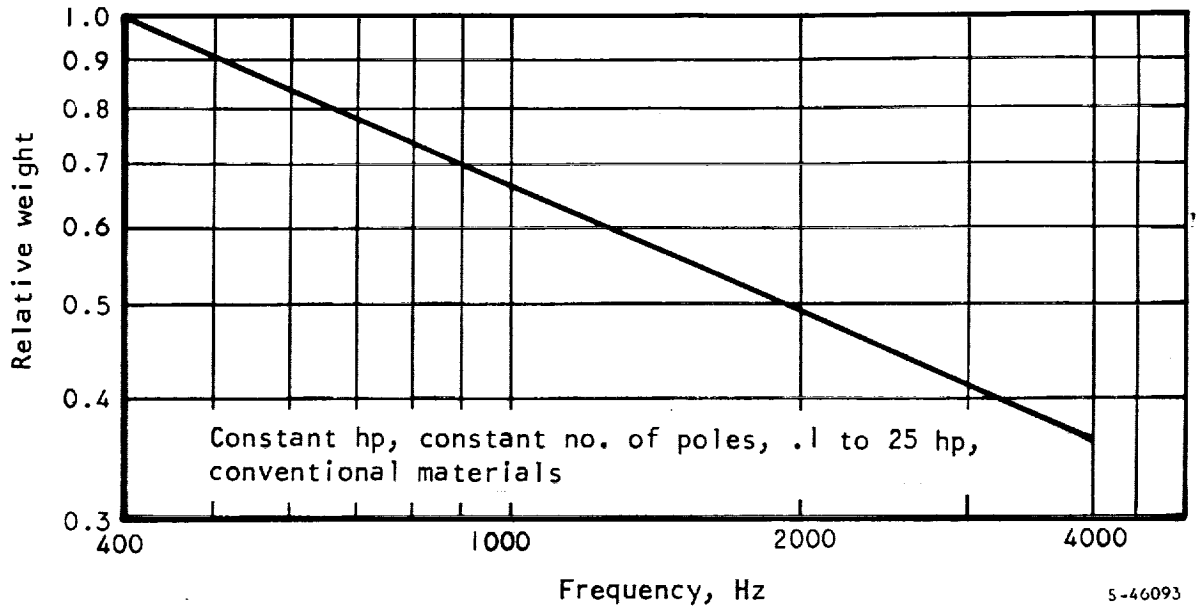


Figure 69. Average Relative Weights of Induction Machines vs Frequency

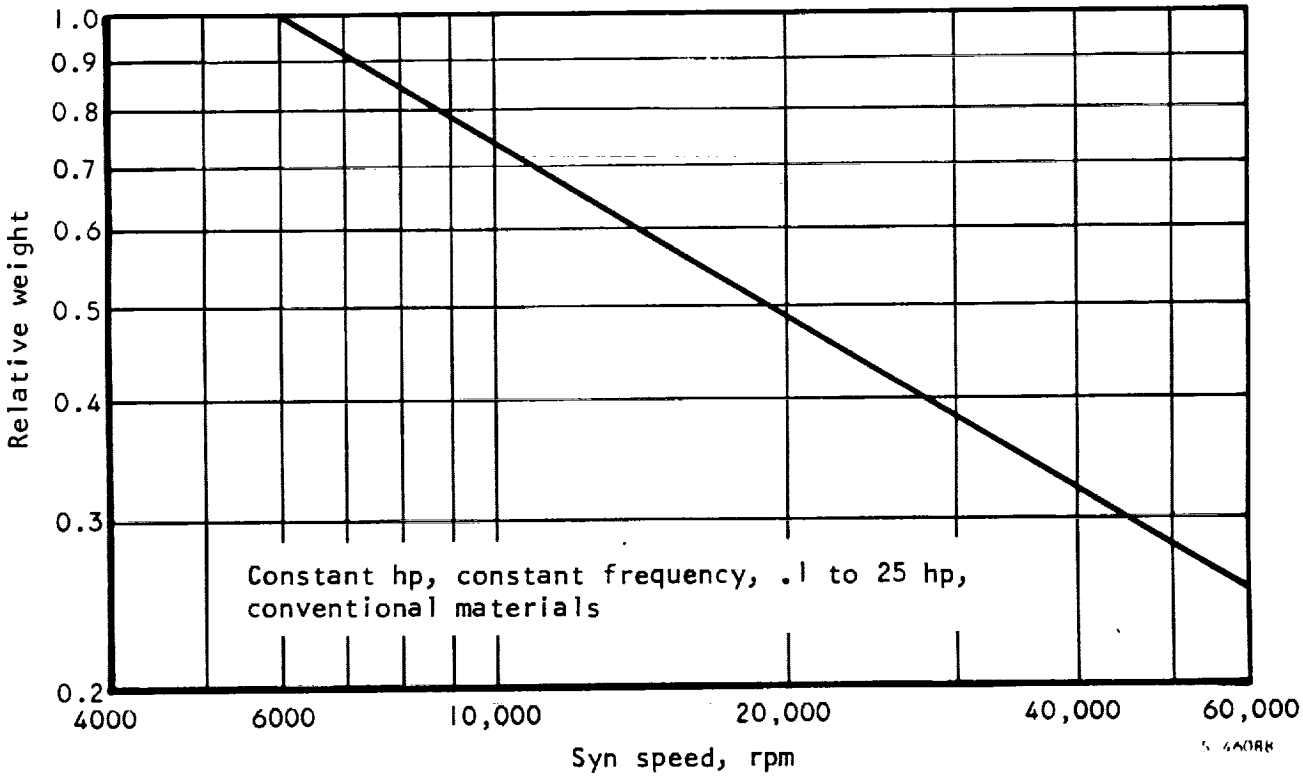


Figure 70. Average Relative Weights of Induction Machines vs Speed

where Hp = horsepower transmitted, (kw/0.7457)

R_o = gearbox output in rpm

N = gear ratio

Assume that a certain load must be driven at 6 000 rpm and the weight of a 400-Hz, 8-pole, 6 000-rpm motor is the reference weight. Then the combined weight of a higher-speed motor and a reduction gear is shown in fig. 71 higher-speed motor also has 8 poles, but is supplied by higher operating frequency. Similar relative weights for output speeds of 8 000; 12 000 and 24 000 rpm are shown in figs. 72, 73 and 74, respectively. These figures are based on the curve of motor weight vs frequency given in fig. 69.

Wild-frequency induction motor.--The induction motor in existing aircraft will not satisfy the load requirements if wild-frequency (2:1) power is input to the motor. This is illustrated in fig. 75a. When a 400-Hz induction motor driving an axial-flow fan is supplied by wild-frequency power of 400 to 800 Hz at constant voltage, the relative capabilities of the motor and load are as given in table 50. The fan torque increases approximately as the square of the speed; consequently, at 800 Hz the fan power is 8 times that at 400 Hz. Although this obviously generates excess airflow across the fan, use of a smaller fan would result in insufficient throughflow at 400 Hz. The maximum torque T_{max} of an induction motor is given by:

$$T_{max} = \frac{1}{4\pi f}\left[\frac{mV^2}{R_1 + \sqrt{R^2_1 + (X_1 + X_2)^2}}\right]$$

where f = frequency

V = phase voltage

R_1 = stator resistance

X_1 = stator reactance

X_2 = rotor reactance

m = number of phases

If V is constant, doubling the value of frequency f (which will double the values of X_1 and X_2) will reduce T_{max} to approximately 25 percent (R_1 is small in comparison with X_1 and X_2). While satisfactory operation is obtained at point A of fig. 75a (400 Hz), at 800-Hz input the motor output speed and torque are reduced to that at point B.

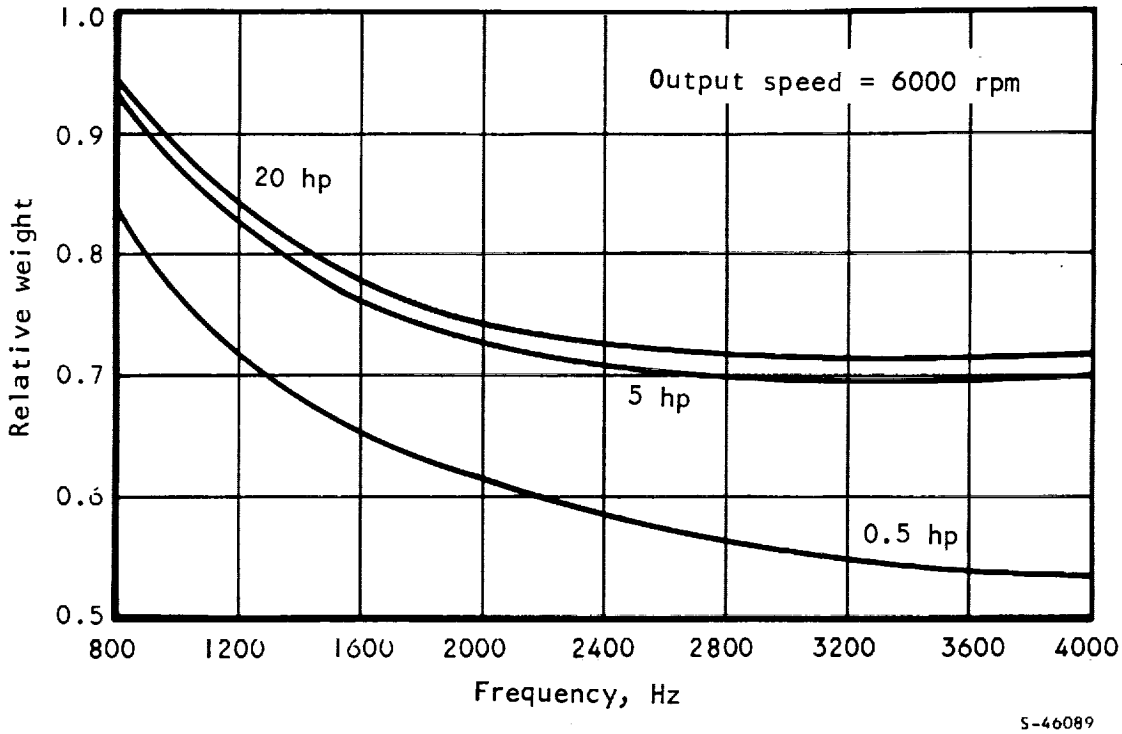


Figure 71. Relative Weight of Gear Motor to Direct-Drive Motor for 6000-rpm Output speed

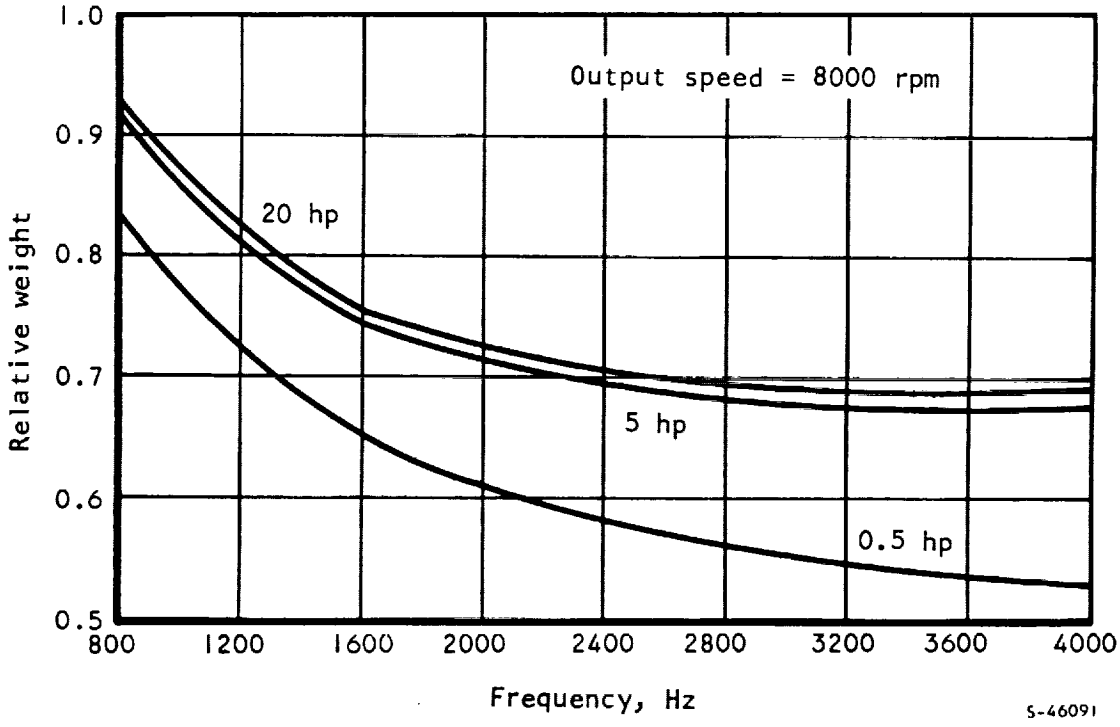


Figure 72. Relative Weight of Gear Motor to Direct-Drive Motor for 8000-rpm Output Speed

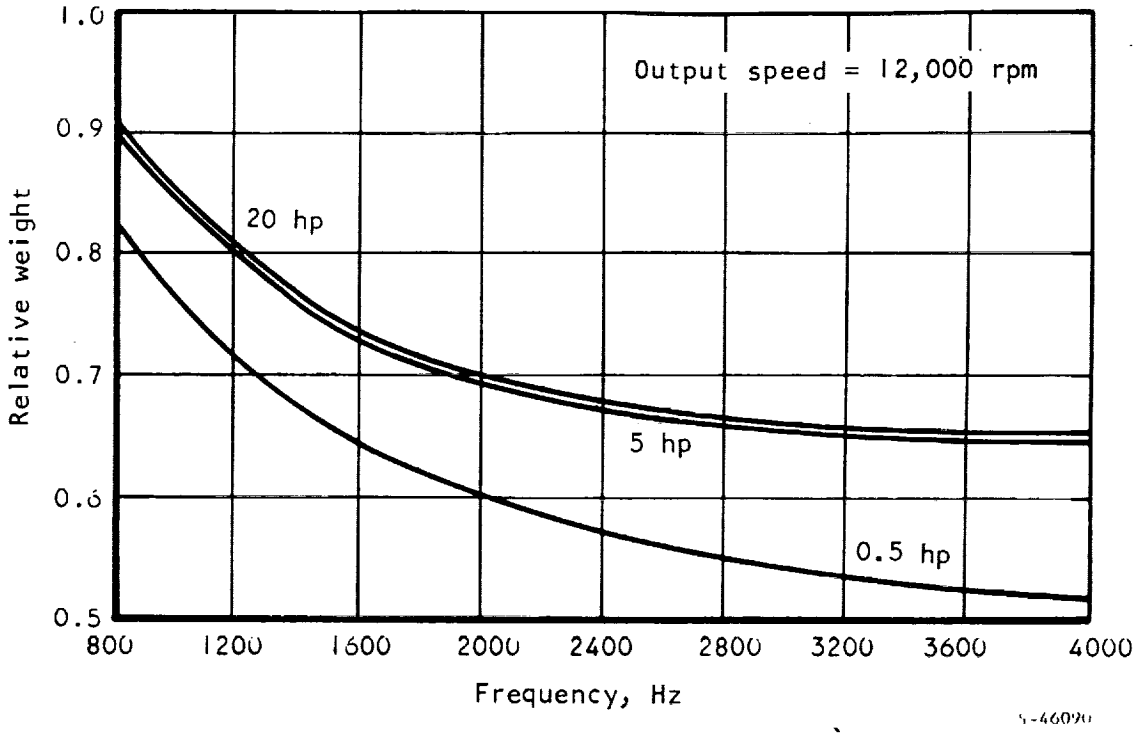


Figure 73. Relative Weight of Gear Motor to Direct-Drive Motor for 12000-rpm Output Speed

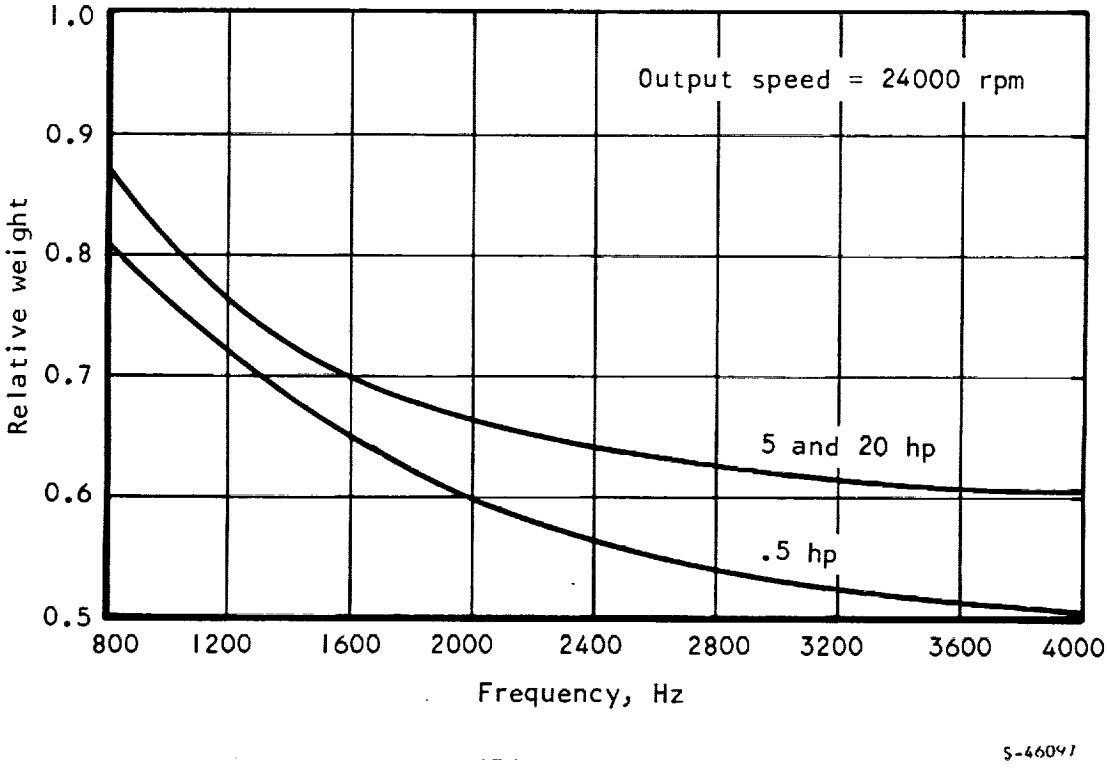
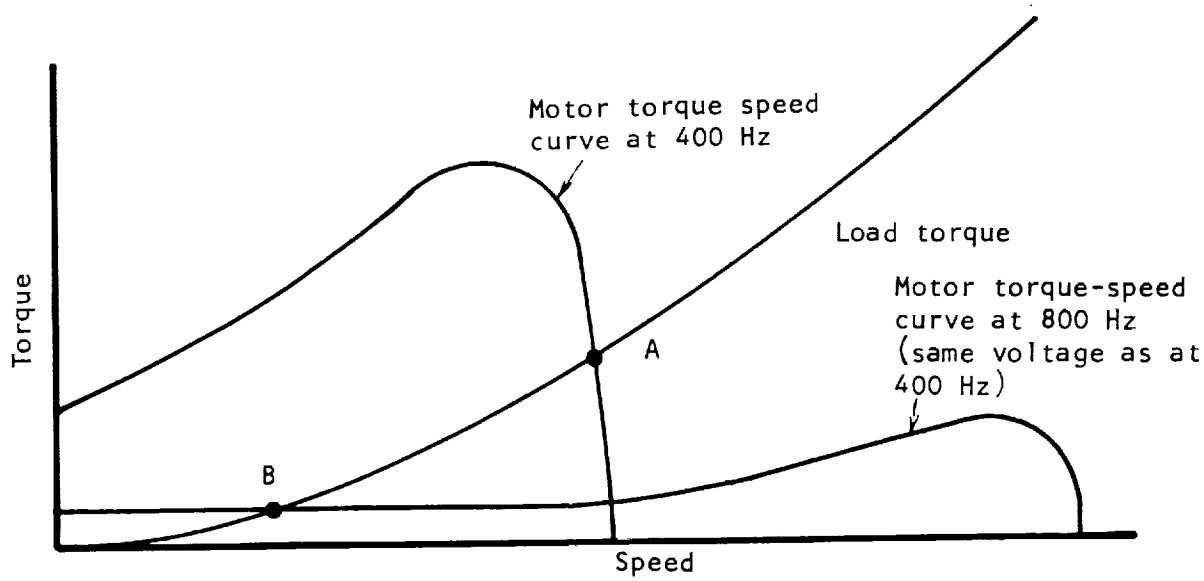
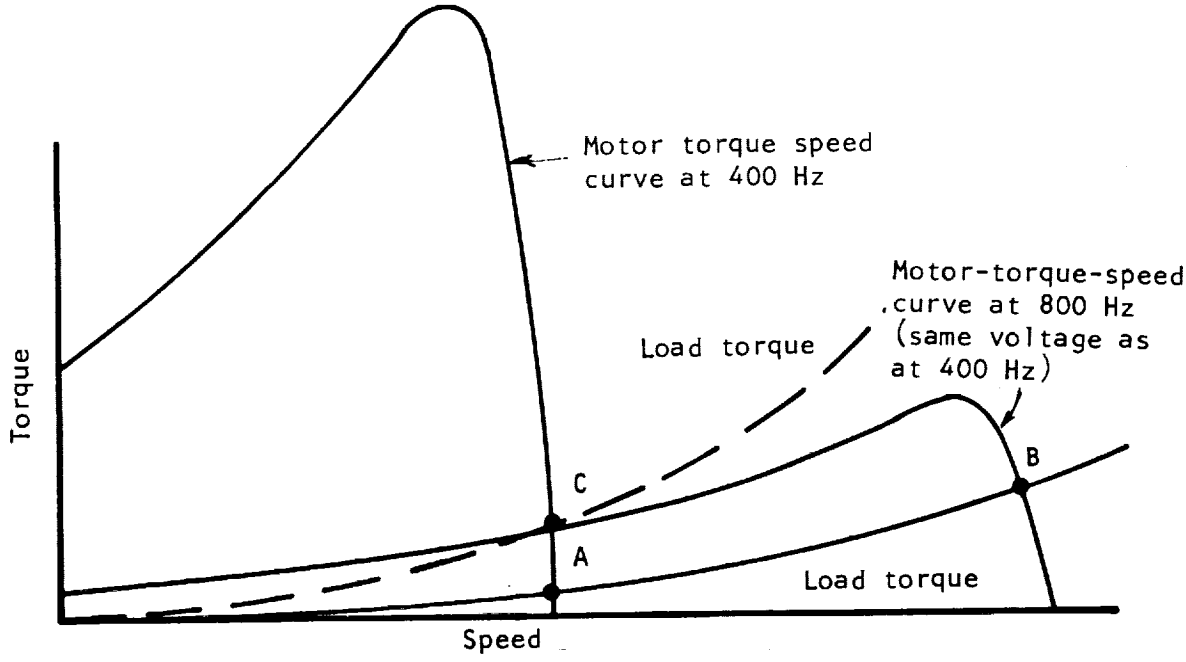


Figure 74. Relative Weight of Gear Motor to Direct-Drive Motor for 24000-rpm Output Speed



(a) With motor designed for constant frequency condition



(b) With motor designed for wild frequency operation

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Figure 75. Induction Motor with Wild-Frequency Input

TABLE 50. --MOTOR LOAD REQUIREMENTS AT WILD-FREQUENCY (2:1) OPERATION OF AN AXIAL-FLOW FAN

Torque/power of an axial-flow fan	Input power	
	400 Hz	800 Hz
Relative fan torque	1	4
Relative fan power	1	8
Relative motor torque	1	.25
Relative motor power	1	.50

Because the power output from the motor at 800-Hz input is insufficient for the fan to create the necessary airflow, a large motor with a new design point must be used. This is illustrated by fig. 75b. The motor must be designed for point B, or if the load torque curve crosses the intersection of the 400- and 800-Hz torque curves for the motor, then the motor can be designed for point C. Either point will cause the motor to have a power rating several times that of the current constant-frequency motor. Thus, operation of loads with wild-frequency power will increase in-utilization equipment weight and in-generation equipment weight (because of increased power consumption).

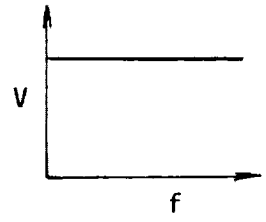
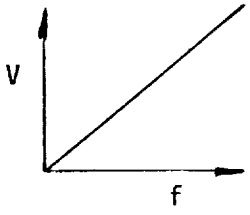
The purpose of a wild-frequency system is not to reduce weight, but to eliminate the constant-speed drive, which is expensive to maintain. The relative weight of a motor designed for wild-frequency operation (with 2:1 speed variation) to the weight of the same motor designed for constant-frequency (average of the maximum and minimum frequencies in the wild-frequency range) operation is shown in table 51.

If a wild-frequency system is used, system voltage will probably be regulated so that it is constant throughout the frequency range as shown in the upper part of table 51 because some of the loads (heating, lighting, rectifier, etc.) require a constant-voltage input. For the motor loads, however, it is advantageous to have the system voltage proportional to the frequency as shown in the lower part of table 51 (better performance, lighter weight).

There are three types of aircraft motor loads. The first is the constant-power load. A variable-displacement hydraulic pump exhibits the approximate characteristic of constant power as the speed varies. The second is the constant-torque load. A fixed-displacement hydraulic pump belongs to this group. The third is a load in which torque varies as the square of the speed. Centrifugal pumps, fans, and blowers belong to this group.

TABLE 51. --RATIOS OF MOTOR WEIGHTS

Ratio of weight of motor designed for wild-frequency operation (1:2 speed range) to weight of motor designed for constant frequency (= average of wild-frequency range)

Supply voltage	Type of load	Hp of constant-frequency motor	Approx. weight ratio
Voltage constant at all frequencies 	Constant hp	Same as the rated hp of the wild-frequency motor	1.2
	Constant torque	Maximum horsepower of the wild-frequency motor	1.5
	Torque proportional to square of speed	Minimum horsepower of the wild-frequency motor	5.2
		Maximum horsepower of the wild-frequency motor	1.5
Voltage proportional to frequency 	Constant hp	Same as the rated hp of the wild-frequency motor	1.2
	Constant torque	Maximum horsepower of the wild-frequency motor	.72
	Torque proportional to square of speed	Minimum horsepower of the wild-frequency motor	3.4
		Maximum horsepower of the wild-frequency motor	.88

The basis of comparison between a wild-frequency motor and a constant-frequency motor depends on the load that is driven by each motor. Most fans and blowers must deliver a constant amount of cooling air, independent of the main propulsion engine speed. When a constant-frequency motor is used to drive this kind of load, the rated power of this motor is equal to the power requirement of the load. A wild-frequency motor runs at variable speed. If a wild-frequency motor is used to drive the fan or blower, the minimum power (at minimum speed) delivered by the wild-frequency motor should be equal to the load power requirement. Otherwise the equipment to be cooled by the fan or blower will become overheated when the engine is at low speed. To calculate the weight penalty incurred by using wild frequency, a constant-frequency motor with a rated power equal to the minimum power of the wild-frequency motor should be used as the reference for comparison. This relation is shown in fig. 76a.

For fuel booster pumps, engine fuel consumption is approximately proportional to the cube of engine speed. The load power requirement, therefore, is approximately proportional to the cube of the engine speed. If a constant-frequency motor is used, the rated power of the constant-frequency motor must equal the maximum pumping power requirement. If a wild-frequency motor is used to drive the centrifugal fuel booster pump, the power output of the wild-frequency motor matches the load power requirement. To determine the weight penalty of the wild-frequency motor, a constant-frequency motor with rated power equal to the maximum power (at maximum speed) should be used as the reference for comparison. This relationship is shown in fig. 76b.

The approximate weight ratios in table 5I were calculated using the weight parametric curves of figs. 69 and 70 and the average slope of the weight vs power curves presented in the interim technical report (ref. 1). In the case of constant supply voltage, the working flux density of the motor at top frequency (2:1 frequency range) is assumed to be 60 percent of the nominal value used for a corresponding constant-frequency motor. Also, the pullout torque at top frequency is assumed to be only 170 percent instead of the 200 percent normally used for constant-frequency, general-purpose motors.

The method of determining the weight penalty of a constant-voltage, wild-frequency motor with load torque proportional to the square of speed, is illustrated below.

Consider a motor-fan drive for electronic cooling, with a constant power requirement of 0.75 Kw regardless of main engine speed. Then compare the motor weights for wild frequency from 267 to 533 Hz and for constant frequency at 400 Hz.

In a fan drive, the power is proportional to the cube of speed. Because the cooling requirement is 0.75 kw (1 hp) at any engine speed, the wild-frequency motor must be able to deliver 0.75 kw at 267 Hz and to handle 5.96 kw continuously at 533 Hz without overheating.

Assume that the motor working flux density at 533 Hz is 60 percent of the normal flux density so that the flux density at 267 Hz will not be highly saturated. To partly compensate for the low working flux density, the pullout torque

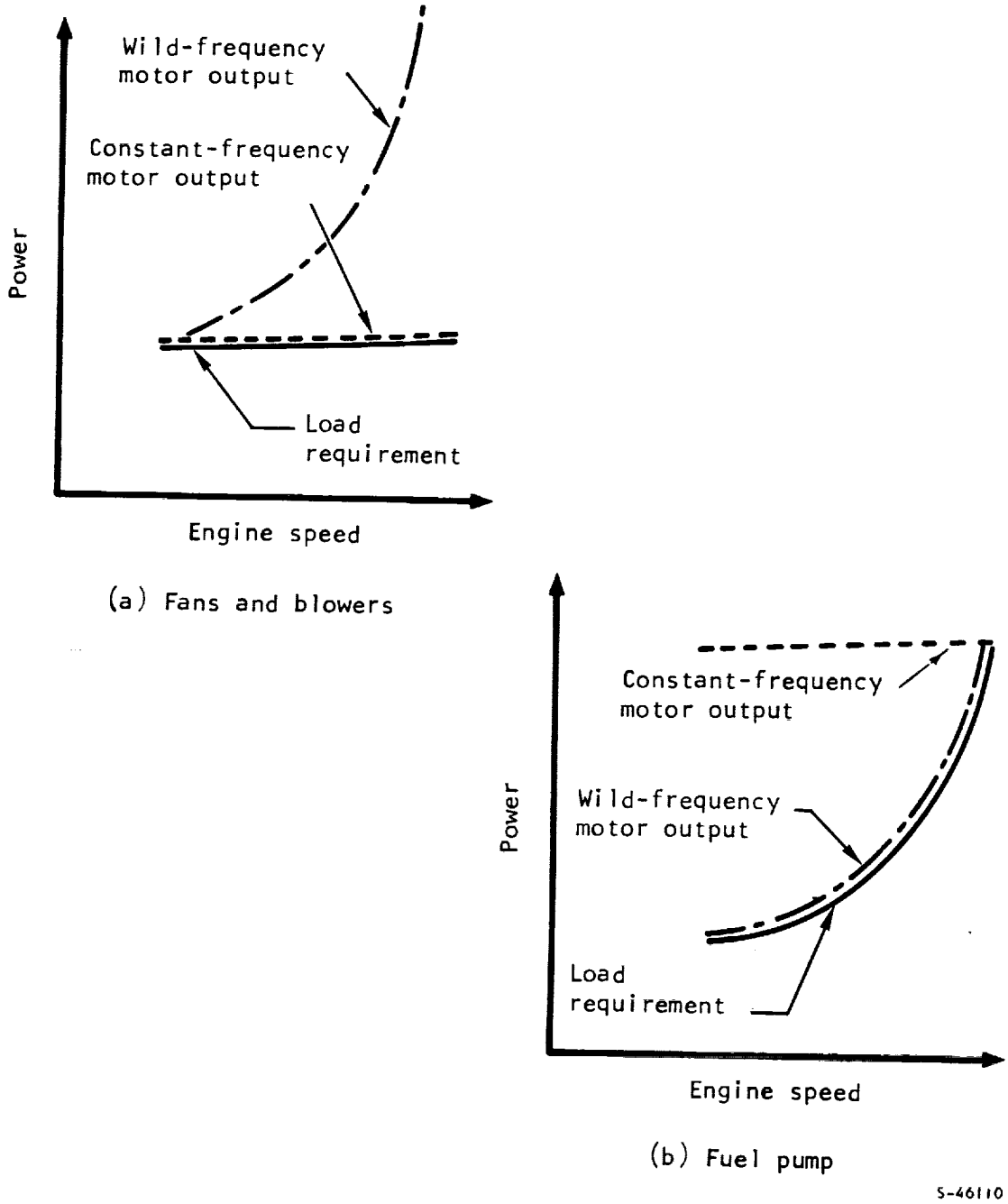


Figure 76. Wild-Frequency and Constant-Frequency Motor Output vs Load Requirement

allowed is reduced from the normal 200 percent to 170 percent. Because the torque is proportional to the square of the motor flux, the power of the wild-frequency motor, at normal flux density, will be:

$$5.96 \times \frac{1}{(0.6)^2} \times \frac{170}{200} = 14.1 \text{ kw}$$

the curve in fig. 69 can be expressed as:

$$\text{motor weight} \propto \frac{1}{(f)^{0.44}}$$

At a given frequency and speed, the weight of a motor varies approximately with power in the following manner (see specific weight vs power curves in ref. 1)

$$\text{Motor weight} \propto (\text{kw})^{0.6}$$

Combining these equations gives

$$\text{Motor weight} \propto \frac{(\text{kw})^{0.6}}{(f)^{0.44}}$$

Comparing the wild-frequency motor (14.1 kw (18.9 hp) at 533 Hz) and the constant-frequency motor (0.746 kw (1 hp) at 400 Hz), the ratio of their weight is

$$\frac{\text{Weight of wild-frequency motor}}{\text{Weight of constant-frequency motor}} = \left[\left(\frac{18.9}{1}\right)^{0.6}\right]\left[\left(\frac{400}{533}\right)^{0.44}\right] = 5.2$$

If the rated power of the constant frequency motor is equal to the power requirement at top speed, i.e., 5.96 kw (8 hp) in this case,

$$\frac{\text{Weight of wild-frequency motor}}{\text{Weight of constant-frequency motor}} = \left[\left(\frac{18.9}{8}\right)^{0.6}\right]\left[\left(\frac{400}{533}\right)^{0.44}\right] = 1.5$$

Rice synchronous motor.--A cutaway view of a Rice machine showing some construction details and the flux circuit is shown in fig. 77. The rotor consists of two symmetrical magnetic parts isolated from each other by a nonmagnetic separator. This separator is furnace-brazed between the two magnetic rotor parts to form a high-strength, solid-metal rotor structure. The design represents current technology.

The magnetic frame of the machine contains two bobbin-type field coils that are excited by a direct current so that the resulting magnetomotive forces (mmf) of the two coils are additive. This exciting mmf establishes a flux that follows the magnetic circuit paths of least reluctance as indicated in fig. 77; i.e., through the frame from the stationary flux distributor across the main air gap to the stator iron. Here, the flux links the armature windings, turns

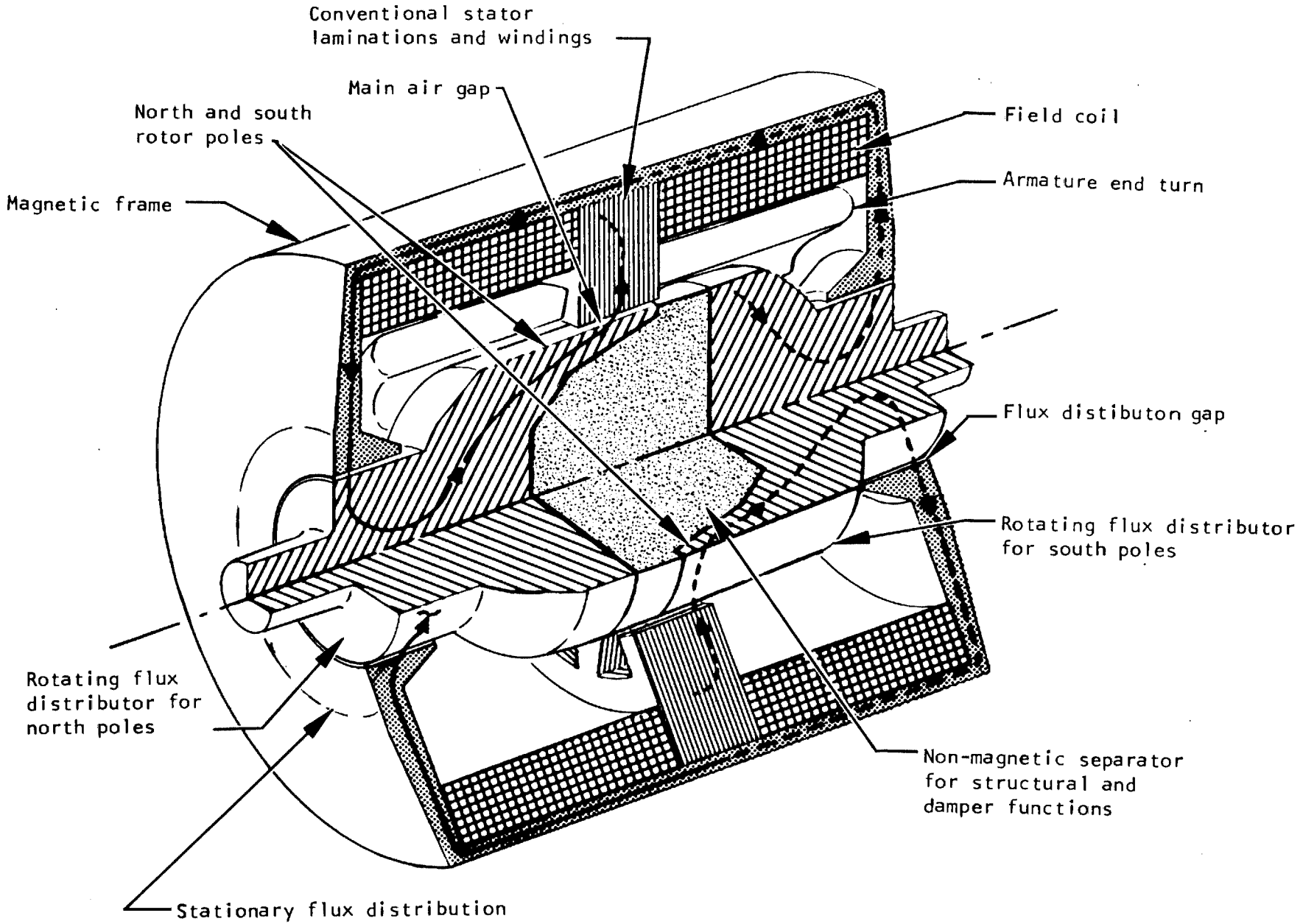


Figure 77. - Rice Machine, Cutaway View

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circumferentially in the back iron of the stator, and proceeds to the south poles of the rotor and back to the opposite end of the frame, thus completing the magnetic circuit.

The advantages of a Rice synchronous motor are that it can be designed to run at unity power factor and that it is capable of very high speed. The peripheral speed of a squirrel cage rotor is normally limited to about 185 m/s (500 ft/sec). The Rice rotor can operate at a tip speed in excess of 300 m/s (1000 ft/sec). When motors of the same speed are compared, the Rice motor is approximately 1/3 heavier than a squirrel cage induction motor with the same horsepower rating. A Rice machine rotor is cylindrical. The windage loss at high speed is reduced to a minimum. The Rice synchronous motor may be started as an induction motor. For a very-high-speed Rice motor, however, the rotor may be overheated during starting. Since a Rice rotor is a high-resistance rotor in induction motor operation, pulling into synchronism where the field is energized may be a problem. Figs. 78 and 79 give weight vs speed and horsepower for Rice machines utilizing current technology as represented by AiResearch motors.

Little weight is saved by using a very-high-speed Rice synchronous motor in aircraft because most electric motors in aircraft are of low horsepower. Consider a load drive of 18.7 kw (25 hp) at 12 000 rpm. An 18.7 kw squirrel cage induction motor can be designed to run as high as 48 000 rpm. A Rice motor that could drive this load probably should not run above 96 000 rpm. Otherwise, a two-stage gearing would be required, resulting in increased weight and decreased efficiency. Weight data presented in this report show that a 18.7 kw induction motor with a 4:1 gearset will weigh about 14 Kg (30 lb). An 18.7 kw, 96 000-rpm Rice motor will weigh about 7.5 Kg (16 lb). The 8:1 gearset is estimated to weigh about 5.5 Kg (12 lb). The Rice motor drive will save only about 1 Kg, or 7 percent, in this particular example. For smaller loads, the induction motor drive may be even lighter than the Rice motor drive. The two types of motors are comparable in efficiency. Because the Rice motor has poorer starting performance, induction motor drive is preferred for aircraft application.

Reliability improvement of electric motors.--Reliability of aircraft electric motors is imparted by various design considerations, materials, and manufacturing practices. Some of these are discussed below.

Many aircraft ac motor windings are wound with a continuous wire instead of inserting separate coil groups for each pole. For example, in a 3-phase, 4-pole (12 coils) conventional motor utilizing separate coil groups for each pole, 24 electrical connections are required. If this motor is wound with the single-wire method, the number of internal electrical connections is only 4. Fig. 80 illustrates this difference. When the number of electrical connections is reduced, the reliability of the motor is increased. This increase in reliability does not increase the weight.

Another feature which will improve the reliability of a 3-phase ac motor is to design the machine such that when one line opens or one phase is out, the motor will continue to operate and perform the load function. Two cases should be considered. For 3-phase, 4-wire (grounded neutral) motors, 2-phase operation results when one line is open or one phase is out. For 3-wire motors, such a

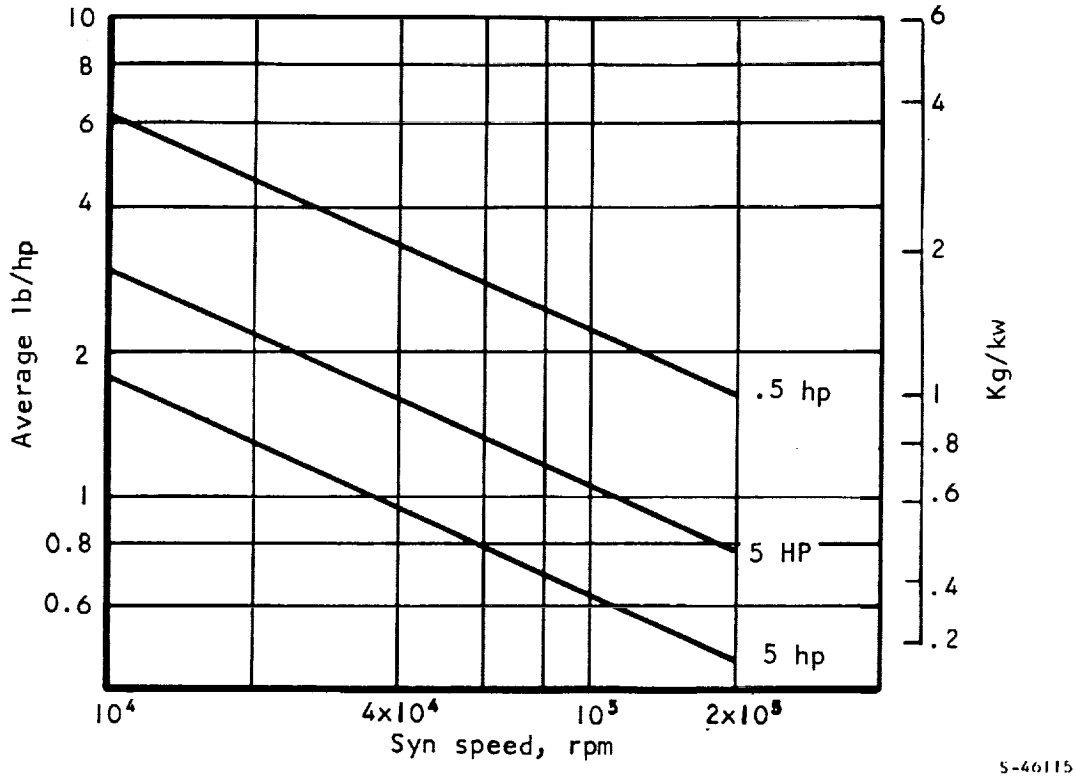


Figure 78. Rice Synchronous Motor Specific Weight vs Speed

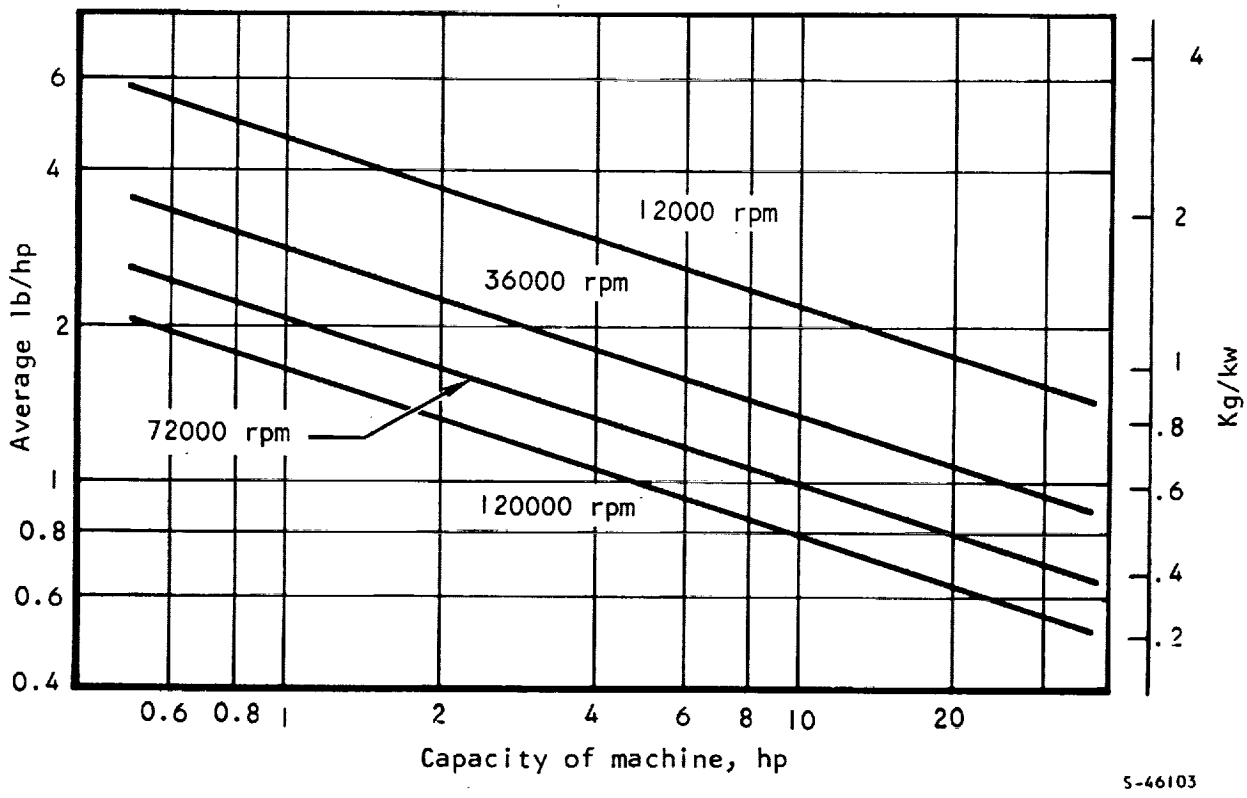
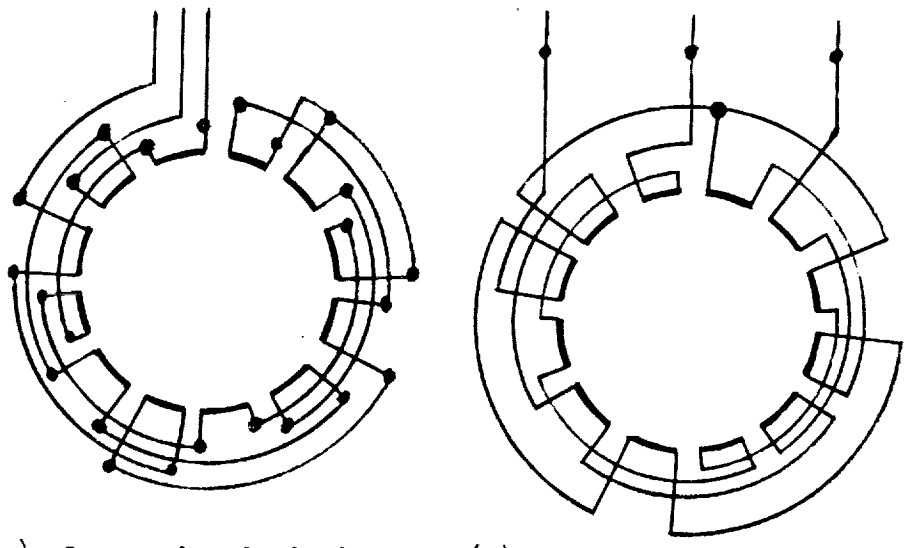


Figure 79. Rice Synchronous Motor Specific Weight vs Power Output



(a) Conventional winding (b) Continuous-wire winding

Figure 80. Wiring Diagram, 3-Phase, 4-Pole Motor

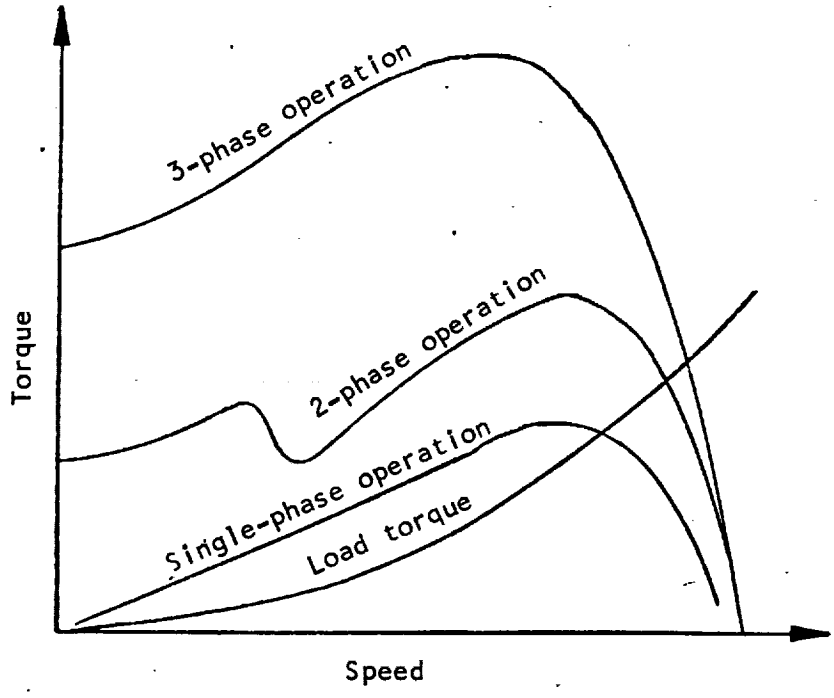


Figure 81. Torque Speed Curves, 3-Phase, 4-Wire Motor at 1-, 2-, and 3-Phase Operation

fault will result in single-phase operation. When a 3-phase motor is reduced to 2-phase or single-phase operation, motor torque capability will be reduced, and motor losses will be increased. Fig. 81 illustrates the relative torque at difference modes of operation.

Because the single-phase motor has no starting torque, a 3-wire motor will not start if one line is open or one phase is out. However, the motor may continue to run if one line or one phase is out after the motor is started. If an aircraft 3-phase induction motor is required to operate with one line or one phase out, it must be designed with higher torque and thermal capacities so that under 2-phase or single-phase operation the motor will still be capable to deliver sufficient torque without becoming overheated. A motor that is designed with consideration for 2-phase operation will have about a 25-percent weight penalty; and one that is designed with consideration for single-phase operation will have a weight penalty of about 50 percent. (In a delta-connected motor, the case of one line open is not as bad as one phase out.)

Shrink-fitting the ac motor stator to the frame makes a stronger assembly and facilitates heat transfer from the stator to the frame.

The slot liner insultation for some ac and dc aircraft motors is formed by melting epoxy resin powder in the preheated stack. This slot liner improves the heat transfer and reduces space requirement.

Bearings are weak links in the electric motor. Because aluminum frames are used for aircraft motors, stainless steel bearing inserts are used to prevent seizing of the bearing outer race or balls at low temperatures. (Aluminum has a larger temperature coefficient of thermal expansion.) Sometimes the outer race of one of the motor bearings is locked against axial movement to enable the motor to withstand severe shock and vibration. The bearings are preloaded to prevent ball skidding and axial shaft movement, thus increasing bearing life and quietness in operation. Bearing clearances should be optimized for long operating life.

A proper lubricant for the bearings should be used to suit the motor speed and environmental conditions. Seals and shields are used for aircraft motor bearings to retain lubricant and keep dirt out. Submerged fuel transfer pump motors and submerged cryogenic pump motors are usually lubricated by the fluids they pump.

Brushless dc motor.--The dc motor is superior to the conventional ac motor in performance and in control characteristics. The major drawback has been the brush-type commutator, which requires frequent maintenance and is entirely unsuitable in some environments. Dc motors are being manufactured in large quantities despite the availability of simple and inexpensive ac induction motors; this may be taken as proof of the superiority of the dc motor in many applications.

The inverter-driven induction motor is a form of brushless dc motor when variable-frequency, constant-volt-second excitation is applied to the windings. This combination, with its complex control system, still lacks the performance of a true dc motor. This is particularly apparent at higher power or voltage levels, where thyristors replace transistors in performing the power switching

functions. The inverter-driven induction motor requires forced commutation, while the brushless dc motor, except at stall, is self-commutating.

Principles of operation.--In a conventional dc motor, the commutator serves the dual functions of a power switch and a position sensor. In the brushless dc motor, a rotor position sensor is used to actuate solid-state power switches which apply dc voltage to the coils. The rotor and the stator functions are reversed; the rotor is the dc field and the stator is the armature. Since each stator coil requires a switch, economics dictates a minimum number of coils. For simplicity, the rotor is usually a permanent magnet in low-power machines but it also can be the pole structure used in Lundell and Rice machines. Here, the flux is transmitted to the rotor across an air gap to avoid slip rings. Since the field in this machine is provided by a separate stator coil, an additional dimension in control becomes available. The stator can be either ironless for low-power machines or iron-cored for large machines.

Fig. 82 depicts the principle of the brushless dc motor from the point of view of circuit design. This figure is a simplified diagram of the stator of a half-wave machine representing current AiResearch motors. As stated, these machines have transistor switches, and all but one have infrared optoelectronic position sensors. Other types of position sensors have been investigated, i.e., Q-modulated oscillators and Hall-effect devices.

The motor coil is shown in terms of its copper resistance R_w, its leakage inductance L_w, and, essentially, the sinusoidal counter-emf e_g generated by the relative motion between the coil and the magnet. The amplitude of the generated voltage is proportional to the flux of the magnet and to the speed of the machine. Obviously, during startup and at stall this voltage is zero and will be a problem in thyristor commutated motors.

Major electrical phenomena studied in the circuit of a half-wave four-winding machine for steady-state operation are shown in fig. 7-15. Fig. 83a shows the voltage waveforms for one winding. The amplitude of the generated counter-emf shown is approximately equal to the applied voltage E_M; the voltage across the switch, except when the switch is closed, is the difference between these two voltages. The peak voltage across the switching transistors is twice the applied voltage. In a full-wave machine, this voltage equals the supply voltage; however, this is not a net saving in voltage rating, because a full-wave machine requires twice the number of transistors.

The switch is closed by the position sensor during the 90-deg (electrical) interval when e_{sw} is minimum. This leaves a net circuit voltage e_z to force current flow (fig. 83c). If there were no winding inductance in the circuit, the current would be a scalloped pulse with a waveform identical to the net circuit voltage and of instantaneous amplitude e_z/R_w. The inductance "softens" the current pulse, as shown in fig. 83d Finally, fig. 83e adds the contributions of the other windings to yield the total motor current. The product of e_g and i_z, averaged for more than 90 deg, yields the total shaft power.

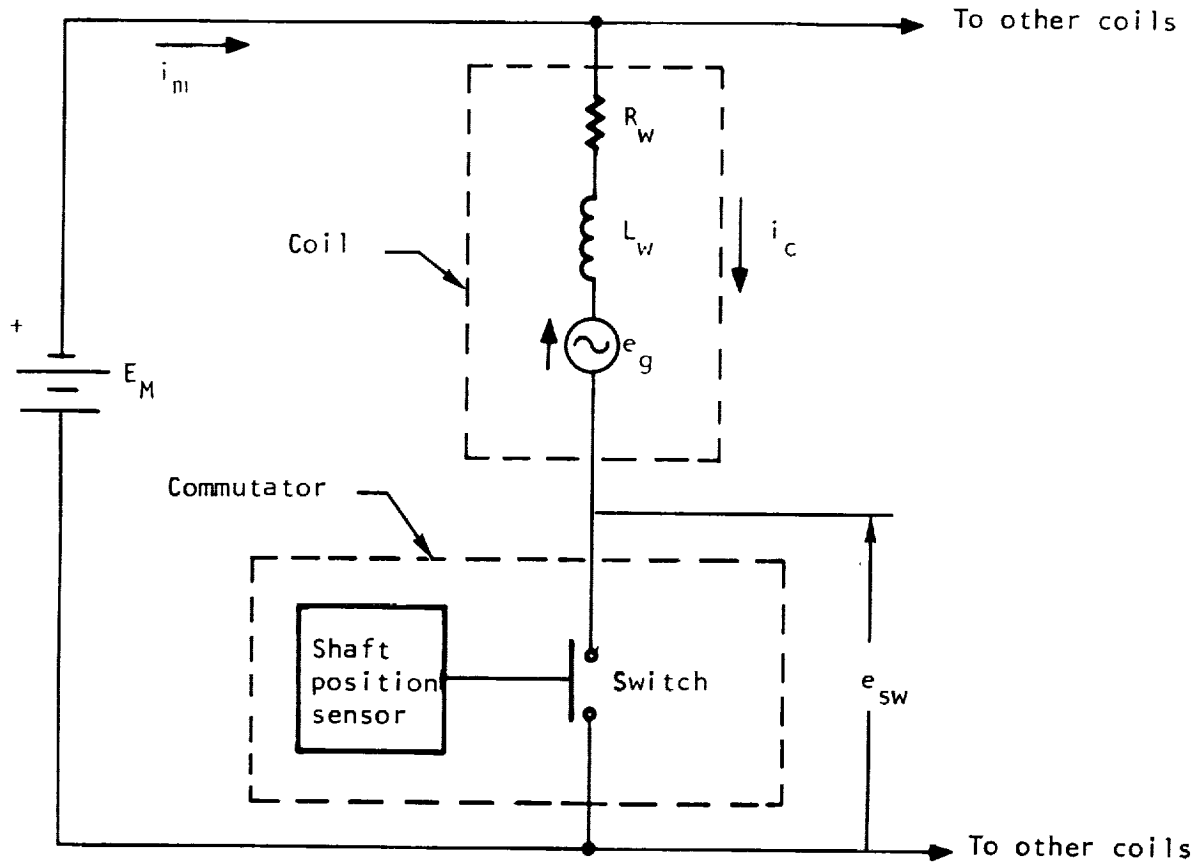


Figure 82. Simplified Diagram of a Half-Wave Winding and its Commutator

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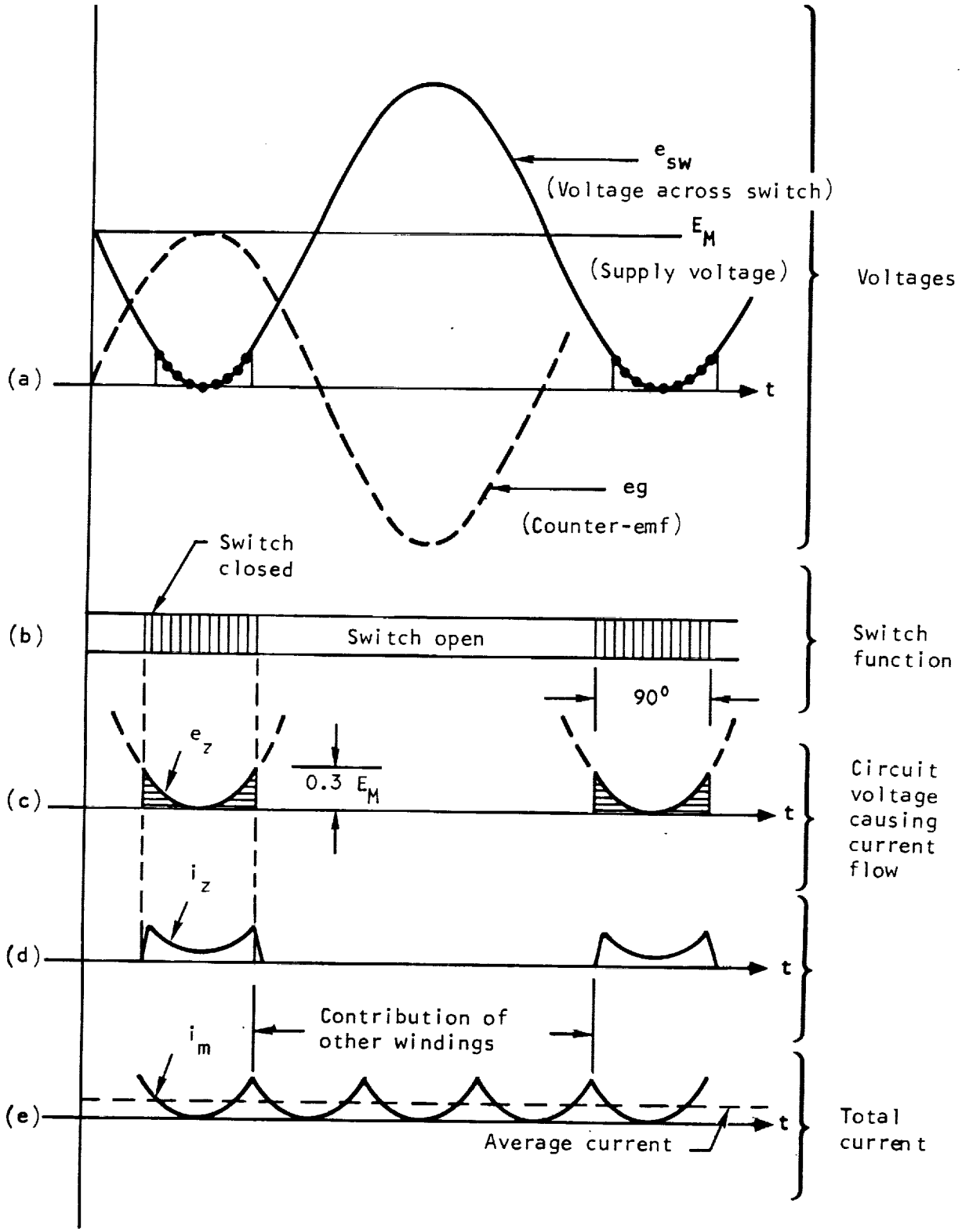


Figure 83. Major Waveforms of Four-Winding Half-Wave Motor with Transistor Commutators

It should be observed that when the switch opens, current is interrupted in an inductive circuit, and the stored energy must be absorbed. In low-power motors, this energy is absorbed in zener diodes to prevent second breakdown in the transistors. In higher-power motors, this energy can be prohibitively high even in an ironless machine, and the energy must be recirculated. This is one of the reasons for the full-wave configuration for larger motors.

When the motor is still, the counter-emf is zero, and the current, unless otherwise controlled, is limited by stator resistance only. This current provides starting torque. As the machine speeds up, the generated voltage builds and counteracts the applied voltage, and the current diminishes until rated current is reached at rated speed. When load is increased, the machine slows down so that the current increase resulting from the generated voltage decrease provides the required additional torque. Exactly as in conventional dc motors, small changes of speed (and counter-emf) caused by load variation result in relatively large changes in armature current, e.g., thr torque-speed characteristic is relatively flat.

Current-switching in a brushless dc machine can be performed either by transistors or thyristors. The operation theory of the thyristor-commutated brushless motor will not be discussed in detail. One major problem encountered in this type of machine is the absence of commutation voltage when the motor shaft is stationary. It has been demonstrated experimentally that if, upon turn on, the rate of rise of motor supply current is slow with respect to the ability of the motor to accelerate, then proper commutation is possible even from start. Some source of auxiliary commutation energy may be required in the process, and ingenuity is needed to supply this source without penalizing efficiency during normal operation.

Performance comparison with induction motor.--It has been mentioned that the brushless dc motor requires less frequent maintenance than the conventional dc machine; it is reliable, and operates in some special environments where conventional dc motors cannot. There are certain areas where load characteristics dictate use of the dc brushless motor instead of the ac motor. A brushless dc motor can be designed to run at very high speed, while the ac motor speed is limited by the power system frequency. The ac power frequency is, in turn, limited by transmission and distribution considerations.

Because the brushless dc motor will play an important role in future advanced aircraft, a comparison of the weight of the brushless dc motor and the induction motor is in order, since weight is an important factor in the system optimization.

Brushless dc motors are heavier than equivalent ac induction motors. Curves showing the weight of present-technology brushless dc motors (using AL-9 permanent magnets) at 24 000 rpm with and without electronics are given in fig. 84. A curve showing the weight of the corresponding induction motor with conventional material is also given for comparison purposes. It can be seen from the figure that the majority of the brushless dc motor weight is in the electronic package.

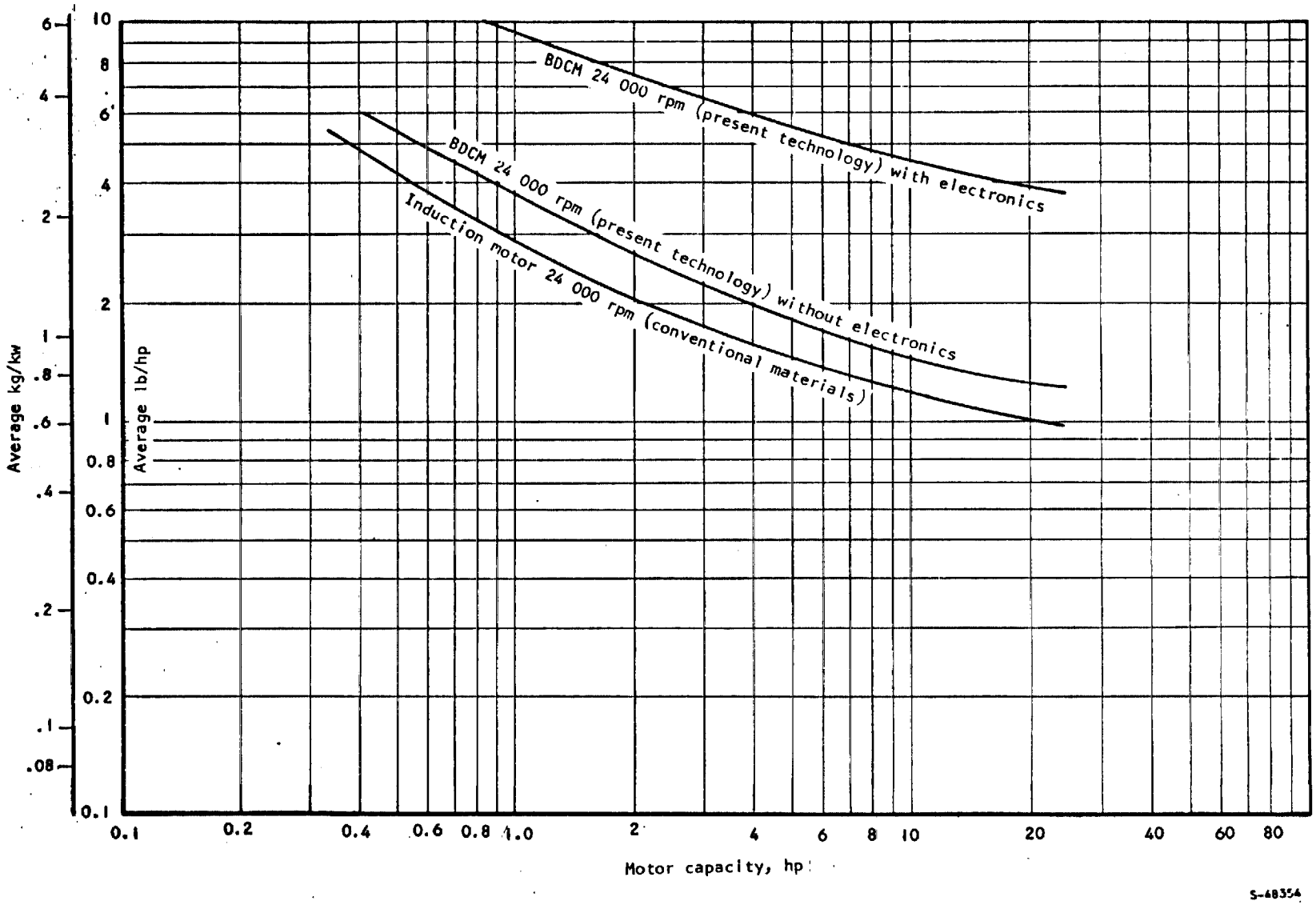


Figure 84. Advanced Brushless Dc Motor Specific Weight

Technological advances promise an appreciable weight reduction of the brushless dc motor. To estimate the weight of the future brushless dc motor of 15 years hence, calculations for three typical designs were performed based on projected trends in materials and technology. Power ratings of 0.0746, 2.99, and 18.7 kw (0.1, 4 and 25 hp) were selected. This is the range of the ratings of motors used in aircraft. With this power range, a permanent-magnet rotor was chosen because it will have the lightest weight and highest efficiency.

The weight of the brushless dc motor is divided between two parts, the motor and the electronics. The estimated weight of electronics (including EMI equipment) for 1985 technology is given in fig. 85. The motor weight is calculated from the actual designs with the following assumptions:

(1) Samarium cobalt permanent magnet, with an energy product of 20×10^6 is used. Motor speed is 48 000 rpm.

(2) The iron core used has the same permeability and core loss at 1.7 wb/m^2 (17 KG) as those presently obtained from Tran-cor T, 4 mil, at 1.4 wb/m^2 (14 KG).

(3) The winding insultation is capable of 703°K (800°F) operation.

(4) The bearings are capable of operating at 48 000 rpm at 643°K (700°F).

(5) The magnetic material permits 2-pole rotor fabrication and operates at 150 m/sec (500 fps) tip speed.

The major steps in motor design calculations are as follows:

(1) From an existing design, using simple rules of scaling, determine the stack length and the outside diameters of rotor and stator.

(2) Determine the effective flux density from the demagnetization curve shown in fig. 86.

(3) Determine the total flux per pole and the number of conductors required by selecting a suitable voltage.

(4) Calculate yoke thickness, tooth width, slot area, conductor area, and wire resistance.

(5) Calculate iron losses, bearing loss, and windage loss.

(6) From the selected power rating and the assumed efficiency, calculate current, copper loss, and stray-load losses.

(7) Calculate the total loss and the efficiency as compared with the assumed value.

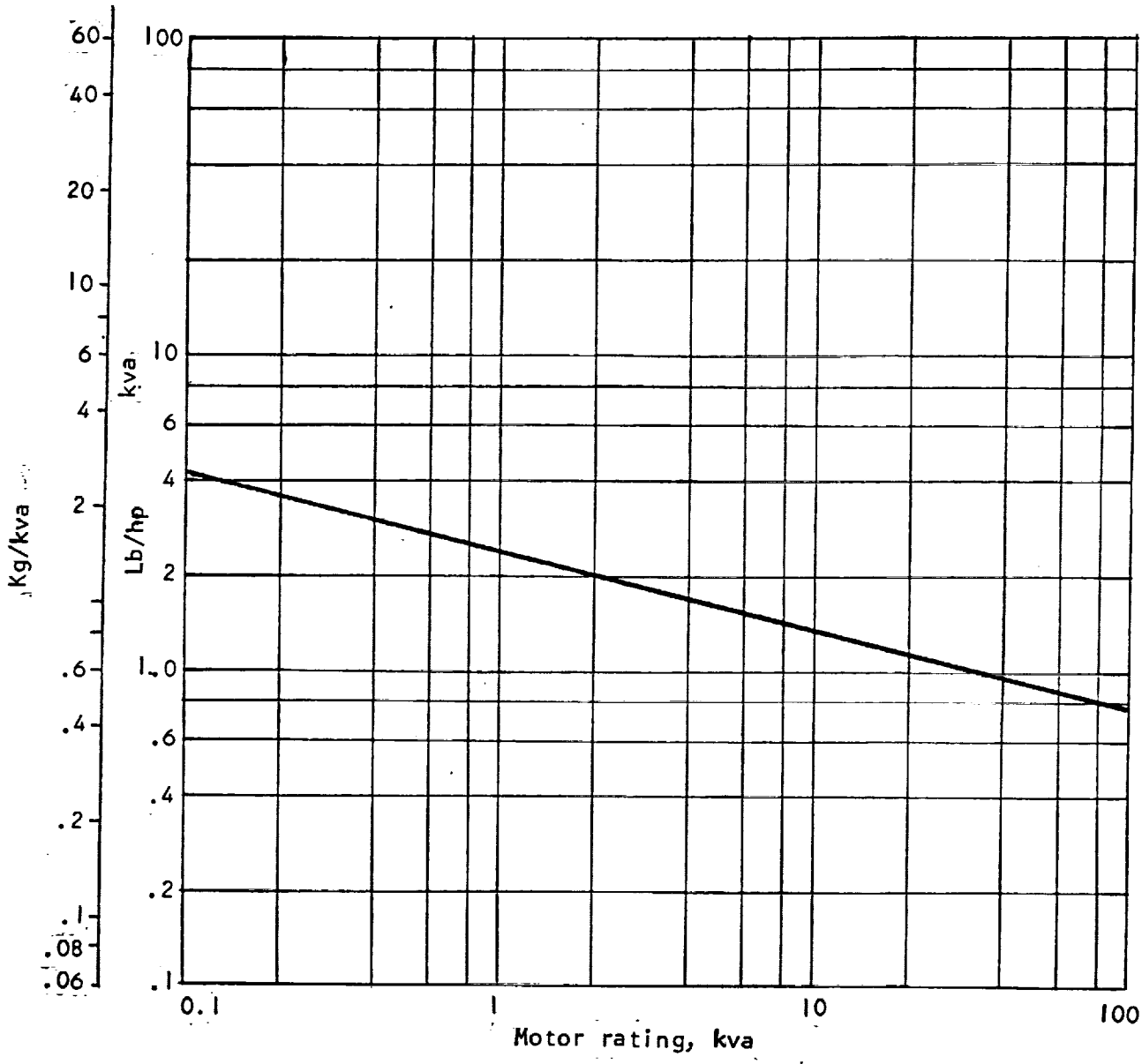


Figure 85. Brushless dc Motor Electronics Weight (1985 Technology)

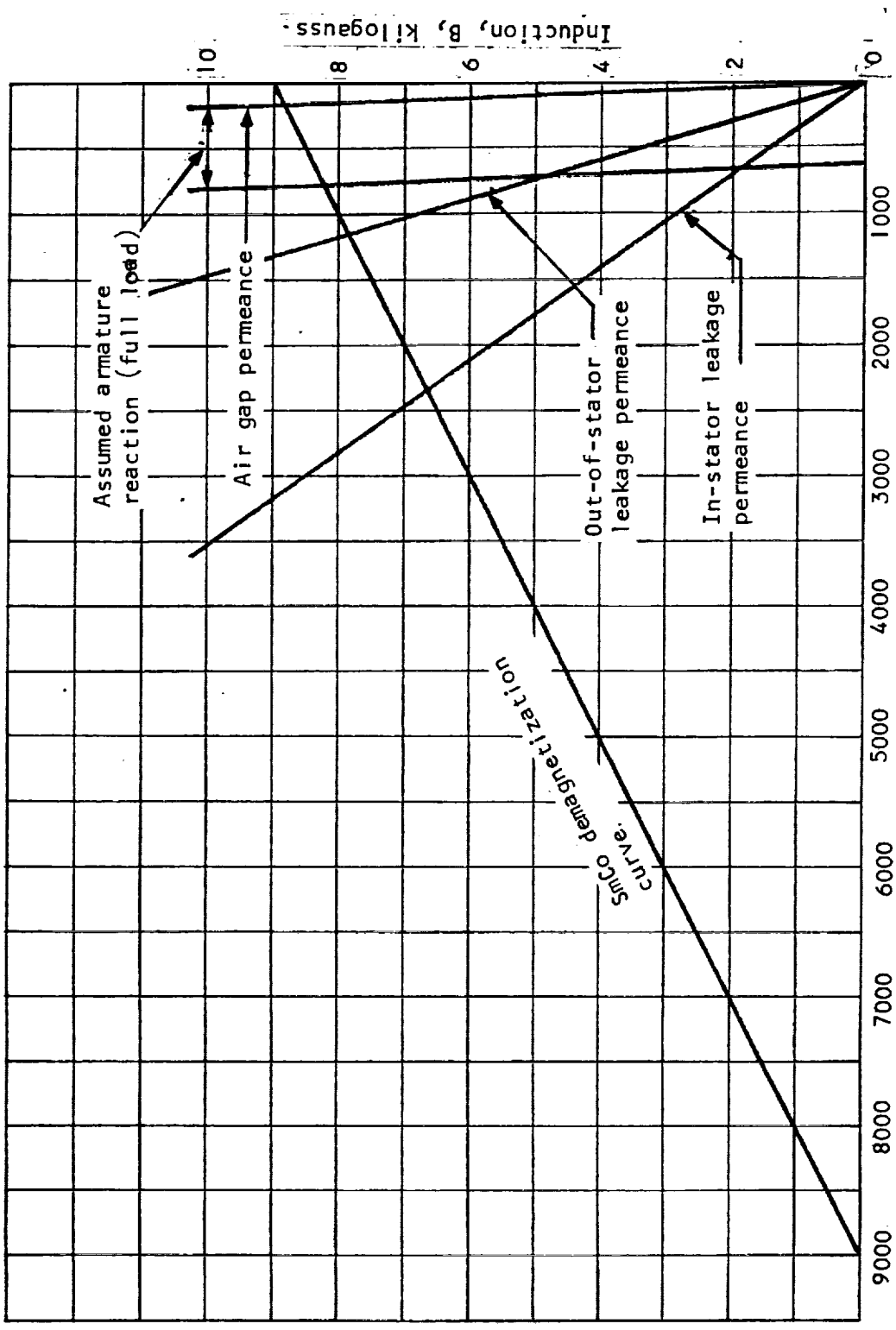


Figure 86. Demagnetization Curve of Samarium Cobalt

(8) Iterate step (7), if necessary, until the difference between the calculated efficiency and the assumed efficiency is within allowable tolerance.

(9) Determine the total weight, and weight per kw of the motor.

Table 52 shows the result of the design calculation. The weight (in kg) per kilowatt of the motor, and the complete unit (motor and necessary electronics, including EMI circuitry) are plotted as a function of horsepower in fig. 87. For comparison, curves of current induction motors are also included. Without electronics a brushless dc motor is almost as light as a corresponding induction motor; however, without the electronic package the dc motor cannot run. The electronic package gives the dc motor a variable speed capability.

TABLE 52.--DESIGN CALCULATION

hp rating	kVA rating	Motor weight, kg	Electronics weight, kg	Total weight kg	kg/kw
0.1	0.124	0.1	0.24	0.33	4.4
4.0	3.97	1.1	3.1	4.2	1.4
25.0	24.3	6.4	12.2	18.1	.995

Fig. 88 shows the weight per kilowatt as a function of motor speed (for three different ratings) for the motor alone and the complete unit, respectively. These curves are obtained by using the curve of relative weight vs frequency shown in fig. 69.

To get an idea of the operating efficiency of brushless motors, an expression for electromagnetic losses, i.e., copper loss, eddy current losses in the conductors, and iron loss in the laminated flux containment ring, was derived. The copper loss is dependent on the number of conductors in series per phase, the cross-sectional area of those conductors, and the current per phase. With the established geometric and magnetic relationships and an arbitrary voltage level, the necessary parameters were determined. The eddy loss in the copper conductors varies (1) with the second power of frequency, flux density, and wire diameter, and (2) inversely with wire resistivity. All these parameters are known except wire diameter. To compensate for the higher eddy losses at high speeds, a table was set up to progressively reduce wire strand size as design speed increased. The iron loss was found to be dependent on the determination of a flux density.

The flux will have fringed before reaching the iron ring; thus the ring thickness was set to operate at a density of 55.8 kilolines/sq in. Trans-cor-T

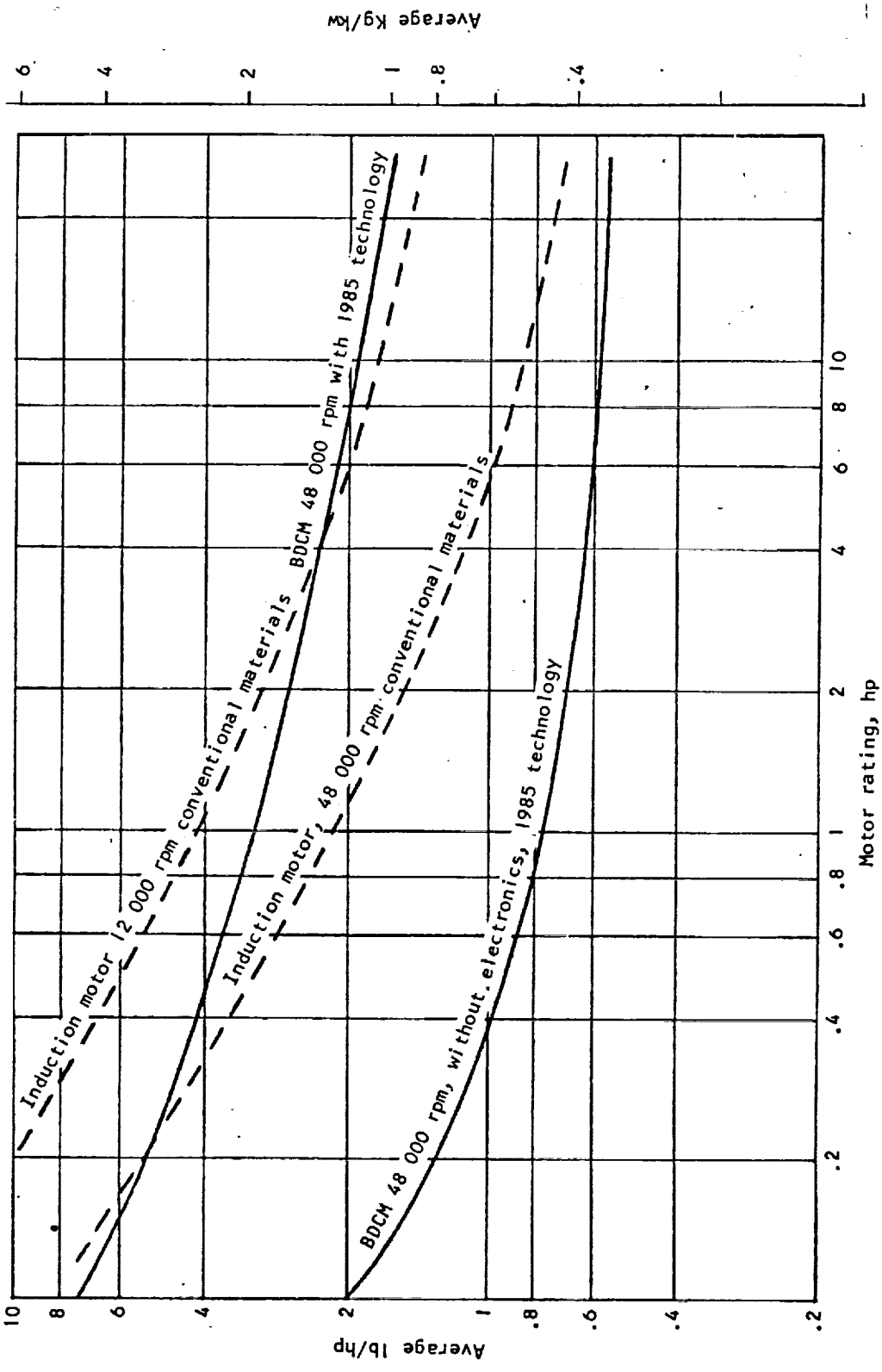
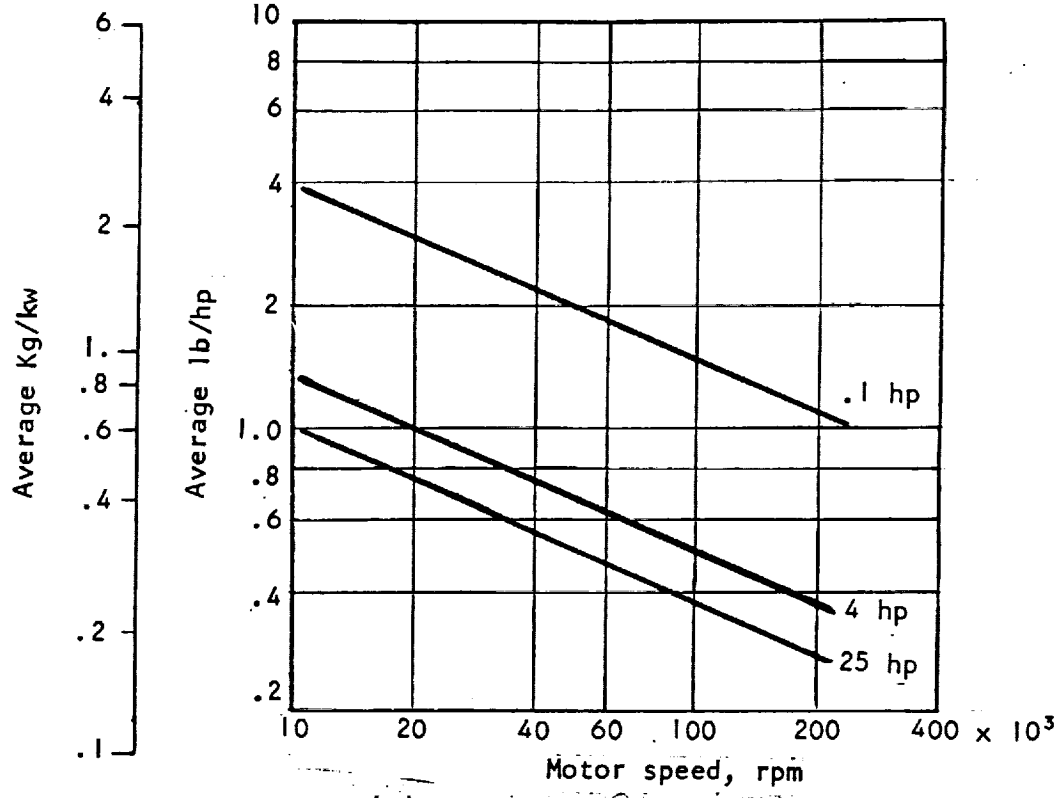
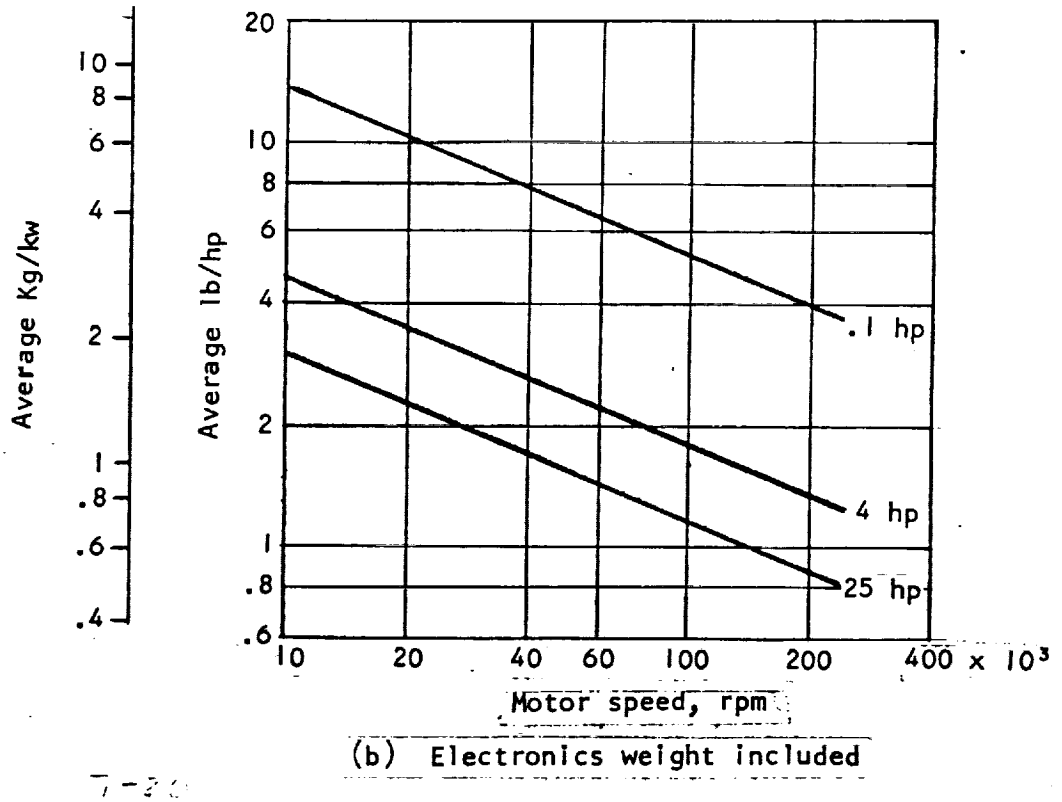


Figure 87. Advanced Brushless dc Motor Specific Weight



(a) Electronics weight excluded



(b) Electronics weight included

Figure 88. Brushless Dc Motor Weight Vs Speed (1985 Technology)

4-mil lamination material was used in the calculations. The iron loss was calculated to vary with the 1.6 power of speed. The total losses are thus defined.

$$\text{Electromagnetic loss} = \frac{1.065 \times 10^{10}\ p^2\ (2L + 3.78D)}{D^4\ N^2\ L^2}$$

$$+ 16.9 \times 10^{-6}\ N^2\ d^2\ LD^2 + 8.05 \times 10^{-8}\ D^2 LN^{1.6}$$

where P = motor rating in horsepower

L = stack length in inches

D = rotor diameter in inches

N = speed in rpm

d = wire diameter ininches

An efficiency using the electromagnetic loss only is called the electromagnetic efficiency. Fig. 89 shows the average electromagnetic efficiency of brushless dc motors as a function of output power for a rotor diameter-to-length ratio of unity (L/D = 1). As explained above, this electromagnetic efficiency is for the motor only, losses in the electronic circuit are not included.

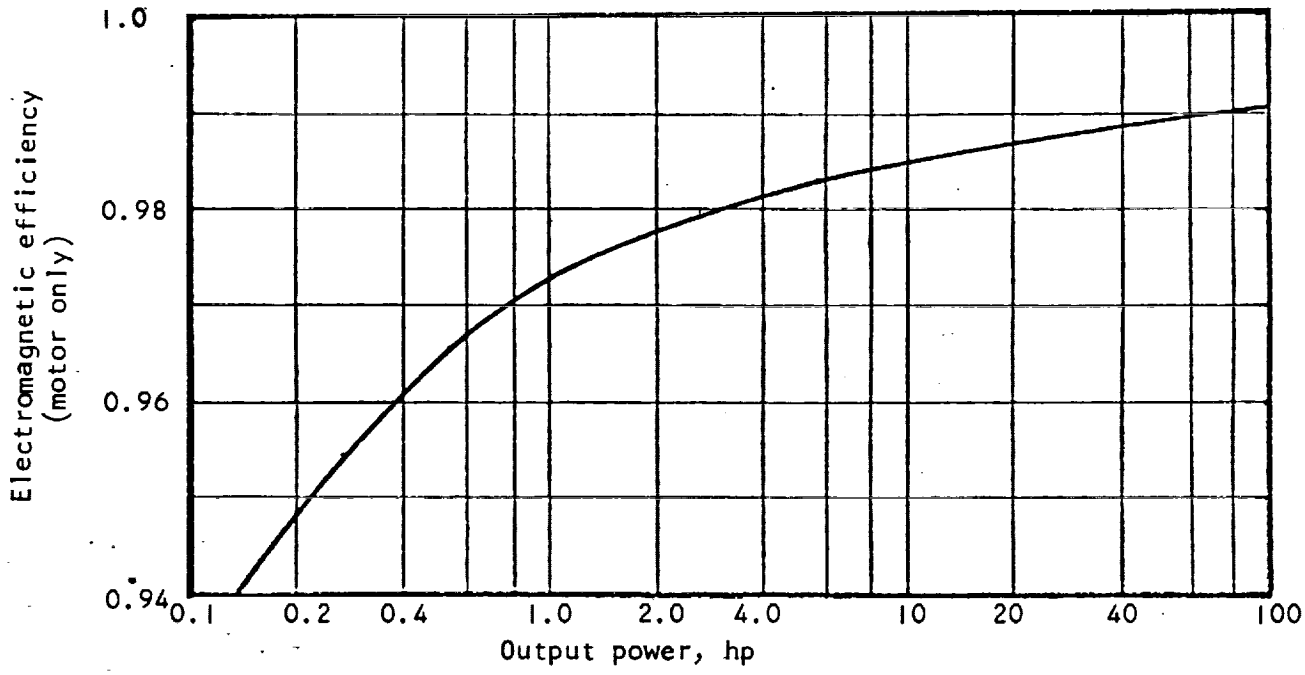


Figure 89. Estimated Electromagnetic Efficiency of Brushless Dc Motor Using SaCo Magnet (Electronics not included)

Electric Generators

Ac generator.--Various types of generators can be used in the conventional, constant-speed, constant-frequency (CSCF) system. The salient-pole, rotating-rectifier generator is used most often because of its inherent advantages in weight, size, performance, and efficiency.

Other types of generators offer the advantage of eliminating rotating rectifiers as well as rotating windings. Some typical solid-rotor generators are the Bekey-Robinson, The Lundell, the Rice and the Homopolar generators. These types, however, are longer, heavier, and less efficient; they exhibit poorer performance because their leakage reactance is higher than that of the conventional machine. They are best suited for high-speed, high-frequency applications or for extreme environmental conditions. General information comparing various types of generators is given in table 53.

TABLE 53. --COMPARISON OF VARIOUS TYPES OF ALTERNATORS

	Conventional	Homopolar	Lundell	Bekey-Robinson	Rice	Axial air gap permanent magnet
Maximum tip speed m/s (ft/min)	102 (20 000)	51 (35 000)	178 (35 000)	178 (35 000)	406 (80 000)	254 (50 000)
Weight per kVA at constant speed	Lowest	Highest	High	Medium	Next highest	High, except in small ratings
Voltage waveform	Best	Fair	Good	Good	Good	Fair-good
Reactance	1.0 (ref.)	2.0	1.7	1.1	1.1	-
Response time	1.0 (ref.)	1.8	2.5	1.7	1.7	-
Environmental capability	Poor	Best	Fair	Fair	Good	Good

Fig. 90 compares the weight and operating speed of several 400-Hz generators. All generators are 60-kVA-rated and satisfy typical overload requirements. They are oil-cooled machines with 422°K (300°F) maximum oil inlet temperature and permanent magnet pilot generators for self-sufficiency. The generators are single-bearing designs because it was assumed that the output bearing of the constant-speed drive would be used to support the input end of the generator rotor. The overload requirement of 3 PU zero power factor load at rated voltage results in

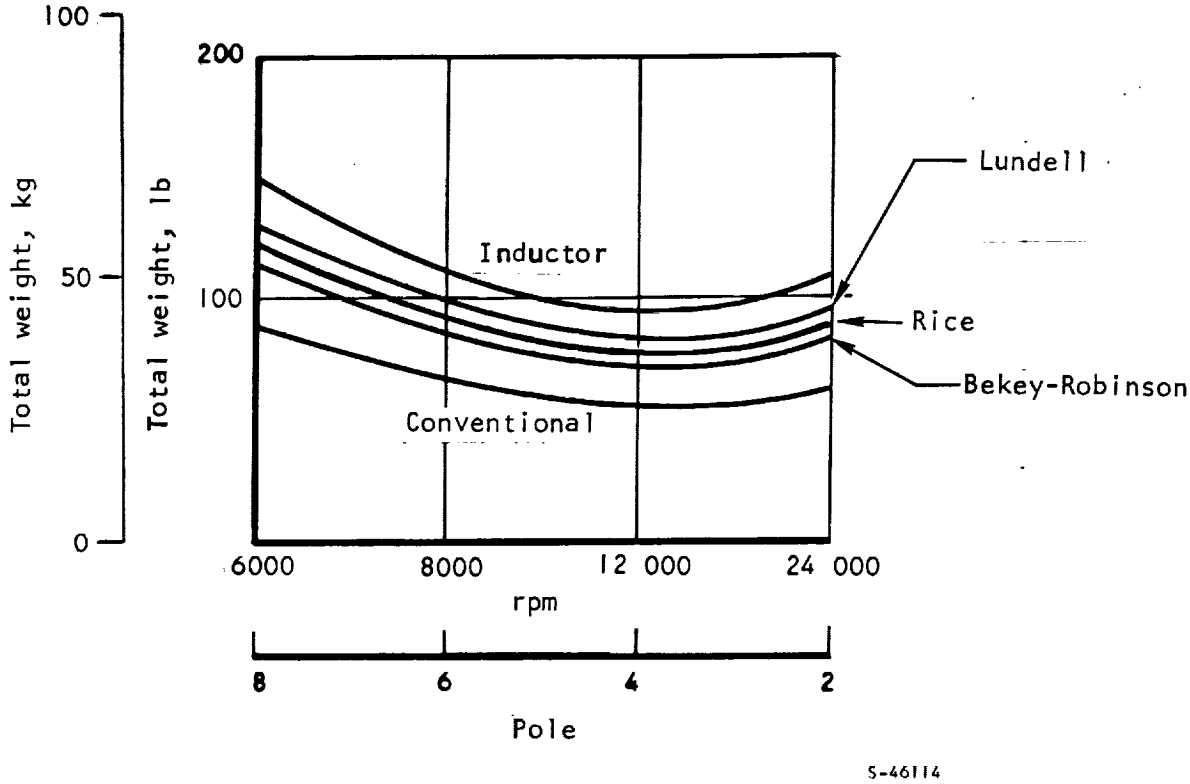


Figure 90. 60-kVA Generator Weight vs Speed for 400-Hz Output

all solid-rotor generators being larger and heavier because their excessive field flux linkage requires a greater excitation increase for a given load increase. As a result the nonconventional generator must be built for a larger rating than required so that it does not operate in the saturated region. Minimum generator weight is indicated at approximately 12 000 rpm. A slight weight increase is associated with speed increase toward 24 000 rpm because of the existing mechanical and magnetic unbalance of the solid-rotor generator and the requirement for containing the rotating field windings on the conventional generator. In addition to weight disadvantage, solid-rotor generators have a slower transient response. Because these generators inherently have a higher value of transient reactance than conventional generators, the higher transient reactance will cause a higher initial voltage deviation during load switching and disturbances and a longer time to return to rated voltage. This, together with a slower change in flux, results in a longer recovery time for the nonconventional generator.

Unless extreme temperature conditions make the application of solid-rotor generators mandatory, the best suited generator for a CSCF system is the conventional machine with respect to weight, size, and performance. Because this generator approaches its design limit at 112 m/s (22 000 ft/min) top speed, its rating and size are confined unless an additional weight penalty for structure enforcement or odd shape generator construction is accepted.

Sleeved salient pole alternator.--The sleeved salient-pole alternator has inherent advantages in weight, size, performance and efficiency. A disadvantage, however, is that its allowable tip speed is relatively low compared with solid-rotor generators. This is due to the fact that the centrifugal forces exerted on the field coils are supported through wedges by pole tips which have limited strength. To overcome this problem, a particular manufacturing technique has been developed that is promising for future aircraft application.

As shown in fig. 91, the rotor is composed of three major parts: (1) the pole body, (2) the field coils, and (3) the rotor sleeve. The rotor sleeve is a metal cylinder consisting of magnetic and nonmagnetic materials arranged alternately. The magnetic and the nonmagnetic materials can be joined by either welding or cast-bond techniques. When the rotor sleeve is press-fitted over the pole body and field coils, the magnetic sections of the sleeve serve as pole heads while the nonmagnetic sections serve as separators magnetically, but mechanically they enhance the strength for retaining field coils, and thus higher tip speed can be achieved. In general, the sleeved salient pole alternator has the following advantages:

(1) It combines the best features of round-rotor and salient-pole construction.

(2) The field coil is supported throughout its full length by a solid bimetallic sleeve of high strength and stiffness. Separate end hoops to retain coil ends are, therefore, not required; thus, coil flexing and shearing at ends is eliminated at all speeds and temperatures.

(3) It has low magnetic leakage compared to conventional round rotor machine.

(4) It has low windage loss at high speed due to the smooth rotor surface.

(5) It offers low construction cost because concentric coils with elaborate coil bracing and wedging are eliminated.

Table 54 shows the design specifications of a sleeved salient-pole alternator manufactured at AiResearch. The alternator is of the rotating-rectifier type. Figs. 92 and 93 show the stator and rotor assemblies.

Although the unit manufactured at AiResearch is of relatively small rating, it is believed that the fabrication techniques can be applied well to larger machines for aircraft applications. It is estimated that the allowable tip speed of the sleeved-salient-pole machine can be increased to about 250 m/sec (50 000 ft/min) from the present 100 m/sec (20 000 ft/min) for conventional salient-pole machines. The increase in operating speed would reduce the weight significantly with little sacrifice in machine performance.

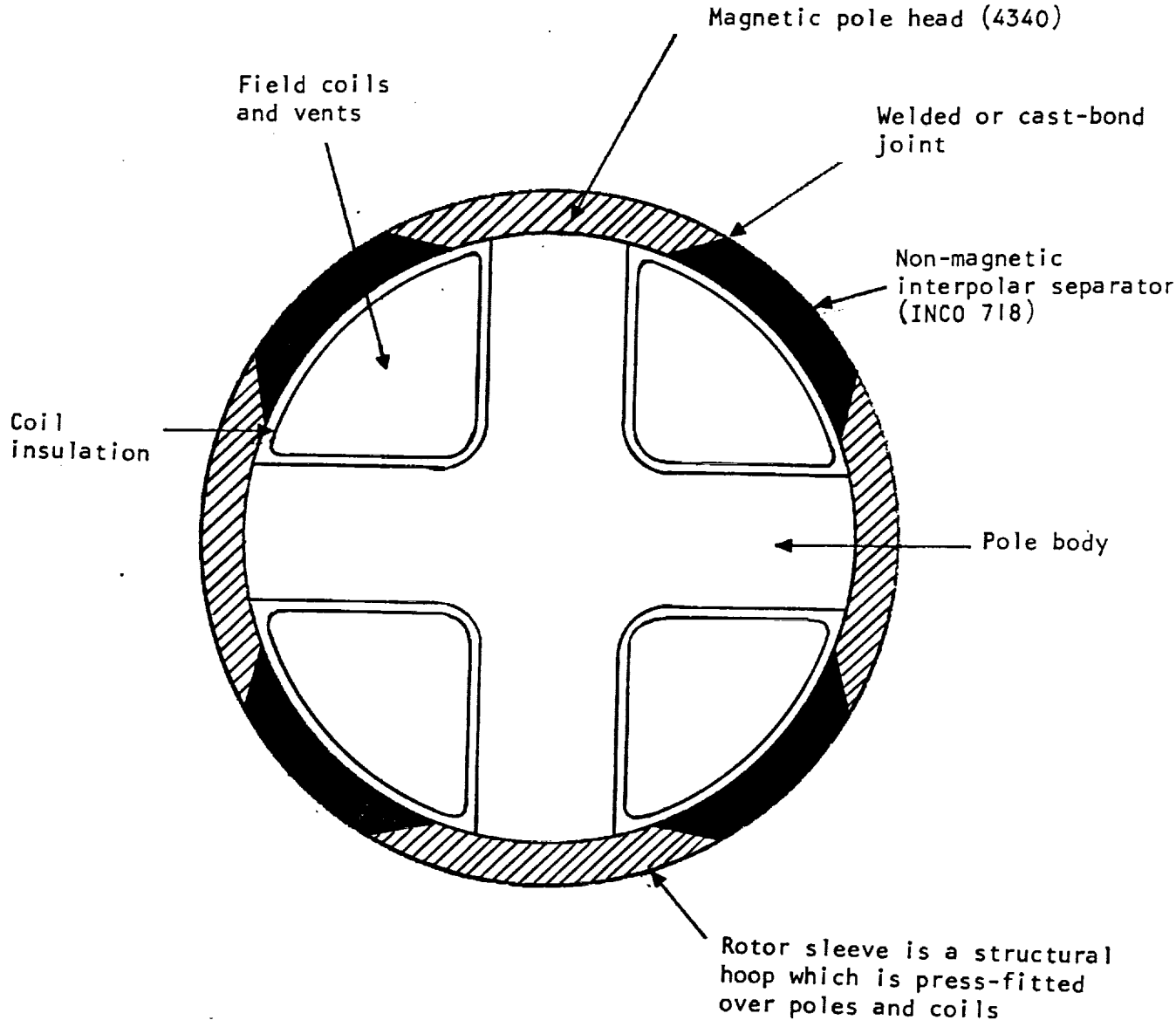


Figure 91. Section of Sleeved Salient Pole Rotor (4 pole)

Figure 92. Stator and Rotor Assembly, Sleeved Salient Pole Alternator

Figure 93. Sleeved Salient Pole Alternator

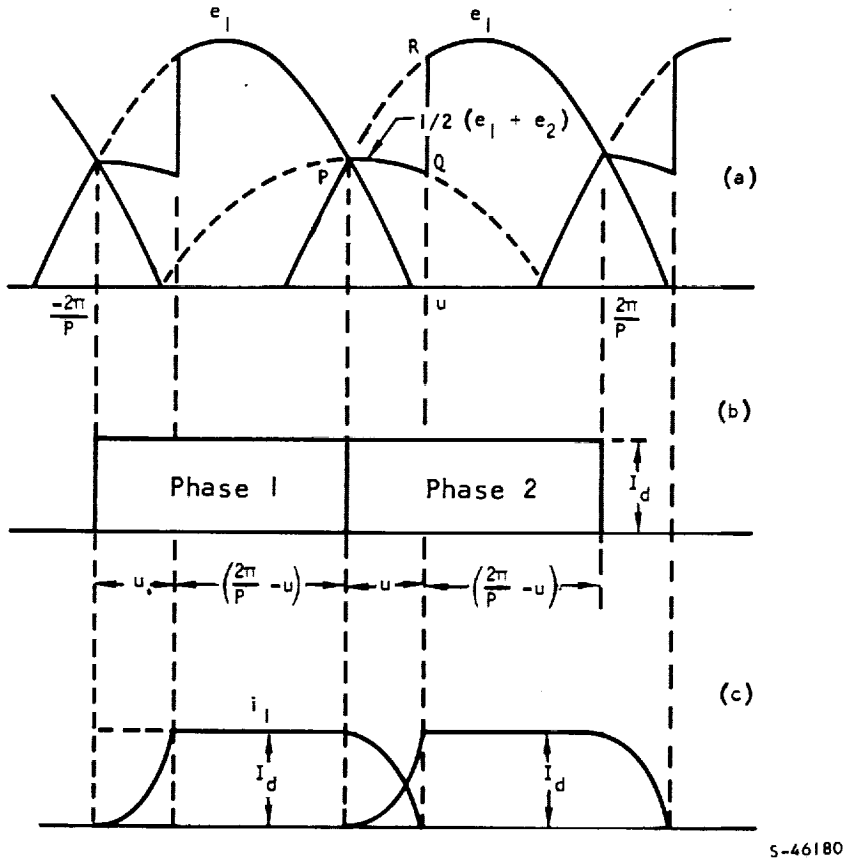
TABLE 54. --ROTATING RECTIFIER ALTERNATOR
(SLEEVED, SALIENT-POLE)

Rating:	641 VA, .9 PF, 16.6/28.8Vac, 3-phase, 6 poles, 125 to 275 Hz. (For 500-W, 32-Vdc system)
Speed:	2500 to 5500 rpm, 6 000 rpm overspeed
Ambient:	5.51×10^7 N/M^2 (8 000 psi), 406°K (270°F) drilling mud, rotor sealed in Dow-Corning 331 Silicone Fluid
Design parameters:	X_l = .136 pu X_d = 2.05 pu X_q = 1.14 pu Z = 1.293 R_{apu} = .1284 at 461°K (188°C)
Exciter:	203 VA, .9 PF, 4 poles, 31.5/54.5 Vac

Dc generator.--One of the most desirable requirements for generating systems on aircraft is that of brushless operation. A modern approach for a pure dc generating system (and also for the various dc-link systems) is that of rectifying the output of a variable-speed alternator, and keeping the output voltage constant by regulating the generator field. Conventional wound-rotor or salient-pole, rotating-rectifier generators, or also solid rotor generators, may be used to supply a three-phase bridge rectifier. This circuit provides double-way conduction in the alternator stator windings, relatively low dc ripple, and 120-deg conduction in the rectifying elements.

The subtransient reactance X''_d of the alternator is referred to in rectifier terminology as the commutation reactance X_c. Due to the presence of this reactance, a definite time is required for the phase currents to build up at the beginning of each conducting period in the phase-voltage cycle, and again to decay to zero at the end of the conducting period (fig. 94a); hence, commutation no longer occurs instantaneously. As a result, the phase-current wave is altered from the rectangular form in the ideal case (fig. 94b) and assumes the shape shown in fig. 94c.

There is a voltage loss during commutation (voltage drops from PR to PQ), that causes a lower dc output voltage. To maintain a specified dc output requirement a higher generator kVA is necessary if there is source reactance. This increases the size and weight of the alternator. The percentage increase in alternator power rating as a function of the commutation reactance X_c is shown in fig. 95.



e_1, e_2 = rectified voltage of phase 1,2

i_1, i_2 = rectified current of phase 1,2

I_d = magnitude of rectified output current

p = number of phases

u = angle of overlap

Figure 94. Voltage and Current Waveform in Polyphase Rectifier Circuit (Two Phases are Illustrated)

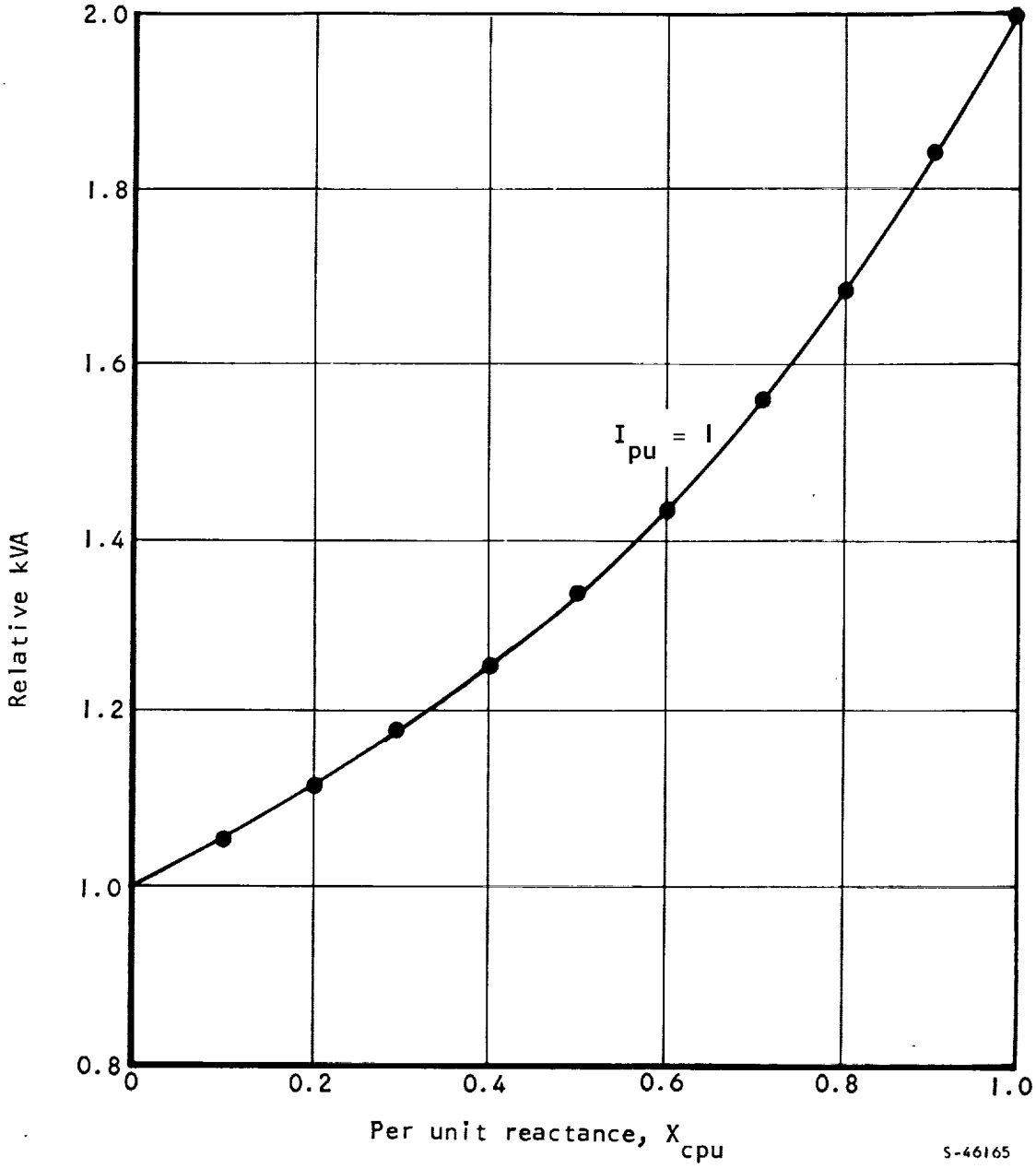


Figure 95. Effect of Source Reactance on Alternator with Three-Phase Bridge Rectification

The rectifier rectifies the three-phase ac power with a frequency range of approximately two to one, to a 2-wire output. The ripple on the rectified dc is filtered by an inductor in one of the two dc leads. Circuits also are provided to perform radio frequency interference (RFI) suppression on ac input lines, and to perform surge suppression on the dc voltage when a large load is suddenly removed from the generator.

The rectification and filtering follow standard engineering practice. The inductance L in the rectifier section combined with the capacitance C at the input to the inverter must limit the voltage ripple on the capacitance to less than 1 percent in order to limit the modulation of the output ac voltage from the inverter. The required LC combination is achieved by adopting a relatively low LC ratio and permitting the dc to be discontinuous at loads less than about 0.3 PU. With this approach, only a small fraction of the average dc is suddenly switched from one ac line to the next. This eases the problem of RFI suppression on ac lines from the generator.

Recent developments in low-voltage spark gaps show good promise for controlling surges to 120 percent of the maximum normal operating level. A spark gap in series with a resistor for 2-PU load is connected across each phase of the ac lines. The weight of this form or other similar forms of surge suppression is about 0.045 kg/kW for three-phase suppression.

Internal Engine Generator (IEG).--The internal (or integrated) engine generator (IEG) previously discussed in the subsystems section is currently under study and development. Four generator types were studied by Boeing. These are:

- The wound rotor, salient pole, rotating-rectifier generator
- The modified Lundell or Rice generator
- The homopolar inductor generator
- The permanent magnet generator (PMG)

The rotating rectifier generator is currently preferred by Boeing because of weight and risk advantages. Cooling by the oil-spray method is preferred in view of its forward cavity location in the engine.

There are unusual IEG requirements. These include, physical constraints, speed range, engine starting and reliability. Since the generator rotor must be designed to permit mounting on the periphery of a relatively large (e.g. 20 cm) diameter engine shaft, a large generator airgap variation is probable. The projected speed ranges of up to 10,500 rpm cause high stresses in the large diameter rotor. The engine startup requirement requires high power rating and an ability to operate in the motoring mode. Both the dc-link and cycloconverter VSCF systems were considered. It was concluded that the dc-link implementation would require a generator kVA rating and feeder rating of approximately 110% of the converter output as compared with 145% for the cycloconverter approach.

High reliability is mandatory because a generator failure would require an engine removal and paetial disassembly for replacement. The aim is a MTBF (mean-time-between-failure) of 50,000 operation hours. Thus, design improvements are called for. It is expected that current development work will be continued in order to solve the difficult problems associated with the IEG requirements.

Power Conversion Equipment

Introduction.--The variety of loads on an airplane places specific demands on the generating system that cannot be satisfied by one power source alone without utilizing power conversion and conditioning equipment. Usually, power is generated at constant frequency and voltage levels. Some loads need high voltages and frequencies (fluorescent lights); some loads need low voltages at the same fixed frequency (windshield heat, servos, lights). A number of loads require dc power of various voltage levels (controls and electronics). For emergency operation it is also necessary to obtain ac power from batteries. A number of conversion components are, therefore, necessary to change ac power to dc power, dc power to ac power, and ac or dc power of one voltage level to ac or dc power of a different voltage level.

This subsection presents a general description of the possible conversion systems and summarizes the advantages and disadvantages of each. It also presents parametric curves that can be used to estimate the weight of the various conversion methods.

Performance guidelines.--With low weight and high efficiency as goals for the systems under consideration, the following general guidelines for performance have been established:

- Conversion voltage--Solid-state devices, when operated in their switching mode, demonstrate a relatively fixed low voltage in their conducting state that is fairly independent of the current flow when the devices are operated in their normal regions of safety. Hence, it is desirable to convert power at the highest possible system voltage to achieve both higher system efficiencies and lower equipment weights. The choice of operating voltage, however, must be compatible with both system requirements and safe operating conditions for available devices.

- Circuit components--Large capacitors and magnetic circuit elements such as transformers and reactors involve higher weights for unit power than do most semiconductors. It is, therefore, desirable to minimize the use of these heavier components, at least in positions where they are required to handle large amounts of power and/or low frequencies.

- Power flow--Series components tend to produce losses and decrease reliability. For an optimum system, power should be converted from its initial to its final form with only the operational steps necessary to remain within the practical limitations or performance requirements.

- Filtering--Passive filtering components increase the weight-to-unit power ratio of static power conditioning equipment. High-power devices, however, operate in the rapid switching mode for maximum efficiency. Because the output power is most usable in smooth waveforms a certain amount of filtering is generally mandatory. In some configurations static power conditioning apparatus will present a rather poor power factor to the power source. The correct choice of filter, in this instance, may actually improve the overall system weight-to-unit power ratio because of a more optimum utilization of the power source. A similar condition exists with poor-power-factor loads. Output filtering that tends to waveshape as well as power-factor-correct will allow better utilization of most power conversion techniques. This can improve the weight and efficiency of a complete system.

- Complexity--It is generally considered beneficial to use complex switching circuitry so that the desired output waveform can be closely approximated or synthesized. This means a greater variety of switched components, magnitudes, or pulse durations from which the output can be constructed.

- EMI suppression--EMI suppression by conventional LC circuits can contribute 20 to 40 percent or more of the total system weight. Solid-state EMI suppression techniques should be considered for appreciably reducing this large portion of equipment weight. This technique could use switching or Class A operation of devices that will generate currents to cancel the EMI currents from the power conversion switches.

Ac-to-ac conversion techniques.--There are two fundamental concepts of ac-to-ac power conversion. One is the direct conversion from ac-to-ac (cycloconverter with natural commutation to obtain lower frequencies, or cycloconverter with force commutation to obtain higher frequencies). The other concept is conversion of ac power at a given frequency (or band) to ac power of higher or lower frequency via the dc-link process.

Dc link: A dc link concept is shown in fig. 96. It includes rectification, dc filtering, inversion, and ac filtering. System regulation, one of the primary concerns, can be achieved by several techniques outlined in the following discussion. Each of these techniques can use many different internal device configurations for the controlled or uncontrolled rectifier, dc-to-dc regulator, regulated inverter, and ac-to-ac regulator.

Most of the dc-link techniques can operate directly from dc sources if only dc-to-ac conversion is necessary. The implementation of such a system would produce slightly higher efficiencies, reduced complexity, lower weight, and increased reliability when compared with comparable ac-to-ac conversion schemes. This dc capability also makes the dc-link techniques attractive for instantaneous or emergency power systems. These systems generally employ batteries or other dc energy storage elements that can be disconnected, floated, or recharged during normal system operation.

It should also be noted that the dc link is produced with techniques that are considered if only ac-to-dc conversion is necessary. Although basic rectification is fairly easy to accomplish, output regulation providing controlled voltage and/or current can be achieved by many different configurations.

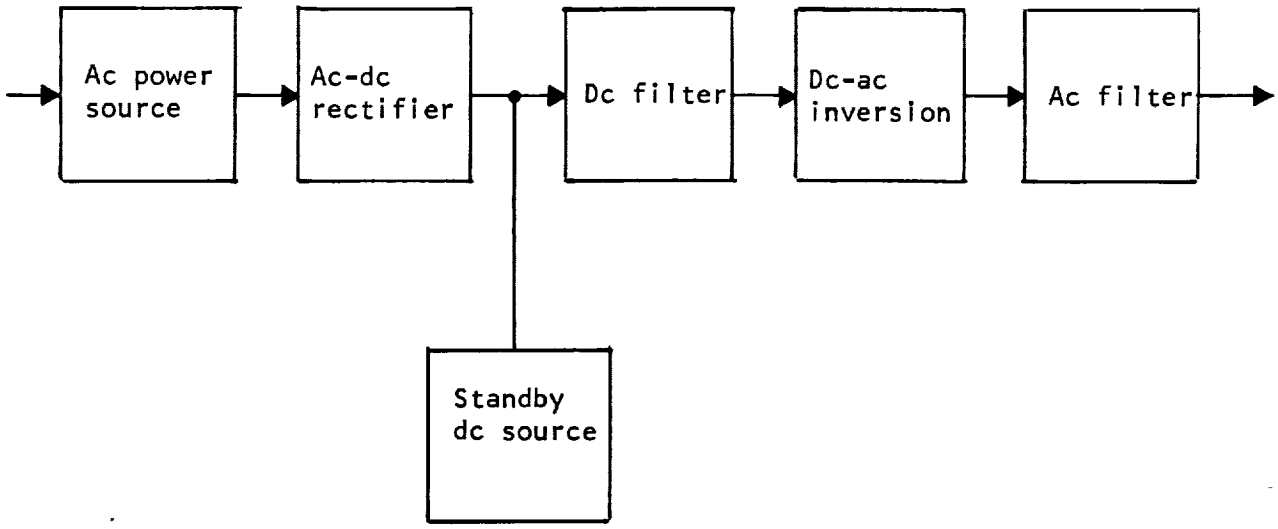


Figure 96. Dc-Link Block Diagram

(1) Controlled rectification: Fig. 97 indicates one of the more common techniques of dc-link power conversion. The source power is delivered to a controlled rectifier which provides, in conjunction with a dc filter, regulated dc power to an inverter and ac filter. System regulation because of source and/or load variation is compensated with the control established on the dc link by the ac-to-dc converter. This is true for a hybrid electrical system where the generator output supplies two or more different power branches. For this, voltage regulation cannot be simply affected by controlling the generator field, because of different load characteristics and varying operational modes of the connected loads.

One possible configuration for such a system is shown in fig. 97b. The input capacitors represent input filtering that might be required to filter and possibly power-factor-correct the effect of the phase delay rectifier (PDR) on the power source. The PDR can assume many forms and would probably be most effective in a six-phase form with the power source providing a two three-phase sets of voltages displaced by 30 electrical degrees. This would permit a relatively wide range of control with a substantial reduction of source ripple components and the ripple due to the controlled rectification. The dc filter can be a single L-section circuit containing a series reactor and shunt capacitor. With a high-frequency source and polarized capacitors, this filter can be constructed with little size and weight penalty. The output capacitors of this dc filter also serve to handle the ripple currents that may be produced from the inverter when handling reactive loads. The inverter, most practically, would be of a three-phase bridge without the internal commutation and device protection elements (which assume configurations based on specific system performance requirements). The inverter portion of this system may also assume more complexity in the form of more vertical legs or multipulse placement such that a lower harmonic content can be achieved in the waveform delivered to the ac filter.

Weight and size can be improved by provision of interphase reactors and harmonic traps.

The system is simple and efficient. It is also adaptable for no-break power applications. Disadvantages are:

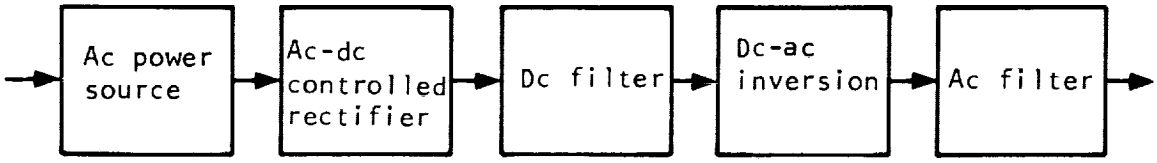
(1) Varying power factor presented to power source

(2) High harmonic filter currents

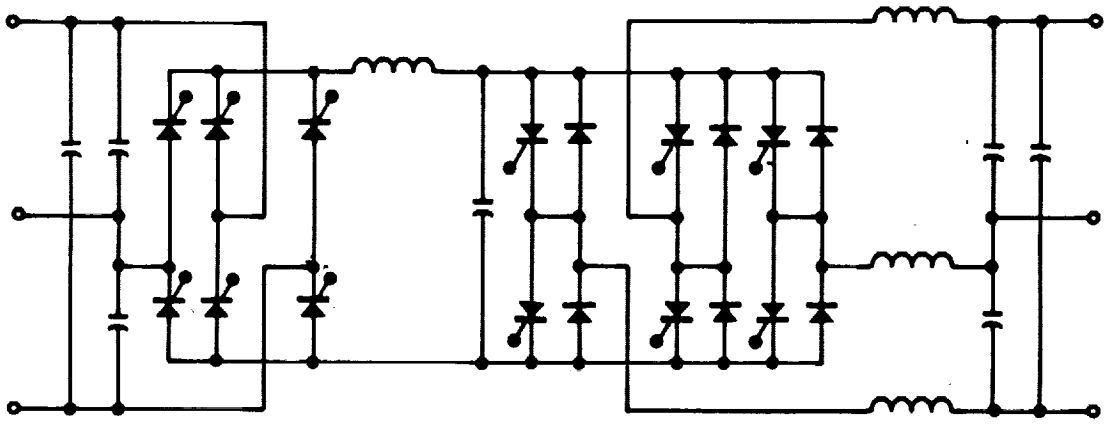
(3) Power, handled four times

(4) Slow response

(2) Controlled dc link: Fig 98 indicates a slightly different technique for establishing control over the dc link. As shown in the block diagram of fig. 98a the source power is delivered to an uncontrolled rectifier which provides unregulated dc power to a dc-to-dc regulator and filter. The position of the dc-to-dc regulator can be either in front of or behind the dc filter, depending primarily upon the type of regulator used and the input power requirements of the inversion stage. The regulated dc energy is then made available



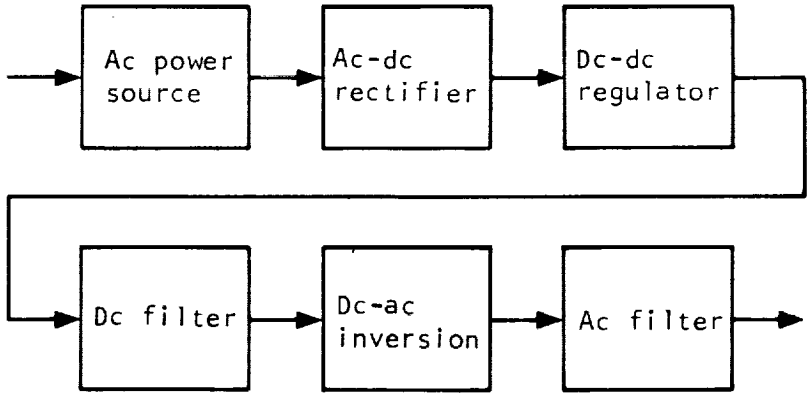
(a) Block diagram



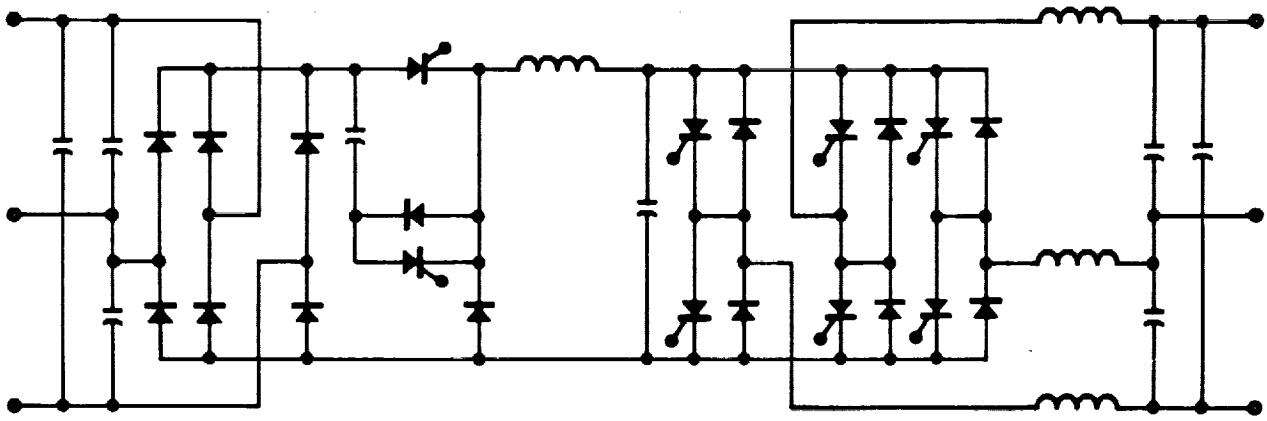
(b) Representative power device configuration

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Figure 97. Controlled Rectification



(a) Block diagram



(b) Representative power device configuration

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Figure 98. Controlled Dc Link

to the inverter and ac filter. Regulation because of source and/or load variation is compensated with the control established on the dc link by the dc-to-dc regulator. One possible power device configuration for such a system is shown in fig. 98b. The input capacitors represent input filtering that might be required to filter and possibly power-factor-correct the effect of the diode rectifier on the power source. The rectifier can assume many forms and would probably be most effective in a six-phase form with the power source providing two three-phase sets of voltages displaced by 30 electrical degrees. In aircraft systems, however, a three-to-six phase transformer would be necessary to obtain the two three-phase sets of voltages. For most aircraft applications it is unlikely that the additional transformer weight could be justified.

The rectifier is followed by a dc-to-dc regulator in the form of a series chopper. The chopper can operate in several modes, the most applicable being a fixed high-frequency, variable-pulsewidth operating condition. This chopper could be replaced with other types of controllable dc links such as series buck and/or boost systems receiving power from the source or bootstrapping power from the output to perform the regulation. The regulation link, in any case, would be a high-frequency switching system to achieve optimum efficiency and would, therefore, include the requirement for dc filtering. High-frequency regulator operation makes possible a relatively small dc filter with which to smooth the modulated output of the regulator and handle the ripple current from the inverter. Inverter and ac filter possibilities are similar to those described in the preceding controlled rectification system.

Weight and size can be improved in a manner similar to that suggested for controlled rectification.

The system is simple and moderately efficient. It is easily adaptable to no-break power requirements and presents a relatively fixed power factor to the source. Disadvantages are:

(1) Difficulty in providing high short-circuit currents

(2) High harmonic filter currents

(3) Power handled five times

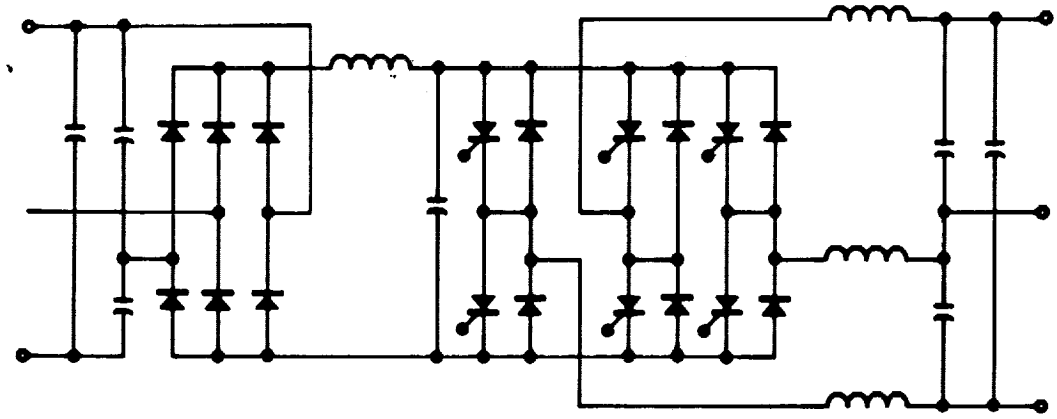
(4) Slow response

(3) Controlled inversion: Fig. 99 presents a technique in which the source power is delivered through an uncontrolled rectifier and dc filter to a more sophisticated inversion process which includes internal provision for regulation of the fundamental component in the inverter output. The technique concludes the inversion by passing the ac power through an ac filter to the output. Regulation because of source and/or load variation is compensated with the control established on the dc-to-ac inversion stage.

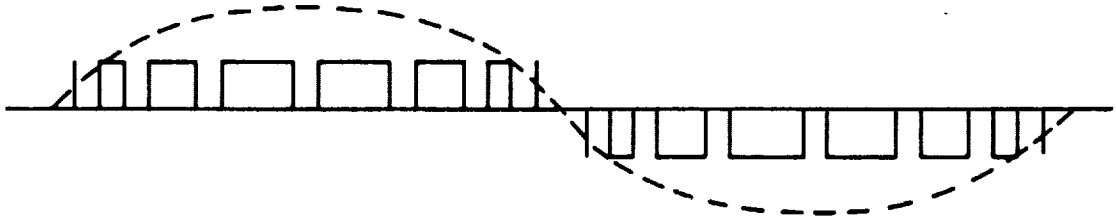
A representative device configuration for such a technique is shown in fig. 99b. Some small input filtering, represented by the shunt capacitors, might be required due to the effect of commutation overlap introduced in the



(a) Block diagram



(b) Representative power device configuration



(c) Representative pulsewidth modulation waveform S-44869

Figure 99. Controlled Inversion

rectifier. The filter also might power-factor-correct the rectifier input power for more effective utilization of the power source. The three-phase rectifier presents full-wave rectification which could be accomplished with a six-phase, full-wave system for reduction of dc ripple components. The six-phase input generated by the power source provides two three-phase sets of voltages displaced by 30 electrical degrees. A small amount of dc filtering would smooth the rectifier output voltage and also provide a low source impedance for ripple currents produced by the inversion scheme. These ripple currents can be produced by some commutation techniques and/or inverter reactive loading. The inversion process would include an internal method of controlling the fundamental component of the output waveform. A good method of achieving this characteristic in an efficient system is that of pulsewidth modulation (PWM). PWM attempts to produce output waveforms that not only vary in fundamental components, but also contain a minimum amount of harmonics. One example of PWM is shown in fig. 100. The choice of pulse frequency is usually dependent upon the available characteristics of the inverter devices and the method of device commutation. The placement of pulses and their width variation process is determined by waveform analysis and implemented to achieve acceptable harmonic profiles over the desired control range. Other methods of inverter output control are available and include such configurations as two inverters with variable phase displacement, step-wave techniques with summation transformers or reactors, or several switched dc sources to produce step-wave synthesis of the output waveform.

Bulk filtering can be minimized by inclusion of shunt harmonic traps or interphase transformers to produce acceptable waveforms.

The system should be efficient and adaptable to no-break power applications and short-circuit currents should be easy to produce.

Disadvantages are:

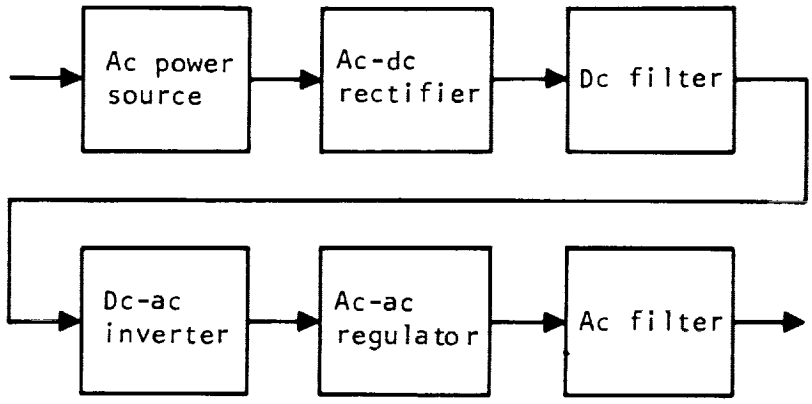
(1) Complex inverter and filter circuits

(2) Inverter requirements difficult to meet

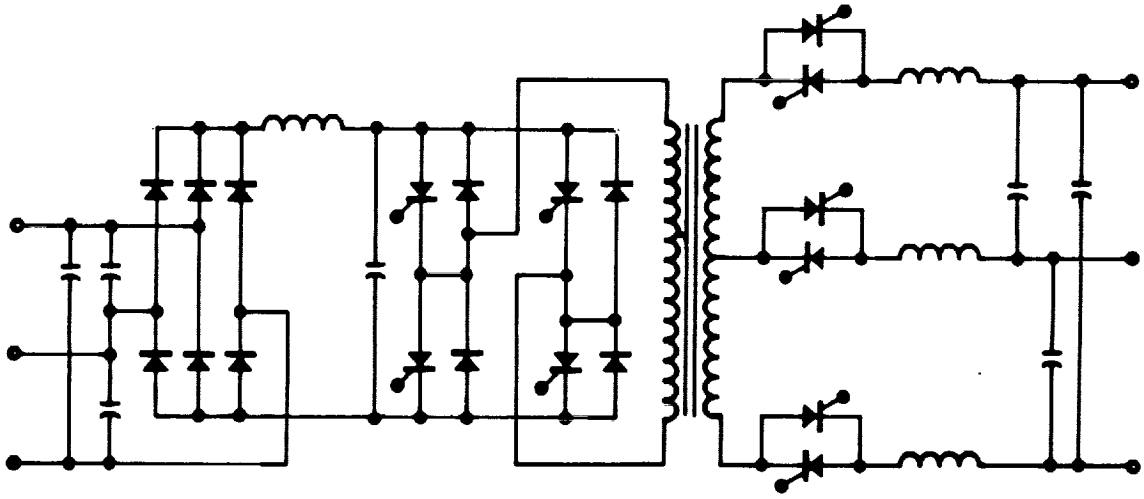
(3) Possibility of high harmonic filter currents

(4) Power handled four times

(4) Controlled ac-to-ac link: Fig. 100a represents a system that delivers the source power through an uncontrolled rectifier and dc filter to an inverter. The output of the inverter, which will reflect any amplitude variation in the source and therefore be accurate in frequency only, is then delivered to an ac-to-ac regulator that can provide amplitude regulation in response to variations in the source and/or load. The position of the ac-to-ac regulator can either be in front of or behind the ac filter, depending primarily upon the type of regulator that is used and the power requirements of the ac filter and load.



(a) Block diagram



(b) Representative power device configuration

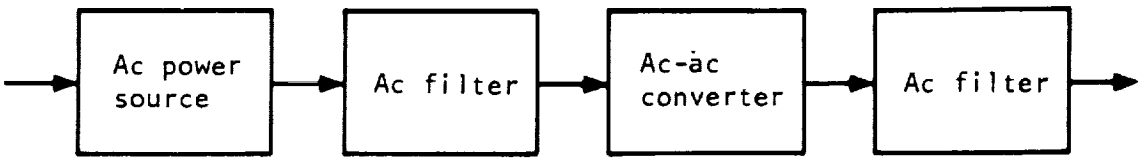
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Figure 100. Controlled Ac-to-Ac Link

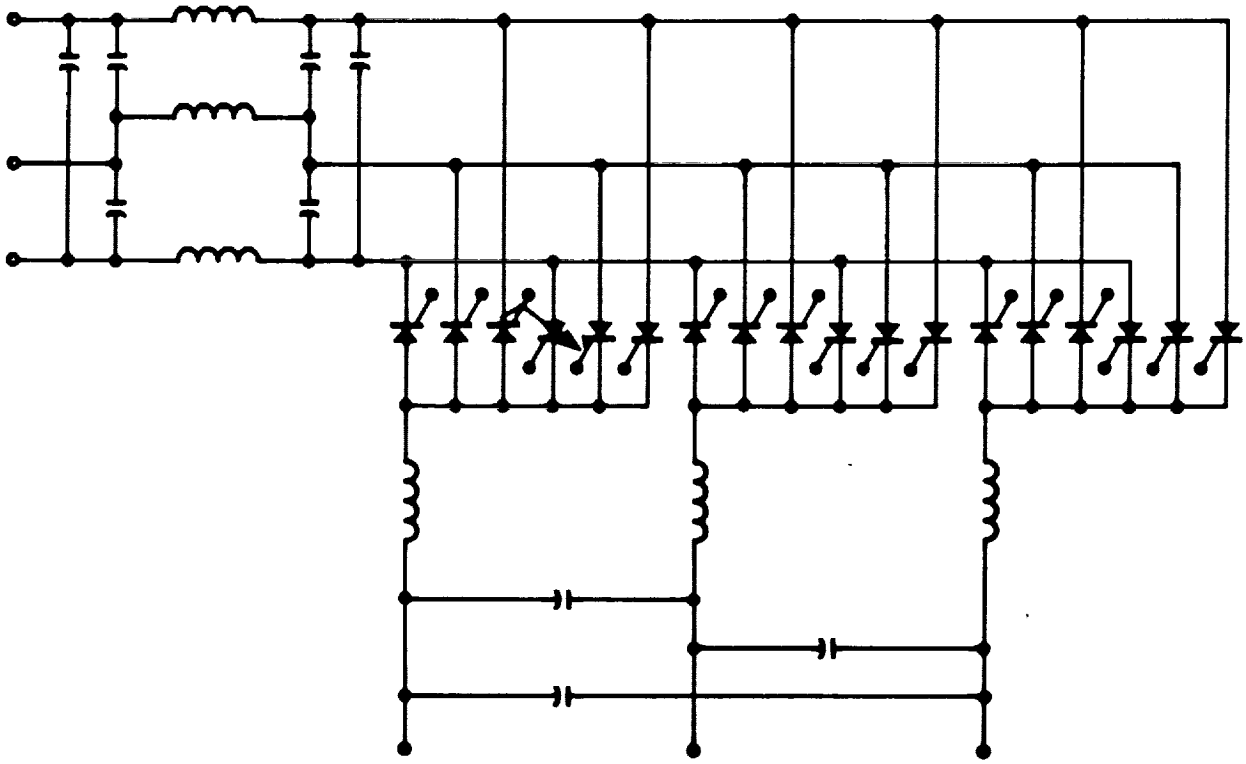
A possible configuration for this technique is shown in fig. 100b. Although not widely used in the past because of stringent component requirements, this technique may be considered because of the rapid development of high-performance power semiconductors. The power is delivered from the source to full-wave rectification and dc filtering. The rectifier would probably be in a six-phase form with two sets of three-phase voltage provided by the power source. Filtering similar to that used on the systems previously described would be used to buffer the detrimental effects of the rectification process and provide fuller utilization of the power source capabilities. The dc power is converted to precise high-frequency power by an inversion process. The high frequency can be generated at an integral multiple of the desired output frequency. The inverter output is then presented to a synchronous switching arrangement that synthesizes an output waveform from the high-frequency components. The use of high frequency reduces the size of magnetic components and permits highly accurate output waveform synthesis such that the ac filter is relatively small. Other device configurations that could be used within this ac regulator framework include such schemes as self- or externally regulated output filters, static tap changing with forced or natural device commutation, and regulating output transformers that may also provide some amount of filtering.

A system of this nature will be reasonably efficient and easily adaptable to no-break power applications. It will have rapid speed of response and wide control range. The disadvantages of the system are the complex switching and filtering, the stringent device requirements, the possibility that the output filter may handle high harmonic currents, the difficulty in producing high short-circuit currents, and the weight, which is slightly heavier than in other techniques.

Direct ac-to-ac techniques: The second fundamental concept for ac power conversion utilizes techniques that provide for direct ac-to-ac power conversion. The concept is shown in block form in fig. 101a. In general, this concept will include some ac filtering on the source, ac-to-ac conversion, and an ac filter on the output. The techniques for this concept are rather limited and can be adequately described by the conceptual block diagram. However, the device configurations that can be and have been employed to utilize this concept vary widely. A representative power device configuration is shown in fig. 101b. The principle of operation is to use multiphase high-frequency input power to generate lower-frequency output power. Output waveforms are constructed from sampling techniques applied to the input phases. The rapid switching and source current chopping generally require some source filtering to prevent damaging transients, commutation, overlap angles, ripple currents, and poor power factors from interfering with acceptable operation. The conversion process from ac to ac is relatively complex and, until recent years, placed performance requirements on the semiconductor devices that were very difficult to achieve with the normal yield of large production device characteristics. The output of such an ac-to-ac conversion stage requires some ac filtering because of the distortion introduced by the sampling techniques of waveform synthesis. The amount of output filtering depends, to a large extent, upon the ratio between the input and output frequencies. If the input frequency is high compared to the output frequency, relatively little filtering is required because



(a) Block diagram



(b) Representative power device schematic

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Figure 101. Ac-to-Ac Conversion

the output waveform synthesis can be done with a fair degree of accuracy. However, with this high frequency ratio and an output frequency that may also be high, the ac converter and the source experience stresses due to rapid switching sequences and extreme voltage excursions. Circuitry must be used to control these internal stresses and can become so unwieldy as to obviate the apparent advantages of the direct ac-to-ac conversion concept.

There are several other characteristics of direct ac-to-ac conversion that must be eliminated or controlled to produce precise output power. These undesirable traits are primarily related to the fundamental limitations of the sampling technique. For example, the zero crossing of the output voltage waveform will depend upon the zero crossing of the last input sample of that particular half cycle. Since this sample may be chosen to yield only the correct amplitude at some time previous to the desired zero crossing a timing error may be produced. When this effect is considered on a cycle-to-cycle basis it can be seen that a frequency beat is produced that reflects the input to output frequency difference. One method of overcoming this effect is to utilize an auxiliary circuit that force commutates the conducting link precisely at the desired zero crossing time. The remaining portion of the output half cycle may use the natural commutation process that is available with the basic device configuration.

The sampling error can also be reflected in an amplitude modulation that involves the input and output frequency difference. The input component that is used for one portion of the output waveform is not generally available for the same portion of the next half cycle (unless the input and output frequencies happen to be synchronous). Since another waveform will have to be used during this portion of the output waveform a modulation is produced. This effect can be minimized, of course, with a high input to output frequency ratio. Another method of minimizing this effect is to create a greater number of input phases from which to derive samples. This increases the number of active devices but, since the load will be equally shared, does not appreciably affect the effeciency or weight of the equipment. A multiphase configuration of this nature also reduces the high frequency stresses that would have to be tolerated if the input frequency were increased. For instance, the number of available samples could be doubled if the power source were to produce two sets of three phase voltages displaced by 30 electrical degrees.

Another internal device configuration that can be considered to minimize both the frequency and amplitude modulation is an implementation of total forced commutation capability. Although the attractiveness of the basic concept lies in the natural commutation capabilities, forced commutation can be instituted to overcome some of the disadvantages encountered in the naturally commutated configuration. If the forced commutation scheme is correctly implemented the flexibility of the conversion process is greatly increased. As an example of this increased capability it can be seen that the system would not require an input frequency higher than that of the output frequency. However, this increased flexibility is achieved at the expense of complexity and device utilization because of the auxiliary commutation circuitry.

Between the natural commutation and forced commutation schemes there is the opportunity for hybridization or blending of the two methods. Although these hybrid systems generally require increased logic and sensing circuits they can produce more efficient and lower weight systems with precise power capability. The improvement is achieved because of fuller utilization of the semiconductor devices and reduced power circuit complexity.

It can therefore be seen that optimization procedures can be instituted to choose a device configuration that is compatible with practical semiconductor technology, source characteristics, and filter parameters such as size, weight, and cost. This basic conversion concept will generally employ more active semiconductors than a dc-link approach and will require more attention to the power source and load interfaces with the power conversion equipment. It can, however, provide a lower weight and more efficient system than the dc-link concept.

A concept of this nature should be highly efficient. It will have rapid response, a wide range of control, a conversion process that handles the power only three times, and a slightly lighter weight than the other techniques. The disadvantages of the system are the extremely complex device configuration and control, the possibility of interference from source ripple and frequency, the inability of the system to be used for no-break power applications, and severe device demands.

Dc-to-dc conversion techniques.--Although only brief mention has been made of the dc-to-dc control and conversion techniques in the discussion of the dc-link systems, this particular area of power conditioning can become very important to a fully integrated power system. It is possible that with the growth of efficient, low-weight control processes, the majority of the aircraft power systems will be concerned with dc power conditioning. With the technology and capability within grasp, bulk dc power conversion should be considered even for subsystems that require close-tolerance, wide-range power sources. For general-purpose utilization, chopper systems provide efficiencies in excess of 90 percent (approaching 98 percent at higher conversion voltages) and excellent weight-per-unit-power ratios when operated at reasonably high frequencies.

Dc chopper: One of the most useful techniques of dc-to-dc power conversion is the dc chopper. Loosely defined, a chopper could be any circuit that produces a discontinuous voltage and/or current waveform. To specify a chopper in more detail requires definitive performance parameters. The specification can then be used to choose the requirements for chopper performance. Representative areas for chopper performance include:

- Function--step-down, boost, step-down/boost
- Power flow--unidirectional, bidirectional
- Operation--constant frequency-variable pulsewidth, variable frequency-constant pulsewidth, variable frequency-variable pulsewidth
- Commutation technique--momentary shunt of the pass element, load commutation (natural commutation) front-end interruption, pass element control (device turn-off)

The choice of any particular technique depends primarily upon the specific application and desired performance parameters such as minimum output power, range of control, lock-up possibility, complexity, response time, size, and weight.

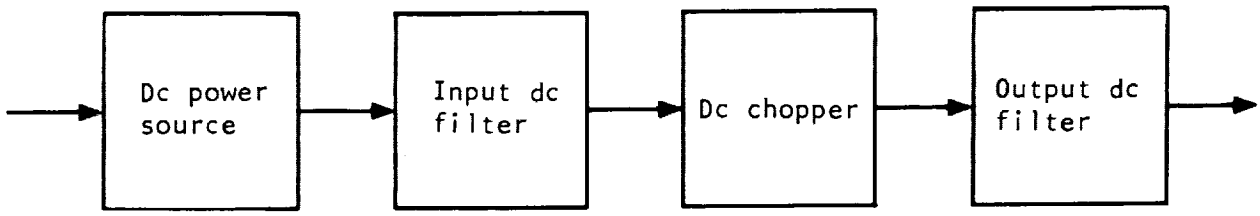
Dc-to-dc power conditioning displays most of the high efficiency and low weight advantages in dc-to-dc step-down applications where continuous output current is a requirement. The circuitry then generally contains a "free-wheeling" circuit to maintain a load current path when the main pass element is nonconducting. This free-wheeling path and other chopper functions are shown in fig. 102. Where relatively high voltage and high currents are required, a thyristor (silicon controlled rectifier) is generally employed as the pass element. Chopper circuitry that is not closely associated with the pass element or the free-wheeling path can be grouped as commutation circuitry. Turn-off characteristics of the main element (both inherent and desired) are the single most important factor in determining the commutation circuitry.

The commutating circuit of high-power choppers is a major contributor to size, weight, complexity, cost, and losses. Any optimizing procedure should, therefore, place a great deal of emphasis upon the commutation requirements and implementation of the main pass element. The versatility of a chopper system can be seen by the following examples of applications:

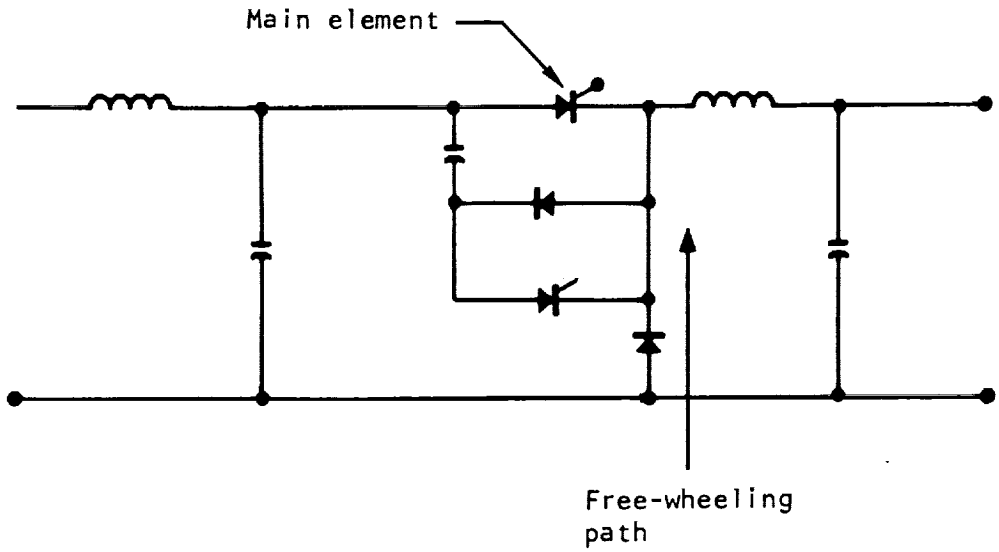
- Continuous operation--motor drive control, regulated power for battery systems, load control systems, efficient low voltage power from high voltage sources, voltage or current sampling in servo loops, and pulse coded information systems
- Intermittent operation--ultra fast control systems, program load

The use of a dc chopper is highly efficient. It has rapid response, wide range of control, a conversion process that handles the power only three times, light weight, relatively simple circuitry, and capability of application to no-break and emergency systems. Disadvantages of the system are the possibility that the system may require a relatively larger amount of input and/or output filtering, the necessity of tailoring the optimum system closely to the expected load, and the possibility of lock-up under some failure modes.

Buck-boost: Where wide ranges of dc control are not required, a buck-boost system can provide an optimum approach. The implementation of the concept involves placing a variable source in series with the primary power source such that it can add or subtract potential to provide output control. Systems of this nature are usually applicable in situations where a relatively limited range of control is necessary (generally not more than ±30 percent). A buck-boost concept becomes slightly more attractive where auxiliary ac power is available for use in the buck-boost source. A schematic of such a system is shown in fig. 103. Very little, if any, input filtering is required because the output filter also reduces source ripple. There are many techniques for developing the series source. Since this source is variable dc any of the various ac-to-dc or dc-to-dc schemes would be acceptable. System investigation should decide whether the unit should act only to add or subtract potential



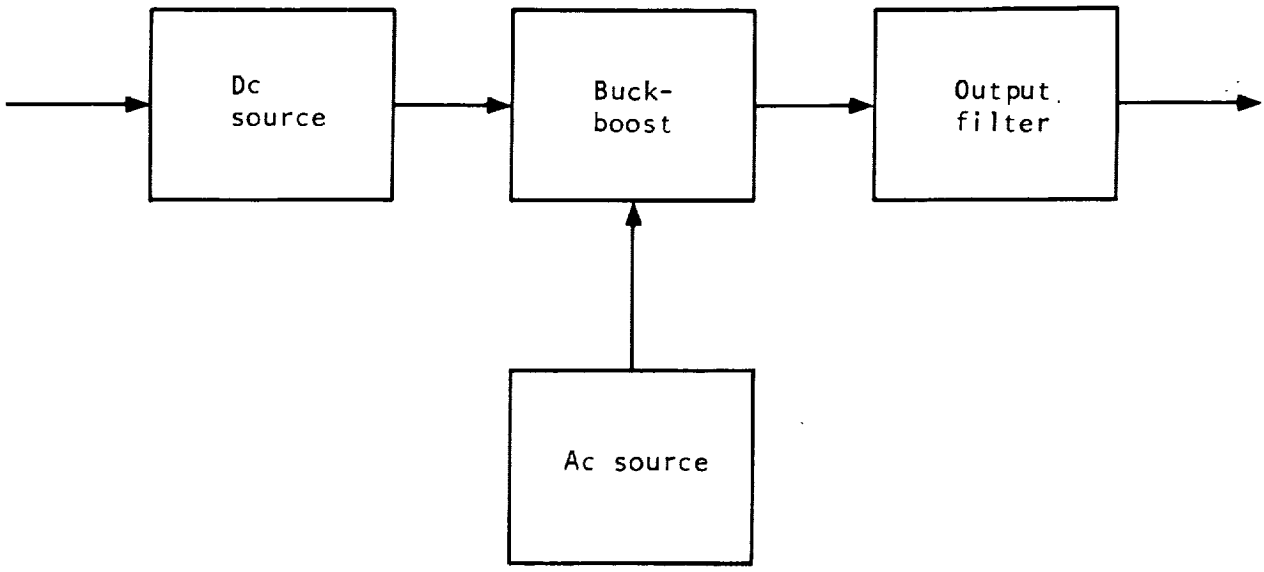
(a) Chopper block diagram



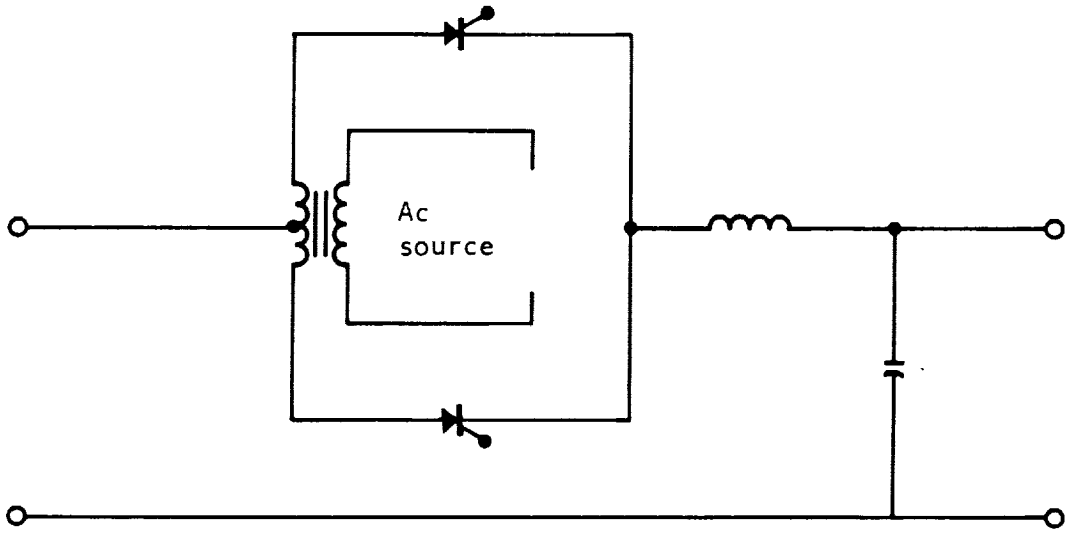
(b) Representative power device configuration

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Figure 102. Dc-to-Dc Conversion



(a) Buck-boost block diagram



(b) Representative power device configuration

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Figure 103. Dc-to-Dc Conversion,
Buck-Boost Source

from the primary source or whether it should be capable of both the buck and boost modes of operation. When the system is operated in the buck mode (subtracting potential) the series element becomes a power sink and must be capable of reverse power flow. This can be an important factor in determining which techniques are available for developing the series source.

If this concept is to be used to develop regulated power for dc-to-ac conversion equipment, it is possible to use a portion of the resultant ac output power as the auxiliary source of power for the series regulating element. Bootstrapping of power can cause difficult starting sequences but is an acceptable method of developing the buck-boost source.

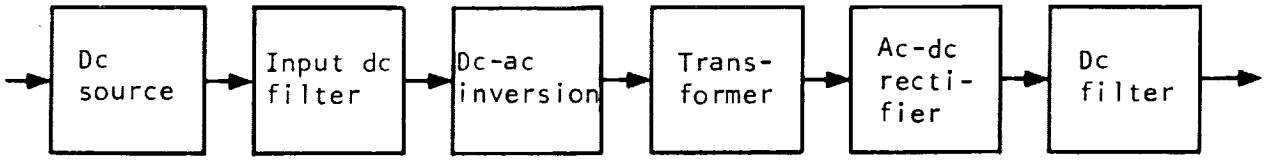
The buck-boost concept of dc-to-dc power conversion should be highly efficient, relatively low in the required amount of filtering, and light in weight. The conversion process handles the power only twice; the system is relatively simple. Disadvantages of the system are the general requirement for an auxiliary ac source, limited range of control, and difficulty in adapting to no-break power systems.

Inversion-rectification: When the application for dc-to-dc power conversion includes a requirement for high ratios of input to output voltage the inversion-rectification concept should be considered. (This is especially true in the step-up direction.) The dc-ac-dc process first inverts the dc input to create ac power suitable for transformation. The transformer then acts to change the voltage to a level where ac-to-dc rectification can produce the desired potential. This particular system can be regulated by control of the inversion process and/or the rectification process. Although both regulating techniques are acceptable, control of the rectification stage can produce a more efficient and less complex system. This may require development of control devices that can handle the resultant dc voltage.

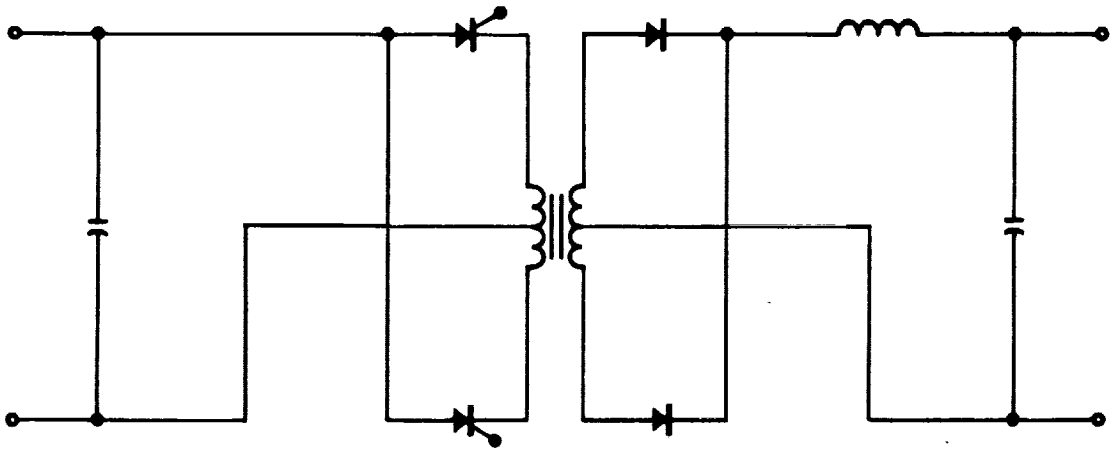
Dc-ac-dc power conversion techniques should also be considered when electrical isolation is required between the source and the output. Although this type of conversion is generally characterized by the use of an auto-transformer for low weight, the transformer can be constructed on a multi-winding basis to provide electrical power that is isolated from the source.

A typical inversion-rectification system is shown in fig. 104. The inversion stage that is shown is single phase but any inversion concept is acceptable. Indead, if low ripple is a requirement then multiphase inversion can reduce the overall weight by reducing the amount of filtering. This scheme is particularly attractive in systems where appreciable amounts of ac power may be required to service other loads. A single unit that integrates the power systems to produce ac and dc should reduce the number of redundant components and improve the reliability of the overall system.

Inversion-rectification techniques are capable of very high input to output ratios, of providing isolated dc power or auxiliary ac power, and oil applicable to no-break or emergency power systems. The system is moderately efficient. Disadvantages of the system are that it generally includes relatively heavy magnetic elements, has a conversion process that handles the power five times, and has a relatively complex method of producing regulated power.



(a) Inversion-rectification block diagram



(b) Representative power device configuration

S-44873

Figure 104. Dc-to-Dc Conversion, Inversion Rectification

Weight data of conversion equipment using current technology.--

Data description and assumptions: The weight of conversion equipment for a certain kva rating may vary over a wide range depending upon the output power quality and EMI suppression requirements. The data given in this section represent current technology and are based on good filtering and EMI protection that will meet normal aircraft specifications.

To generate useful curves for the weight of power conditioning apparatus, several assumptions must be made. The information contained on the curves of figs. 104 and 105 have been derived based on the following assumptions:

(1) Input leads from power source and output leads to load contribute little to the equipment weight.

(2) Unit is constructed to meet reasonably high shock requirements.

(3) Unit contains all the necessary elements to provide complete conducted and radiated EMI shielding.

(4) A 373°K (100°C) heat sink is readily accessible.

(5) Distortion should be less than 10 percent to ideal input waveforms.

(6) Output waveforms will be within 5 percent of ideal waveforms.

(7) Operating voltage of the system is high compared to semiconductor device forward drop when conducting.

Weight deviation: The weight of the equipment is not heavily influenced by the actual solid-state devices, but depends, primarily, upon the peripheral apparatus such as EMI suppression, transformers, waveshaping filters, device protective networks, electromechanical contactors, and connectors. This being the case, the graphical data should be interpreted as representing general power conditioning equipment. Particular applications will deviate from these curves. The weight deviation from the curves due to solid-state motor drive applications is severe enough to deserve special attention in the graphical results. Since solid-state power conditioners can be closely related to the motor itself and only a minimum amount of waveshaping is required, substantial reductions of weight can be achieved. The resulting weight curves for dc-to-ac, ac-to-dc, and dc-to-dc motor drive configurations are included with the general results.

In some special applications where the requirements for power conversion from ac-to-dc or dc-to-ac do not include internal transformers (either for isolation or potential transformations), equipment weights are best described by the comparable motor drive curve.

The relationships of weights of magnetic components versus efficiency and input voltage waveform were discussed in the Interim Technical Report (ref. 1) and will not be repeated here.

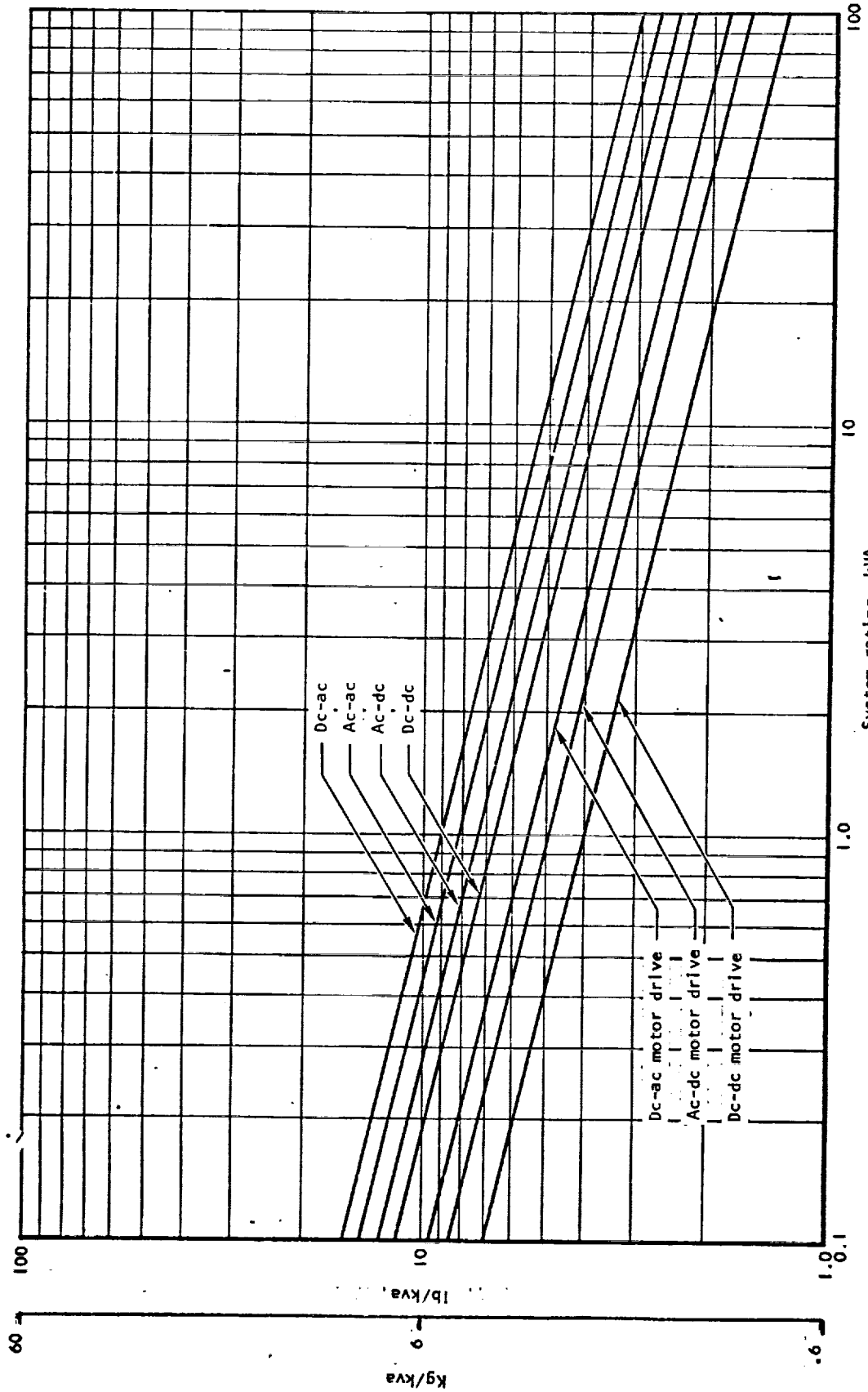


Figure 105. Power Conditioning Equipment Weight for 400 Hz

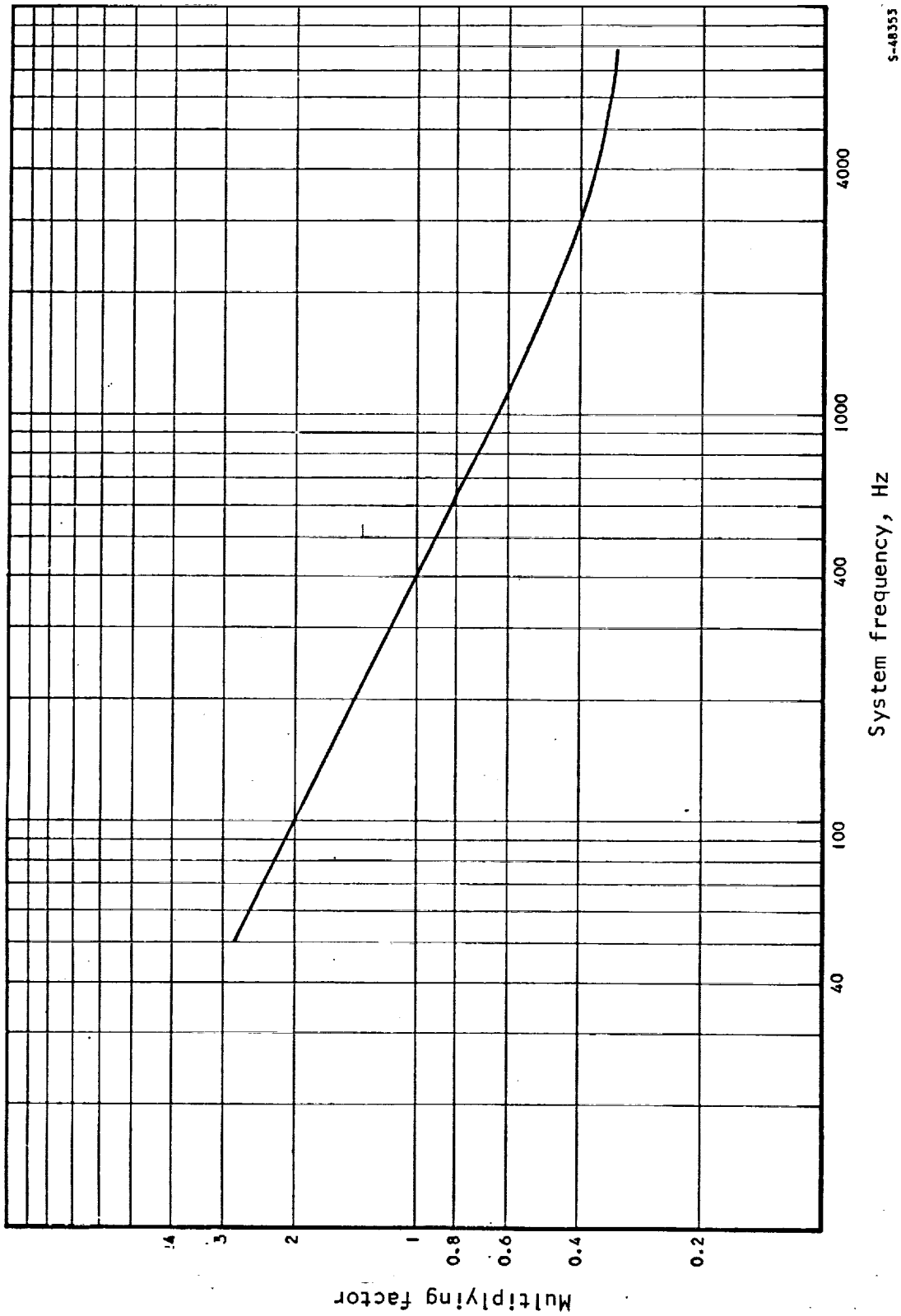


Figure 106. Power Conditioning Equipment

Application: To determine the weight of a particular system the following information is required:

(1) System rating (kva)

(2) Conversion process (ac-to-dc, dc-to-ac, combinations, etc.)

(3) System frequency (of each separate process)

With these parameters, the weight per unit power at 400 Hz can be determined from fig. 105. This is multiplied by the system rating to obtain system weight at 400 Hz. The actual system weight is determined by multiplying the 400-Hz weight by the appropriate frequency factor obtained from fig. 106.

Example 1.--Determine the weight of a 40-kva dc-link frequency converter with 60 Hz input and 50-Hz isolated output.

a.	ac-to-dc; 60 Hz; 40 kva (3 lb/kva) (40 kva) (2.3_{fm})	= 125 kg (276 lb)
b.	dc-to-ac; 50 Hz; 40 kva (3.7 lb/kva) (40 kva) (2.45_{fm})	= 164 kg (362 lb)
c.	Total system weight	= 289 kg (638 lb)

Example 2.--Determine the weight of a 15 kva dc-link frequency converter with 400 Hz input and 60 Hz output. No internal transformation required.

a.	ac-to-dc; 400 Hz; 15 kva (3.8 lb/kva) (15 kva) (1.0_{fm})	= 26 kg (57 lb)
b.	dc-to-ac; 60 Hz; 15 kva (2.9 lb/kva) (15 kva) (2.3_{fm})	= 45 kg (100 lb)
c.	Total system weight	= 71 kg (157 lb)

Weight apportionment:

(1) Capacitors: Except for semiconductors, ac capacitors are the lightest components per kva. In the voltage range from 140 to 330 Vac and the current range from 0.5 to 5 amps per microfarad, the weight of a capacitor is 0.045 to 0.09 kg/kva (0.1 to 0.2 lb/kva).

The specific weight of capacitors per kva is independent of kva value. However, the value of kg/kva increases rapidly as the voltage decreases below 100 Vac, as the frequency decreases below 300 Hz, or as the current decreases below 0.3 amp per microfarad.

Dc electrolytic capacitors can be evaluated on the basis of kg/kva using the dc rating for voltage and the allowable rms ripple current for amperes. Minimum weight per kva occurs at voltage ratings above 100 V. The power factor of a good electrolytic capacitor is about 5 percent and its maximum operating temperature is between 358 and 398°K (85° and 125°C). Therefore, to achieve minimum weight per kva it is essential to provide good cooling to these components. Under these conditions a value of 0.4 to 0.6 kg/kva (0.9 to 1.3 lb/kVA) is achievable (corresponds to about 0.007 amp/mf). The volume would be 32 to 65 cu cm/kva (2 to 4 cu in./kva).

(2) Logic, control, and instrumentation circuits: With discrete components, the weight of these circuits is less than 0.14 kg/kva (0.3 lb/kva) of output. Using integrated circuits, the weight is less than 0.045 kg/kva (0.1 lb/kva) of output. The combined weight of current and potential transformers is 1 to 1.5 kg (2 to 3 lb) per phase.

(3) Packaging structure and wiring: In well-designed packages, the weight of structural parts is about 0.2 times the total weight of the electrical components for converters with ratings of 10 kw and larger. The weight of the wiring is between 2 and 10 percent of the total electrical component weight, assuming conventional insulated copper wire. It appears quite feasible to reduce this weight 40 percent by using insulated copperclad aluminum wiring.

Future weight improvement of conversion equipment.--The weight and size of the semiconductor converter has been decreasing every year with the normal evolution of technology. It is estimated that in 1985 the weight of the converters given in fig. 105 may be reduced approximately 35 to 40 percent.

An area of promising weight reduction is the solid-state EMI suppression technique mentioned earlier in this section. If the development of this technique is successful, the weight reduction of converters is expected to be as much as 50 percent by 1985.

Distribution Equipment

Aircraft cables.--There is a distinct trend with advanced aircraft towards smaller cables. In many modern aircraft, nearly half of the cable weight is contributed by cables of size 20 or smaller. The development of lightweight insulation material is important since the percentage of weight due to insulation in small cables is greater than that in larger ones. In many cases, wire size is determined by the mechanical strength requirements rather than by current density or voltage drop limitations. For these cases, weight reduction can be accomplished by using alloys with acceptable combination of electrical and mechanical properties. The copper alloys give the least sacrifice of conductivity whereas cadmium-chromium-copper alloy gives the best balance of mechanical properties and conductivity. The mechanical and electrical properties of alloys containing rare elements are very attractive. The high cost, however, limits their use to applications where weight savings are extremely important.

Aluminum alloy appear attractive because of their substantial weight savings. Some new alloys may permit the successful introduction of aluminum wire down to size 22. However, the termination problems which have been the major drawback for aluminum cables have yet to be overcome.

Kapton wire and cable insulation.--Several years ago, two types of Kapton polyimide films were developed by the DuPont Company and are now in commercial production. One, called Kapton polyimide film type H, is a condensation product of pyromellitic dianhydride and an aromatic diamine. The other, known as type HF, is an infusible product, a heat-sealable modification with one or both sides coated with Teflon FEP-fluorocarbon film. With superior electrical, mechanical, and thermal properties, these insulation materials offer distinct advantages in wire and cable applications.

Strong and tough, these Kapton films are capable of retaining good electrical properties at very high temperatures. The heat-sealable type HF film has increased resistance to water vapor permeation and chemical attack.

Table 55 compares typical properties of Kapton films, Mylar polyester film, and Teflon FEP-fluorocarbon film.

The Kapton films are available as tapes in width of 3/16 in. and up in 1/16 in. increments. These tapes are normally applied as a spiral wrapping with a 50 percent overlap. Depending on the requirement, single or multi-ply tapes can be used; either unidirectional or cross-lapped constructions are possible. After proper processing, the following properties of the wrapped wire are noted:

(1) Weight and space comparison: Table 56 shows the weight and space comparison of 600-volt aerospace wires using different insulations. Obviously, substantial savings in weight and space are afforded by using wires insulated with Kapton polyimide film.

(2) Dielectric strength: The Kapton polyimide films have very high dielectric strength. At 298°K (25°C) the dielectric strengths of Type HF and Type H films are approximately 0.16 and 0.28 V/cm (4.5 and 7 kV/mil), respectively.

(3) Temperature capabilities: Wires insulated with Kapton films can sustain temperatures as high as 473°K and as low as 257°K without serious degradation in dielectric strength and flexibility.

(4) Toughness: Wires insulated with Kapton films have superior cutthrough resistance.

(5) Radiation resistance: Wires insulated with Kapton Type HF film exhibit good dielectric strength and flexibility after exposure to radiation.

(6) Nonflammability: Wires insulated with Kapton films will burn if exposed to sufficiently high temperature flames. However, Kapton is self-extinguishing upon removal of the heat source.

TABLE 55. --PROPERTIES OF KAPTON, MYLAR, TEFLON

Material / Property	Kapton Type HF	Kapton Type H	Mylar	Teflon
Thickness, mm	3.8×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}
Tensile strength, $MN/_m 2$ 298°K	110	172	159	20
Tensile strength, $MN/_m 2$ 373°K	69	117	48	14
Elongation, percent 298°K	75	70	100	300
Elongation, percent 373°K	75	90	High	175
Tear propagating, kg/m (Elmendorf)	790	310	590	4 920
Tear initial, kg/m (Graves)	3 100	2 000	3 500	1 100
Water vapor permeability, g/m^2 (24 hr)	12	84	28	6.2
Specific gravity	- -	1.42	1.39	2.15
Melt point (°K)	- -	none	523 - 538	533 - 553
Zero strength temp. (°K)	- -	1 088	521	528
Cut-through temp. (°K)	- -	708	463	- -
Flammability	- -	self-extinguishing	slow to self-extinguishing	self-extinguishing
Dielectric strength, kV/cm 298°K	180	280	280	200
Dielectric strength, kV/cm 473°K	160	240	200	- -
Dissipation factor, 1 Hz 298°K	0.0035	0.003	0.0047	0.0002
Dissipation factor, 1 Hz 473°K	- -	0.002	0.01	0.0002
Dielectric constant, 1 Hz 298°K	3.0	3.5	3.1	2.0
Dielectric constant, 1 Hz 473°K	- -	3.0	- -	1.95

TABLE 56. --SPACE AND WEIGHT COMPARISON OF 600-VOLT AEROSPACE WIRES

Insulation	AWG 22				TPSJ AWG 22			
	Weight (Nom.) g/m	OD (Nom.) (mm)	Weight Savings Percent	Space Savings Percent	Weight (Nom.) g/m	OD (Max.) (mm)	Weight Savings Percent	Space Savings Percent
Kapton Type HF (0.152 mm)	4.11	1.07	22.3	35.3	19.1	2.84	26.6	49.8
Teflon Type E (0.280 mm)	5.28	1.32	0	0	26.0	4.02	0	0
Teflon - M.L (0.178 mm)	4.45	1.12	15.8	28.7	22.95	3.38	11.8	29.1
IMP Type R (0.254 mm)	2.89	1.27	17.2	8.1	24.2	4.02	7.7	0

Recently, the McDonnell-Douglas Corporation developed the Micro Miniature Compact (MIMI) wiring system for the F-15 aircraft. The characteristic of the MIMI system as given in ref. 29 are:

(1) All conductors have unilay stranding.

(2) 24 and 26 AWG conductors use high strength alloy 135 (to replace 22 AWG conductors where electrically compatible).

(3) 0.128 mm (5 mil) insulation wall comprised of two 616-616 polyimide-fluorocarbon tapes with FEP Teflon topcoat.

(4) Miniature coaxial cable with a polyimide-fluorocarbon construction.

(5) Coaxial cable and one conductor shielded and jacketed cable with shields terminated in special coaxial pins.

(6) Subminiature, environmental seal connectors.

(7) Connector compression discs to alleviate side loading on grommet seal.

(8) Thermofit shrink boots for strain relief.

(9) Braided polyester protective harness jacket.

According to McDonnell-Douglas, the size and weight of MIMI hookup wire are only 24 percent and 39 percent of conventional wire respectively.

A comparison of the various cabling system used by MCAIR is given in table 57 below:

TABLE 57. --COMPARISON OF CABLING SYSTEM CHARACTERISTICS

		Conventional	Compact (used in F-4)	Minicomp	MIMI (used in F-15)
Hook up wire	Insulation Wall Thickness (in mm)	0.53	0.25	0.18	0.13
	Minimum AWG	22	22	26	26
Coaxial Cable	Cable O.D. (mm)	4.19	4.19	1.88	1.88
	Minimum AWG	26	26	28	28

High temperature wire enamels: For operating temperature around 480°K (400°F), organic enamels are usually used. There are several organic enamels with good thermal stability; each has its advantages and disadvantages. Polyimide wire enamels offer all the heat resistance required in magnet wire insulation for copper conductors. They exhibit good properties up to 480°K. However, polyimide enamels are expensive and the application process is rather difficult. Therefore, low-cost, easily applied enamels are eagerly sought, even if it is necessary to sacrifice some of their high-temperature advantages. Polyamide-imide enamels have excellent mechanical, chemical, and electrical properties, and show satisfactory stabilities up to 495°K. Their abrasion resistance is superior to the polyimide enamels. However, they are relatively expensive and require special coating techniques. Polyester-imide enamels that are compatible with existing enameling equipment are less expensive than polyimide and polyamide-imide enamels. Polyester-imide enamels have good heat resistance and outstanding windability. However, their operating temperature is relatively low (460°K). Further, because of their ester linkage content, these enamels can cause problems in sealed applications where moisture cannot escape.

Solventless varnish trickling: The use of solventless varnishes for impregnating random-wound stator and rotor coils has become popular for rotating machinery encapsulation. The major advantage of the varnish is increased reliability due to the elimination of voids. Therefore, mechanical and thermal properties are enhanced.

In the new trickling process, a stream of low-viscosity resin is poured onto the slowly rotating winding. The varnish penetrates into the winding uniformly and then sets up, encapsulating the winding. Compared with dip-dry processes, the trickling process is faster and can result in better uniformity and reduced masking. However, cure time of the resin, temperature of the winding, and rotation speed must be properly governed.

Continued improvement of the trickling process for applying solventless varnishes will result in their wider use in smaller machines. This technique enables the manufacture of better encapsulated windings at relatively low cost.

Feasibility of sodium conductors: The use of sodium as an electric conduct for power transmission might result in significant weight savings in the aircraft electrical power system. To evaluate the feasibility of this unconventional conductor, the following analysis comparing sodium with aluminum was performed.

In order that the sodium conductor and the aluminum conductor have the same performance, (i.e., same total resistance) for a given transmission distance, the ratio of the cross-sectional areas must be equal to the ratio of their resistivities. Thus

$$\frac{A_{Na}}{A_{Al}} = \frac{\rho_{Na}}{\rho_{Al}} = \frac{V_{Na}}{V_{Al}}$$

where A = cross-sectional area of the conductor

ρ = resistivity of conductor

V = total volume of the conductor

the subscripts Na and Al refer to sodium and aluminum respectively. The ratio of the total weight is, therefore

$$\frac{W_{Na}}{W_{Al}} = \frac{V_{Na}\ d_{Na}}{V_{Al}\ d_{Al}} = \frac{\rho_{Na}\ d_{Na}}{\rho_{Al}\ d_{Al}}$$

where d is the density of the conductor.

Based on an operating temperature of 328°K it is found that

$$\frac{W_{Na}}{W_{Al}} = \frac{2.125 \times 0.971}{1.263 \times 2.7} = 0.605$$

A weight reduction on the order of 39.5 percent can therefore be realized. It should be noted, however, that the sodium is an extremely active metal. It has a low melting point of 371°K and can cause fire hazard when in contact with moisture. Some means of containment therefore, must be utilized.

The diameter of the No. 00 aluminum wire is 9.27 mm while the equivalent sodium conductor has diameter of 12.0 mm. Assuming a stainless steel tube of 0.152 mm thickness is required for the sodium conductor, then the weight of the tube per unit length is

$$\pi \times 12.0 \times 0.152\ d_{st}$$

The weight of the sodium conductor per unit length is

$$\frac{\pi \times 12.0}{4} \times d_{NA}$$

therefore

$$\frac{W_{tube}}{W_{Na}} = \frac{0.609}{12.0} \times \frac{7.7}{0.971} = 0.402$$

The weight ratio of the sodium conductor (with the stainless steel tube) to the aluminum conductor is

$$(1 + 0.402) \times 0.605 = 0.848$$

Therefore, the weight savings has been reduced from 39.5 percent ot 15 percent.

Practically, the stainless steel tube of 0.152 mm thickness is probably too thin to satisfy the mechanical strength requirements. However, a 0.254 mm tube will increase the weight ratio to 1.01 and hence, the sodium conductor (include the stainless steel tube) is slightly heavier than the aluminum conductor.

Other materials, such as fluoroelastomers (Viton) and polytetrafluoroethylene (PTFE), might be suitable for confining the sodium conductor. These materials have much lower densities (about 2.0 g/cc) compared to stainless steel. They can also serve as part of the insulation material and offer flexibility. However, since the change of state of the sodium conductor (solid state to liquid state, or vice versa) must be considered, relatively high mechanical strength might be required. This must be accomplished by ensuring adequate reinforcement in the tubing. A practical construction of the cable using sodium as a conductor cannot be established without detailed analytical research and experimentation. Therefore, the weight savings, if any, cannot be determined.

The sodium conductor has many disadvantages:

(1) Because a tube is necessary to confine the sodium conductor, the conductor has poor flexibility (or none).

(2) The relatively large volume adds insulation weight to the wire.

(3) The high corrosivity can cause a fire hazard.

(4) Because of the nature of the conductor, special techniques are required in termination and installation.

(5) The change of state of the sodium conductor from solid to liquid, or vice versa, may result in discontinuity or degraded performance in current conduction.

It was found that the use of sodium as an electric conductor creates many new problems and may not offer substantial weight savings. It is not likely that the weight savings will justify the sacrifices in other areas.

Transformers and inductors.--Recent developments indicate that the use of aluminum foil for transformers in both commercial and aerospace applications has the following advantages over that of conventional copper wires.

(1) The resistivity of aluminum is higher than that of copper; however, because of its lighter weight, a better conductivity-to-weight ratio is observed.

(2) An aluminum strip conductor is easier to wind than copper wire, thus reducing manufacturing costs.

(3) With proper insulation, better space factors can be realized, creating a tightly wound unit.

(4) Strip wound coils permit greater overloads because of better cooling capabilities; hot spots usually experienced in copper wire coils can be eliminated.

(5) The turn-to-turn voltage stress is relatively lower.

Aluminum foil has two major disadvantages: lower volume conductivity in comparison to copper, and lead connection problems. It is determined that the aluminum-strip winding is about 50 percent the weight of an equivalent copper winding. (The resistivity-density product of aluminum is half that of copper.) The volume of the unit, however, is larger. Lead connections can be made properly but the connection cost is higher. In addition, multiple connections are frequently required.

The most difficult problem is aerospace application is turn-to-turn insulation where the foil thickness is small. Mylar has been used for turn-to-turn insulation but the temperature capability is limited to 423°K. The anodic coating, although satisfactory in regard to operating temperature and insulation thickness, is an expensive process for coating thin gages and often results in crazing of the coating, burred foil edges due to poor flexibility. Coating ML enamel on one side of anodized aluminum is another approach being used. The performance is satisfactory but the cost is relatively high.

Recent developments of polyimide and polyamide insulating materials have brought new hope to the turn-to-turn insulation problems. Kapton and Nomex (both of which have superior electrical, mechanical, and thermal properties) are available in thicknesses of 0.00127 and 0.058 mm, respectively. Since Kapton and Nomex are high temperature materials, it is expected that by using them for interleaving insulation for the aluminum foil construction, good high temperature, lighter weight, and lower cost transformers can be realized for aerospace applications.

Switchgears.--Many types of circuit breakers can be considered for aircraft application:

(1) Conventional circuit breaker (either magnetic or thermal type)

(2) Conventional circuit breaker with added solenoid for remote control

(3) Conventional mechanical relay with electronic circuits for sensing and control-hybrid remote power controller

(4) Vacuum switch

(5) Self-healing fuse

(6) Solid state switch

Power transistor

Thyristor

Gate-turn-off thyristor

Tables 58, 59 and 60 give data on some of the circuit breakers listed above. These tables are taken from ref. 8.

Gate-turn-off thyristors and self-healing switches are very promising for future aircraft applications. Both of these are still under development. Self-healing switches are discussed in refs. 30, 31 and 32. A good survey type article on gate-turn-off thyristor is ref. 33.

Avionic Loads

Power requirement.--The amount of power required for the electronic and avionic loads on large transport aircraft typically ranges from 5kW to 10kW. Positive and negative low Vdc levels are mainly used by the loads. Although ac power is input to most of the equipment, it is converted into dc power internally. Only a small portion of the ac is used to supply synchros and resolvers. Ac power is also used as required by cooling fans inside some of the electronic packages. Power of the ac type is used instead of dc because of transformation and isolation conveniences. In addition, the ac system exhibits a better regulation characteristic than the airplane dc system. The dc is derived from the ac system via unregulated transformer-rectifier (TR) units. There are many voltage and regulation levels of dc power used in aircraft electronic devices. A survey (ref. 15) revealed that the following voltage levels are most frequently in use: +5 Vdc, ±12 Vdc, ±15 Vdc, and +28 Vdc. The survey results are given in table 61. Among these voltage levels, +5 Vdc finds wide adoption in digital circuits and ±12 Vdc and ±15 Vdc are commonly used for analog circuits.

For all electronic equipment insensitive to momentary power interruptions, the power input circuit generally consists of a three-phase transformer with multi-taps on the secondary. The lower secondary voltages are then individually rectified, filtered, and regulated to provide the various low-level, dual-polarity dc voltages.

TABLE 58.--CIRCUIT BREAKER DATA

	Weight kg	V Fwd Volts	P Drive Watts	P Off Watts	λ 10^6 Hrs	Cost $
Remote controlled circuit breaker						
Dc	0.226 + 0.068P	0.4	0	0	20	50 + 10P
Ac - 1Ø	0.226 + 0.0454P	0.4	0	0	20	50 + 10P
Ac - 3Ø	0.226 + 0.091P	0.4	0	0	20	50 + 10P
Solid state						
Dc - (trans)	0.0454 + 0.0454P	0.5	1 + I	.2 + .1P	1	400
Ac - (scr)	0.0454 + 0.0454P	1.5	1.5	.3 + .05P	1	300
Hybrid						
Dc	0.454 + 0.068P	0.3	1.0	.5	10	300
Ac - 1Ø	0.454 + 0.0454	0.3	1.0	.5	10	300
Ac - 3Ø	0.454 + 0.091P	0.3	1.0	.5	10	300

P = Load power in kw

I = Load current in amp

TABLE 59.--TYPICAL LOW POWER CB CHARACTERISTICS[1]

Frequency	RCCB[2]		Solid State			Hybrid	
	Dc	400 Hz	Dc	Dc	400 Hz	Dc	400 Hz
Load voltage V_L - Vrms	30	115	30	80	115	30	115
Load current I_L - amp	5	1.3	5	2	2	5	1.3
Interrupt capacity - amp	500	500	2000	12[3]	400	500	500
V_{fwd} (at rated I_L)	0.4	0.8	0.5	0.25	1.5	0.2	0.2
P_{ON} - watts	2.0	1.5	4.5	6.3	3.3	2.5	2.0
P_{OFF} - watts	0	0	0.16	0.2	0.3	0.5	0.5
Turn off time - msec	30		<6	5	1.25	10	
Trip current accuracy	±30%		±5%	±5%	±5%	±5%	
Failure rate per 10^6 cycles	10-100		1	1	1	10	
Availability	Production		Devel	Devel	Devel	Prototypes	
Vendor	Airpax		Various	Wstgh.	Wstgh.	Bendix	
Reference	Vendor data		MIL-P-81653A	NAS8-26425	MIL-P-81653A	Vendor data	
Weight - kg	0.317		0.068	0.068	0.0566	0.150	
Estimated production cost	$60		$200	$200	$200	$200	

(1) Load power ≤150 watts.

(2) Mechanical breaker with solenoid actuator.

(3) Transient overload rating.

TABLE 60.--TYPICAL HIGH POWER CB CHARACTERISTICS[1]

	RCCB		Solid State			Hybrid		Type AGB[6]	
Frequency	Dc	400 Hz	Dc[3]	Dc[4]	400 Hz	Dc	400 Hz/	Dc	60 Hz
Rated load voltage V_L - volts	30	115	120	120	115	120	230	250	500
Rated load current I_L - amp	80	25	20	20	35	20	12	100	100
Interrupt capacity - amp	500	1500	4000	4000	400	120	1000	10^4	1.5×10^4
Max V_{fwd} - volts	0.5	0.4	1.5	0.7	1.5	0.2	0.2	<0.5	
P_{ON} - watts	40	10	40	30	62	5	3.5	<50	
P_{OFF} - watts	0	0	0.6	1	0.7	0.5	0.5	0	0
Turn OFF time[2] - msec	30		0.15	1	1.25	10	10	30-50	
Trip current accuracy	±30%		±5%	±5%	±5%	±5%	±5%	±30%	
Failures per 10^6 cycles	20-100		1	1	1	10	10	50-100	
Availability	Spec order		Concept	Concept	Devel	Devel	Devel	Prod.	
Vendor	Various		-	-	Wstgh.	Bendix[5]		QPL	
Reference	TRW est		TRW est	TRW est	MIL-P-81653A	Vendor data		Vendor cat.	
Weight - kg	0.36		3.6	0.23	0.14	0.91	0.91	4.5	
Estimated production cost	$80		$500	$400	$300	$300	$300	$70	

(1) Load power approximately 2.5kw.
(2) Resistive load.
(3) SCR switch.
(4) Transistor type.
(5) With Hartman R102 relay.
(6) Manual reset, sea level operation.

TABLE 61.--THE MORE COMMONLY USED VOLTAGE LEVELS IN AIRCRAFT AVIONICS SYSTEMS

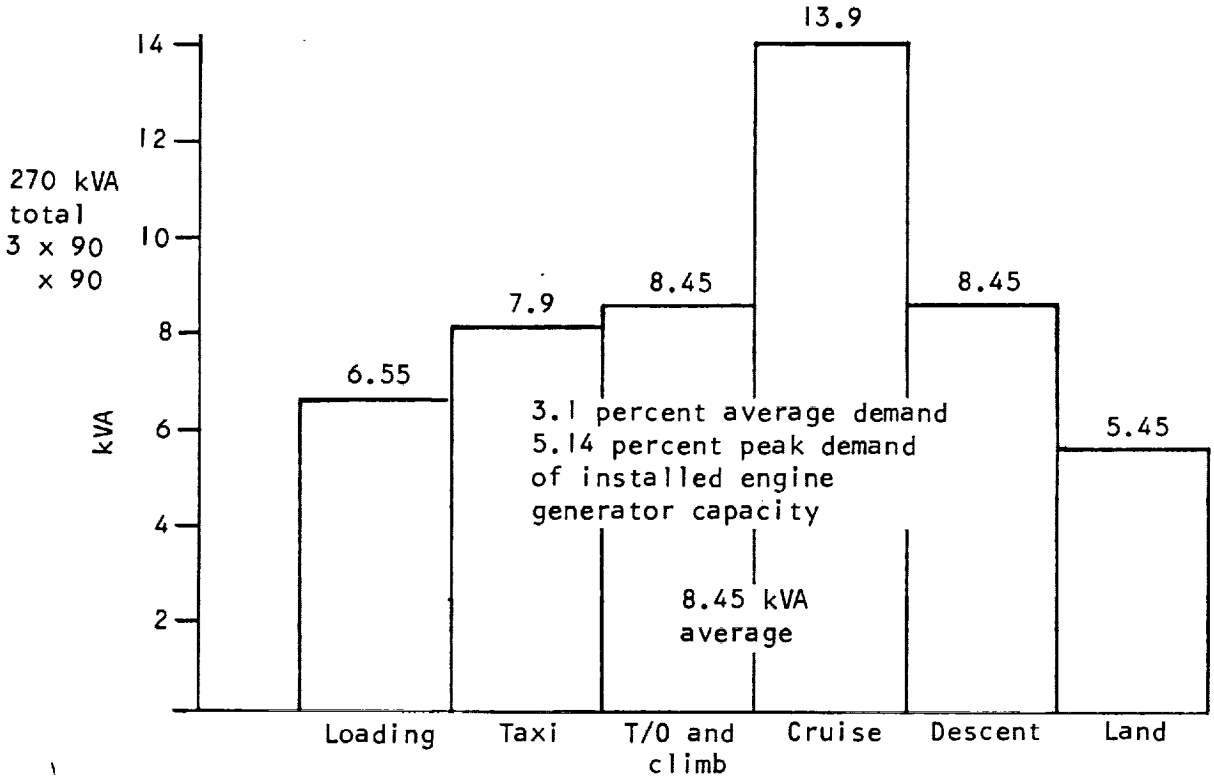
Dc voltage levels	Number of using systems	Percent regulation (average)
+5	11	±2.70
+12	6	±1.33
+15	6	±4.50
+28	6	±4.00
-12	5	±2.25
-15	5	±1.50
+30	3	±1.70
-5	3	±1.33
-6	3	±2.00
-10	3	±2.25
+20	3	±5.00
-20	2	-
-28	2	-

The trend in future aircraft is the increase in types and utilization of avionics equipment. Table 62 provides a comparison between the avionics typically provided in a large contemporary aircraft and the avionics recommended for future transports.

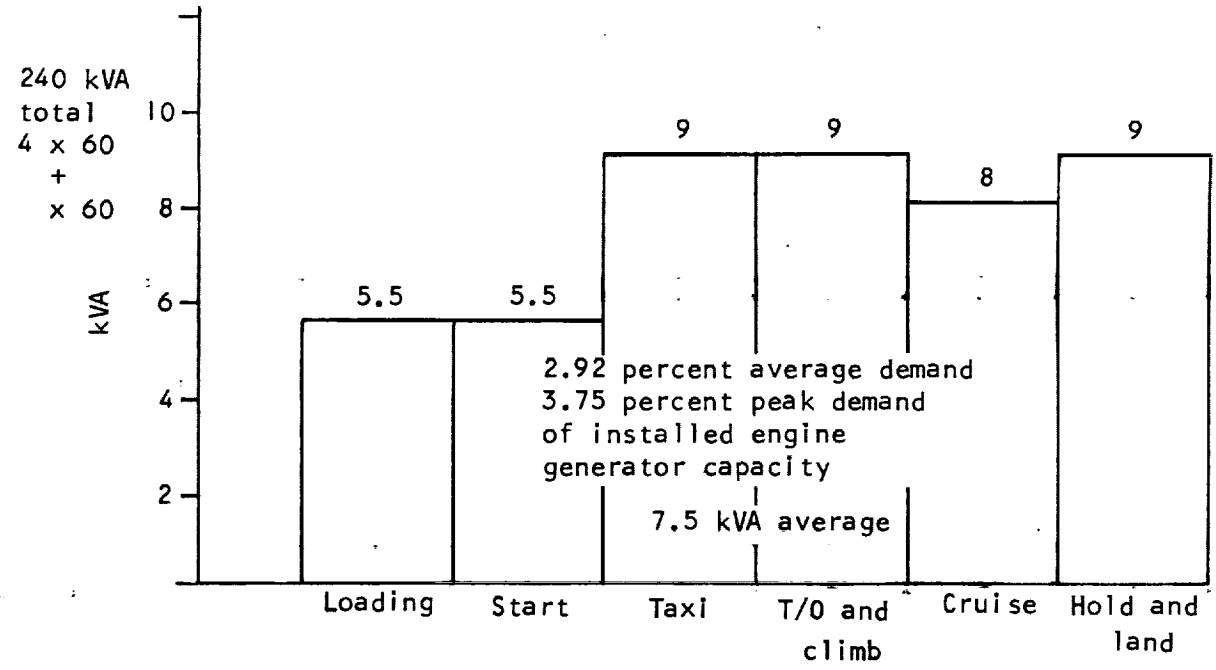
The avionics system load profiles for the last generation large transports L-1011 and 747 are shown in fig. 107. As can be seen, the power demand for these avionic loads represents approximately 6 to 8 percent of power consumption of all connected loads.

TABLE 62.--AVIONICS EQUIPMENT IN LARGE TRANSPORT AIRCRAFT

System Component	Number used on	
	Contemporary Aircraft	Future aircraft
Inertial navigation system	2	3
Automatic flight control	1	3
Electronic command and stability system	--	4
Communications HF receiver	2	2
Communications VHF receiver	2	3
Automatic direction finder	2	2
VHF satellite communication system	--	2
VHF omni range	2	2 to 3
Weather radar	1	2
Air data system	1	3
Aircraft integrated data system	--	1
Distance measuring system	2	2 to 3
ATC transport	2	2
Radio altimeter	2	2
Marker beacon	1	1
Collision avoidance system	--	1
Gear air turbulence detection	1	1
Selective calling system	1	2
Public address system	1	1



(a) Load profile for Lockheed L-1011



(b) Load profile for Boeing 747

Figure 107. Avionics System Load Profile

Power conditioning equipment for avionics loads.--The weight of power conditioning equipment for avionics loads can be obtained from fig. 105. Typical efficiency values of these power conditioning units is shown in fig. 108 which is taken from ref. 8.

One of the critical requirements of the power conditioning modules is the need for low output impedance (0.01 ohm from dc to 100 Hz). While this is easier to obtain with larger power supply units, it is partly offset due to the longer distribution lines which become necessary. Extra output impedance added by a twisted pair of various length of cable are depicted in fig. 109 which was taken from ref. 34. These curves do not include dc resistance.

In order to furnish precise regulated power by the conditioning module, whether it be several levels of dc or high frequency ac, a regulator must be employed. The low 5V supply required by many digital IC's suggests the use of switching regulators for these loads since power dissipation using series pass regulators would be extremely severe. The penalties of using switching regulators are a greater number of components and the extra problems encountered because such circuits result in a substantial increase in output impedance at higher frequencies and increased RFI generation. The output impedances of pass and switching type regulators are shown in fig. 110 which is taken from ref. 34. Efficiencies for switching regulators are on the order of 85 to 90 percent whereas pass regulators can offer only about 40 to 50 percent.

Because weight is important, a fairly high chopping frequency for the regulator should be chosen (50 KHz to 150 KHz) to keep down the size and weight of the filter choke and capacitors. For these higher chopping frequency, the transistors cut off frequency should be at least 15 to 30 MHz. The highest current transistors in this category are specified for saturation voltage and life at about 60 to 75 amp. The regulator should always precede the inverter because inverters are easiest to design and give best performance with a fixed input. Paralleling of power transistors at high switching frequencies will become cumbersome, and is not easily achievable. Also dc current balance requires power wasting emitter resistors. Therefore separate regulators and inverters will probably be preferred. The multiple regulator approach is practical because the outputs of the two switching regulators can be combined in such a manner that the load current is shared equally within a fraction of one percent.

Effects of New Materials

Trends in future development of electrical system components favor compact, lightweight design, higher operating voltage and temperature, and more stringent safety and reliability requirements. Improved design techniques and configurations will partially satisfy these requirements. Major advances, however, depend largely on improved properties of various materials. For electrical system components, these materials include:

(1) Soft magnetic materials

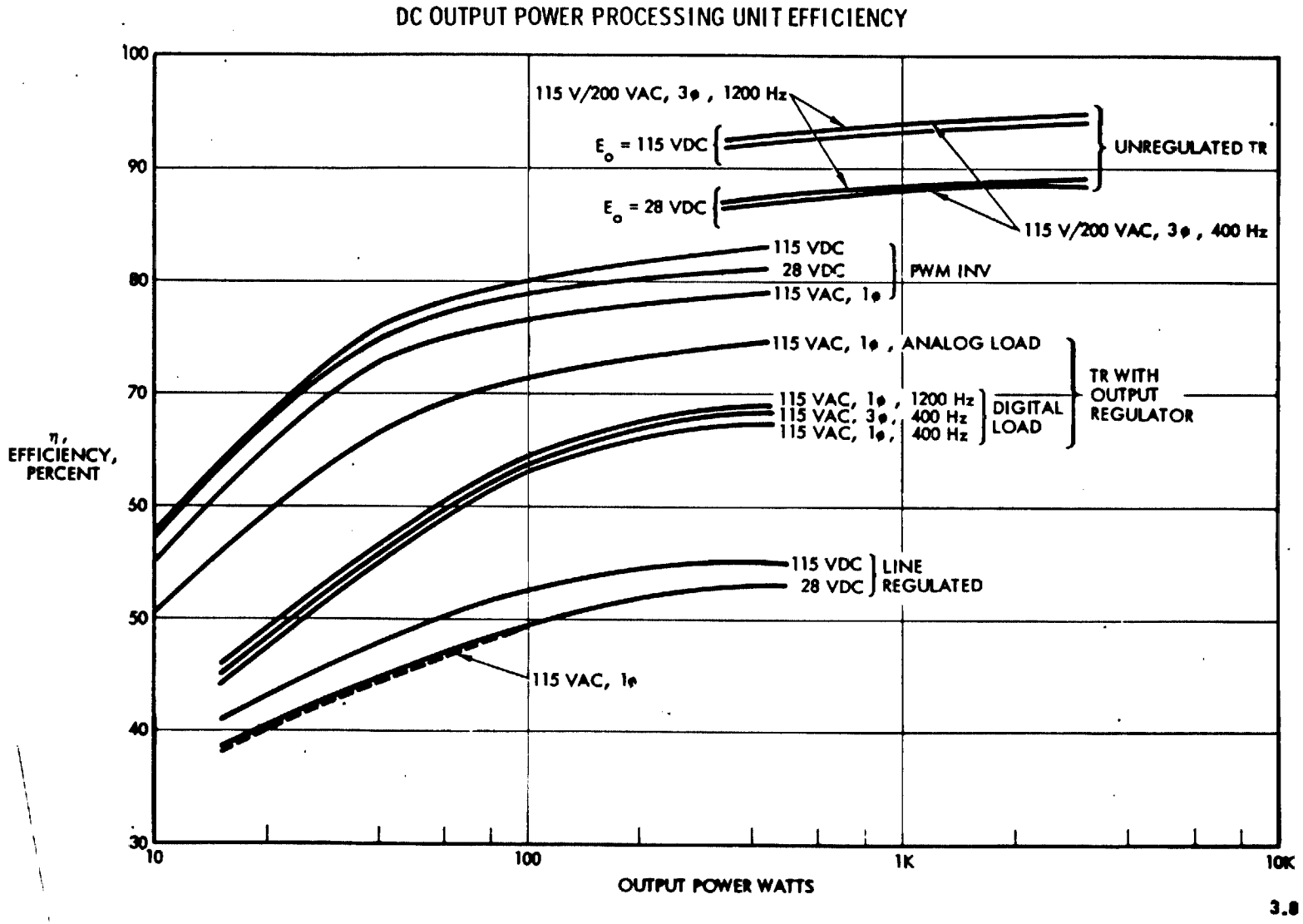


Figure 108. DC Output Power Processing Unit Efficiency

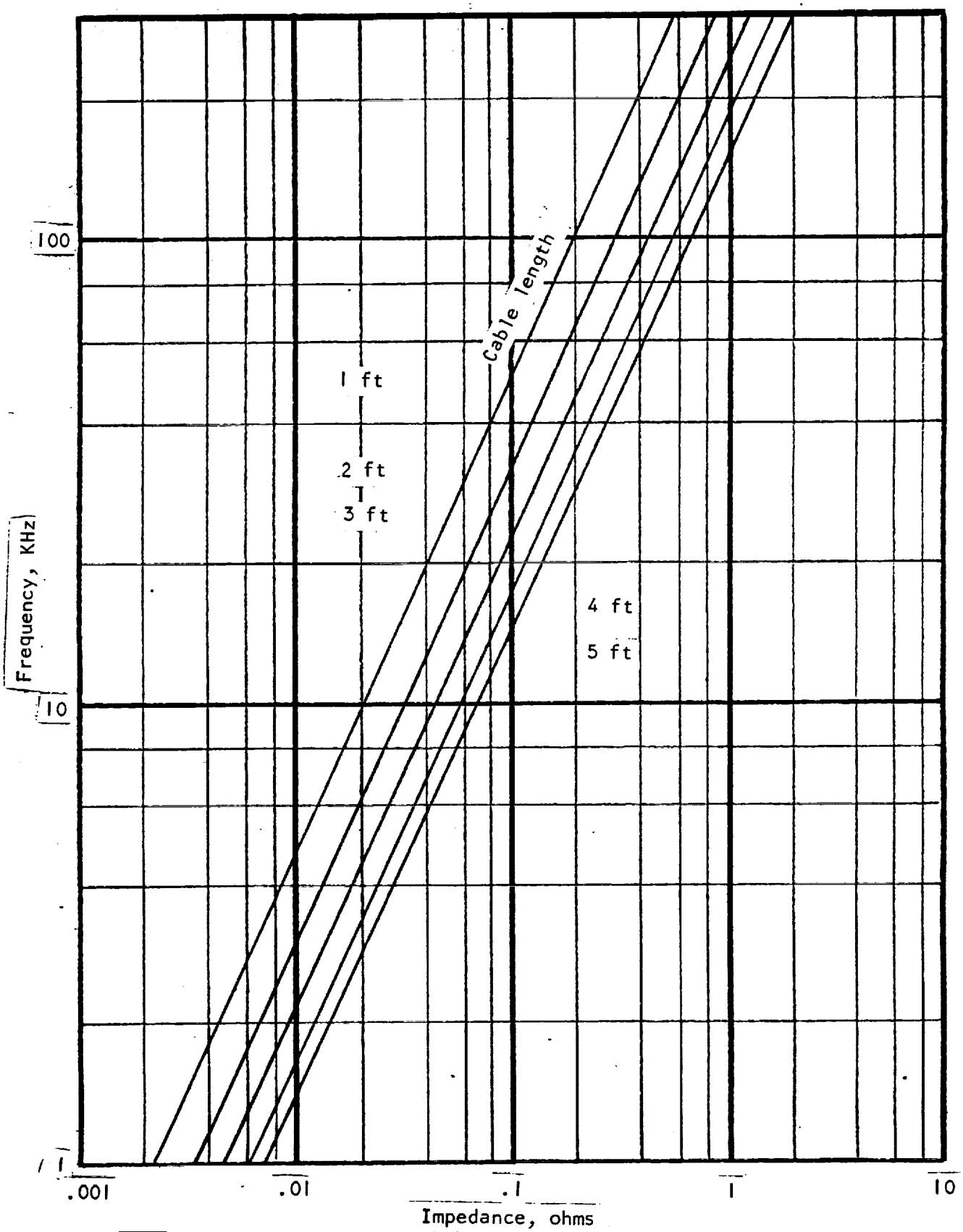


Figure 109. Output Impedance vs Freqeuncy of Twisted Lead Cable

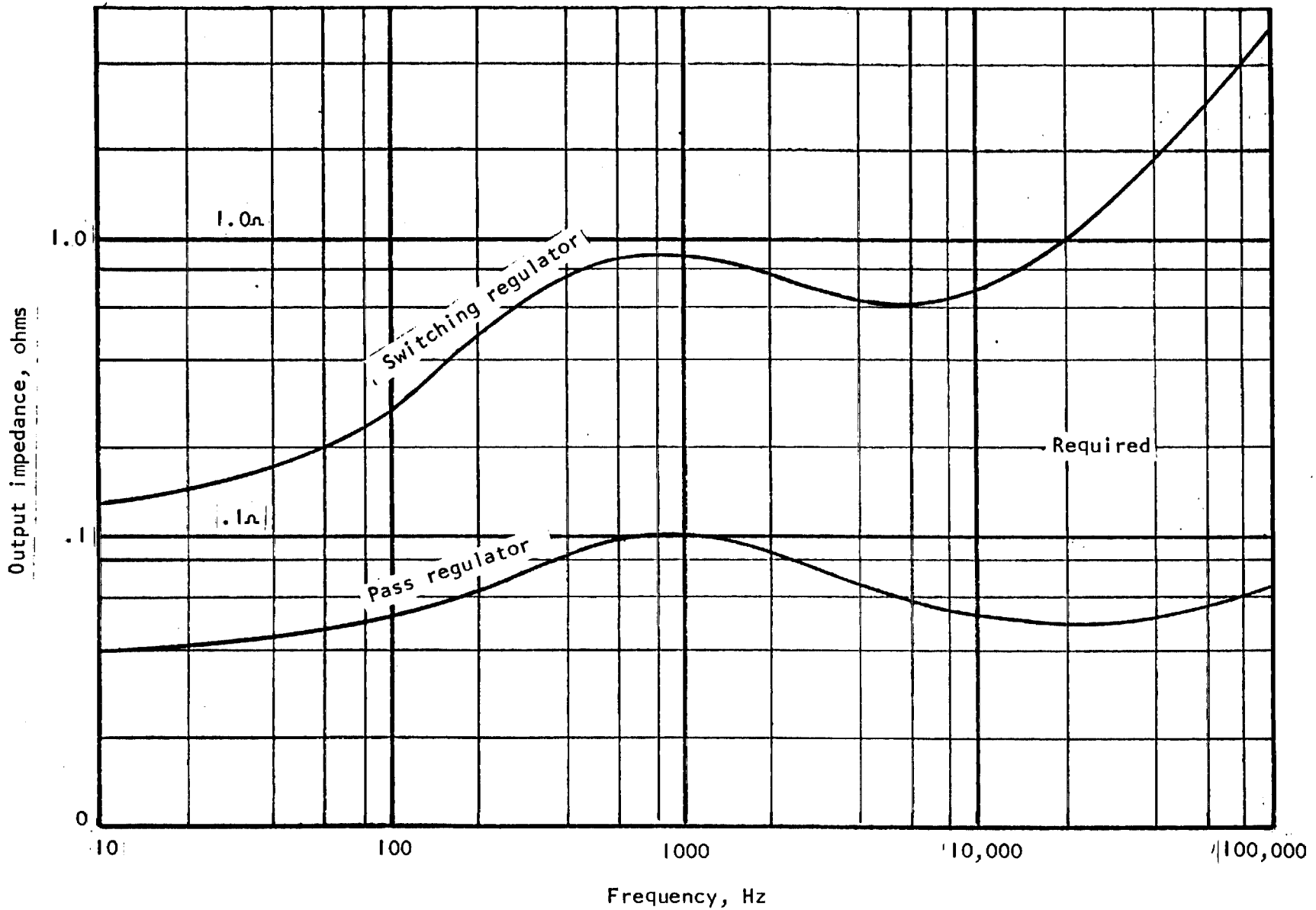


Figure 110. Output Impedance of Switching and Pass Regulators

(2) Permanent magnet materials

(3) Insulation materials

(4) Conductor materials

(5) Structural materials

Soft magnetic materials.--In an aircraft electrical power system, a great variety of electrical and electronic devices employ soft magnetic materials. These include: generators, motors, transformers, reactors, magnetic amplifiers, transductors, and solenoids. All these devices use soft magnetic materials to carry flux in the magnetic circuit. Therefore, the general requirement for magnetic materials is high-saturation induction, which must be achievable with low exciting fields and low coercive force. To be suitable for high temperature operation, the magnetic materials used in rotating parts must have high-strength capabilities, especially in resisting creep. Good magnetic properties are desirable but are secondary in this application. The magnetic amplifier requires a material that has a square hysteresis loop. Since the magnetic amplifier is a static device and is not subject to mechanical stress, the mechanical capabilities are less important. Some devices, such as the solenoid, have only dc flux in the magnetic circuit. Magnetic losses of the material, therefore, are not important.

There are four major groups of soft magnetic materials:

(1) Silicon-iron alloys

(2) Nickel-iron alloys

(3) Cobalt-iron alloys

(4) Soft ferrites and other materials

The silicon-iron alloys are the most widely used magnetic materials for power applications. These alloys, which contain about 0.5 to 4.5 percent of silicon, are commonly termed electrical steel or silicon steel. By cold rolling and annealing, preferred orientations in silicon steels can be obtained. During the last few years, silicon steel with a "cube-on-face" orientation has been developed. Its magnetic properties closely approximate those of a single crystal. Therefore, grain-oriented silicon steel has almost reached the limit of possible development.

New nickel-iron alloys usually have low core losses within the range of flux density at which they are used. Due to their relatively low saturation flux densities, nickel-iron alloys are not used for power frequency applications, they are used principally for electronics and communications transformers. The important nickel-iron alloys include various types of Permalloy, Hipernik, Nicalloy, and Supermalloy.

Electric motors sometimes operate at temperatures of 570 to 870°K (300 to 600°C). In such applications, silicon and nickel alloys cannot be used because their Curie temperatures are low and the magnetic properties of these alloys deteriorate rapidly at elevated temperature. Cobalt-iron alloys have very high Curie temperatures and therefore, are the only magnetic materials suitable for high-temperature service. New cobalt-iron alloys include Hiperco 27, Hiperco 35, 2V permendur, and supermendur. With the exception of supermendur, these alloys have relatively low permeability and high hysteresis loss. However, their saturation induction is very high (about 2.4 Wb/m^2), which is a preferred property for miniaturization.

The new materials have not been widely used due to their relatively high cost and unfamiliarity to the designers. Several new materials are briefly discussed herein.

Cubex steel: Cubex is a new magnetic material that is available from Westinghouse Electric Corporation. This material, which offers weight reduction potential in aircraft generators at nominal cost increase, is a doubly grain-oriented, high quality, 3.25 percent silicon steel. The so-called "cube-on-face" orientation of the material offers almost equally high permeability and low loss in both the rolling and transverse directions. The material responds to annealing in a magnetic field, which imparts further improved magnetic properties to the alloy. The stress-relief-annealed condition is usually used in rotating machinery, while the field-annealed condition is reserved for high-performance transformers and magnetic amplifiers. By comparing the properties of Cubex with those of conventional silicon steel, it is found that for a given magnetizing field, the flux density of Cubex is approximately 10 percent higher. This means that by using Cubex, less material is required to carry a certain amount of flux in the magnetic circuit of the device, resulting in reduced volume and weight. It should be noted that the weight reduction is not limited to electromagnetic weight. Due to the reduction in volume, additional weight savings in the frame, shaft, and housing can be realized.

Since the magnetic properties of Cubex are approaching those of a single crystal, it is believed that the oriented silicon steel has almost reached the limit of possible development. The in-plant processing required for Cubex is similar to that required for conventional silicon steel. The properties of Cubex are shown in table 63.

Hiperco 27 alloy: Hiperco 27 alloy, which contains 27 percent cobalt, is a high saturation, cobalt-iron alloy developed by Westinghouse Electric Corporation. Although Westinghouse has been manufacturing this material for almost 20 years, it was not until about 1960 that the problems in rolling the material into thin sheets were solved. When Hiperco 27 was initially applied, the brittle laminations introduced many manufacturing difficulties. Now, after several years of production experience, no manufacturing problems are encountered with this alloy.

Hiperco 27, because of high saturation induction and high Curie temperature, is suitable for use in aircraft generators and motors, where reduced size and weight are relatively important. Using Hiperco 27 instead of silicon steel

TABLE 63.--PROPERTIES OF SOFT MAGNETIC MATERIALS

Physical properties	Silicon steel (M-15)	Cubex	Hiperco 27	Hiperco 50		Supermendur
				Optimum magnetic properties	High mechanical strength	
Curie temperature (^{o}K)	1 030	1 030	1 200	1 210	1 210	1 210
Solidus temperature (^{o}K)	--	1 740	1 770	1 750	1 750	1 750
Specific heat (J/kgK)	--	457	427	410	410	410
Density (gm/cu cm)	7.64	7.64	7.45	8.17	8.17	8.17
Thermal conductivity (W/mK)	15	29.5	54.7	29.5	29.5	29.5
Coefficient of thermal expansion x 10^{-6} (cm./cm.-^{o}K)	3.6	3.93	3.12	2.93	2.93	2.93
Commonly used thickness (mm)	0.356	0.305	0.254	0.254	0.254	0.101
Saturation induction (Wb/m^2)	1.97	2.0	2.35	2.35	2.41	2.41
Core loss for above thickness at 400 Hz, 1.5 Wb/m^2 (W/kg)	40	33	79	42	240	12
Electrical resistivity x 10^{-6} (ohm-cm)	53	45	19	35	35	46
Ultimate tensile strength (MN/m^2)	510	280	520	550	1 380	--
Yield strength (MN/m^2)	410	230	280	330	1 050	--
Elongation (percent)	13	14	12	4	10	--
Modulus of elasticity x 10^{6} (kN/m^2)	191	152	216	199	199	239
Rockwell hardness	80B	--	85B	97B	--	--
Relative material cost (1966 est.)	1.0	3.5	20.0	35.0	35.0	--

in a machine can reduce electromagnetic weight up to 15 percent. In turn, reduced machine size makes possible a corresponding decrease in frame and shaft weights.

Being a single-phase material, Hiperco 27 follows the patterns expected at high temperatures. As temperature increases, the magnetization curve rises more rapidly at lower fields and then flattens out and saturates at lower inductions. The residual induction, coercive force, and core loss decrease as temperature increases. Hiperco 27 has good stability at elevated temperature. The 1000-hr stability test at 810°K (540°C) revealed that dc and ac magnetic properties after the stability test showed no significant change from those measured before testing. The tensile strength of Hiperco 27 follows the general pattern for solid solution alloys. At elevated temperature, there is a considerable change in slope, and the decrease in strength with increasing temperature becomes more rapid.

During manufacturing, Hiperco 27 alloy requires special handling in all stages. Additional annealing and melting are sometimes required to develop the required magnetic and mechanical properties. The normal heat treatment for material used in electric generators involves heating at 1070 to 1115°K (800° to 845°C) in pure dry hydrogen, followed by rapid cooling in the same atmosphere. The complicated processing, together with the high cost of cobalt, makes the cost of Hiperco 27 relatively high. This has been a major drawback to the extensive application of this material. Properties of Hiperco 27 are shown in table 63.

Hiperco 50 alloy: Hiperco 50 is a Westinghouse trade name for a high-saturation, cobalt-iron alloy similar to Hiperco 27. The composition of Hiperco 50 is: 2-percent vanadium, 49-percent iron, and 49-percent cobalt. The vanadium is added to improve the mechanical properties.

The magnetic and mechanical properties of Hiperco 50 vary according to the annealing process; the primary annealing parameter that affects the properties of Hiperco 50 is temperature. At present, two different annealing processes are used for different requirements: No. 1 for laminations with optimum magnetic properties, No. 2 for high mechanical capabilities.

The No. 1 annealing process produces material suitable for stators and rotors that are not highly stressed. For rotors operating at higher speed, process No. 2 should be used, although a little sacrifice in magnetic properties is unavoidable.

The saturation induction of Hiperco 50 alloy is higher than that of Hiperco 27. Therefore, more weight savings can be expected with Hiperco 50. Replacing conventional silicon steel in a machine with Hiperco 50 can reduce electromagnetic weight up to 24 percent. In addition, the frame and shaft weight can be reduced because of the smaller size. Table 7-14 summarizes the properties of Hiperco 50 alloy.

Supermendur: Supermendur is a highly purified vanadium-iron-cobalt alloy originally developed by Bell Telephone Research Laboratories. This alloy, consisting of 2-percent vanadium, 49-percent iron, and 49-percent cobalt, has exceptional physical and magnetic properties, which are achieved by close control and extreme care in the melting, rolling, and annealing processes. The alloy is compounded by melting the three elements in a controlled atmosphere furnace, using dry and wet hydrogen. Raw materials must be carefully selected and the melting process precisely controlled to minimize the concentration of impurities in the alloy. Unlike other soft magnetic materials, supermendur cannot be purified by heat treatment at high temperatures after all processing is completed. This limitation is due to a phase change in the alloy system that limits the temperature of the heat treatment to a relatively low level. Purification, therefore, must be completed during the melting procedure.

The ingot from casting is usually hot rolled to approximately 2.3 mm strip, then quenced in ice water from 1180°K to obtain the required malleability for cold rolling to the desired thickness. Without intermediate anneals, the 2.3 mm strip can be cold rolled to 0.0076 mm sheet that has good ductility.

The temperature, time duration, and cooling rate of the heat treatment are not critical if they are fairly closely controlled. The heat treating temperature should be below the alpha-gamma transformation temperature (approximately 1120°K); otherwise the magnetic properties are degraded by the phase change. The time duration at temperature should be sufficient--a cooling rate of 1°K per minute is suitable. Very fast or very slow cooling produces a material with inferior magnetic properties. To obtain superior magnetic properties and rectangularity of the hysteresis loop, the final heat treatment should be performed in a magnetic field of 80 A/m or greater.

Supermendur marked by its rectangular hysteresis loop, high saturation induction, low coercive force, and core loss, is suitable for use in transformers, inductors, magnetic amplifiers, and saturable reactors. When supermendur is used to replace the silicon steel, for the same size core, approximately 30 percent more power output can be realized in transformers. For magnetic amplifiers a size reduction of approximately 20 percent can be expected for the same output. The characteristics of the hysteresis loop of supermendur indicate that the gain of the magamp can be increased 80 percent by changing from grain-oriented silicon steel to supermendur. In some cases, this increase in gain may even reduce the number of stages from two to one.

Recently, supermendur has been successfully fabricated into cut "C" core that are easily used in transformer and inductor manufacture. Properties of supermendur are listed in table 63.

Weight reduction in induction motors: To evaluate a new material for rotating machinery application, it is desirable to determine the weight reduction afforded by replacing the conventional material with the new material. However, the weight of the machine depends on many design parameters and requirements. The design goal may be maximum efficiency, minimum weight, or satisfaction of a given performance requirement. To accomplish a certain design goal, tradeoffs are employed. For example, the weight of the machine can be traded

for efficiency--or the cost can be traded for weight--and vice versa. Also, the machine design includes many nonlinear processes because many parameters are related to the geometry of the machine, and thermal and magnetic problems are inherently nonlinear. It is therefore almost impossible to determine the weight of the machine without detailed analysis and design work based on a specific machine. The objective here, however, is to estimate the weight reduction for typical machines by using simplified relations. Since Hiperco 50 is known as the best magnetic material for rotating machinery application, the evaluation of weight reduction by change from silicon steel to Hiperco 50 in a cage-rotor induction motor is performed. When motor speed is relatively high, depending on the rotor diameter, Hiperco 50 may not be applicable for rotor material because of limited strength. In such a situation (Example 3) only the stator material can be replaced. When motor speed is low and mechanical strength is not a problem (Example 4) both rotor and stator cores are replaced by Hiperco 50 to achieve maximum weight reduction. Fig.III illustrates the motor dimensions. The derivation and results of weight reductions for both situations are as follows: (Note: The calculations in this subsection were initially done in English units. However, since the results are all dimensionless quantities, intermediate equations were left unchanged.)

Example 3 --The following assumptions prevail:

(1) The comparison is made with cage-rotor induction motors using silicon steel in the stator and operating at 400 Hz.

(2) The rotor requires high strength material; therefore, Hiperco 50 can only be used to replace the stator core material.

(3) Flux density of the Hiperco 50 unit is 1.4 times that of the silicon steel unit.

(4) The difference in total loss between the two units is relatively small and can be ignored.

(5) Stacking factors and fill factors for the two units are the same.

(6) The rotor configuration remains unchanged.

Since the stack length cannot be shortened, the width of the tooth and the yoke must be reduced while the slot area remains unchanged. Therefore we have (see fig. III).

$$\frac{1}{2}(d_1 + d_2)H = \frac{1}{2}(d_1' + d_2')H' \qquad (12)$$

The primed variables refer to the Hiperco 50 unit.

$$d_2 = d_1 + \frac{2\pi H}{S} \qquad (13)$$

$$d_2' = d_1' + \frac{2\pi H'}{S}$$

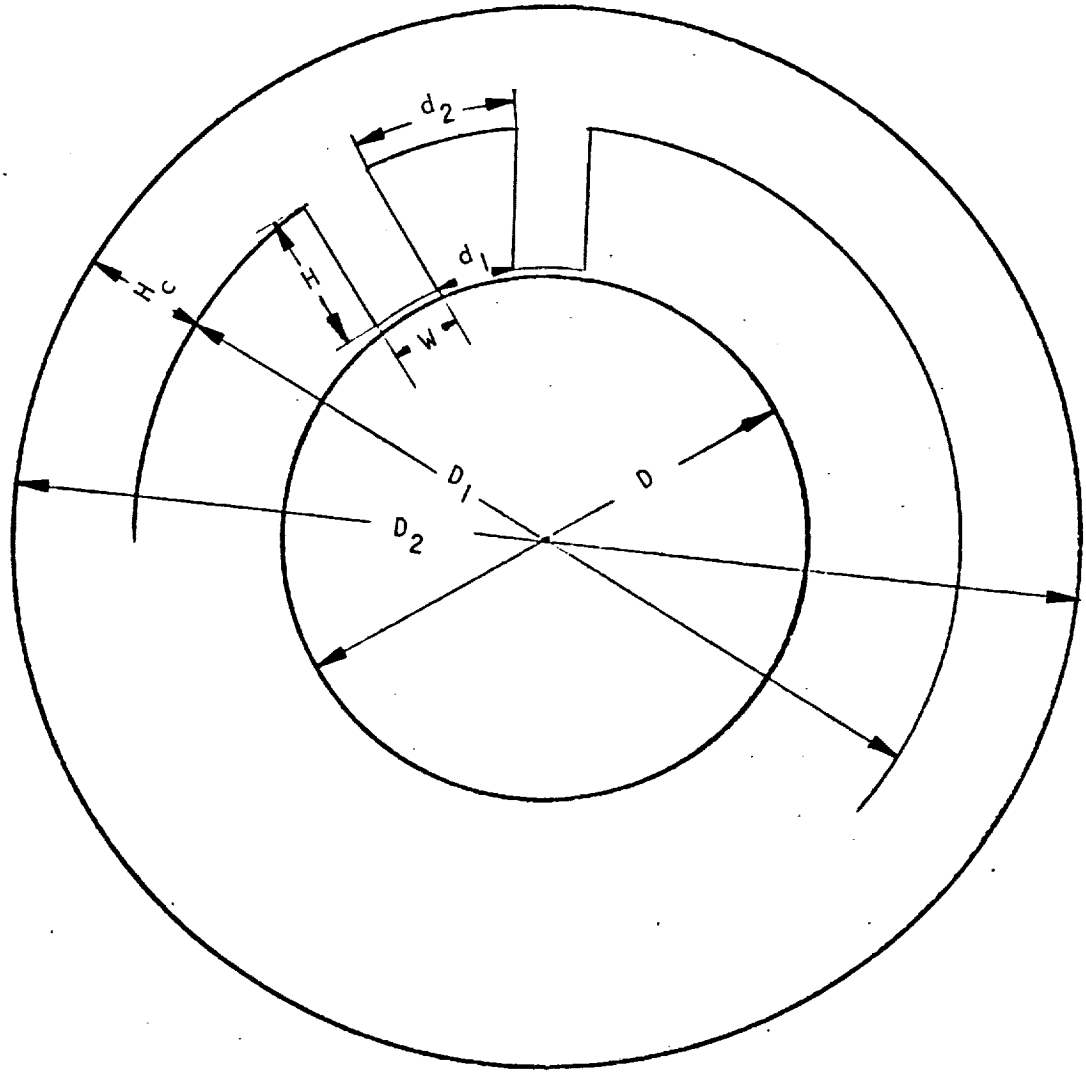


Figure III. Illustration of Motor Dimensions

where S is the number of stator slots.

Substituting eq. (13) into eq. (12) yields

$$H' = \frac{-d_1' + d_1'^2 + 4\frac{\pi}{S} H \quad d_1 + \frac{\pi H}{S}}{2\frac{\pi}{S}} \tag{14}$$

In a typical design the tooth width is approximately 45 percent of the slot pitch, or

$$W = 0.82\ d_1 \tag{15}$$

Since $d_1 + W = \frac{\pi D}{S}$, eliminating W,

$$d_1 = 1.73\ \frac{D}{S} \tag{16}$$

The rotor diameter remains the same, therefore

$$W + d_1 = W' + d_1' \tag{17}$$

Since the stack length is unchanged, the tooth width is inversely proportional to the flux density

$$W' = \frac{W}{1.4} \tag{18}$$

Substituting eqs. (18), (15), and (16) into eq. (17) yields

$$d_1' = 2.14\ \frac{D}{S} \tag{19}$$

The yoke width H_c can be expressed as

$$H_c = \frac{Bg\ D}{Bc\ P\ S_f}$$

where

Bg = air gap flux density

Bc = flux density in yoke

P = number of poles

S_f = stacking factor

For a typical design

$$Bg = 0.62 \text{ Wb/m}^2$$
$$Bc = 1.55 \text{ Wb/m}^2$$
$$S_f = 0.93$$

then

$$H_c = 0.43 \frac{D}{P} \tag{20}$$

Design experience indicates that the ratio (R) of stator outside diameter to rotor diameter is approximately a function of the quantity of poles. Values for different quantities of poles are as follows:

Pole	2	4	6	8
$R = \frac{D_2}{D}$	2	1.7	1.5	1.33

From this relation it is seen that for a certain number of poles, the tooth length H can be expressed as a function of D, hence

$$H = K D \tag{21}$$

where $$K = \frac{R-1}{2} - \frac{0.43}{P}$$

Substituting eqs. (16), (19), and (21) into eq. (14) yields

$$H' = \frac{-2.14 + 4.57 + 4\pi \ 1.73 \ K + \pi K^2}{2\pi} D = K'D \tag{22}$$

$$H'_c = \frac{H_c}{1.4} \tag{23}$$

The rotor weight

$$W_R = \frac{\pi D^2}{4} \alpha \ S_R \ \rho_R \ D$$

where

α = L/D

L = stack length

S_R = stacking factor of rotor lamination

ρ_R = density of rotor material

The core weight

$$W_c = \frac{\pi D^2}{4} \alpha \quad 0.9 \quad f_1 - 1 \quad + f_2^2 - f_1^2 \quad S_c \rho_c D$$

$$f_1 = D_1 \quad D$$

$$f_2 = D_2 \quad D$$

S_c and ρ_c are the stacking factor and the density of the stator laminations, respectively.

The copper weight

$$W_{cu} = \frac{\pi D^2}{4} \quad f_1^2 - 0.9 \; f_1 - 0.1 \quad S_{cu} \rho_{cu} \quad B \; (1 + K) + \alpha \quad D$$

S_{cu} and ρ_{cu} are the fill factor and the density of copper, respectively, and B is a function of the quantity of poles. Typical values are as follows:

Pole	2	4	6	8
B	1.31	0.736	0.598	0.57

Similarly, rotor, core, and copper weight for the Hiperco 50 unit can be obtained

$$W_R' = \frac{\pi D^2}{4} \alpha \; S_R \rho_R D$$

$$W_c' = \frac{\pi D^2}{4} \alpha \quad 0.644 \quad f_1' - 1 \quad + f_2'^2 - f_1'^2 \quad S_c \rho_c' D$$

$$W_{cu}' = \frac{\pi D^2}{4} \quad f_1'^2 - 0.644 \; f_1' - 0.356 \quad S_{cu} \rho_{cu} \quad B \quad 1 + K' \quad + \alpha \quad D$$

where ρ_c' = the density of Hiperco 50

and $f_1' = D_1' \quad D = D + 2H'$

$$f_2' = D_2' \quad D = D + 2 \quad H' + H_c'$$

The weight ratio of the silicon steel unit to the Hiperco 50 unit is therefore

$$\frac{W'}{W} = \frac{W_R' + W_c' + W_{cu}'}{W_R + W_c + W_{cu}}$$

By using proper stacking factors and densities, curves relating the weight ratio and the number of poles are plotted in fig. 112 for several α values.

Example 4. --The following assumptions prevail:

(1) The comparison is made with cage-rotor induction motors using silicon steel in the stator and rotor, and operating at 400 Hz.

(2) The rotor is not subject to high mechanical stress and therefore both stator and rotor core materials can be replaced by Hiperco 50 alloy.

(3) Flux density of the Hiperco 50 unit is 1.4 times that of the silicon steel unit.

(4) The difference in total loss between the two units is relatively small and can be ignored.

(5) Stacking factors and fill factors for the two units are the same.

(6) Rotor and stator diameters remain unchanged; only the stack length is varied.

From these assumptions, it is obvious that the rotor, stator core, and copper weights of the silicon steel unit can be expressed as follows:

$$W_R = \frac{\pi D^2}{4} \alpha S_R \rho_R D$$

$$W_c = \frac{\pi D^2}{4} \alpha \left[0.9 \left(f_1 - 1 \right) + f_2^2 - f_1^2 \right] S_c \rho_c D$$

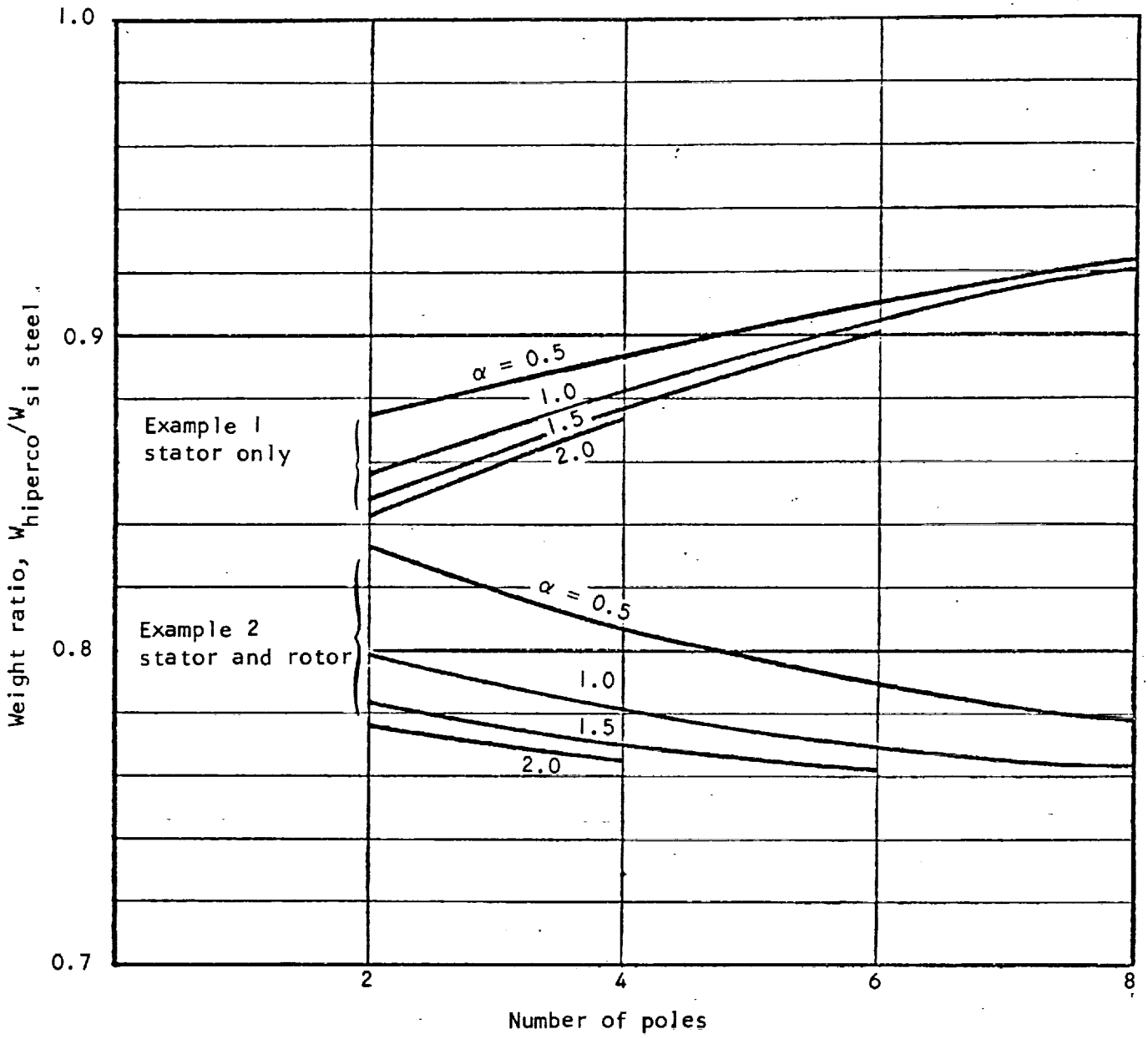
$$W_{cu} = \frac{\pi D^2}{4} \left[f_1^2 - 0.9 f_1 - 0.1 \right] S_{cu} \rho_{cu} B \left(1 + K + \alpha \right) D$$

Since only the stack length is shortened by the factor of 1.4 (flux density ratio), the parameters in the Hiperco 50 unit that differ from those of the silicon steel unit are the density and the ratio of stack length to rotor diameter.

$$L' = \frac{L}{1.4} = \frac{\alpha D}{1.4} = \alpha' D$$

where

$$\alpha = \frac{\alpha}{1.4}$$



Example 1 = only stator core is replaced by Hiperco 50

Example 2 = both stator and rotor cores are replaced by Hiperco 50

α = stack length/gap diameter

Figure 112. Estimated Weight Reduction in Induction Motor when Magnetic Material is Changed from Silicon Steel to Hiperco 50

By substituting α' for α and using a different density value in the weight equations, the rotor, stator core, and copper weights of the Hiperco 50 unit can be obtained.

Curves relating the weight ratio and the quantity of poles for this case are plotted in fig. 112 for several α values.

Weight reduction in transformers: Another major component of the aircraft electrical power system is the transformer, for which oriented silicon steels have been used as core material.

The invention of supermendur permits considerable weight savings to be realized by changing the silicon steel to supermendur, which has superior magnetic properties and is known as the best material for this application. As with rotating machinery design, transformer design depends on many parameters and requirements. Unless extensive design work is performed for a specific design, no accurate values of weight reduction can be obtained. However, by using simplified relations based on reasonable assumptions, approximated results of weight savings can be derived. The following assumptions prevail:

(1) The comparison is made with a transformer using oriented silicon steel and operating at 400 Hz.

(2) The silicon steel operates at 1.7 Wb/m^2 (110 kilolines/sq in.)

(3) The supermendur operates at 2.2 Wb/m^2 (140 kilolines/sq in.)

(4) Total losses of the two units are the same.

(5) Stacking factors and fill factors for the two units are the same.

(6) The geometric proportionality is retained and the linear dimensions of the two units differ by a factor of x.

For a given voltage and frequency, the rating of the transformer is proportional to the current density, the copper area, the flux density, and the cross-sectional area of the core. Hence

$$P_o \propto J_{cu} A_{cu} B_m A_{fe}$$

If flux density is increased by a factor of 1.272 (the ratio of 140 to 110) and the linear dimension is changed by a factor of x, the factors for the various parameters are

$$A_{cu} = x^2$$

$$A_{Fe} = x^2$$

$$B_m = 1.272$$

To retain the same rating, the current density J_{cu} must be changed by a factor of $\frac{1}{1.272\ x^4}$.

The copper loss and the core loss are

$$W_{cu} = J_{cu}^2\ \rho_{cu}\ V_{cu}$$

$$W_{Fe} = W\ V_{Fe} \times d$$

where

ρ_{cu} = resistivity of copper

V_{cu} = total volume of copper

W = core loss in watts/kg

V_{Fe} = total volume of core

d = density of core material

Therefore the factors for W_{cu} and W_{Fe} are

$$W_{cu} = \left(\frac{1}{1.272\ x^4}\right)^2 \cdot x^3 = 0.617\ x^{-5}$$

$$W_{Fe} = \frac{12}{12.2}\ x^3 \cdot \frac{8.15}{7.65} = 1.05\ x^3$$

Assuming the ratio of copper loss to core loss for the silicon steel unit is β, in order to keep the total losses of the two units the same, the following expression must be satisfied:

$$1.05\ x^3 + 0.617\beta\ x^{-5} = 1 + \beta$$

or

$$1.05\ x^8 - (1 + \beta)\ x^5 + 0.617\beta = 0$$

For a fixed β, the value of x can be solved from the equation. The weight ratio of the supermendur unit to the silicon steel unit is, therefore

$$\frac{W'}{W} = \frac{8.15}{7.65}\ x^3 = 1.065x^3$$

Fig. 113 shows the weight ratio as a function of β.

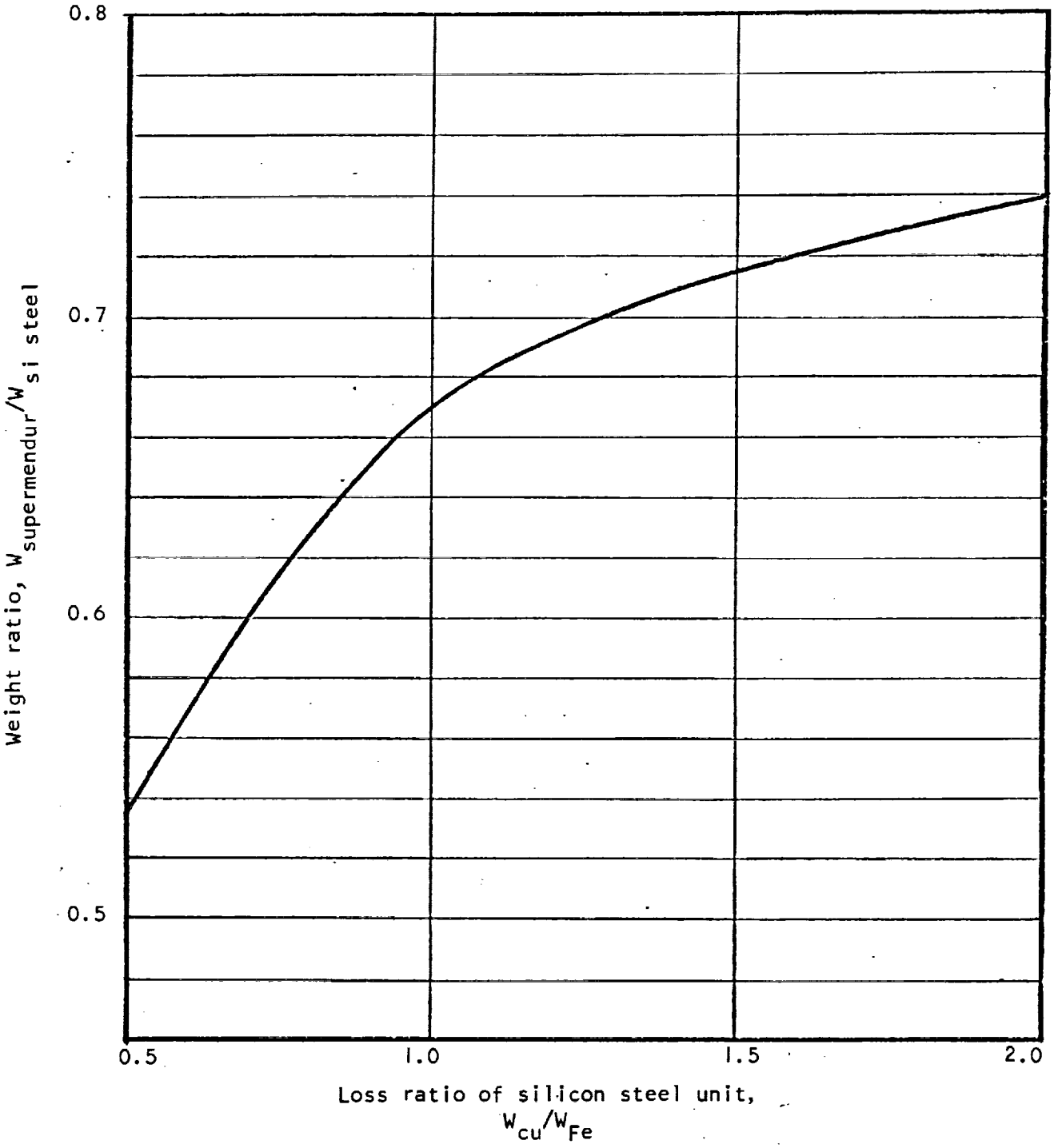


Figure 113. Weight Reduction in Transformer by Changing the Core Material from Oriented Silicon Steel to Supermendur

Permanent magnet materials.--Permanent magnet materials are ferromagnetic materials that retain an appreciable amount of residual magnetism after a sufficiently high magnetic field was applied and then removed. In a present day aircraft, hundreds of permanent magnets are used, either with air gaps or with magnetic poles alone. The devices include small motors and generators, microwave tubes, relays, telephone receivers, and loudspeakers.

The mechanism of permanent magnetism has four classifications, as follows:

(1) Anisotropy due to strain

(2) Anisotropy due to directional order

(3) Magnetocrystalline anisotropy

(4) Shape anisotropy

In the first category, only Vicalloy (an iron-cobalt-vanadium alloy) is in substantial production. Its magnetic properties are improved by cold rolling.

The second category, anisotropy due to directional order, is caused by the arrangement of different kinds of atoms in the lattice. No commercial material of this type, however, is produced in quantity.

In the third category, barium and strontium ferrites are the most useful materials in general application. Recent theory indicates that PtCo alloy also belongs in this category because its magnetic properties are due to the cubic crystal anisotropy. Intermetallic compounds with uniaxial anisotropy include materials such as MnBi, MnAlGe, and MnAl. Recently, a new material in this category has been developed: $SmCo_5$. This rare earth-metallic compound is known as the strongest permanent magnetic material ever manufactured.

The last category includes the whole family of cobalt-nickel-aluminum-iron alloys, known as Alnico, and the new elongated single-domain particle (ESD) magnets. Improved Alnico permanent magnet materials have increased the coercive force to over 2000 oersteds for Alnico 8C, and the maximum energy product to approximately 10 MG-Oe for columax 9. These values indicate that the progress with Alnico alloys is approaching the limit of possible development, unless a technological breakthrough can be accomplished.

Platinum cobalt: Platinum cobalt magnetic material, an alloy of approximately 77 percent platinum and 23 percent cobalt, has been acknowledged as the strongest permanent magnetic material in commercial production. It has a coercive force of 0.4 ma/m (5 000 oersteds) and a maximum energy product of 0.074 WbA/m^3 (9.5 MG-Oe). PtCo has been used in brushless dc motors, microwave tubes, and other devices where (1) extreme resistance to demagnetizing fields, (2) small volume, or (3) exceptionally good corrosion resistance is an important consideration. However, because of the high cost of platinum cobalt magnets, scientists have been seeking a substitute for many years. In early 1969, Raytheon Company announced the development of a new permanent magnet material: samarium cobalt.

Samarium cobalt: This new material, made from cobalt and the rare earth element samarium, has a coercive force of 0.7 MA/m (9000 oersteds) and a maximum energy product as high as 0.16 WbA/m^3 (20 MG-Oe). Samples manufactured by Raytheon test between 0.13 and 0.16 WbA/m^3 (16 and 20 MG-Oe). This shows that the new material is four times as strong as most Alnicos, and twice as strong as platinum cobalt.

Samarium is not a rare and precious element. Its present cost is about $160 per pound; this will drop substantially when large amounts of the material are used. It is estimated that samarium cobalt will be cheaper than platinum cobalt by a factor of 20 per unit weight. In addition, since the density of the new material is almost one-half that of platinum cobalt, in a microwave tube samarium cobalt can substitute for four times its weight in platinum cobalt. This means that if samarium cobalt is used to replace platinum cobalt in a microwave tube, a magnet cost reduction factor of 80 can be realized.

The new material also shows good high temperature stability, with a Curie temperature of 1120°K (850°C), which exceeds that of platinum cobalt. Experiments indicate that SmCo magnets perform well in microwave tubes at 540°K (265°C); at this temperature, PtCo degrades 50 percent.

According to Raytheon, the processing involved for SmCo magnets is generally similar to that used in preparing ferrite ceramic magnets. Several steps are unique and proprietary. The new material will be commercially available in the near future. It will not only lead to cheaper, smaller, and lighter microwave tubes operating at higher power and frequency, but is also expected to be used in gyros, motors, generators, and other devices. The permanent-magnet, brushless dc motors have been using platinum cobalt magnets. When this material is replaced by samarium cobalt, considerable reduction in volume and weight will result. Table 64 compares the properties of platinum cobalt with samarium cobalt. Fig. 114 shows the demagnetization characteristics of several important permanent magnet materials.

Brushless dc motors: The discovery of samarium cobalt will not only lead to smaller, lighter, and cheaper motors, but also will raise the capacity of permanent magnet machines to higher levels, for which the use of platinum cobalt seemed unrealistic. The following is a design study using samarium cobalt for permanent-magnet, brushless dc machines.

Because of the lack of tensile strength in samarium cobalt, it is necessary to support the rotor magnets. AiResearch analysis of support of permanent magnets in radial-gap rotor assemblies indicates that a high-strength steel sleeve shrunk over the fabricated rotor is the best means of support. The study was therefore based on the use of the nonmagnetic Inconel 718 sleeve, which must occupy some of the allowable airgap region. It was determined by brief iteration that a rotor support using 30 percent of the gap would approximate an optimum condition.

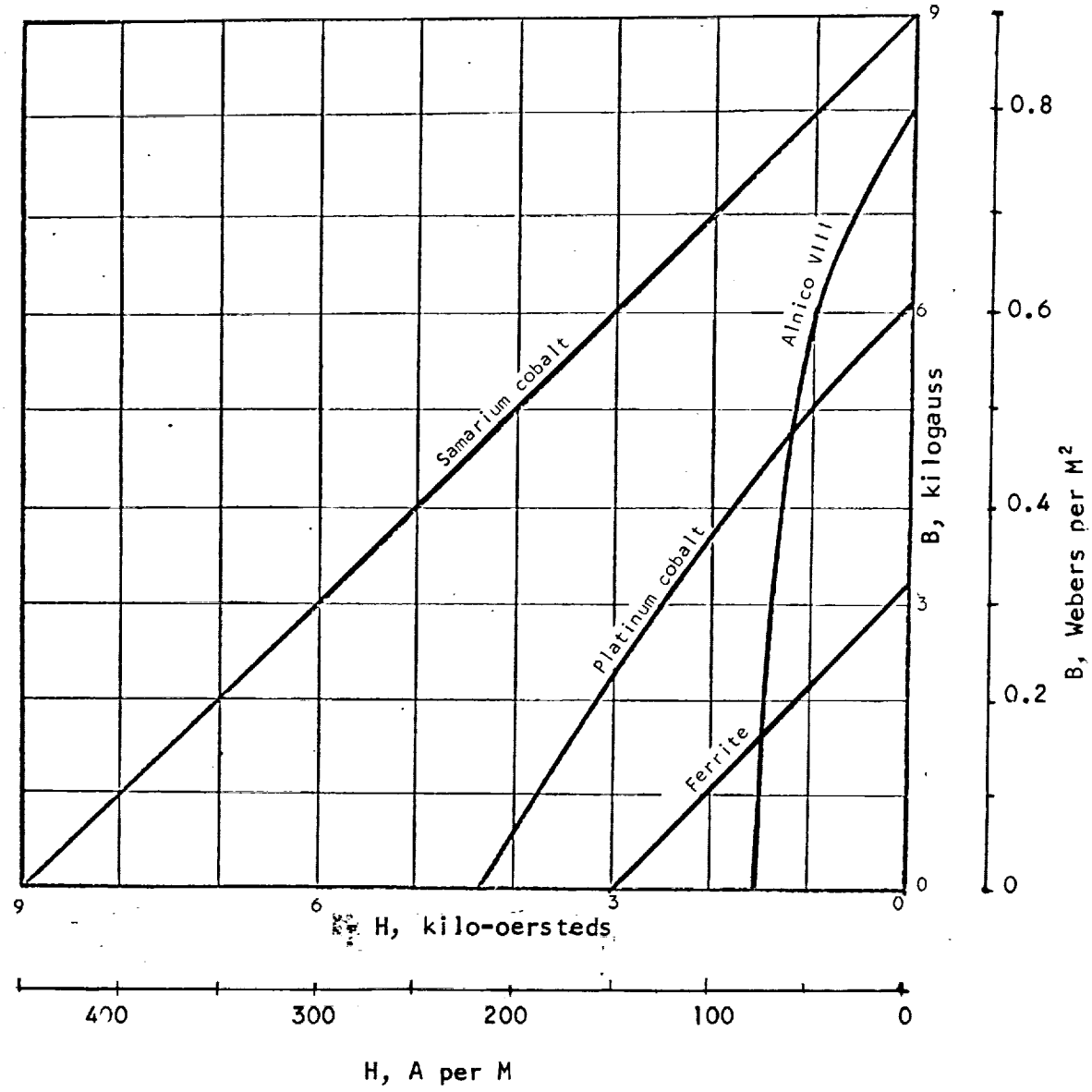


Figure 114. Demagnetization Characteristics of Magnet Materials

TABLE 64.--PROPERTIES OF SAMARIUM COBALT AND PLATINUM COBALT

Properties	Platinum cobalt	Samarium cobalt
Specific gravity, gm/cm^3	15.5	8
Electrical resistivity, ohm-cm	28×10^{-6}	5×10^{-4}
Coercive force, MA/m	0.34	0.72
Intrinsic coercive force, MA/m	0.42	2.0
Residual induction, Wb/m^2	0.645	0.900
Energy product (maximum), Wb A/m^3	0.075	0.16
Curie temperature, ^0K	750-770	1120
Tensile strength, MN/m^2	~6 900	550
Compressive strength, MN/m^2	--	>>690
Flexural strength, MN/m^2	--	825

From this configuration, various relations were established. By using a suitable sizing process based on a certain design, machine performance as a function of output power and speed was determined. The following are the basic assumptions for the analysis:

(1) All motors are designed as four-pole machines, representing a practical compromise between fabrication and electromagnetic considerations.

(2) The maximum allowable tip speed of the rotor is 195 M/sec. (640 fps). This is determined from the loading of the support ring based on a 20 percent overspeed requirement and an Inconel 718 yield strength of 1 030 MN/m^2 (150 000 psi).

(3) When the size of the machine is varied, a certain geometric proportionality is maintained.

(4) The magnet material, samarium cobalt, has twice the magnetic energy product of platinum cobalt.

(5) The cooling capability is 1.2 W/cm^3 (20 W/cu in.) If this limit is exceeded, the capacity of the machine is derated while maintaining the same weight.

The electromagnetic weight of the machine is contributed by the rotor, stator iron ring, copper winding, potting, and winding support. From the analysis, expressions for the volume of each component were assigned and multiplied by the densities of the respective materials. The final equation for the electromagnetic weight in terms of the rotor diameter, D, and the stack length, L, reduced to the following:

$$W_{em} = 0.169\ D^2\ L + 0.029\ D^3\ Kg$$

The estimated motor weights (electromagnetic weight plus the structure weight) of brushless dc motors (electronics not included) using samarium cobalt and the conventional alnico 9 permanent magnets is shown in fig. 115. Use of SmCo in brushless dc motor results in a weight saving of about 1/3. If the mechanical strength of SmCo can be improved in the future such that Inconel sleeve in the rotor is not required, further motor weight saving can be achieved.

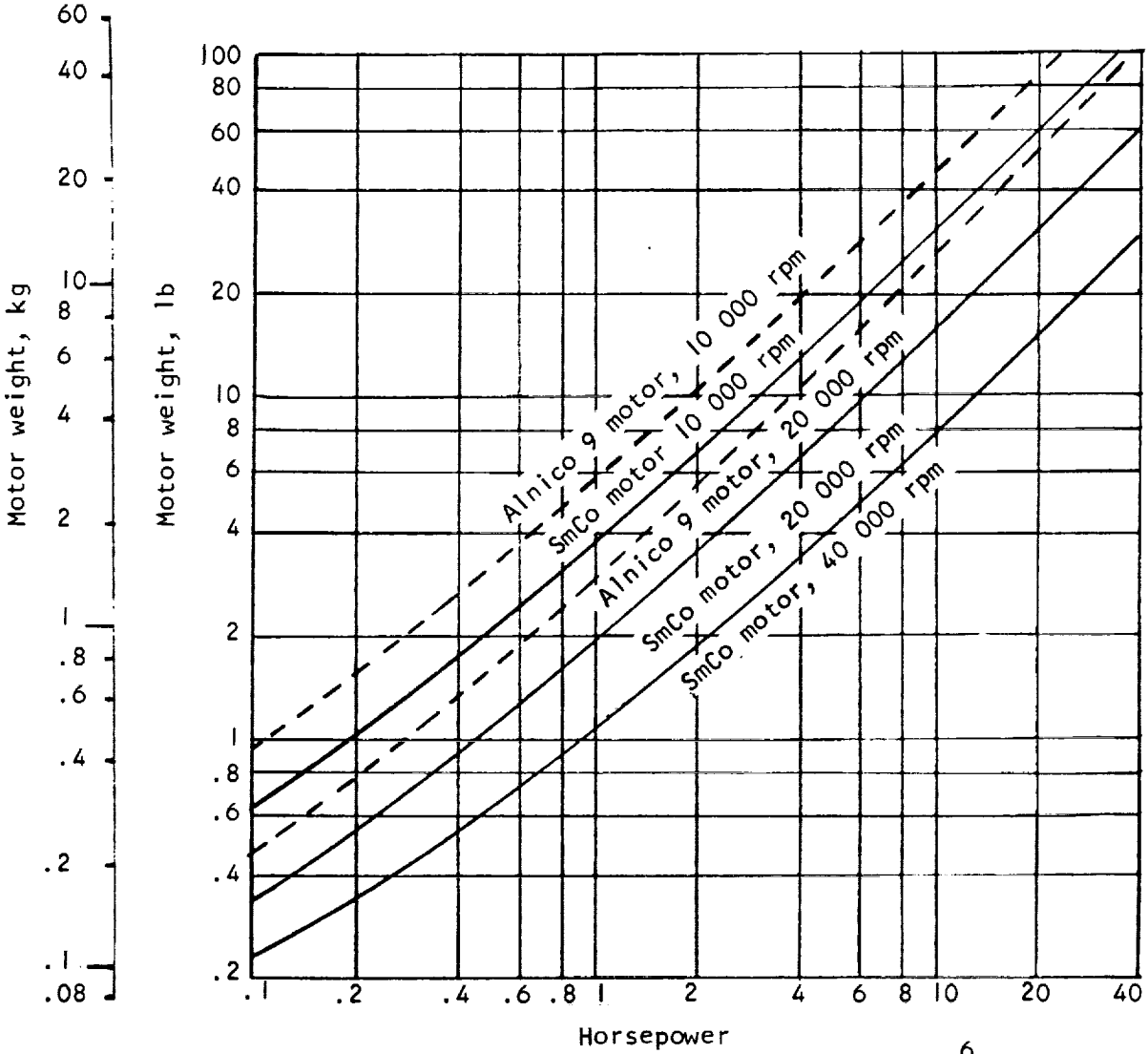
Insulation materials and conductor materials.--The effect of new insulation and conductors materials on the size and weight of aircraft cables and wire and on high temperature application were discussed earlier in this section.

Structural materials.--Structural materials comprise a large percentage of the total weight of various electrical components in the aircraft electrical power system. Structural materials are used in the shaft of the rotating machinery, the frame, case, chassis, and other supporting structures. Except for the shaft, relatively low mechanical strength is usually sufficient. Light weight, therefore, becomes the major interest. Research and development in lightweight structural materials has been conducted for years. Recently, Northrop Corporation announced development of a graphite composite that can effect great weight savings in the aircraft industry.

Graphite filaments are created by burning rayon fibers. The fibers break down into graphite under intense heat and the filaments are then bonded with industrial glues or resins into yarn with an 8-mil diameter. The yarn is formed into a sheet with several layers glued together. By applying pressure to the sheets in a heated environment, the final material is produced. According to Northrop Corporation, the new material is 40 percent lighter than aluminum, and reputedly can withstand a temperature of 530°K (500°F). It is expected that the graphite composite will find ready acceptance in aircraft parts such as engine cases, fan blades, flaps, stabilizers, speed brakes, and other components.

This graphite material presently costs about $770/kg ($350 per pound), which is extremely high compared with aluminum. Northrop predicts, however, that the price per kg can be reduced to $45 to $65 in the next few years, as a result of increased production.

In addition to the graphite composite, a boron composite is also under development. The boron composite is produced by depositing boron gas on tungsten fibers that are bound together.



Almico 9 - energy product approximately 10×10^6

SmCo - energy product approximately 20×10^6

Figure 115. Estimated Weight of Brushless Dc Motor Using SmCo and Alnico 9 Permanent Magnets (Electronics Not Included)

Axial flow fans.--The axial flow fan was selected because it is by far the most common type of fan used in aircraft. This is primarily due to its lower weight in comparison to other fan types. Appendix G outlines the graphical method for obtaining the size of axial flow fans for conservatively rated designs. From the flow and pressure rise requirements, the blade tip diameter of the fan is determined. Fig. 116 shows curves for the lightest fans possible without motors versus fan blade tip diameter. This is empirical data, as it is not possible to produce a generalized theory for calculating the weight of a fan. Small fans are disproportionately heavy because connectors, wall thicknesses, ball bearings, etc. cannot be scaled down. Compare the curve for the weight of a cast aluminum fan with the curve $W \propto D^3$. The latter is set up to intersect the former at D = 0.65M (18 in.). If the 0.65 M diameter fan was exactly scaled down to, say, 0.2M (8-in.) diameter, its weight would be 1 Kg (2.2 lb), whereas an actual fan would weigh at least 2.5 kg (5.4 lb).

It should be noted that most designs will weigh more than the curves show as the curves represent the lightest designs. The addition of terminal boxes, heavy blade containment rings, heavy or complicated mounting brackets, inlet screens, thermal protectors, etc., will result in a heavier fan.

Centrifugal compressors.--The discussion of centrifugal compressors here is limited to low pressure type (less than 2.5 N/cm^2), using vaneless diffusers and rotor blades swipt back 45 degrees at the tip. Appendix G gives the graphical method for sizing this type of centrifugal compressor. Fig. 117 shows a curve for the lightest aluminum alloy construction centrifugal compressors. Again, this curve was obtained from empirical data, and the same comments (with regard to increased weight due to appendages) in the last paragraph to axial flow fans apply here. The compressor weight nearly follows the curve which is proportional to the cube of the diameter, and is drawn to pass through 5.5 Kg (12 lb) and 0.14M (5.5-in.) diameter. This is simply because the size range considered is very small, i.e., from 0.05 to 0.14M (2- to 5.5-in.) diameter.

Drive optimization for the axial flow fan and low pressure compressor.--In an effort to reduce power consumption, noise level, and often system weight, an attempt is made to optimize aerodynamic efficiency. With a given rotational speed, the fan can be designed to provide almost any airflow rate at a desired pressure rise. In this case where the speed is fixed or the speed range is confined to the 400-Hz power supply, the system will not always yield optimum weight and efficiency for the specific work to be done. Fig. 118 shows the input power requirement in watts for common fan loads when driven from a conventional 3-phase, 400 Hz supply. For best results, however, there is a unique rotational speed that will produce an optimum aerodynamic efficiency in a machine of a given type. For axial flow fans and low pressure compressors, this occurs at a specific speed (N_S) of approximately 100,000 where:

$$N_s = \frac{RPM\ (CFM)^{1/2}}{[\Delta P(\text{in. } H_2O)]^{3/4}} = \frac{60(RPS)\ [\text{cm } 3/5]^{1/2}\ [2.49 \times 10^{-2}]^{3/4}}{[\Delta P\ (N/cm^2)]^{3/4}\ [472.0]^{1/2}}$$

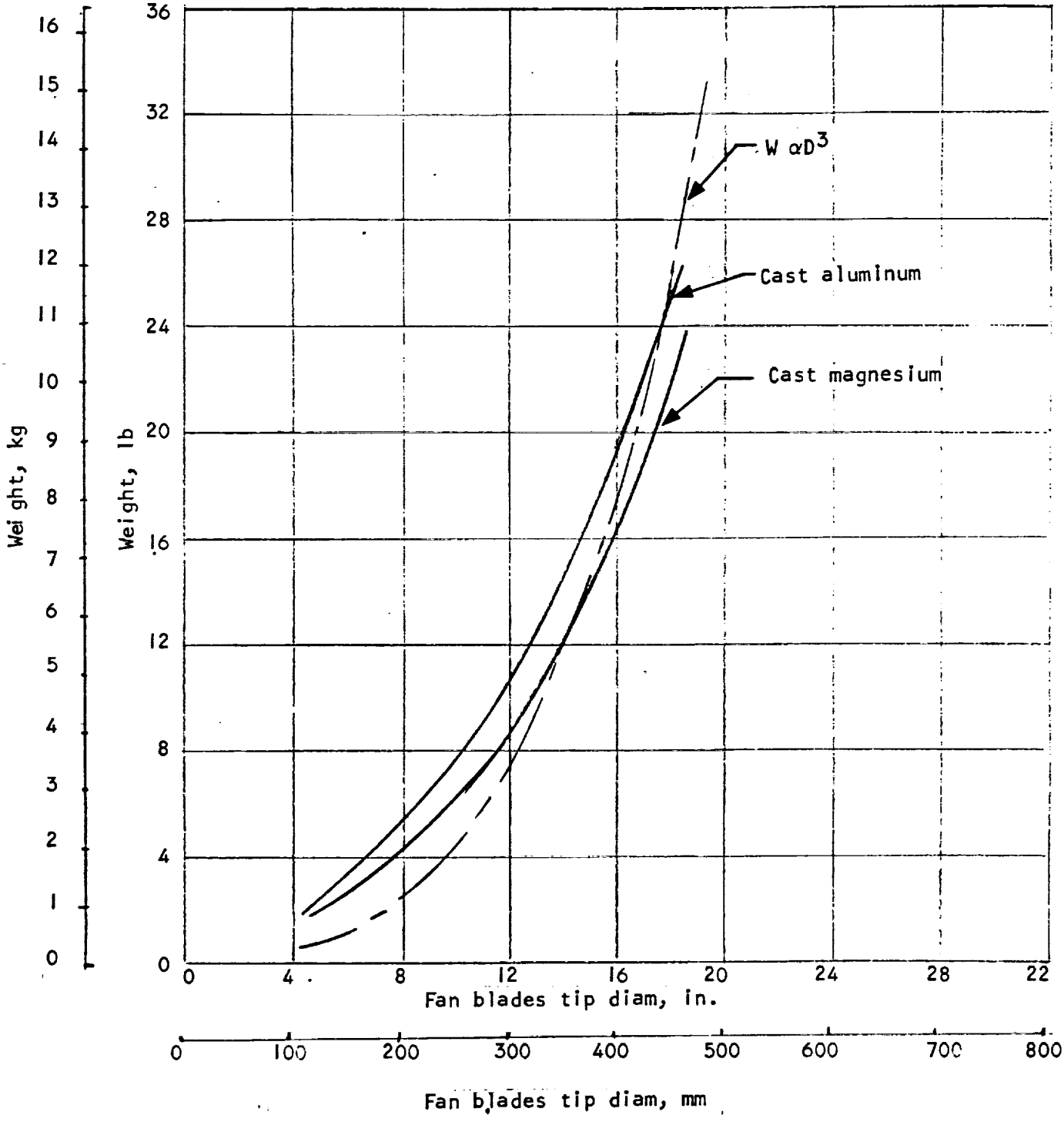


Figure 116. Weight of Lightest Flow Motor Driven Fans Excluding Motor Weight

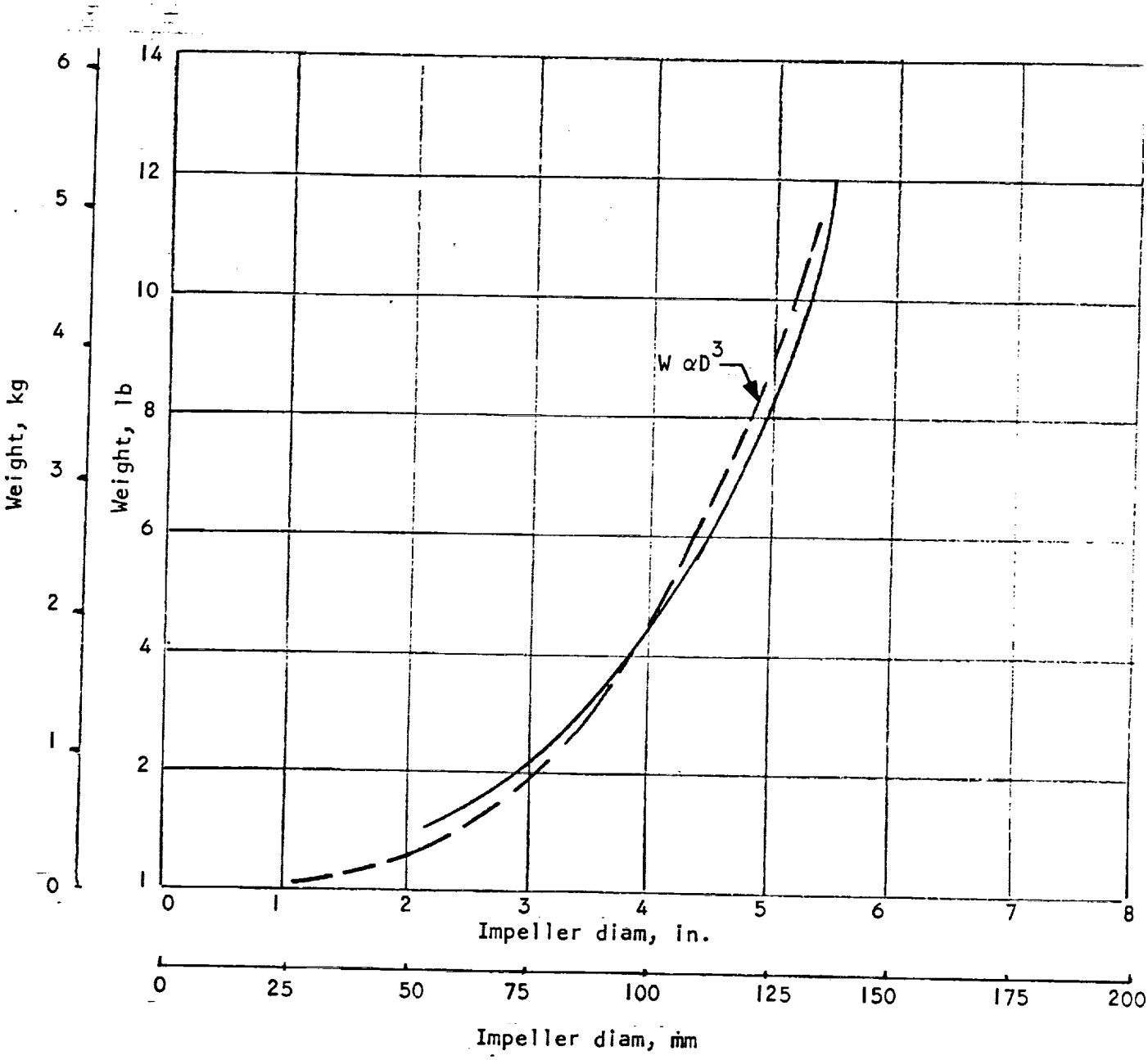


Figure 117. Weight of Lightest Driven Centrifugal Compressors Excluding Motor Weight

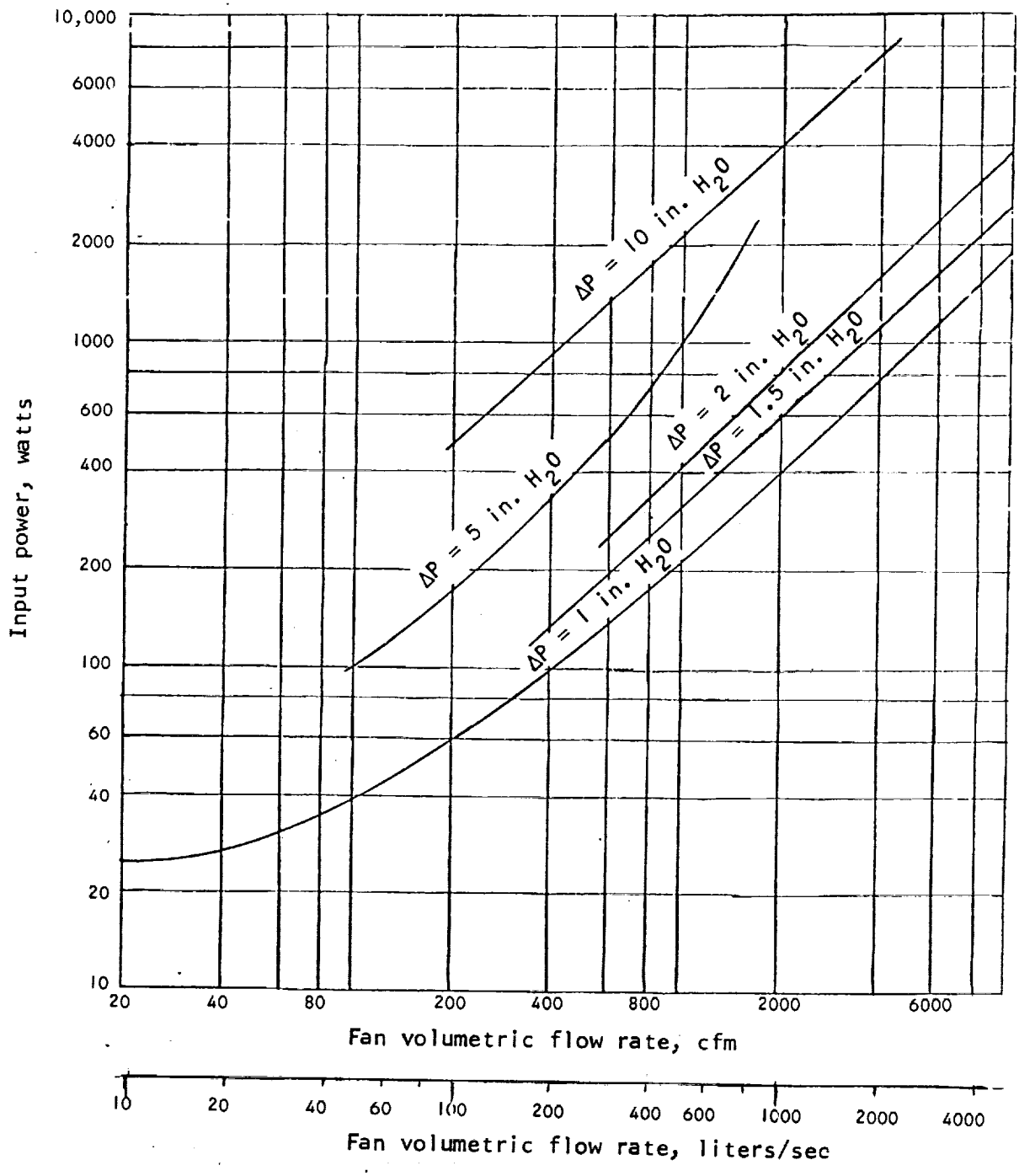


Figure 118. Trend of Power, 3-Phase, 400-Hz, Motor-Driven Single-Stage, Axial-Flow Fans

Fig. 119 shows the relation between volume flue rate, pressure, and optimal fan speed. An indication for best impeller tip diameters for ideal rotational speeds is shown in fig. 120. Notice that these curves present only the optimum conditions for the single-stage axial fan and are of practical value only if the particular motor sizes and speeds, bearing lifes, mechanical configurations, etc., are available. The curves may be best used in comparing the effects of varying flow or pressure rise parameters on fan or compressor size (and, thus, aerodynamic component weight). They are intended to give additional meaning to the "ideal" rotational speed trend curves. Both curves indicate the trend of data only and should not be used for design reference. They are most useful in showing the ways tip diameter and speed would vary as functions of flow and pressure rise for optimum efficiency fans.

It might be argued that it is often possible to produce a fan or compressor having an impeller tip diameter smaller than indicated on the graphs for maximum efficiency. Since the weight of the aerodynamic fan components vary in the range of the second to third power of diameter, a less efficient fan of small impeller tip diameter would probably be more desirable than a more efficient but larger diameter machine. When the increased weight of the drive motor, larger power cables, larger and heavier contactors, larger EMI filters (if required) and possible motor cooling problems are considered, the total system is usually heavier for a faster, low efficiency fan. This is particularly true as the fan or compressor size increases.

Electric blower motors.--Motors have either totally enclosed or open ventilated construction. Most dc motors are totally enclosed because of the increased demand for motors capable of operating in explosive environments that pass the oil splash test, and because of their use of commutators and brushes. Dc motors, ac single-phase and 3-phase induction machines are used for fans and blowers. Open ventilated ac induction motors can often pass the required environmental tests and, thus, are used in the larger motors for continuous duty because of substantial weight savings.

The fan load reflects a characteristic to a driving source having a torque requirement that decreases as the square of the reduction in speed. For the dc motor, the variable torque characteristic will require a constant speed machine such as the compound or the shunt type motor. In an effort to arrive at optimum configuration and motor data, it is impractical to establish a parametric relationship on a purely analytical basis.

The analysis of many specific designs yields data that can be organized and extrapolated on the basis of physical reasoning--an approach used in preparing the data presented here. When this approach is used it is important that the inherent limitations be noted. Each single design characteristic is dependent on many independent parameters. In analyzing, organizing, and presenting data regarding such characteristics, it is necessary to neglect all but the most important. The result is an oversimplification of a complex problem. Such simplication can be both valid and useful, but it must be applied with care. Therefore, it is suggested that these data be used only in the preliminary design of motors.

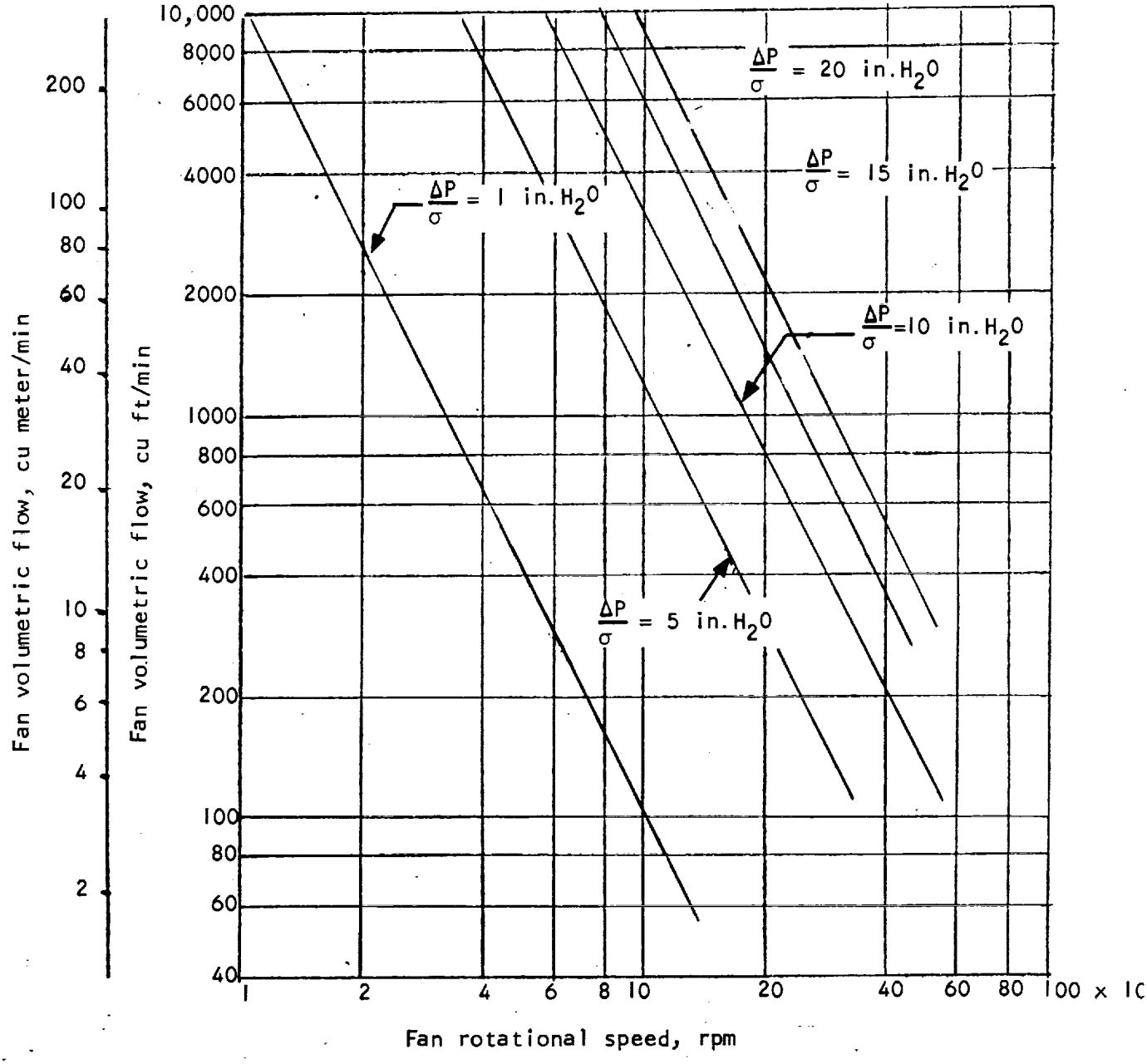


Figure T19. Fan Speed for Maximum Aerodynamic Effieiency of Single-Stage, Axial-Flow Fans and Low-Pressure Compressors

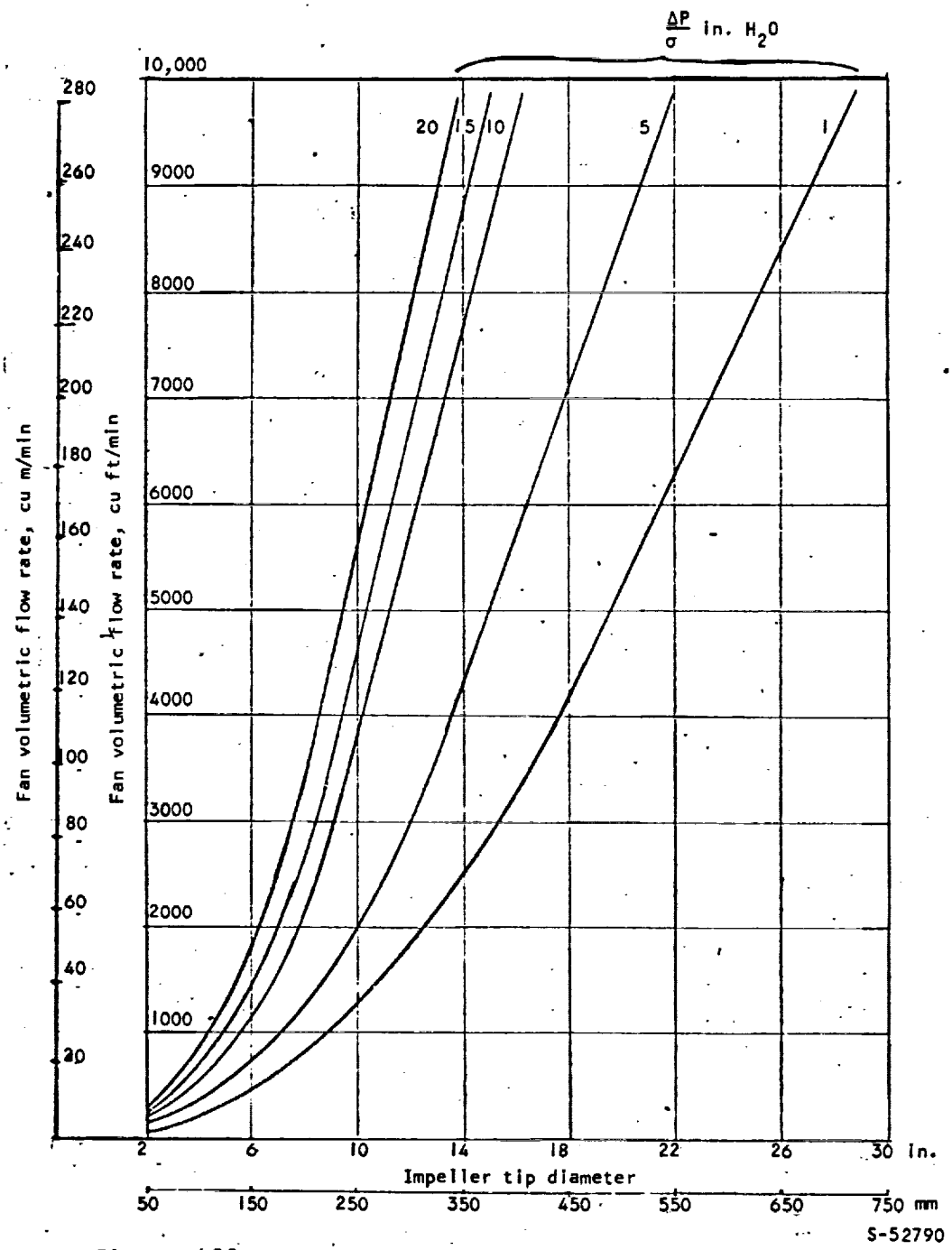


Figure 120. Impeller Tip Diameter vs Volumetric Flow Rate for Ideal Rotational Speeds

Hydraulic centrifugal versus hydraulic displacement pumps.--High-speed centrifugal hydraulic pumps possess attributes which make them particularly attractive for certain applications in modern aircraft systems. A distinct continuous trend toward the use of higher operational speeds for mechanical equipment has been motivated by significant reductions in equipment size and weight. Usually, the state-of-the-art design has been the limiting factor on operational speed for a given type of equipment. Main power plants have followed the trend toward higher operational speeds through gradual transition from low-rotational-speed piston engines to high-rotational-speed jet engines. Other types of equipment are undergoing similar evolutions. Recent advances in the state-of-the-art design for high-speed centrifugal hydraulic pumps will make significant size and weight reductions possible for onboard pump equipment of large transport aircraft. In addition, just as the reduced mechanical complexity of jet engines has greatly increased time-between-overhaul (TBO), life, and reliability as compared to reciprocating engines, the 5,000-hr TBO for a high-speed centrifugal hydraulic pump is well within state-of-the-art design. The application of high-speed pumps, as well as pump requirements and characteristics imposed on the driving source, should be examined. Certain characteristics inherent to the design of both centrifugal and positive displacement hydraulic pumps are given in table 65.

Weight comparison: A weight comparison of centrifugal and reciprocating hydraulic pumps of optimum design is shown in fig. 121 as a function of flow-capacity at a $21 \times 10^6 N/m^2$ (3000-psi) design pressure. Typically, a 9 kg (20-lb) saving, or 36 percent of the total weight, can be achieved if a 6.3 cm^3/sec. (100-gpm), $21 N/m^2$ (3000-psi) centrifugal pump weighing 16.5 kg (36 lb) is used instead of a 25.5 kg (56-lb) reciprocating pump. This saving can be increased for high-flow applications.

Efficiency comparison: The overall efficiency of centrifugal hydraulic pumps is somewhat less than that of reciprocating hydraulic pumps; this difference is more pronounced as the pump size decreases. Fig. 122 gives a comparison of efficiency for centrifugal pumps and reciprocating pumps plotted as a function of flow capacity. Fig. 123 shows a comparison of pump input power for centrifugal pumps and reciprocating pumps as a function of flow capacity for a $21 \times 10^6 N/m^2$ (3000-psi) system. The somewhat higher power required by the centrifugal pump reflects the lower efficiency.

Although lower efficiency is obtained with centrifugal pump use, particularly at part-load operating conditions, the weight savings achieved by the high-power intermittent duty systems, such as the utility hydraulic system of a large transport aircraft, offsets this disadvantage. Also, efficiency is of less importance in intermittent duty systems. Therefore, this system appears to have the greatest potential.

Comparison of constant-speed characteristics: Fig. 124 presents the typical pressure/flow diagram of a centrifugal and a reciprocating variable-flow pump operating at constant speed. The maximum flow of both pumps is 6.3 cm^3/sec. (100 gpm). There is a definite similarity between the operating characteristics of the two designs. The reciprocating machine operates along a flatter pressure

TABLE 65.-- CENTRIFUGAL VERSUS POSITIVE DISPLACEMENT HYDRAULIC PUMP CHARACTERISTICS

Characteristic	Centrifugal pumps	Positive displacement pumps
Working clearance	Tolerates generous working clearances	Requires extremely close working clearances
Rubbing contact	Requires no rubbing contact in the basic pumping element	Involves high-speed metallic rubbing contact in the basic pumping element
Fluid-dirt contamination	Tolerates fluid dirt contamination	Highly sensitive to fluid dirt contamination
Fluid lubricity	Tolerates low fluid lubricity	Highly sensitive to fluid lubricity
Speed	Suitable for high speeds	Speed is limited
Efficiency	Efficiency dependent on size	High efficiency independent of size
TBO	5000-hr TBO quite feasible	Limited TBO
Reliability	Excellent inherent reliability potential	Limited inherent reliability potential, particularly at higher speeds
Performance over time	Performance constant over life of unit	Performance deteriorates with time
Weight	Optimum designs lighter and smaller than positive displaced pumps	Heavier and larger than optimum design of centrifugal pumps

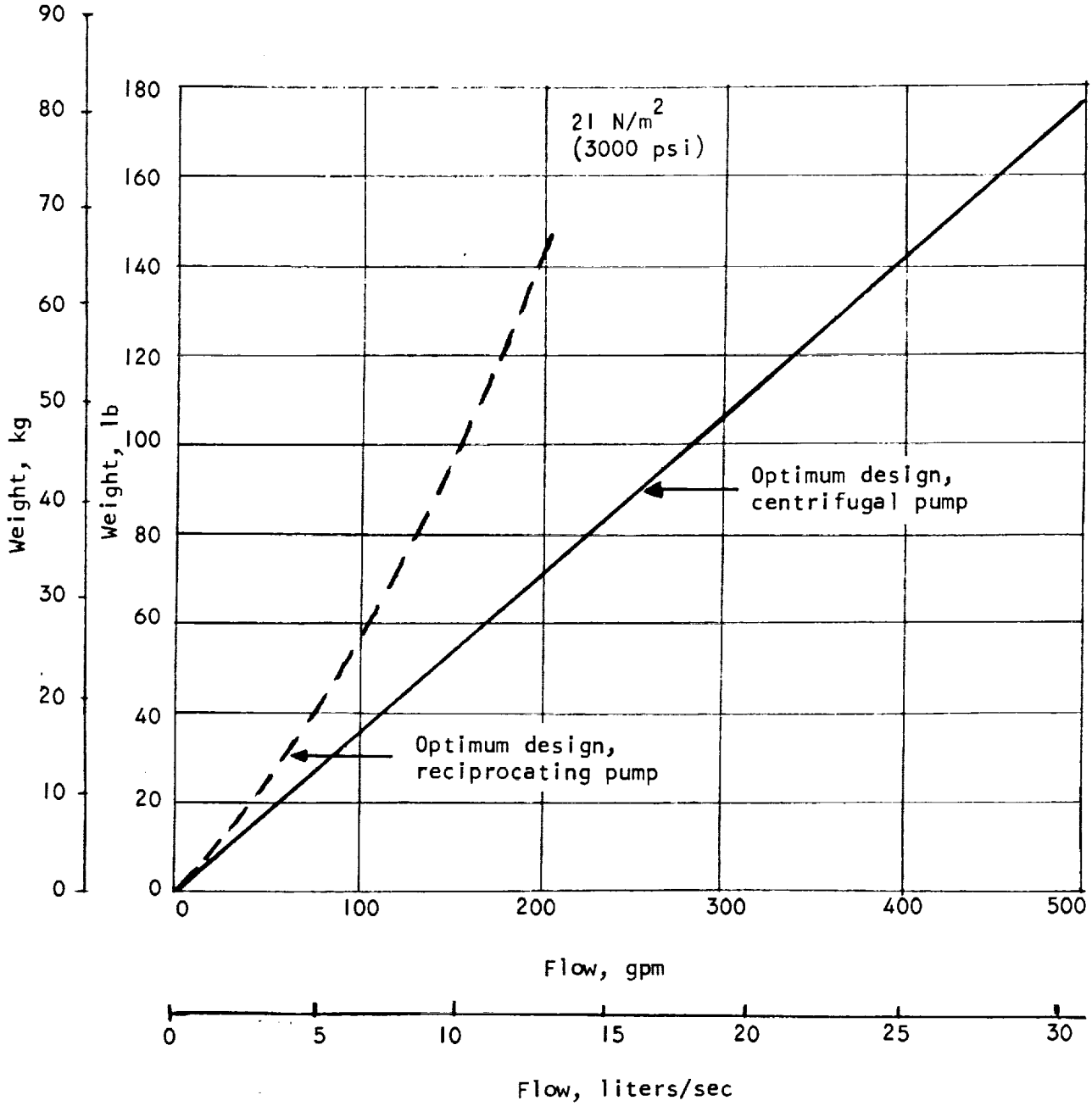


Figure 121. Weight Comparison, Centrifugal Pump vs Reciprocating Pump

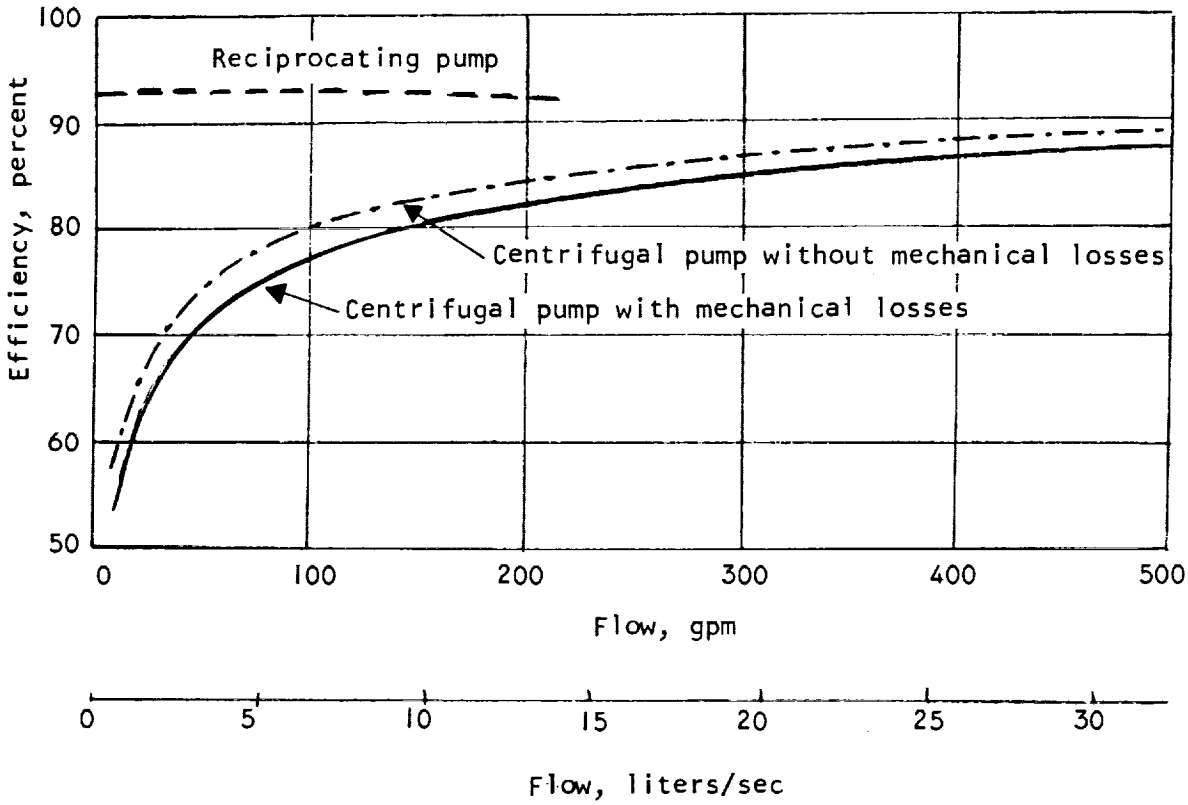


Figure 122. Efficiency Comparison, Centrifugal Pump vs Reciprocating Pump

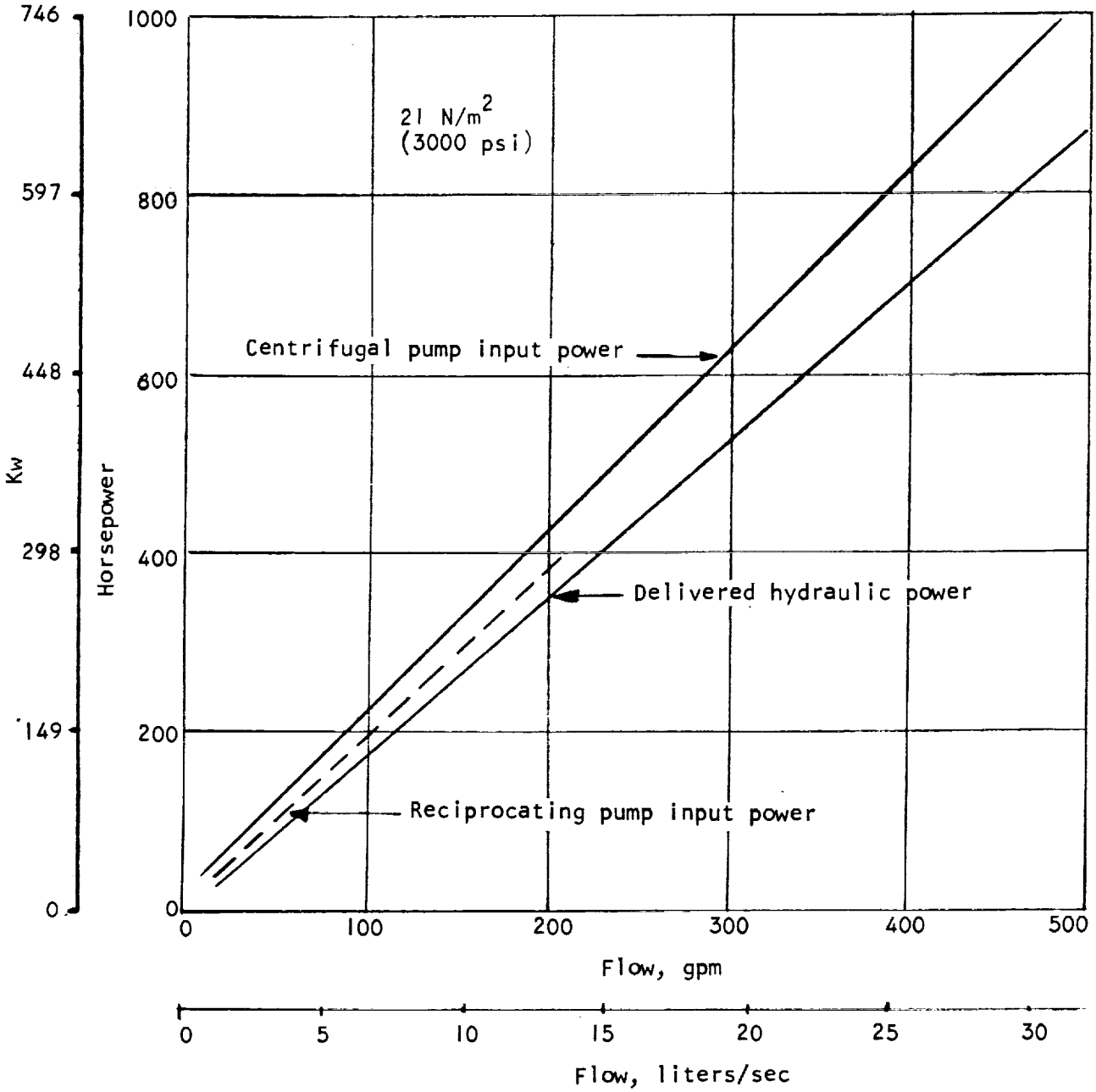


Figure 123. Power Comparison, Centrifugal Pump vs Reciprocating Pump

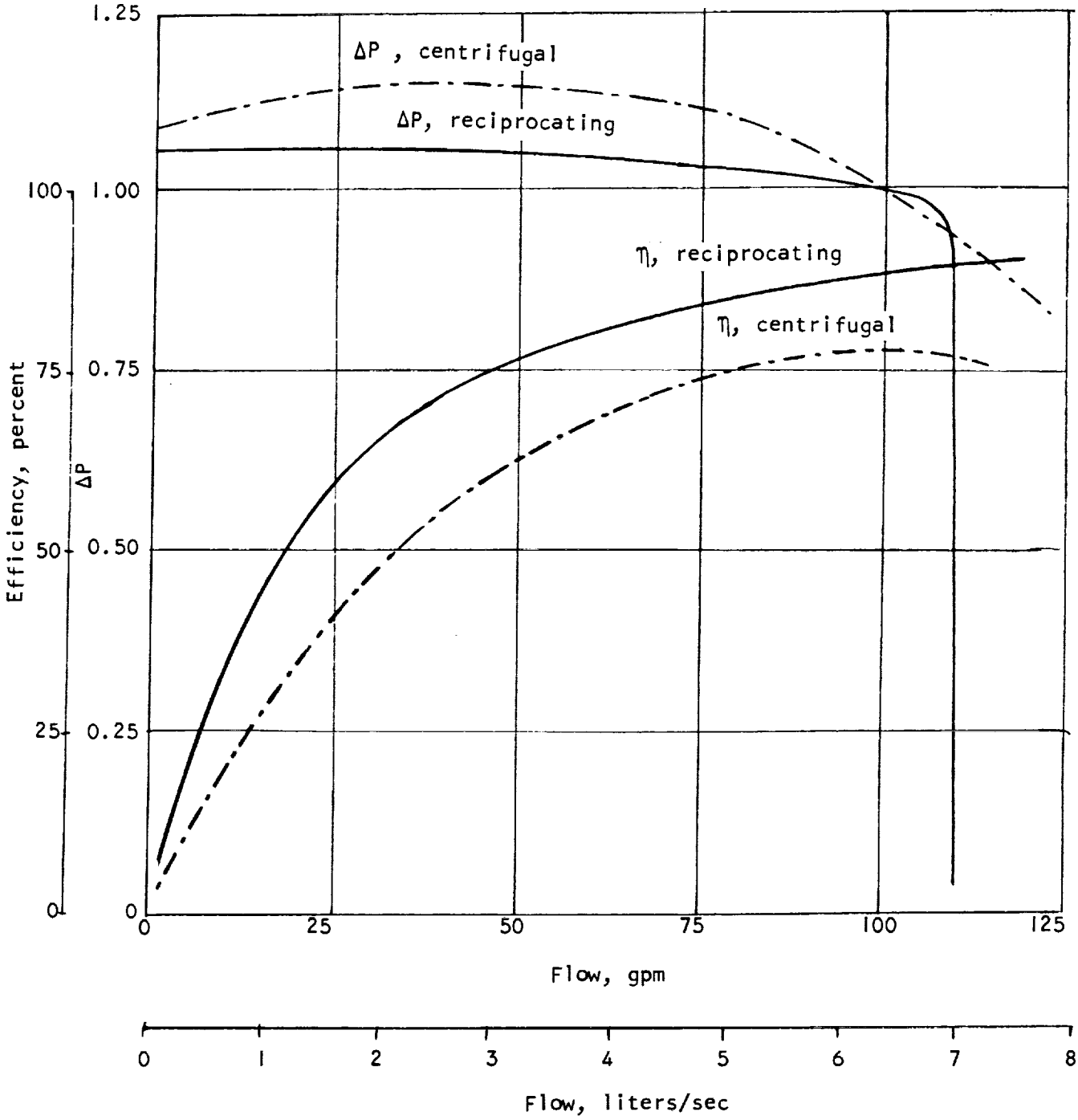


Figure 124. Pressure vs Flow for Centrifugal and Reciprocating Pumps at Constant Speed

curve and provides better efficiency, but its maximum flow is limited by its speed-displacement capacity.

Pump drives.--Since centrifugal pumps require high speed for optimum performance, size, and weight, they are particularly suited for matching to high-speed turbine drives for their shaft power requirements.

The comparison between the reciprocating-type and the centrifugal-type pump in figs. 122 through 125 is for very large-capacity engine driven pumps. Electrically driven pumps for contemporary large transport airplanes rarely exceed the 18.6 kw (25-hp) capacity (water injection). Electrically driven pumps are most commonly used as fuel boost pumps that usually supplement the engine-driven fuel pumps. These electrically driven pumps may require up to 6 kw (8-hp) shaft input from an electric motor. However, when the head pressure is typically between 2 and 2.8 N/m^2 (30 and 40 psi), an increase in speed is undesirable because of the critical noncavitating suction performance, particularly at high-altitude operations.

For requirements of $6.9 \times 10^6 N/m^2$ (1000 psi) head pressure and higher (electrically driven pumps for the emergency hydraulic system), higher operating speeds offer distinct advantages. The trend of impeller tip diameter decrease with rotational speed increase is shown in fig. 125. Since the theoretical synchronous speed of a 400-Hz system is limited to 24,000 rpm, a higher-frequency power source would be a better supply for these specific group loads as well as eliminating step-up gear trains.

Component Heat Transfer Techniques

The methods of cooling electrical components presently used in aircraft were discussed in the Interim Technical Report, ref. 1. The twelve items listed below are selected from a viewpoint of possible application to aircraft cooling designs:

(1) Transient state cooling by thermal capacity

(2) Impingement cooling and special techniques of convective cooling

(3) Vortex (Hilsch) tubes and other miniature refrigerators

(4) Thermal shielding

(5) Cooling by phase-change

(6) Heat pipes

(7) Cooling by expendables

(8) Cryogenic cooling

(9) Improved heat rejection

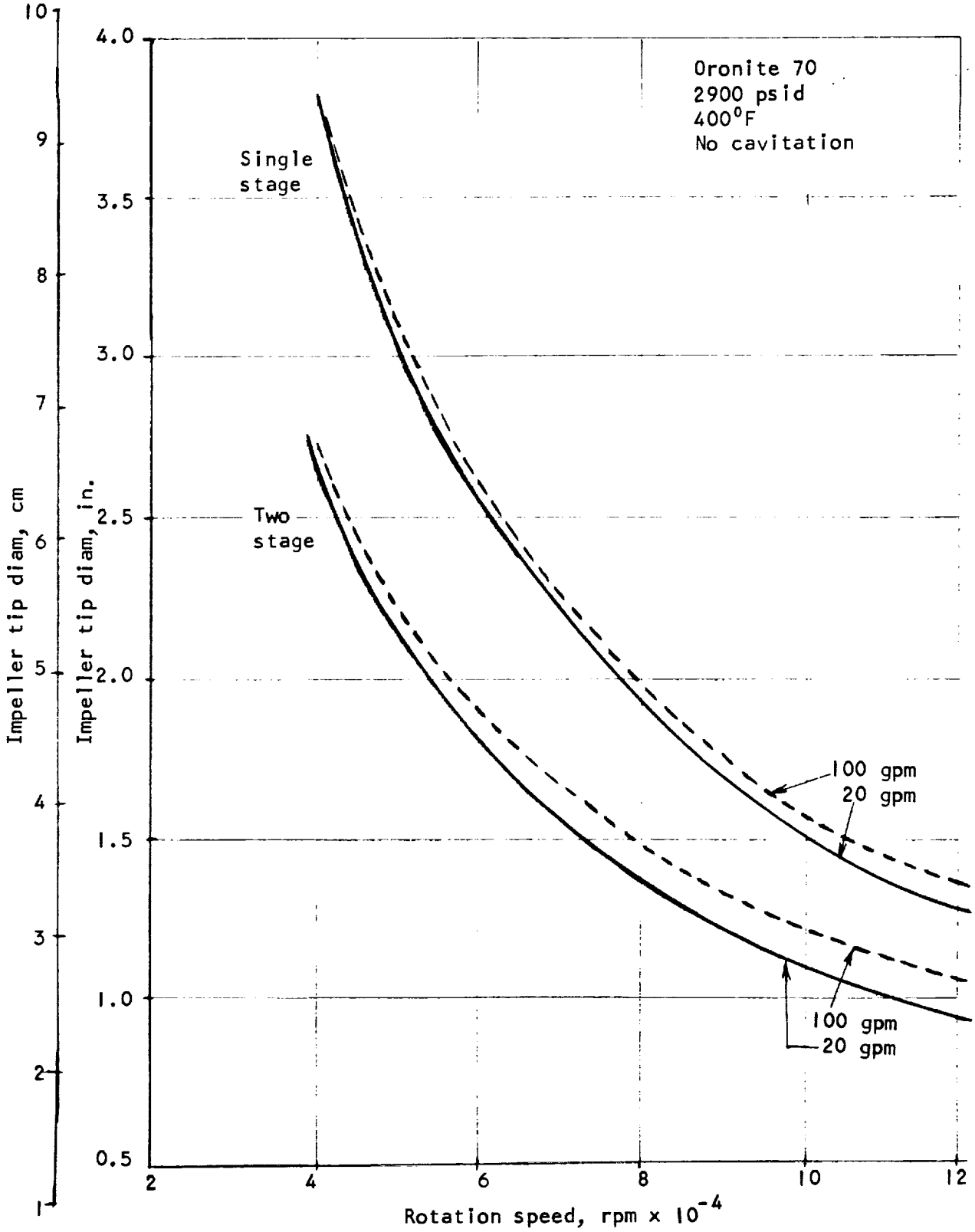


Figure 125. Impeller Tip Diameter vs Rotational Speed

(10) Internal heat ducting from hot spot

(11) Thermal network synthesis

(12) Thermoelectric refrigeration

Transient cooling by thermal capacity.--When the equipment is used for only a short duration, the equipment can be designed to take care of its own heat generation by providing sufficient thermal capacitance (product of mass and specific heat). Its energy-storing capability plus the natural convection and radiation to its surroundings can maintain the maximum temperature for the whole duration below a required level.

One concern about this approach is the existence of internal hot spots. An overall lump-parameter analysis does not always provide this information. The absence of hot spots is ensured by proper conduction-shunting from point of heat generation to area of greatest thermal capacitance.

Fig. 126 shows a turboalternator set designed on this principle.

Impingement cooling and special techniques of convective cooling.--Some additional design features of convective heat transfer that can be applied to aircraft electric cooling are shown in figs. 127, 128 and 129. They represent the considerations of high heat transfer coefficients of an impinging jet (fig. 127) direct contact of coolant and heat source for best efficiency (fig. 128) or utilizing the centrifugal field of rotating machinery (fig. 129)

Fig. 130 shows some typical convectively-cooled rotating electric machines design features.

Power cables can be cooled by an arrangement depicted in fig. 131 where a concentric outer conduit contains the coolant that flows along the cables. The spacers keep the cables from contacting each other, thus providing the maximum surface area for convection cooling. Additional surfaces can be provided by connecting the cables with the conduit, and then connecting the conduit with the structure by good conduction paths.

Vortex (or Hilsch) tubes and other miniature refrigerators.--A vortex tube is an expansion device that utilizes the energy and momentum transfer between concentric gas-layers in a cylinder to produce a lower-temperature core as the gas stream spirals down the tube. The high pressure gas is introduced into the tube in a tangential direction as shown in fig. 132. The energy and momentum transfer takes place as the gas layers tend toward constant angular velocity.

The temperature difference that is obtainable in a vortex tube is in the range of 55°C (100°F) if properly designed. This device, although not efficient compared with some other devices, has the big advantage of its small size. In most cases the tube can be located adjacent to the point of use. The unit has no moving parts and can be located in inaccessible places.

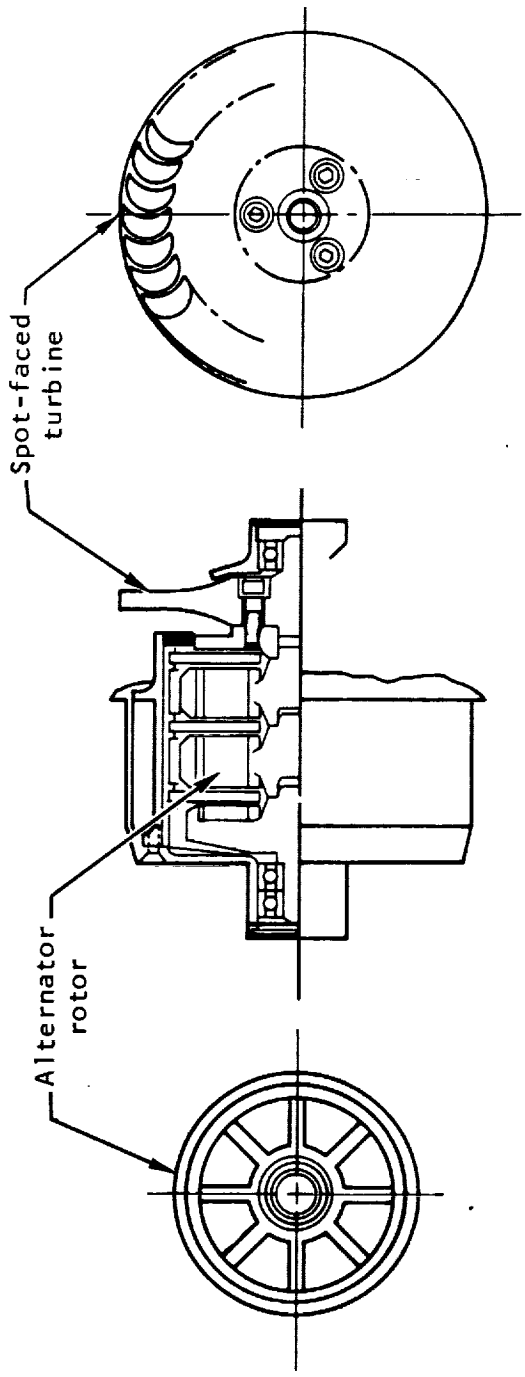


Figure 126. Good Transient Thermal Behavior Provided by the Thermal Capacity of a Turboalternator Set

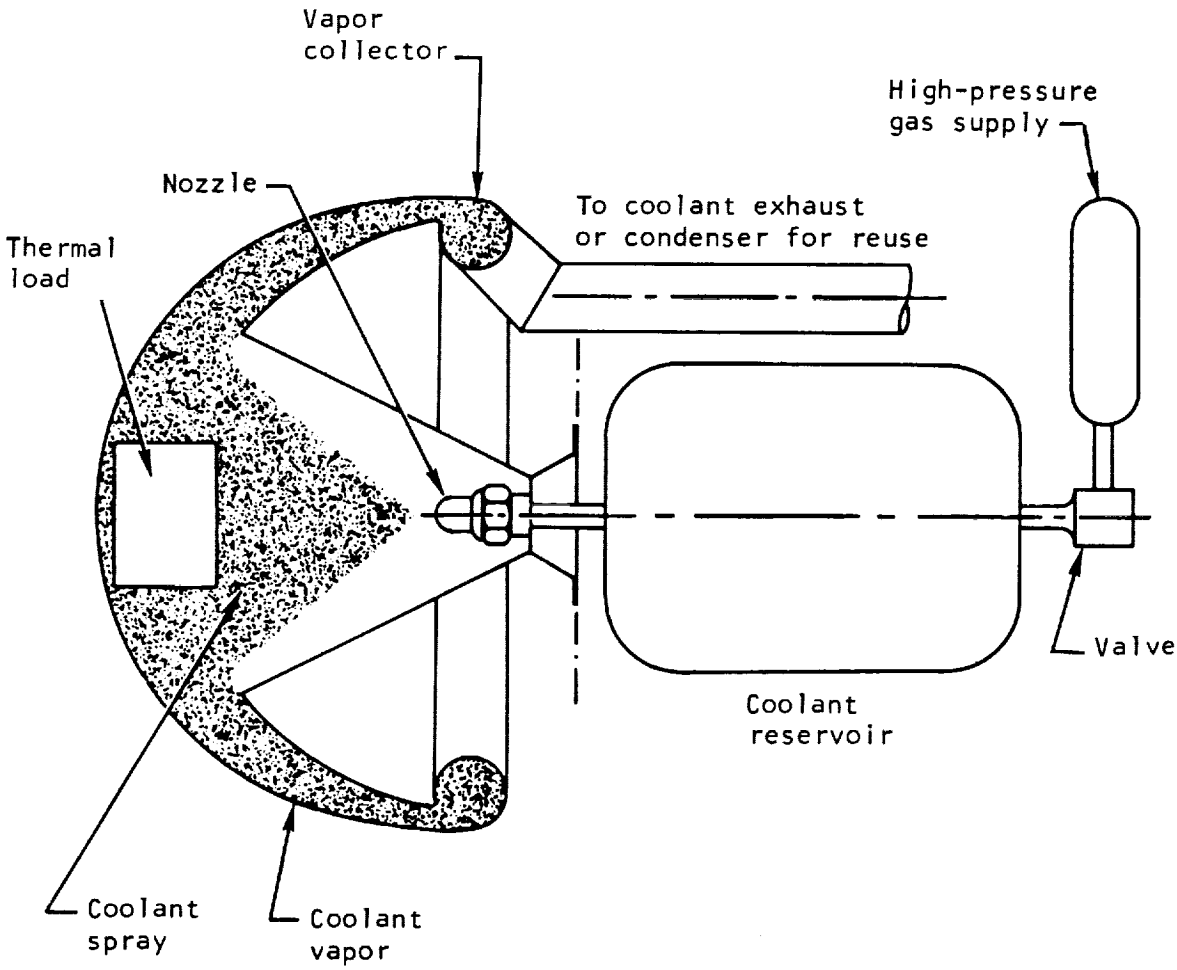


Figure 127. Impingement Method Shown as Liquid Spray Cooling System (The same method can be applied to gas systems)

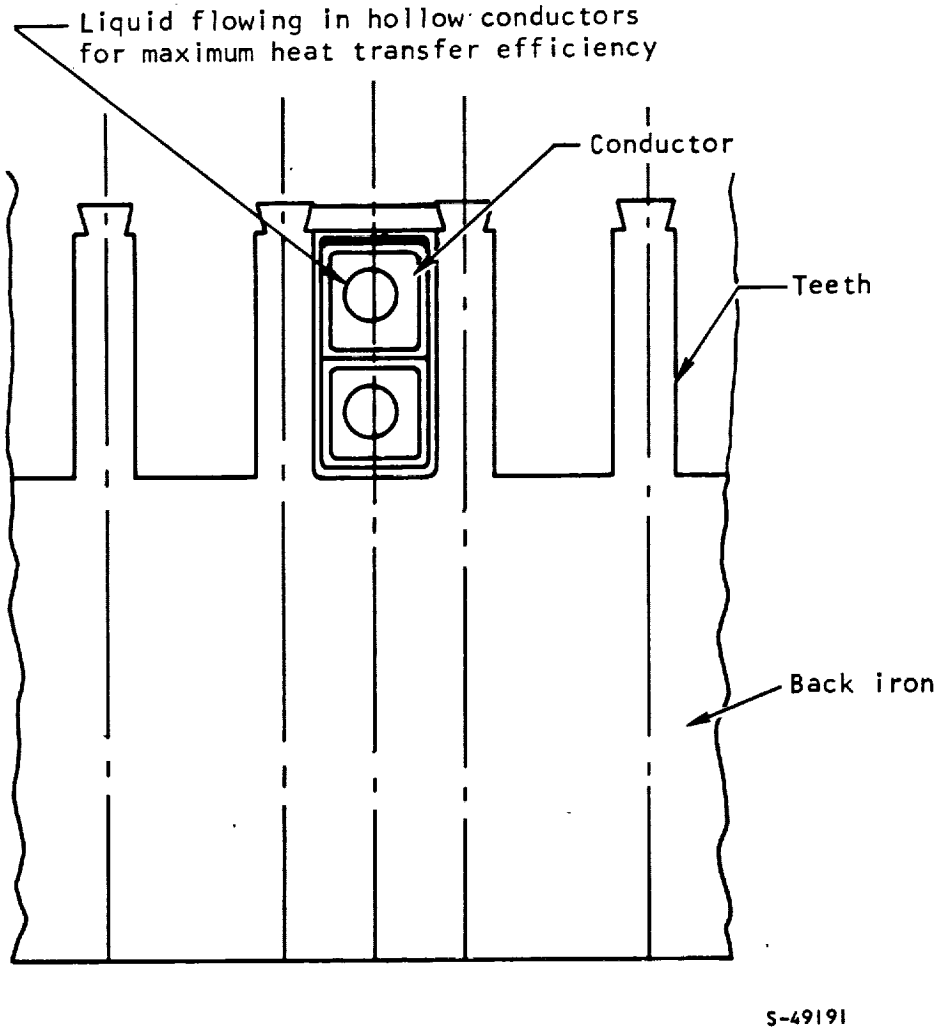


Figure 128. Forced Liquid Cooling for Electric Machines

Figure 129. Void Slots on the Rotor of an Electric Machine Generating Centrifugal Force for Air Cooling

Figure 130. Typical Air-Cooled and Liquid-Cooled Rotating Machines

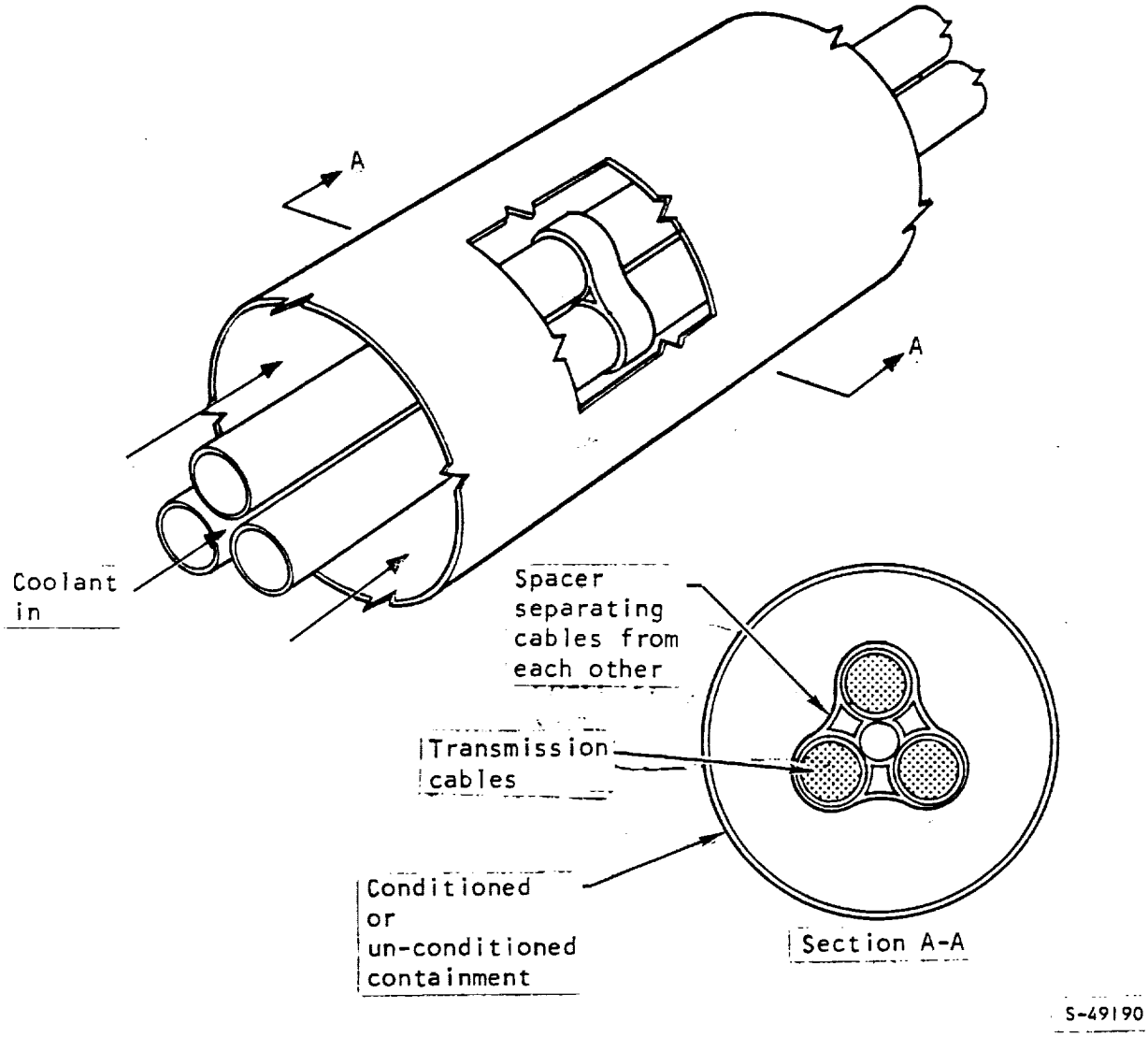


Figure 131. Transmission Cables Cooled by Forced Convection

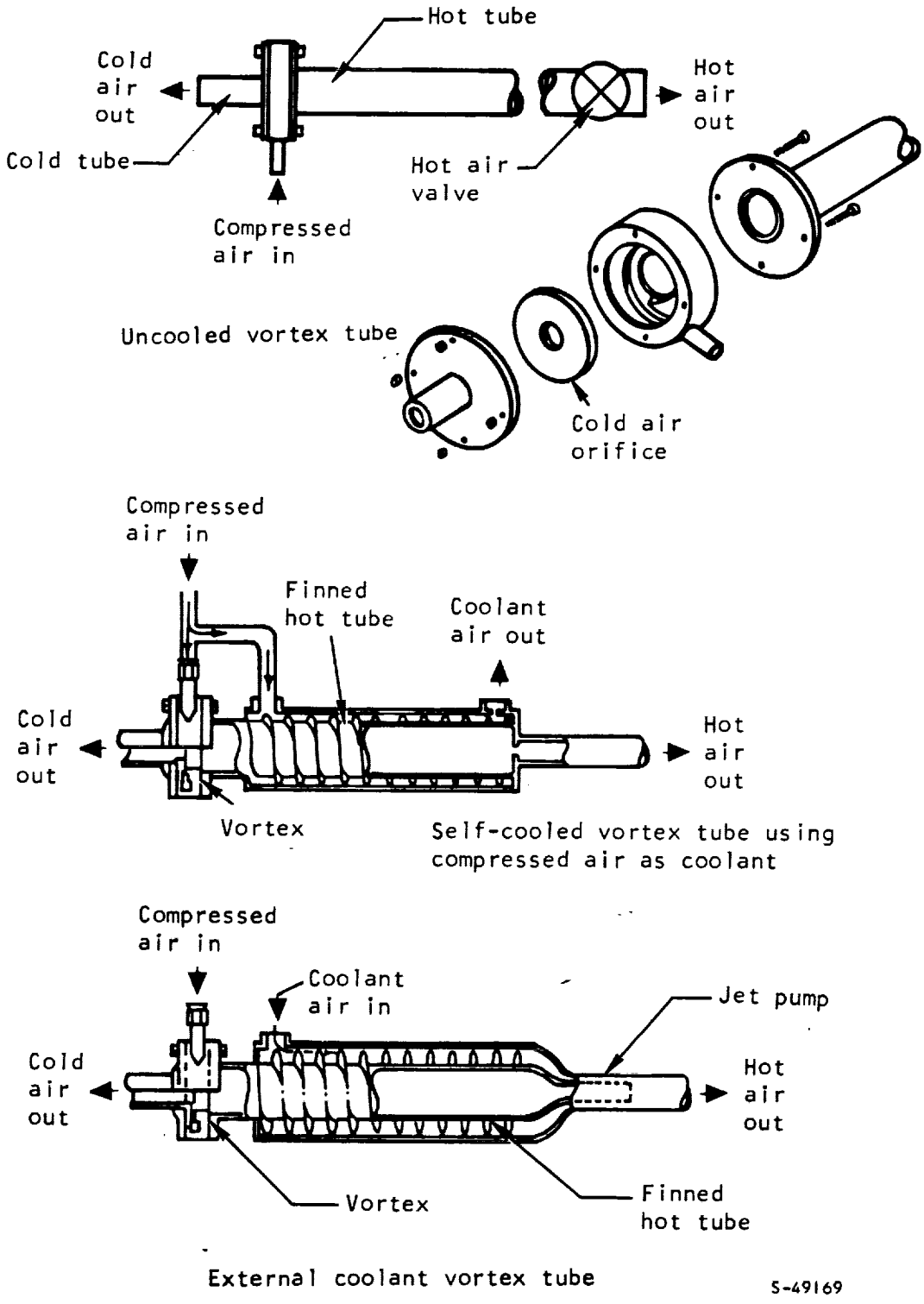


Figure 132. Three Types of Vortex (Hilsch) Tubes

Other devices that utilize the compression and expansion processes of a gas to produce lower-temperature gas or liquid for cooling purposes such as pulse tubes and miniature Joule-Thomson refrigeration systems can also be used for appropriate applications.

Thermal shielding.--To protect electric or electronic equipment at a special location, for instance, close to the leading edge of a pod or wing section, from extreme aerodynamic heating, solar heating or cold of space, the conditioning of its containing structure may be important. Convective, film, transpiration, insulation, ablation, or a combination of these can be used for this purpose. Fig. 133 shows two schemes that this method can be applied.

Cooling by phase-change.--Evaporation, fusion, and sublimation have been used for various cooling applications. The basic transport mechanisms can be quite complicated, but the transport rate can be phenomenal if properly designed. Another feature of cooling by phase-change is that the temperature at which phase change occurs is a function of pressure alone. If pressure is more easily controlled in one application, constant temperature is a direct consequence under equilibrium conditions.

Examples of evaporation/condensation applications were discussed in the Interim Technical Report, ref. 1. All utilizing the high heat transfer rate of phase-change processes. Fig. 134 shows the photograph of an aqua-ammonia evaporative oil cooling system for a typical supersonic aircraft to supplement the cooling by fuel.

In forced convective boiling, swirlers are often used to prevent film-boiling for more efficiency. The swirlers generate a centrifugal force and move the entrained liquid droplets toward the hot metal wall, keeping it always wet. Swirlers may not be practical in some applications, but film-boiling should always be prevented.

Heat pipes.--A specialized application of evaporation/condensation processes for cooling purposes is the heat pipe, in which wicks are used to provide capillary forces to return the condensate to the evaporative end. The basic principle and one application are shown in fig. 135. Heat flux densities as high as 400 w/cm^2 have been obtained using liquid silver as the working fluid and operating at 2270°K (2000°C), see ref. 35.

Cooling by expendables.--The method of expendables utilizes the phenomenal heat transfer rate of the boiling process without the weight and cost penalties of compressors, condensers, and boilers of a refrigeration plant. The vapor produced is dumped overboard.

The problems involved with this method are that the system may need servicing after each flight, and that sealing and corrosion may present difficulties if the operating condition has high pressure and high temperature.

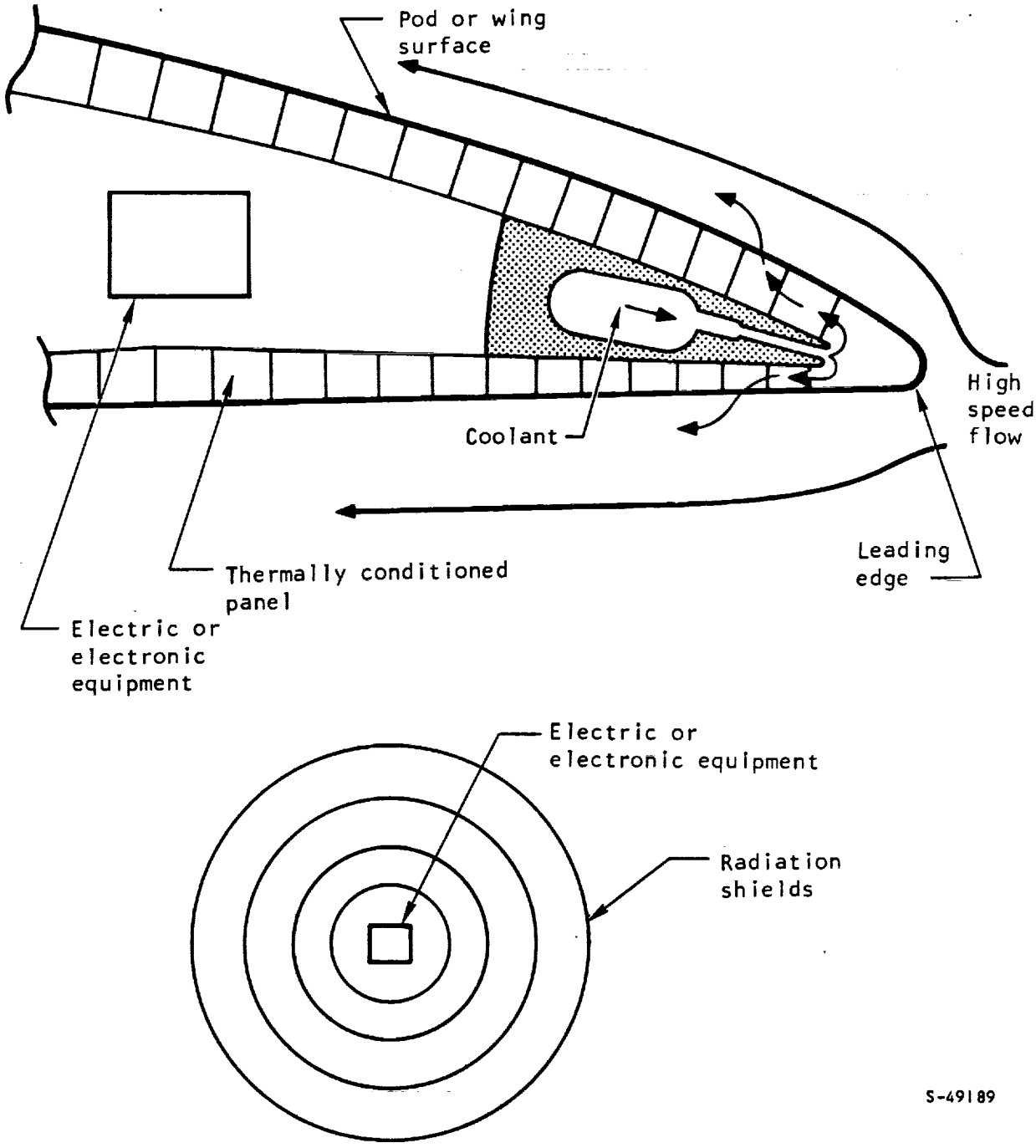


Figure 133. Thermal Shielding

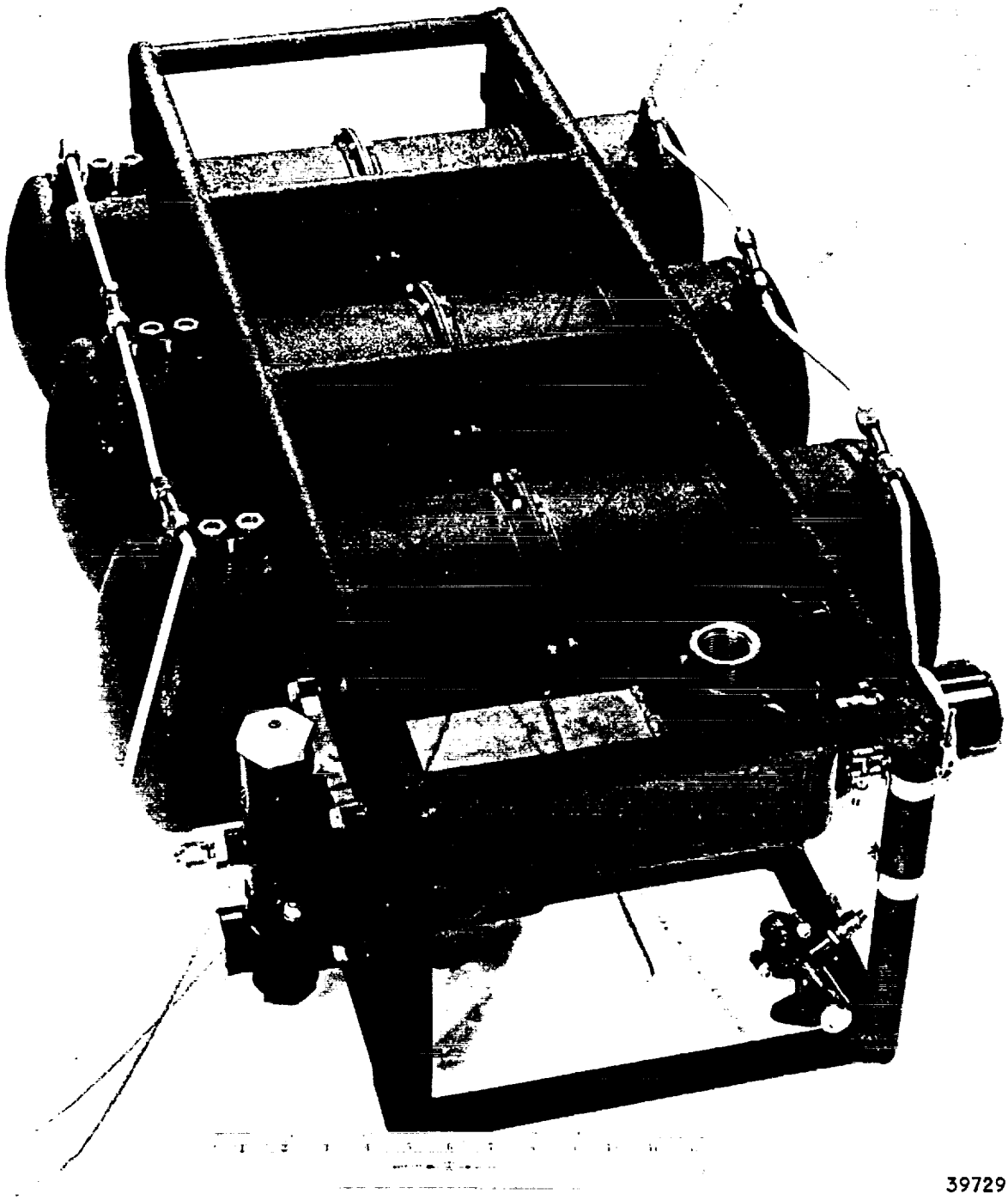
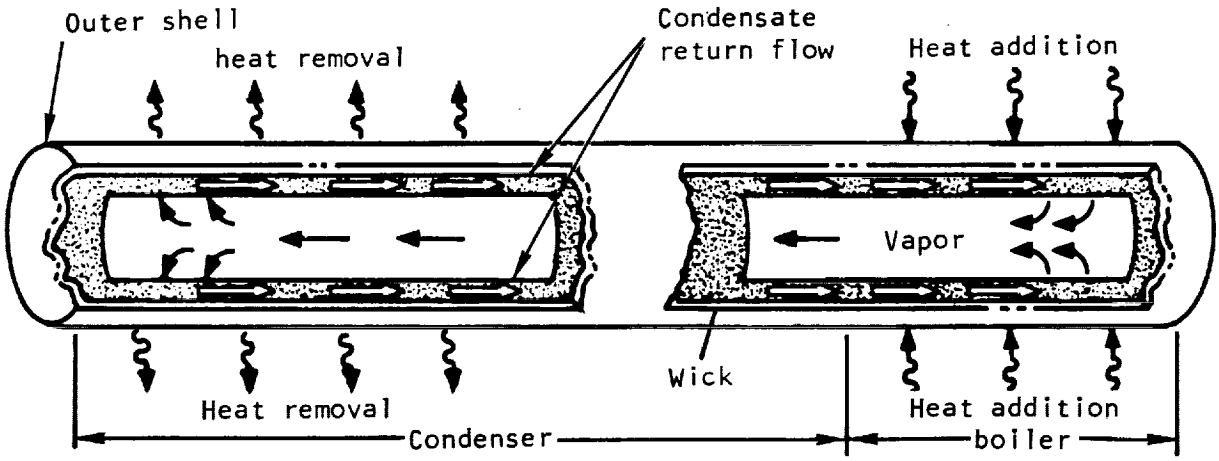
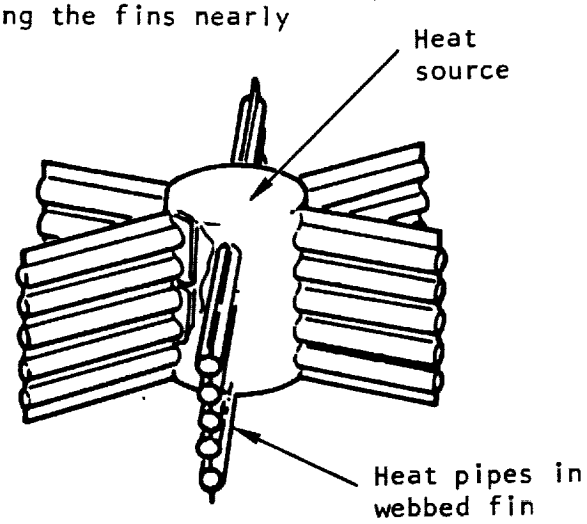


Figure 134. An Aqua-Ammonia Evaporative Oil Cooling System (50-KW Capacity)

Basic heat pipe: Heat is being carried by the vapor from the heat addition (boiler) end to the heat removal (condenser) end at enormous rate. The return of the condensate is accomplished by the capillary action inside the wick.



Heat pipes as an integral part of radiation fins, with the heat pipes keeping the fins nearly isothermal



S-49166

Figure 135. Cooling by Heat Pipes

Fig. 136 shows a stator-rotor assembly that is cooled by the method of expendables. Water flows along the passages in the stator housing and the vaporized water is dumped overboard.

Cryogenic cooling.--One reason cryogenic fluids are attractive in electrical and electronic cooling is the fact that the electric resistances of a lot of conductor materials decrease almost linearly with temperature. This fact has been successfully utilized to transport enormous amounts of electricity over long distances in ground applications. Fig. 137 shows such an arrangement where 3000 mva is transmitted using liquid hydrogen. Cooling is not a problem in this type of application but the prohibitive reason for aircraft usage is that the refrigeration plant amounts to too much of the system weight. On the other hand, the expendable type of arrangement should eliminate the complete refrigeration plant and retain all the advantages of cryogenic cooling.

Improved heat rejection.--For improved heat rejection from high power dissipation electrical components, a liquid or air cooled heat exchanger commonly known as a heat sink is attached to the component. For smaller components such as TO-5 and TO-8 case size transistors, a circular finned heat sink is pressed on the housing. Power transistors, small diodes and SCR's may be bolted to an extruded aluminum heat sink. Large SCR's and diodes may be stud or clamp mounted to large extruded aluminum heat sinks. Improvements in heat sink weight and volume requirements may be achieved by using pin-fin or plate-fin forced convection air-cooled heat sinks or liquid-cooled cast, machined, or plate-fin heat sinks. Table 66 gives the thermal conductance per unit weight and volume for both natural convection and forced convection cooled heat sinks. This table indicates that higher thermal conductance per unit weight and volume is obtained with the small component heat sinks. Forced convection improves the thermal conductance per unit weight and volume by a factor of 2 to 4. Forced convection pin-fin and plate-fin air cooled heat sinks are 4 to 9 times better than extruded heat sinks per unit weight and volume. Liquid cooled heat sinks are 3 to 12 times better than extruded aluminum air cooled heat sinks.

Internal heat ducting from hot spot.--Internal ducting into the heat source has two advantages. One is that additional heat transfer area is obtained as a gain and the other is that the transport medium can make direct contact with the heat source for maximum cooling efficiency. This technique has been successfully used to cool windings of generators of large ratings for the past sixteen years, using pressurized hydrogen gas. Recently water has been used in place of hydrogen gas to obtain even higher performance. The application of this technique to machinery of smaller ratings is certainly feasible but needs further trade-off and design studies.

In case internal ducting can result in the shifting of a hot spot to another location, thermal de-coupling (or isolation) of the heat source from the other portion of the system may be necessary.

Heat pipes described previously can certainly be investigated for future applications in conjunction with this technique.

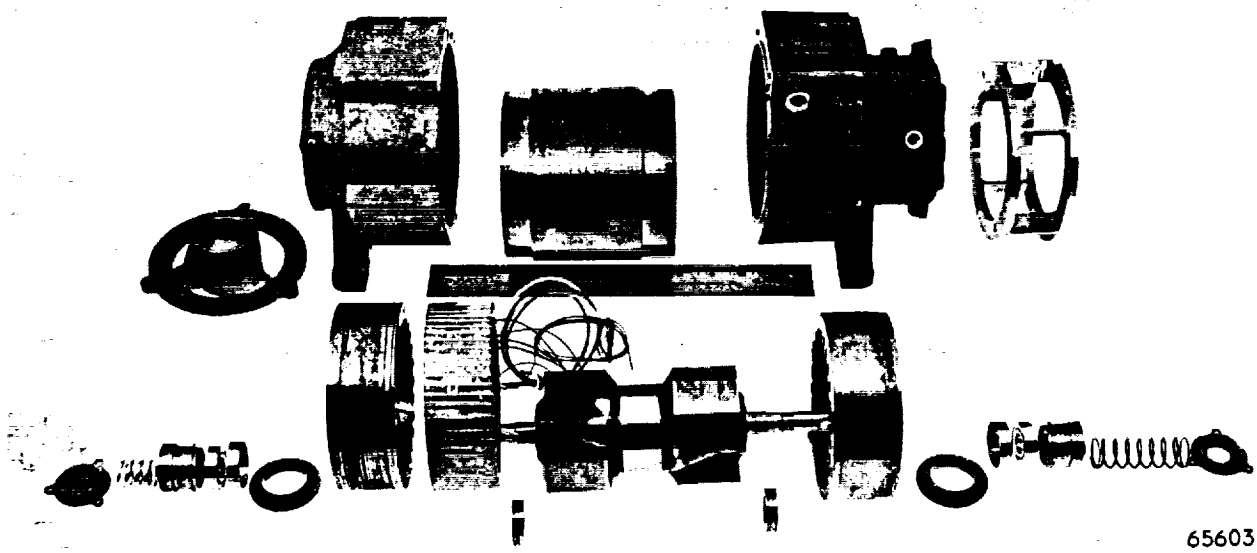


Figure 136. Stator-Rotor Assembly Cooled by Evaporating Water Flowing Through Internal Passages in Rotor and Stator

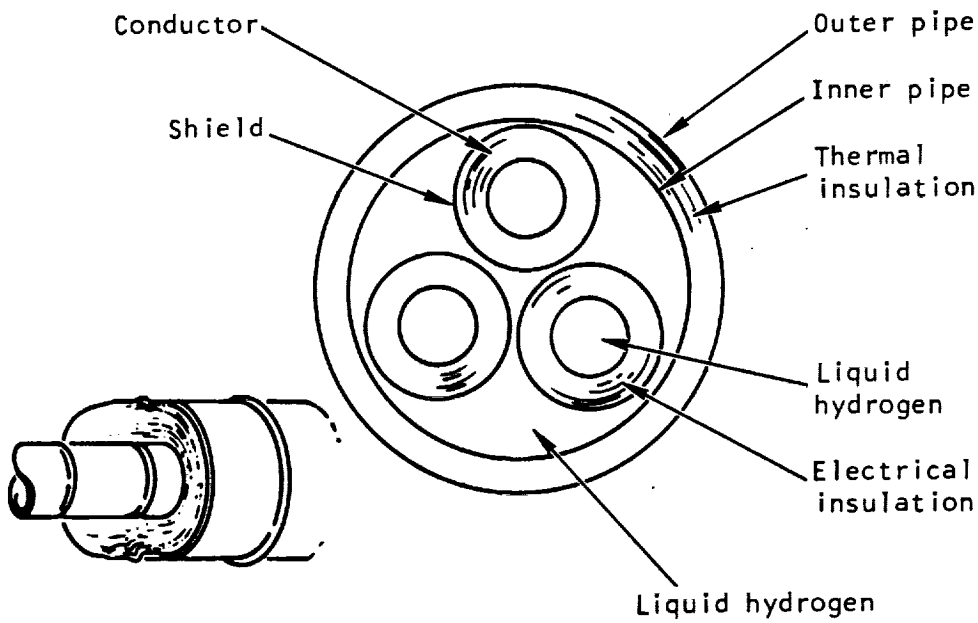


Figure 137. AC Transmission Cables Cooled by Liquid Hydrogen

TABLE 66.--SUMMARY OF HEAT SINK THERMAL CONDUCTANCE PER UNIT OF WEIGHT AND VOLUME

Type of Heat Sink		Coolant	Thermal Conductance per Unit Weight Watts/$^{o}K^{o}kg$	Velocity Air m/s	Thermal Conductance per Unit Volume Watts/$^{o}Kcm^{3}$
Natural Convection	Small transistor (TO-5, TO-8) heat sink	Air 0.1MN/m^2 (1 atm) pressure	13.7	-	5.6
Natural Convection	Power semiconductor (TO-3, TO-36, 2N1016) extruded aluminum heat sinks	Air 0.1MN/m^2 (1 atm) pressure	3.94	-	0.645
Natural Convection	Large SCR, diode extruded aluminum heat sinks	Air 0.1MN/m^2 (1 atm) pressure	1.37	-	0.179
Natural Convection	Press-pak semiconductor extruded aluminum heat sinks	Air 0.1MN/m^2 (1 atm) pressure	1.04	-	0.261
Forced Convection	Large SCR, diode extruded aluminum heat sinks	Air	2.27 4.31	1.02 5.08	0.297 0.562
Forced Convection	Press-pak semiconductor extruded aluminum heat sinks	Air	2.40 5.14	1.02 5.08	0.314 0.67
Forced Convection	Pin fin heat sinks for power semiconductors	Air	16.4 36.75	1.02 5.08	3.86 8.65
Forced Convection	Plate-fin heat sinks for power semi-	Air	21 42	1.02 5.08	7.7 15
Forced Convection	Cast or machined passage (aluminum) for large SCR's and diodes	Oil	12	-	6.9
Forced Convection	Cast or machined passages (aluminum) for large SCR's and diodes	Water	62.5	-	20.8
Forced Convection	Plate-fin (aluminum) for large SCR's and diodes	Oil	14	-	8.63

Thermal network synthesis.--It should be a big improvement in analyzing methods if optimization techniques can be incorporated into existing performance-predicting thermal analysis computer programs to provide information on optimum thermal design and trade-off comparisons. AiResearch has computer programs that give detailed steady-state and transient temperature distributions for systems of any geometrical complexity with a maximum of thirty fluid streams flowing through them. These programs use analogous electrical network for thermal calculations and thus are readily adapted to network synthesis techniques.

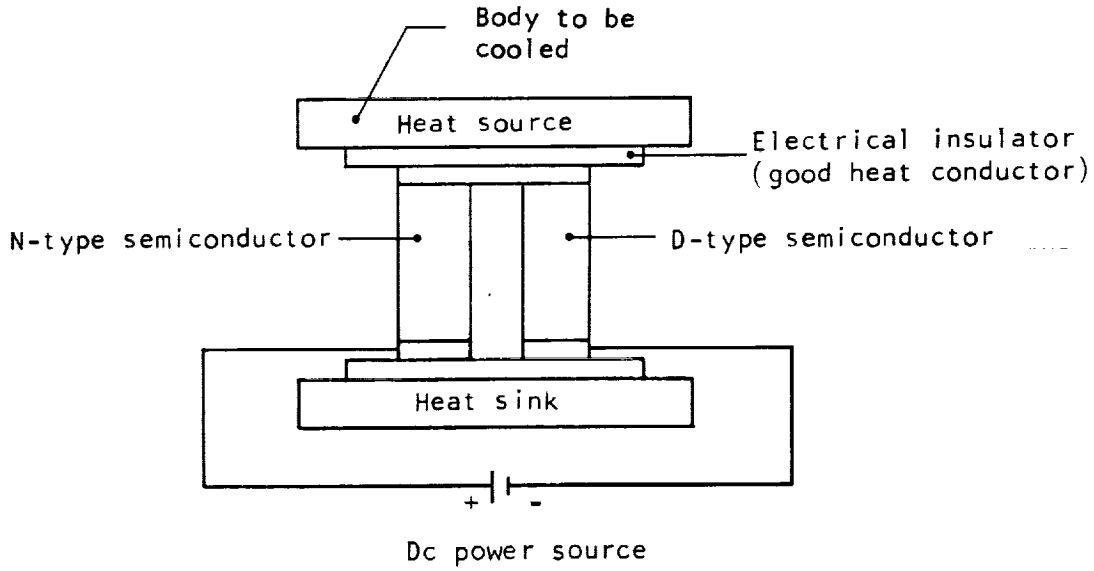
Thermoelectric refrigeration.--The thermoelectric cooling method is finding increased use in industry and electric component cooling. Also, on aircraft it is being used for water coolers and will probably be adopted for a number of other uses as thermoelectric materials improve. The following is a brief review of the principle of operation, requirements, and characteristics of thermo-electric coolers. (Ref. 36.)

Principle of operation: Thermoelectric cooling follows the same basic laws of thermodynamics, and the principles are essentially the same as in conventional refrigeration. The refrigerant in both liquid and vapor form is replaced by two dissimilar conductors. The freezer surface becomes cold through absorption of energy by the electrons as they pass from one semiconductor to another instead of becoming cold through energy absorption by the refrigerant as it changes from liquid to vapor. An electrical dc power source is used instead of a compressor. The power source pumps the electrons from one semiconductor to another. Instead of a conventional condenser, a heat sink is used to set off the accumulated heat energy from the system.

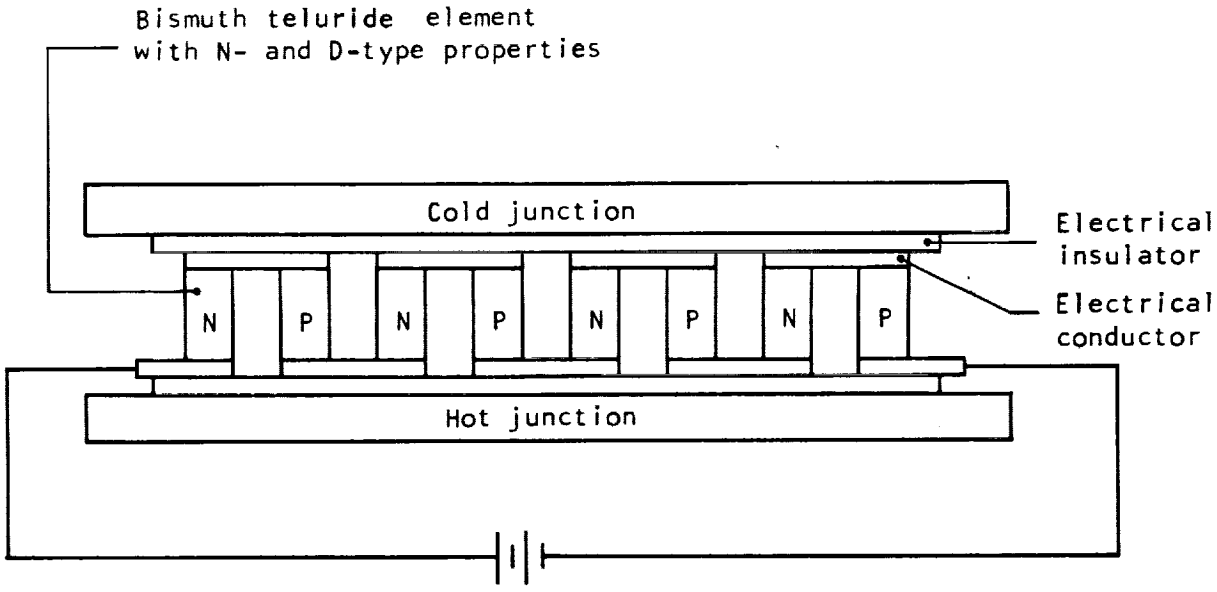
The two refrigeration methods therefore are different in that the thermoelectric cooling system operates without use of mechanical devices or refrigerant. A thermoelectric cooler is schematically shwon in fig. 138a.

Semiconductor materials with dissimilar characteristics are connected electrically in series and thermally in parallel, resulting in two junctions. Heat absorbed at the cold junction is pumped to the hot junction at a rate proportional to carrier current passing through the circuit and the number of semiconductor elements.

Good thermoelectric semiconductor materials, such as Bismuth Telluride, greatly impede conventional heat conduction from hot to cold areas, but provide as easy flow for the carriers. In practical use couples, such as those shown in fig.138a are combined in a module where they are connected electrically in series and thermally in parallel as shown in fig. 138b. Normally a module is the smallest component available. Modules come in a great variety with differences in size, shape, operating current and voltage, number of couples, and range of heat pumping level. Presently, modules with a large number of couples that operate at low currents are mostly used. A module may contain up to 100 couples with ceramic-metal laminated plates at both the hot and cold junctions providing good thermal conduction and electrical insulation. A module has a single pair of connecting leads. The single-stage module is capable of pumping heat when the temperature difference between the cold junction and the hot junction is 343°K (70°C) or less. For applications requiring greater



(a) Single element



(b) Assembly of elements

Figure 138. Thermoelectric Cooler Module Assembly (ref. 36)

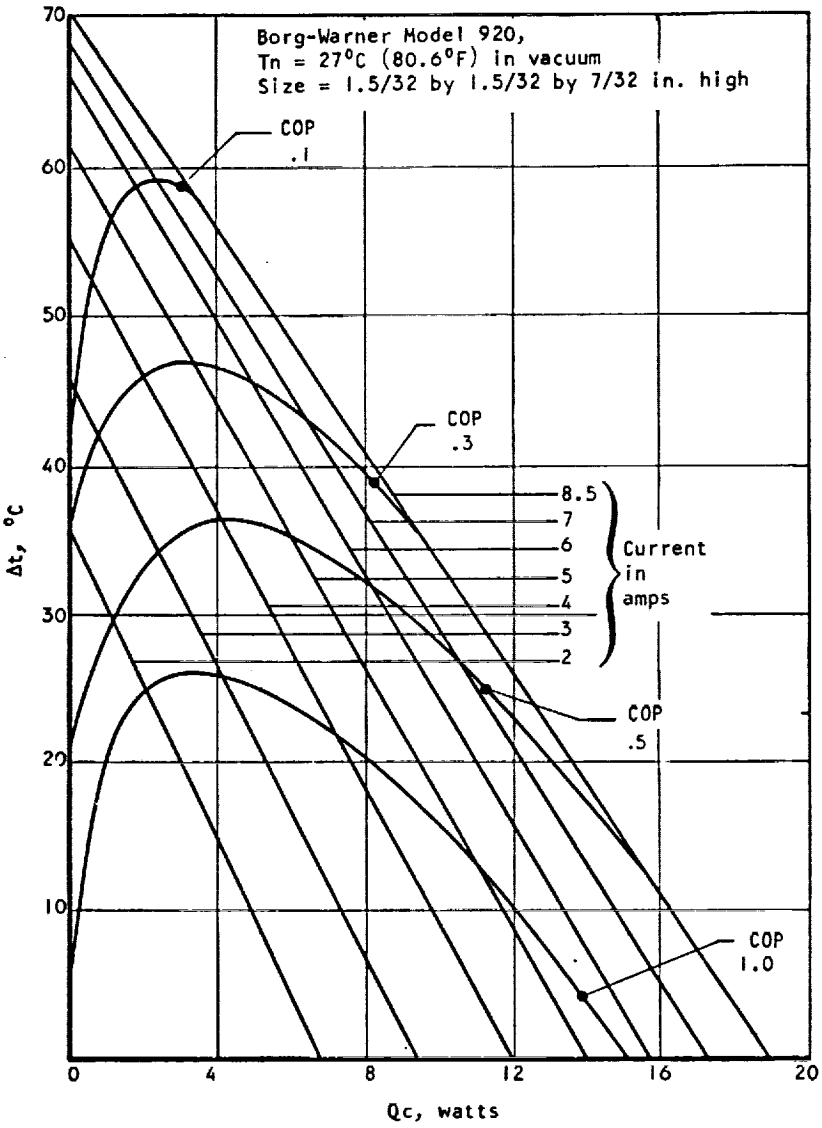
temperature differences, the modules can be cascaded. Practical limits of temperature differences up to 298°K (125°C) are possible with about five stages of cascading. Each module also may be used as an efficient heater by reversing the polarity of the supply. There are two modes of operation which characterize module performance: operation at maximum heat pumping capacity (Qc) and operation at maximum coefficient of performance (COP). COP terminology is used as a measure of cooling process efficiency. COP generally ranges from 0.1 to 1.0 for thermoelectric cooling applications. It is defined as the ratio of the heat absorbed by the module cold face to the electrical power supplied.

Typical characteristics: The important parameters for establishing module performance are (1) total heat load, (2) module current and voltage, (3) required cold side temperature, (4) hot side ambient temperature, and (5) COP. The relationship of these parameters is shown in fig. 139. The thermoelectric module is the Borg-Warner model number 920 designed for a heat sink temperature of 300°K (27°C). To illustrate the utility of these curves, the following example is considered: the desired operating temperature of a diode is 265°K (-8°C) and the hot junction temperature can be maintained at 300°C (+27°C). The cooler is required to pump a total heat load of 6 W from the diode and surrounding environment. In fig. 139a a vertical line is drawn from the point Q_c = 6 W. The total temperature difference 35°K. Now a horizontal line is drawn at the point Δt = 35°K. At the point of intersection, COP = 0.5 and current I = 5 A. The power supply voltage may be selected by using fig. 139b. A vertical line is drawn from the point I = 5 A to a point halfway between Δt max and Δt = 0. Then, a horizontal line is projected to the voltage axis, which yields 2.35 V. A heat load of 60 W at Δt = 35°K and I = 5 A could be cooled by using 10 modules thermally in parallel and electrically in series with a power supply to 23.5 V.

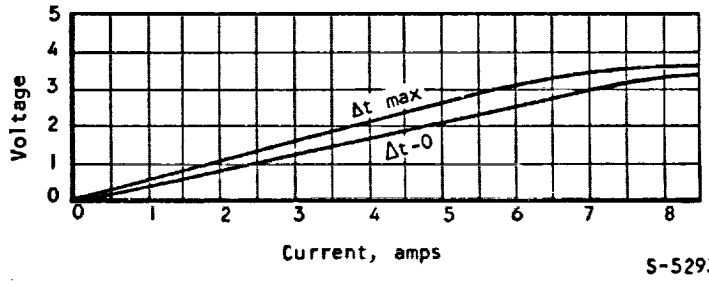
Where desired temperature differences cannot be obtained with a single-stage module, cascaded modules are used. Since the cold-surface temperature is much colder than the ambient temperature, caution should be used to adequately insulate the cold surface from extraneous heat loads (generally, radiation and convection from the surrounding ambient). For a more efficient operation, it is recommended to use encapsulated modules in vacuum packages where feasible. Performance of high-efficiency cascades in ambients other than a vacuum is difficult to predict accurately since the cold side temperature varies greatly with the air density, ambient temperature, relative humidity, frost load, and convective air currents. The performance of a cascaded thermoelectrical device is substantially decreased by operation in dry nitrogen or dry air at atmospheric pressure due to convection (see fig. 140).

Power supply: Model design currents for a system may range from 1 to 100 A and voltages from 0.1 to 100 V. The module functions only with a dc supply that should have less than 10 percent ripple content for best efficiency. Fig. 141 illustrates the effect of dc ripple on the temperature difference a single-stage module may attain. The vertical axis is a ratio of the temperature difference attained with ripple (and Q_c = 0) to the maximum Δt that occurs for Q_c = 0 and zero ripple. The dependancy is:

$$\frac{\Delta t}{\Delta t \text{ max}} = \frac{1}{1 + N^2}$$



(a) Module ΔT vs heat pumping capacity



(b) Module voltage

Figure 139. Thermoelectric Cooler Characteristics (ref. 36)

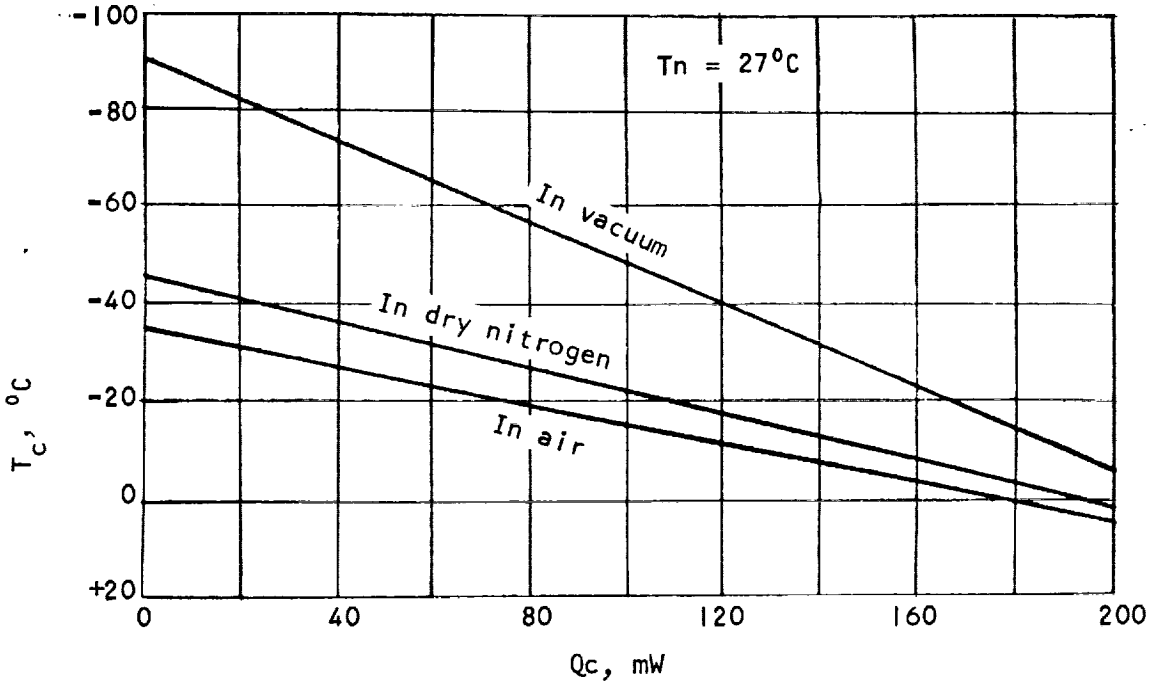


Figure 140. Performance of Borg-Warner Model 670 (ref. 36)

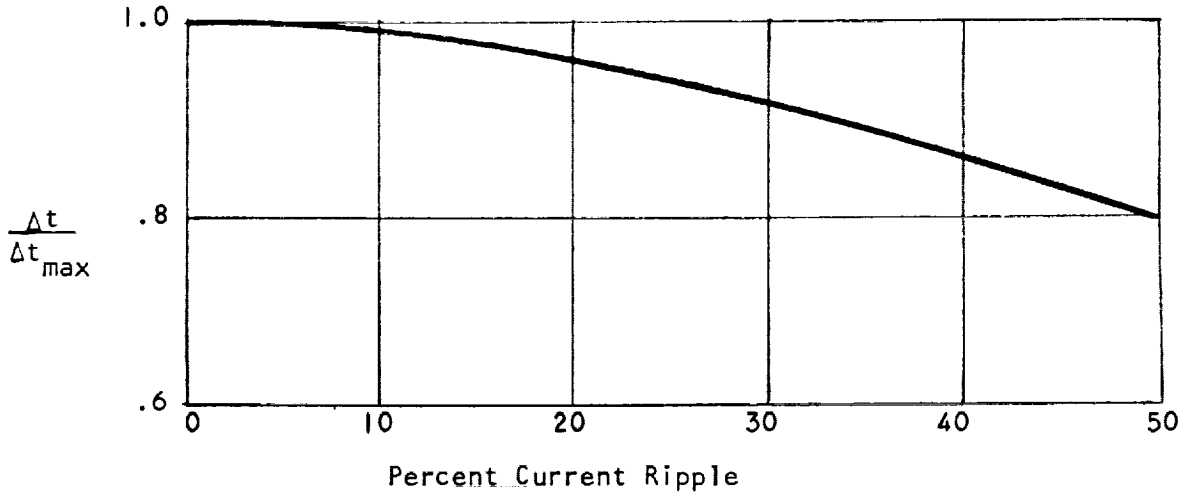


Figure 141. Effect of dc Ripple on Temperature Difference of Junction (ref. 36)

where N is the current ripple in per unit.

Transformer rectifier units used in aircraft are usually in the three-phase full-wave bridge configuration, and there is no separate filtering necessary since this circuit provides inherently a ripple which is 4.2 percent. According to fig. 14[the effect of ripple to junction temperature difference is negligible if the ripple content is less than 10 percent.

Component Reliability Tradeoffs

The reliability of the aircraft electrical power system depends upon the reliabilities of its components. Aircraft electrical components are usually designed for light weight and small size so as to maximize the payload of the vehicle. However, high reliability components are usually accompanied by heavy weight and high cost. Reliability as a function of weight, size, or cost is a tradeoff that often arises, particularly in airborne applications.

The life of an electrical component depends on many factors, typically operating voltage, current, power dissipation, stress, shock, vibration, temperature, cooling, humidity, altitude, corrosion, and radiation. It is not the intent of this study to perform a complete analysis of the reliability and weight tradeoffs of the above factors; only a general method of approach with a few specific examples will be given. Reliability improvements by redundancy and by better system protection are not included in this discussion. The tradeoff between reliability and weight, however, is investigated. In most cases, the component size and cost vary in the same sense as the component weight.

Designing for reliability.--Generally, the life of electrical components is closely related to their physical size, which varies with the designed mechanical strength, electric current and magnetic flux densities, amount of insulation used, operating temperature, etc. Obviously, one way to improve the component reliability is to design the component with more margin of safety. The relationship between the margin of safety and reliability can be derived as follows with the relationship between weight penalty and margin of safety being determined individually for each component and for each factor under consideration.

The actual strengths (mechanical, electrical, chemical, or thermal) of supposedly identical components vary according to the normal or Gaussian distribution. The probability of a component having a strength X is given by

$$\text{Probability} = \frac{1}{\sigma\sqrt{2\pi}}\, \epsilon^{-\frac{(X-S_m)^2}{2\sigma^2}}$$

where S_m = mean strength

σ = standard deviation of strength distribution

This probability curve is shown as Curve A in fig. 142. If this curve is integrated, the resulting Curve B (fig. 142) will show the probability that the component strength is less than X.

p_x = probability that strength is less than X

$$= \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{X} \epsilon^{-\frac{(X-S_m)^2}{2\sigma^2}} dx \qquad (24)$$

Letting

$y = \frac{1}{\sigma}(X-S_m)$, eq. (24) is transformed into

$$p_x = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{X-S_m}{\sigma}} \epsilon^{-\frac{1}{2}y^2} dy$$

$$\left.\begin{aligned} &= \frac{1}{2} - \frac{1}{\sqrt{2\pi}} \int_{-\frac{S_m-X}{\sigma}}^{\frac{S_m-X}{\sigma}} \epsilon^{-\frac{1}{2}y^2} dy \quad \text{if} \quad X \le S_m \quad \text{(a)} \\ &= \frac{1}{2} + \frac{1}{\sqrt{2\pi}} \int_{-\frac{X-S_m}{\sigma}}^{\frac{X-S_m}{\sigma}} \epsilon^{-\frac{1}{2}y^2} dy \quad \text{if} \quad X > S_m \quad \text{(b)} \end{aligned}\right\} \qquad (25)$$

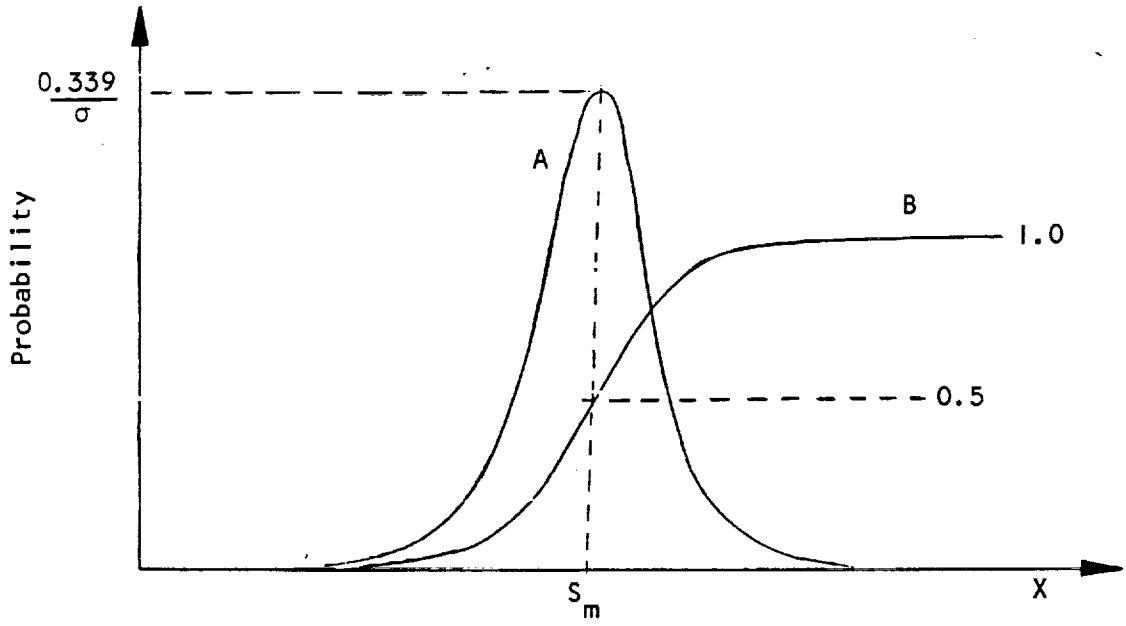
According to J. D. Williams (annual of mathematical statistics, vol. 17, pp. 363-365):

$$\frac{1}{\sqrt{2\pi}} \int_{-X}^{X} \epsilon^{-\frac{1}{2}t^2} dt \cong \sqrt{1 - \epsilon^{-\frac{2X^2}{\pi}}} \qquad (26)$$

and the error in above approximation is less than 0.75 percent for any value of X. Substituting eq. (26) into eq. (25):

$$p_x = \frac{1}{2} \mp \sqrt{1 - \epsilon^{-\frac{2}{\pi}\left(\frac{X-S_m}{\sigma}\right)^2}}$$

$\begin{pmatrix} - \text{ if } X \le S_m \\ + \text{ if } X > S_m \end{pmatrix}$



Curve A = strength distribution

Curve B = probability that strength is less than X

Figure 142. Probability Distribution of Component Strength

The applied load (stress) to the component is also distributed. The probability that the load is equal to X is given by

$$L_x = \frac{1}{\sigma_l \sqrt{2\pi}} \epsilon^{-\frac{(X-L_m)^2}{2\sigma_l^2}}$$

where L_m = mean value of maximum applied load

σ_l = standard deviation for load distribution

When the applied load is X, all the components with strength less than X will fail. Therefore, the integration of the product $p_x L_x$ indicates the probability of failure.

F = probability of failure

$$= \int_{-\infty}^{\infty} p_x \, L_x \, dx$$

$$= \frac{1}{\sigma_l \sqrt{2\pi}} \int_{-\infty}^{S_m} \epsilon^{-\frac{(X-L_m)^2}{2\sigma_l^2}} \left[\frac{1}{2} - \sqrt{1 - \epsilon^{-\frac{2}{\pi}\left(\frac{X-S_m}{\sigma}\right)^2}} \right] dx$$

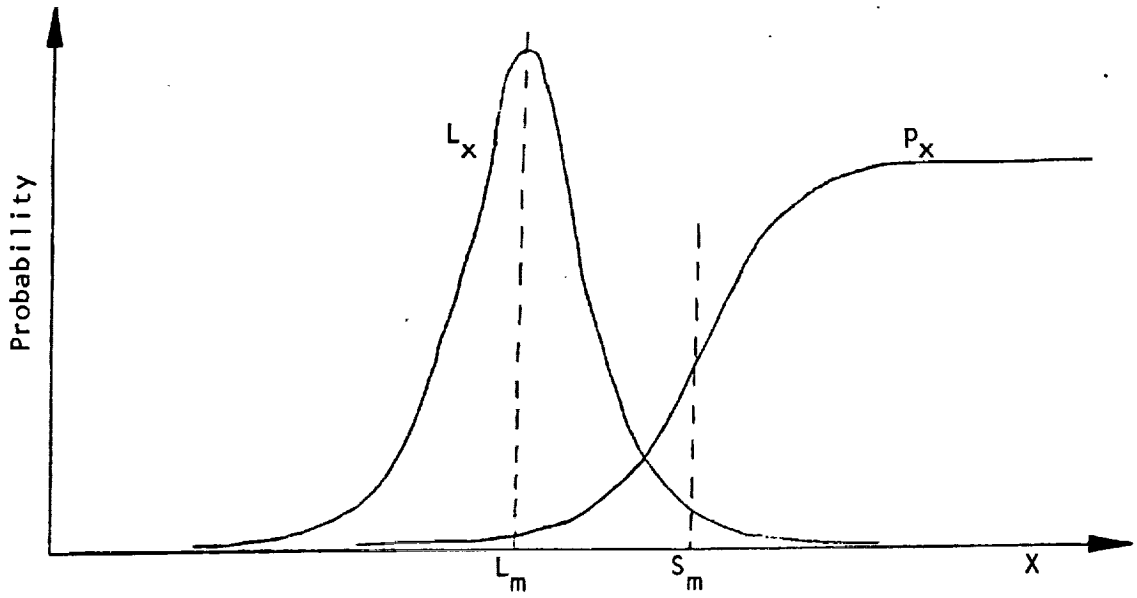
$$+ \frac{1}{\sigma_l \sqrt{2\pi}} \int_{S_m}^{\infty} \epsilon^{-\frac{(X-L_m)^2}{2\sigma_l^2}} \left[\frac{1}{2} + \sqrt{1 - \epsilon^{-\frac{2}{\pi}\left(\frac{X-S_m}{\sigma}\right)^2}} \right] dx \qquad (27)$$

Fig. 143 shows the P_x and L_x curves, and fig. 144 shows the product of these two curves.

The integration of eq. (27) can be performed by expanding the quantity of the square root into an infinite series. The result is:

$$F = \sum_{k=1}^{\infty} f(k) \epsilon^{-\frac{2k}{\pi}\left(\frac{S_m - L_m}{\sigma_l}\right)^2} + \sum_{k=1}^{\infty} f(k) \frac{\epsilon^{-C_{1k}}}{\sqrt{\frac{1}{\sigma_l^2} + \frac{2k}{\pi\sigma^2}}} \sqrt{1 - \epsilon^{-\frac{2}{\pi} C_{2k}^2}}$$

where $f(k) = \dfrac{\frac{1}{2}\left(\frac{1}{2} - 1\right) \cdots \left(\frac{1}{2} - k + 1\right)}{2K!}$



Curve L_x = load stress distribution

Curve p_x = probability that component strength is less than x

Figure 143. Stress and Strength Distributions

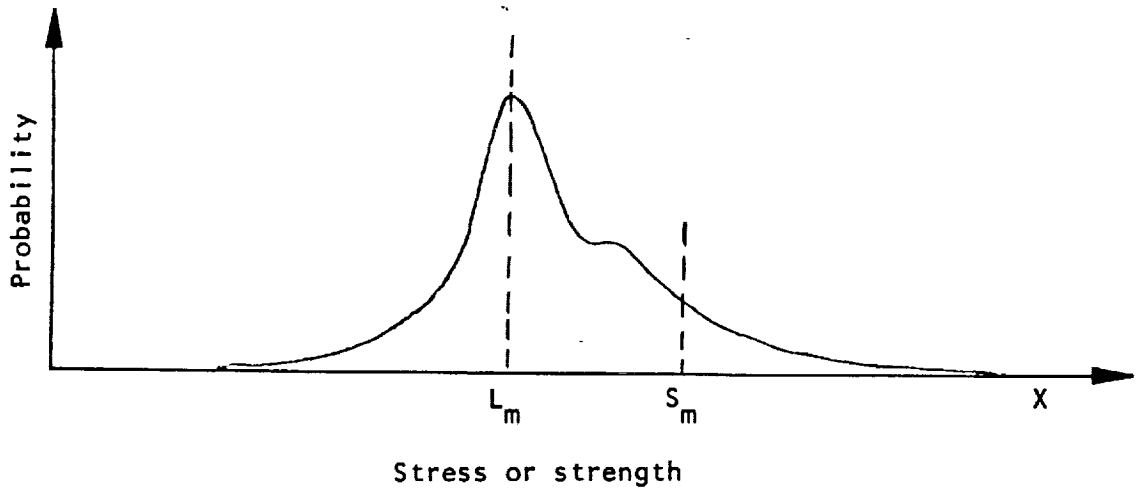


Figure 144. Product of L_x and p_x

$$C_{1k} = \frac{L_m^2}{2\sigma_1^2} + \frac{KS_m^2}{\pi\sigma^2} - \frac{\left(\frac{L_m}{\sigma_1^2} + \frac{2KS_m}{\pi\sigma^2}\right)^2}{2\left(\frac{1}{\sigma_1^2} + \frac{2K}{\pi\sigma^2}\right)}$$

$$C_{2k} = \frac{S_m - \frac{\frac{1}{\sigma_1^2} + \frac{4kS_m}{\pi\sigma^2}}{\frac{1}{\sigma_1^2} + \frac{4k}{\pi\sigma^2}}}{\sqrt{\frac{1}{\sigma_1^2} + \frac{4k}{\pi\sigma^2}}}$$

For a particular case of $\sigma = \sigma_1 = 0.05$, and $L_m = 1.0$, the variation of probability of failure F vs designed strength S_m is given in fig. 145. Another example of F vs S_m for $\sigma = \sigma_1 = 0.1$ and $L_m = 1.0$ is shown in fig. 146.

The ratio:

$$\frac{S_m}{L_m} = \frac{\text{design strength}}{\text{maximum possible load}}$$

is called the safety factor. (Some authors define the safety factor as the ratio of the designed strength to the nominal load. Under that definition, the safety factor is much greater than one.) The quantity $\left(\frac{S_m}{L_m} - 1\right)$ is the margin of safety. According to figs. 145 and 146 when the margin of safety is greater than 4σ of the stress distribution, the component is reasonably reliable (i.e., the probability of failure is less than 0.00093 percent).

Component reliability tradeoffs.--The tradeoffs of reliability and weight of some major aircraft electrical components are discussed below:

Electric motors: The electrical failure rate of aircraft motors can be expressed in the equation

$$\lambda_e = \lambda_b \pi_g \pi_t$$

where λ_b = basic electrical mode failure rate dependent on hot spot temperature and class of insulation

π_g = adjustment factor for environmental service and MIL-T-27A construction grade

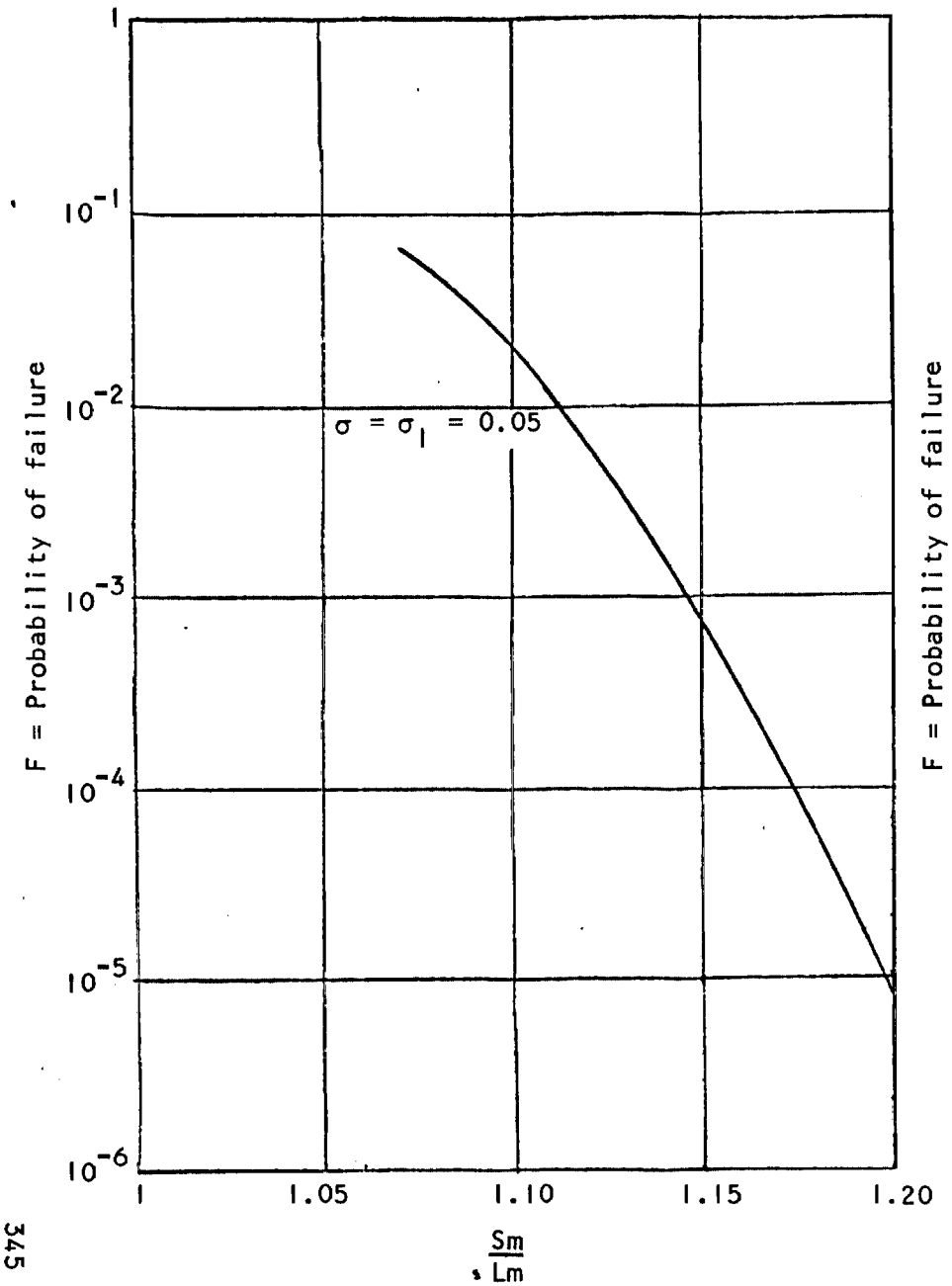


Figure 145. F vs Sm/Lm, $\sigma = \sigma_1 = .05$

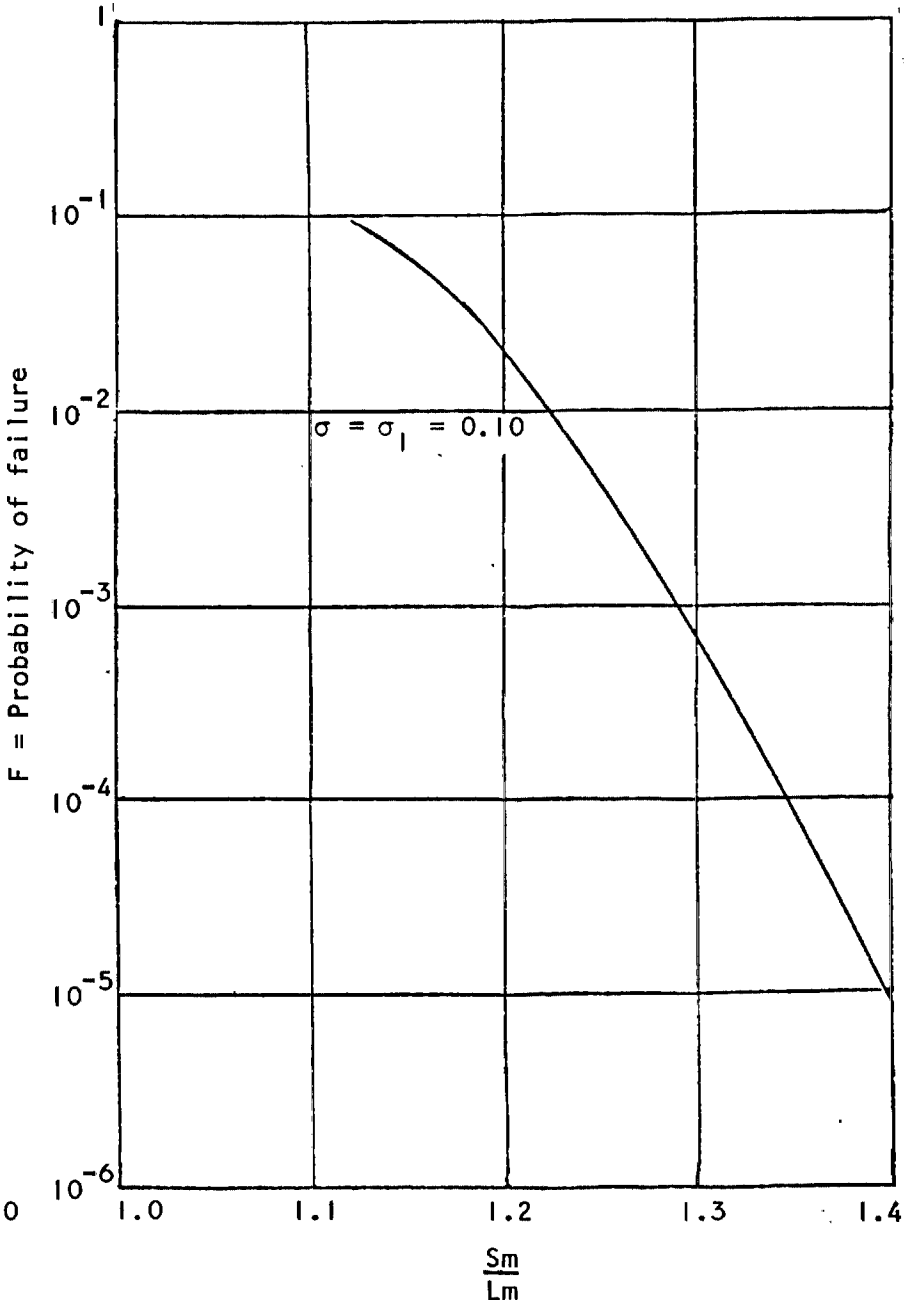


Figure 146. F vs Sm/Lm, $\sigma = \sigma_1 = .1$

π_t = adjustment factor for type of motor

The representative values of λ_b are shown in fig. 147 as a function of hot spot temperature for various classes of insulation. This figure is taken from the RADC Reliability Notebook, vol. II.

An example will illustrate how to use the data in fig. 147 for the tradeoff of reliability and motor weight. Consider a class H ac induction motor running at 453°K (180°C) hot spot temperature. The basic failure rate shown in fig. 147 is about 0.001 percent per 1000 hr. To increase the motor life (considering electrical failure only) by 50 percent, or to reduce the failure rate to 0.00067 percent per 1000 hr, fig. 147 shows that the hot spot temperature should be reduced to 413°K (140°C). If the ambient temperature is 323°K (50°C), the hot spot temperature rise should be decreased from 403°K (130°) to 363°K (90°C). This means approximately that the stator copper losses, hence the stator resistance, should be reduced to (90/130) or 70 percent. Lower operating temperature accounts for about 10 percent lower resistance. To obtain a 70-percent stator resistance, the area of the winding conductor must be increased by about 28 percent (1 x 0.9/1.28 = 0.7). Therefore, to increase the motor life by 50 percent, the new motor must have about 28 percent more copper with slightly more iron. If the copper weight is about 1/3 of the motor weight, the new motor will be approximately 10- to 12-percent heavier.

The representative values of mechanical mode failure rate λ_m for aircraft electric motors are shown in fig. 148 (RADC Reliability Notebook, vol. II). If it is desired to improve the motor reliability by choosing a motor of lower operating speed, the tradeoff between reliability and weight can be obtained by using fig. 148 and the motor weight vs speed curve, fig. 70, p. 202.

Transformers: Like other electromagnetic components, the life of a transformer depends on the presence of moisture, vibration, corona, heat, etc. Heat is a stress of major importance in the steady state, as well as in temperature cycling and thermal shock. In ordinary reliability analysis, the failure rate of a transformer is expressed as

$$\lambda = \lambda_b \pi_g \pi_n \pi_f$$

where λ_b = basic failure rate based on hot spot temperature and insulation class

π_g = modifier based on conditions of environmental service and MIL specification grade

π_n = modifier based on the number of terminals

π_f = modifier based on the relationship between transformer type and effect on failure rate

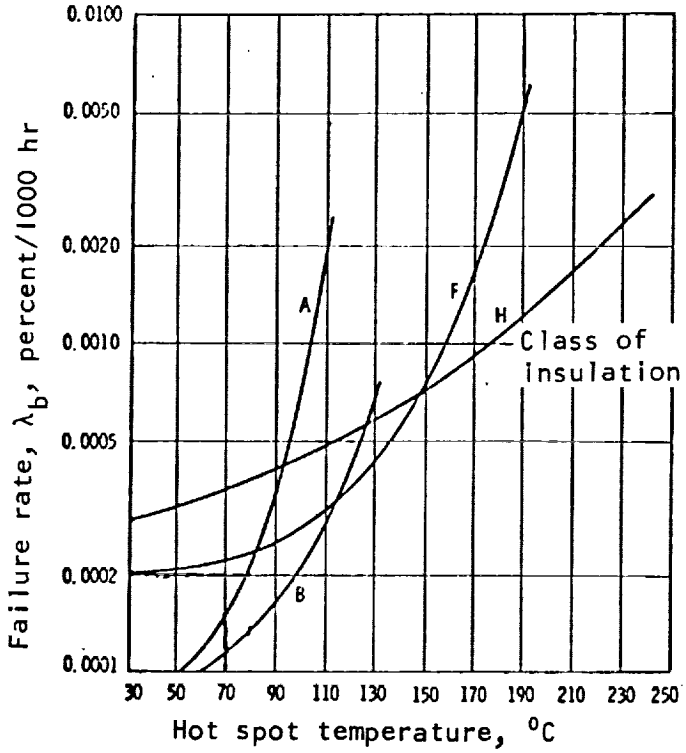


Figure 147. Basic Failure Rate, Rotating Devices (from RADC Reliability Notebook)

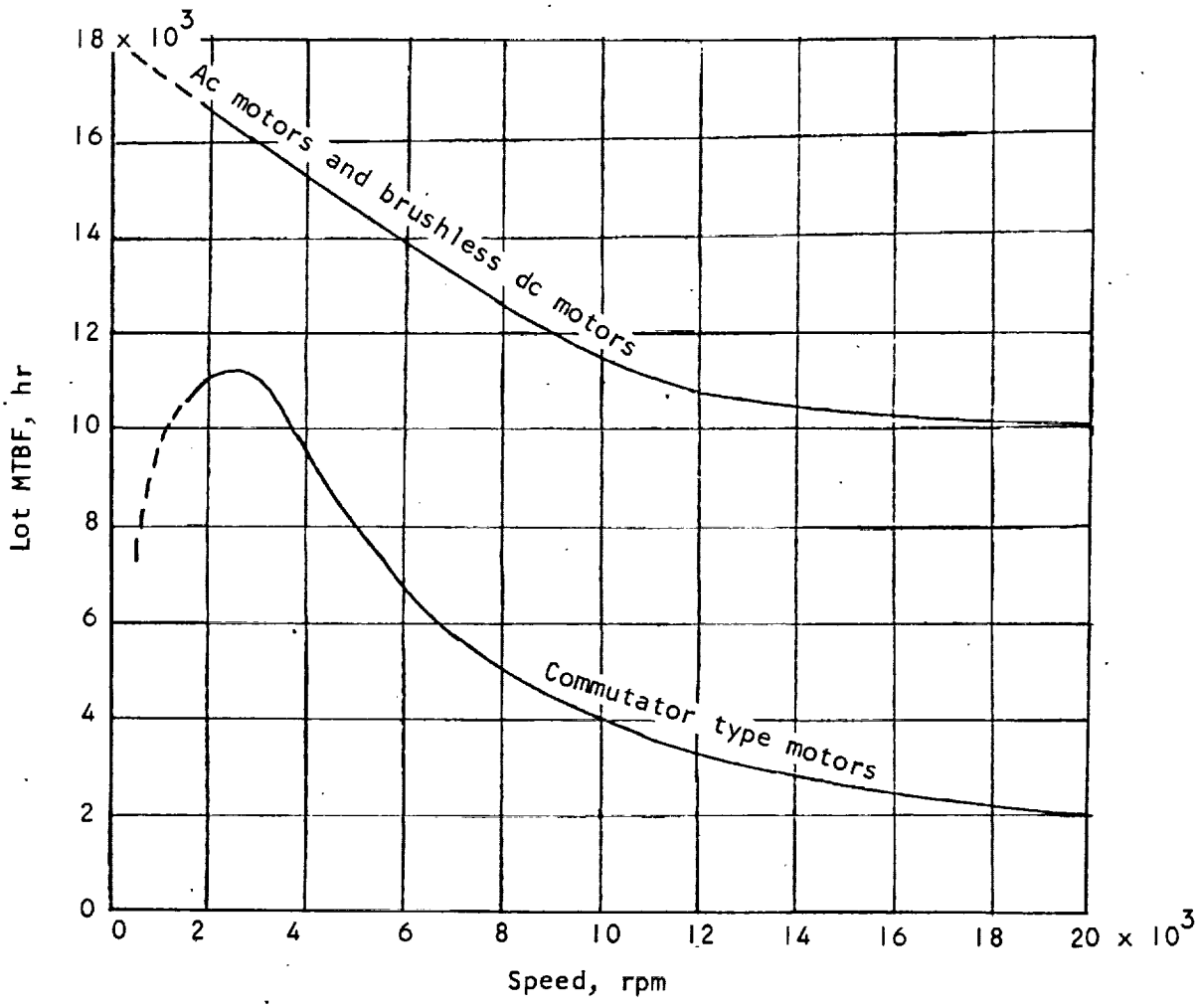


Figure 148. MTBF of Rotating Devices, Mechanical Failure Only (Conventional Design)

The reliability and weight tradeoff for aircraft transformers can be obtained from the curves in figs. 149, 150 and 151 which are taken from the RADC Reliability Handbook, vol. II. Fig. 149 is the basic failure rate with respect to hot spot temperature and class of insulation. Fig. 150 shows the relationship of average temperature rise and power loss for a transformer with various case symbol (MIL-T-27). Fig. 151 shows the average temperature rise vs transformer weight with various power losses.

An example will explain how to use these curves for a reliability and weight tradeoff study. Given a 2-kva transformer, class B insulation, 35 w total loss, 4.5 kg (10 lb) weight, case symbol GA, ambient temperature 303°K. Determine the weight penalty if it is desired to double the life of the transformer.

From either fig. 150 or 151, the average temperature rise of the transformer winding is 80°K. The hot spot temperature is therefore about 403°K (130°C) (ambient + temperature rise + hot spot allowance). According to fig. 149, basic failure rate for this class B transformer at 403°K (130°C) hot spot temperature is 0.0007. To double the life, the failure rate should be reduced to 0.00035. This puts the permissible hot spot temperature to 388°K (115°C) or the average temperature rise to about 65°K. Going back to fig. 150, assume that there is no change in the case. (This is a trail and error process. After determining the final weight of the transformer, if this assumption is off, a new case should then be used and the process will be repeated.) With case GA and 65°K temperature rise, the power loss is found to be about 29 W. Go to fig. 151 with 29 W loss and 65°K rise, the new weight of the transformer is found to be about 5 kg (11 lb). Since the weight increase is only 10 percent, the assumption of same outside case is about right.) The weight penalty is therefore only about 10 percent.

For a 3-phase transformer, Δ Δ connection has some advantage from the reliability point of view. This is because when one phase is out in a Δ Δ connection the transformer can still operate in open dleta and continue to supply 3-phase power. However, there are many other considerations in selecting transformer connections. This is only one of the factors to be included in the selections.

Synchros and resolvers: Synchros and resolvers are low-speed, low-load rotating devices which are basically rotating transformers. They have the same electrical failure modes of transformers plus the additional problems of reliable connection and physical support for the rotating windings. Since they are low speed and low load, mechanical wear out problems are not serious; the electrical and thermal failure modes predominate. For synchros and resolvers which use three or four brushes, the failure rate can be a function of the number of brushes and the rotor activity in a given application. Where differential temperature coefficients are involved, such as between extended motor casings and cast caps, temperature cycling and temperature extremes may result in a cumulative "cocking" of the rotor and the eventual rubbing between thr rotor and stator. Since these devices are built with small air gaps, this differential thermal expansion should be carefully considered in the design. The reliability data of synchros and resolvers can also be applied to other similar devices such as selsyns, servo motors, elapsed time indicators, etc.

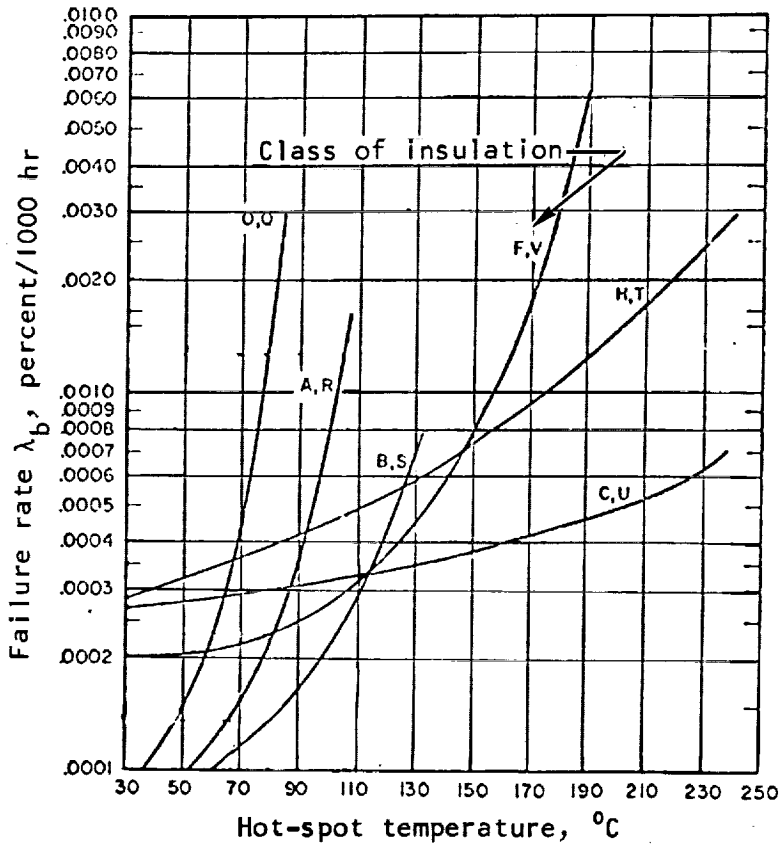


Figure 149. Basic Failure Rate of Transformers (from RADC Reliability Notebook)

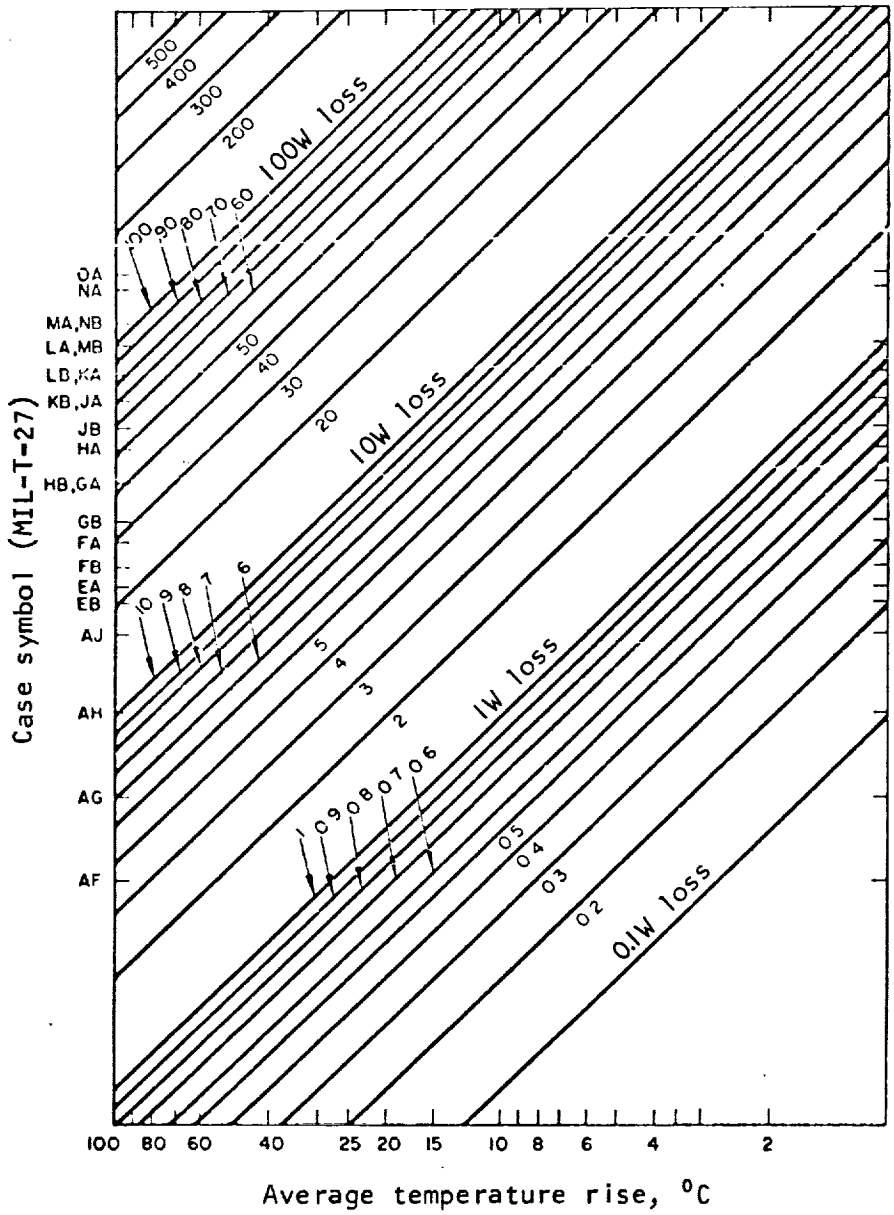


Figure 150. Transformer Case Symbol vs Average Temperature Rise with Power Loss as Parameter (from RADC Reliability Notebook) (Conventional Materials)

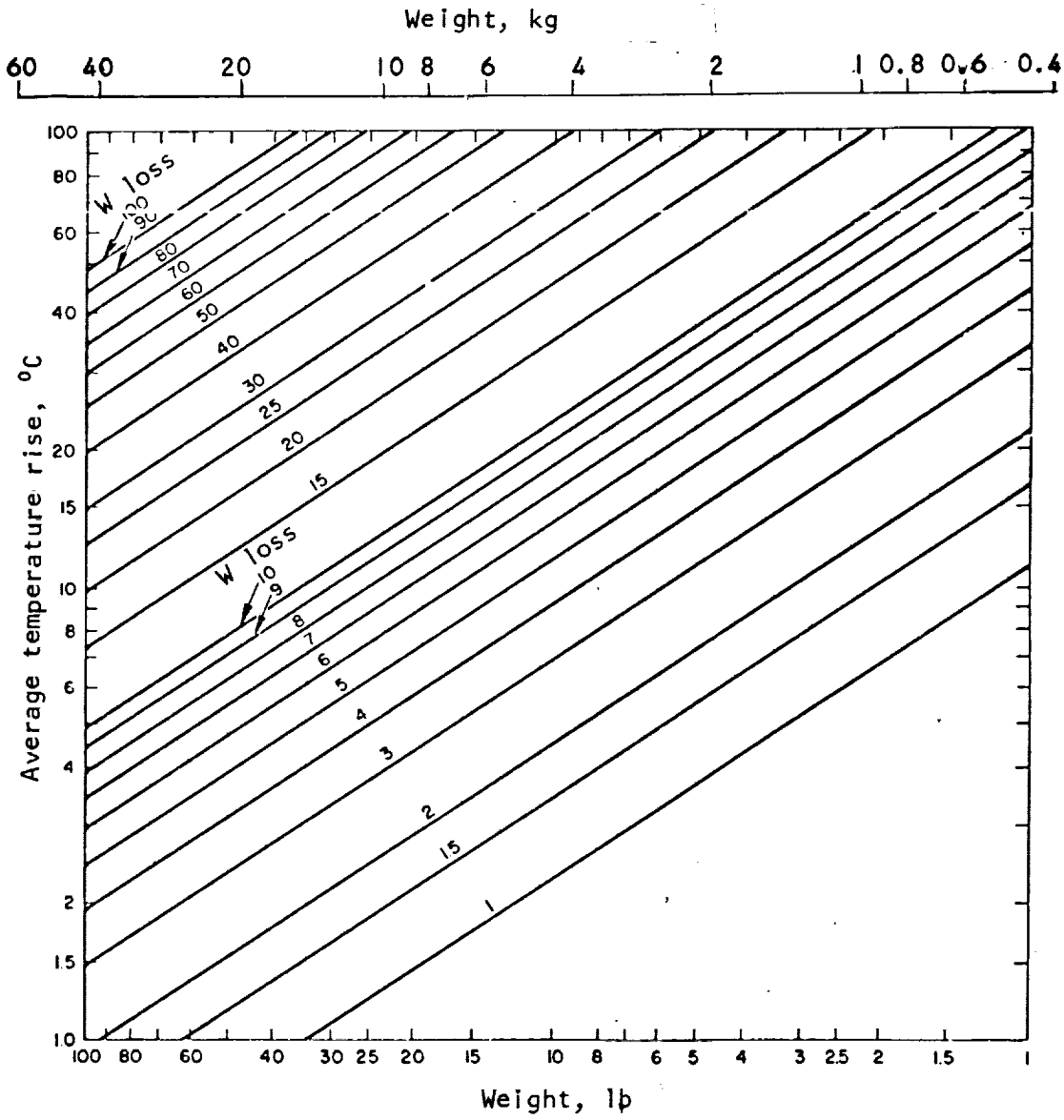


Figure 151. Average Temperature Rise vs Transformer Weight with Power Loss as Parameter (from RADC Reliability Notebook) (Conventional Materials)

The failure rate of synchros and resolvers can be expressed by the following equation:

$$\lambda = \lambda_b \pi_s \pi_n \pi_e$$

where λ_b = basic failure rate depending on the frame temperature

π_s = multiplier based on the type and size of the device

π_n = multiplier based on the number of brushes in the device

π_e = multiplier based on the environmental service

The representative values of basic failure rate as a function of the frame temperature is shown in fig. 152. The frame temperature rise is proportional to the total power loss in the device divided by the total frame surface.

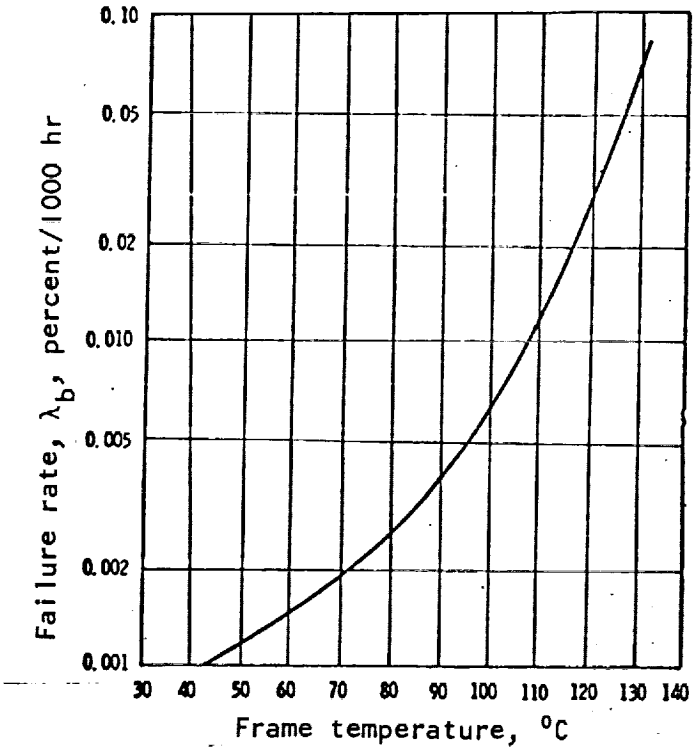


Figure 152. Basic Failure Rate for Synchros and Resolvers (from RADC Reliability Notebook)

In estimating the tradeoff between reliability and weight, the frame temperature rise of the device can be assumed to be inversely proportional to the weight of the device. This can be explained as follows:

Assume that a synchro or resolver is increased proportionally in all three dimensions by a ratio of X. The iron core area is increased by X^2. The working magnetic flux density will decrease by a ratio of $1/X^2$. The iron loss per unit volume can be assumed to decrease by $1/X^4$ approximately. However, since the volume of the iron core is increased by X^3, the total iron losses are decreased by a ratio of $\frac{1}{X}$.

The copper conductor area is increased by X^2, but the length of mean turn is increased by X. Thus, the winding resistance will be reduced by a factor of 1/X. With the same aramature current, the copper losses are reduced by a ratio of 1/X, the same as for the iron losses.

Since the frame surface is increased by X^2, the temperature rise of the frame is proportional to $1/X^3$. The weight of the device is proportional to X^3. Therefore,

$$\text{Frame temperature rise } \alpha \frac{1}{\text{weight}} \text{ approximately}$$

Consider a synchro with a frame temperature of 373°K (100°C) at 303°K (30°C) ambient. The basic failure rate according to fig. 152 is 0.007. To double the life of the synchro, the failure rate should be 0.0035. Again from fig. 152 the frame temperature for $\lambda_b = 0.0035$ is 360°K (87°) or 57°K rise. The weight of the new synchro then will be approximately:

$$\frac{70}{57} = 1.23$$

or a weight penalty of approximately 23 percent.

Connectors: The rate of failure of connectors depends on many factors, including mechanical, electrical, thermal, chemical, and cycling effects. One of the major causes of failure is induced by the growth of films at points of contact. These films can cause either increased contact resistance or an open circuit.

Generally the failure rate of connectors is expressed by the equation:

$$\lambda = \lambda_b \pi_e \pi_p + N \Sigma_{cyc}$$

where λ_b = basic failure rate depending on the operating temperature of the contact insert and the insert material

π_e = factor based on the condition of environmental service

π_p = factor based on the number of active pins

N = number of active pins

Σ_{cyc} = factor based on reconnect cycling in cycles per 1000 hr

Representative values of the basic failure rate for connectors are given in fig. 153. The operating temperature is equal to the sum of the ambient temperature and the contact insert temperature rise.

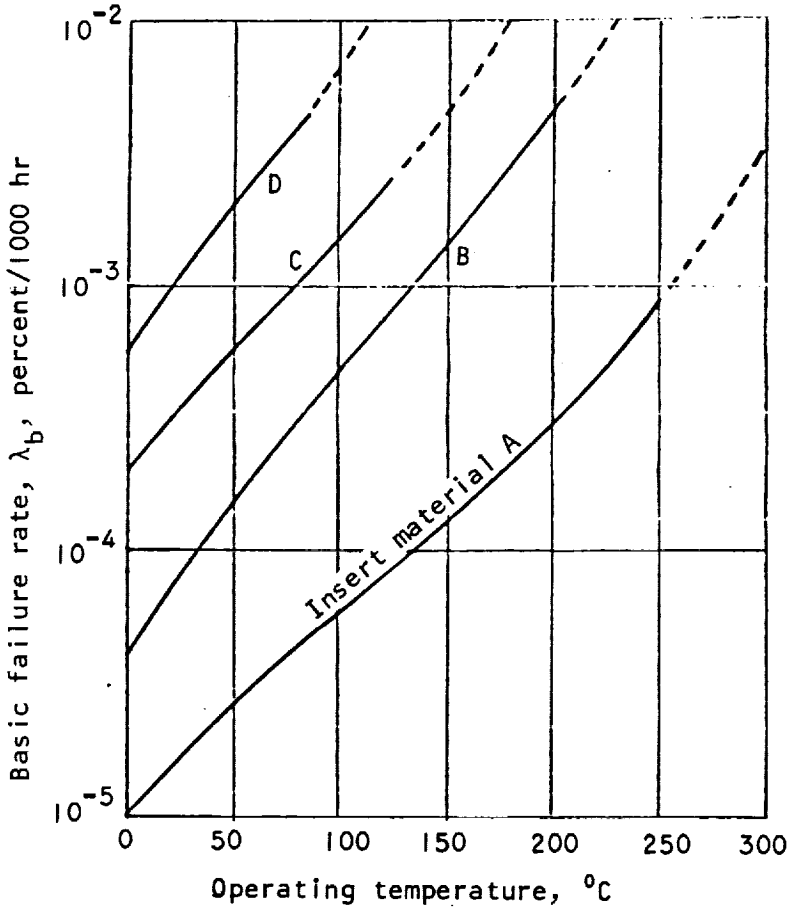
The insert temperature rise is a function of the contact current density. This relationship is shown in fig. 154.

By using figs. 153, 154 and the manufacturer's data on connector's weight vs contact sizes, the tradeoff between reliability and weight for connectors can be determined.

Wires and cables: The most common failure mode for connecting wires is conductor breakage at the termination, in chassis work as well as with interconnecting harness. Where small conductors are used, conductor breakage has been a major source of trouble. In aircraft, copper conductors are limited to size 22 and larger. For special copper alloy conductors, sizes as small as 26 have been used. To avoid the conductor breakage problem, it is advised that proper stress relief of all wires be provided at connectors and extra care be taken in assembly. In this sense, reliability is related to cost more than weight.

Multiconductor cable failures are related to the component wires. Although most failures occur at connectors, a properly designed and terminated cable will have excellent life expectancy. Balanced cable construction (no short wires) and proper stress relief at connectors are important failure preventives.

The only tradeoff between reliability and wire and cable weight would be the use of large size conductor to reduce the operating temperature. Fig. 155 shows the temperature rise of a single copper conductor insulated with 0.25-0.38 mm (10-15 mils) of TFE in still air at normal atmospheric pressure. Temperature rise data for other types and thicknesses of insulation are not available. The temperature rise of a group of conductors at a bundle can be assumed to be twice that of a single conductor. The representative values of life vs operation temperature for three types of insulation are shown in fig. 156.



Insert material code	Common material	Temperature range, °C
A	Diallyl Phthalate, glass, ceramic	-40 to +250
B	Melmine, Neoprene, Si Rubber	-40 to +200
C	Teflon, Kel-F	-55 to +125
D	Nylon, Polychloroprene	-20 to +100

Figure 153. Basic Failure Rate of Connectors (from RADC Reliability Notebook)

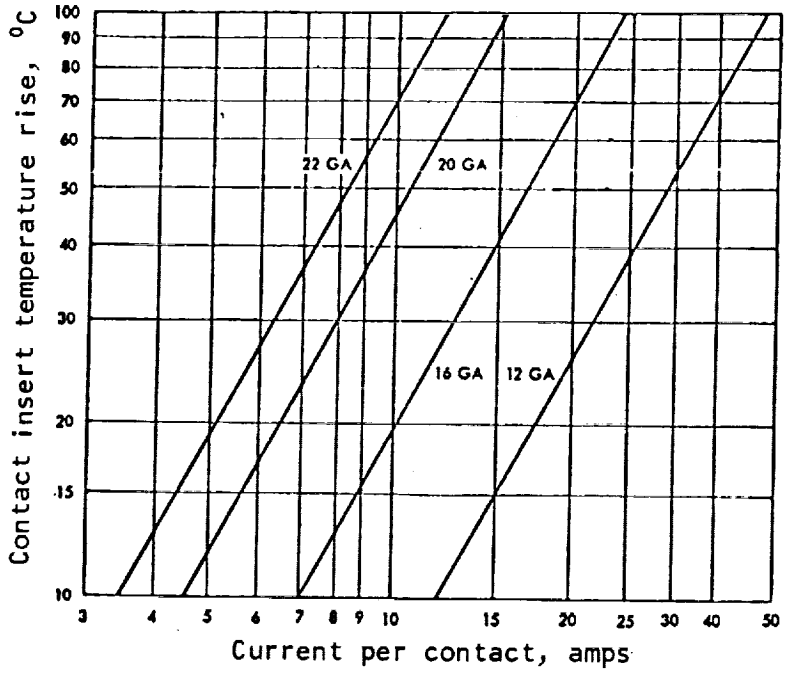


Figure 154. Contact Insert Temperature Rise vs Contact Current and Contact Size (from RADC Reliability Notebook)

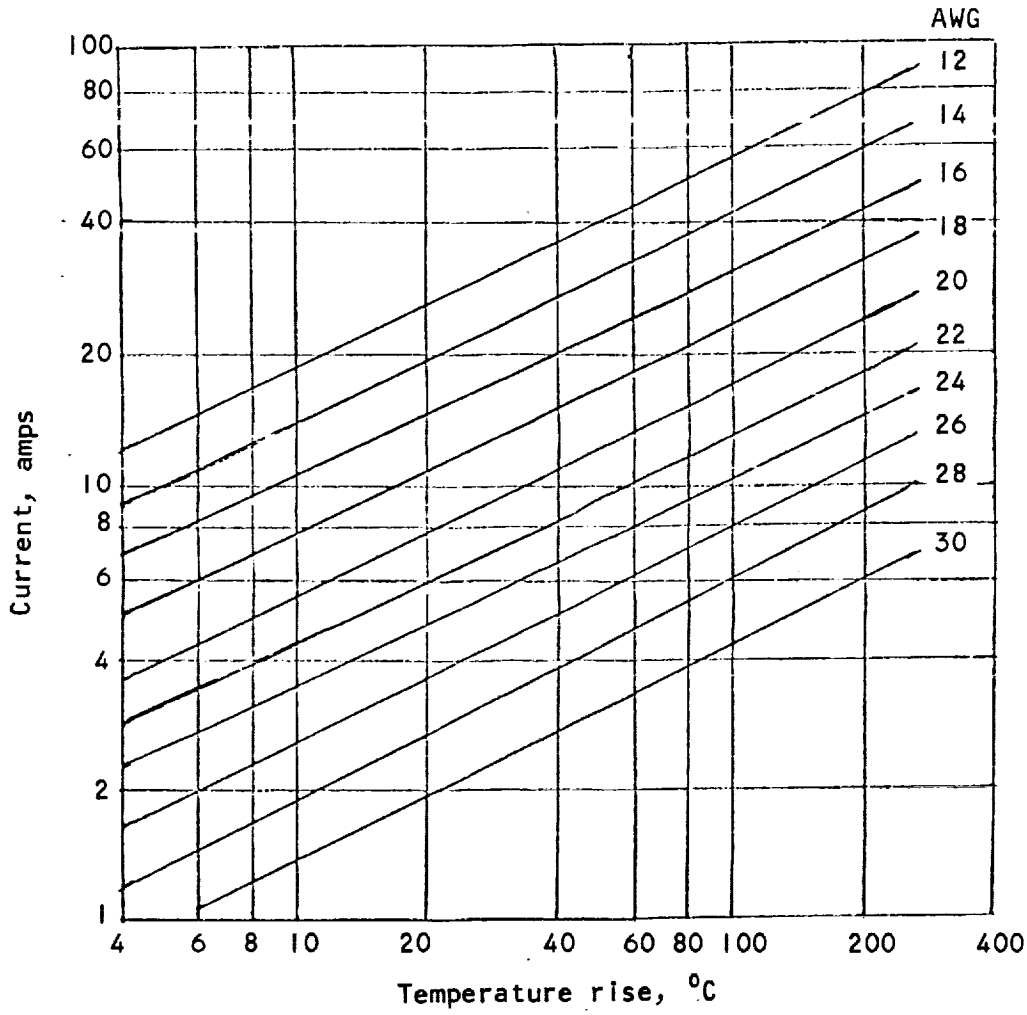


Figure 155. Temperature Rise of a Single Copper Conductor Insulated with 10 to 15 mils of TFE in Still Air and Normal Atmospheric Pressure (from MIL-HDBK-217A)

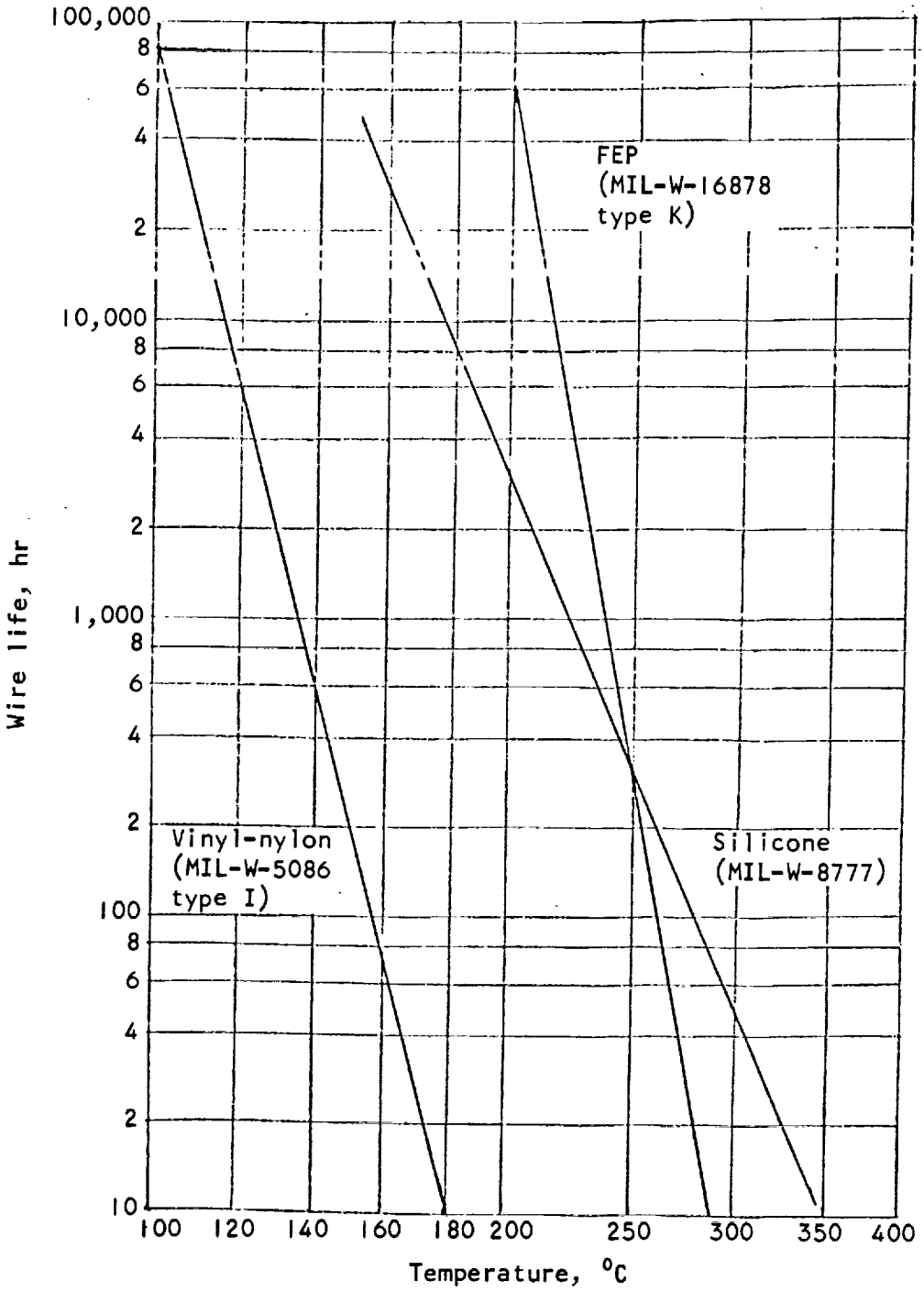


Figure 156. Effect of Operating Temperature on Wire Life (from MIL-HDBK-217A)

Lamps and heaters: For incandescent lamps and small heaters, long life can be obtained by operating these components at low voltage levels. The operating power of lights and heaters is given by

$$P = \frac{V^2}{R} = \frac{1}{\rho} \cdot \frac{V^2 a}{\ell}$$

where V = operating voltage

a = cross-sectional area of the lighting or heating element

ℓ = length of the lighting or heating element

A strong lighting or heating element should have large a and small ℓ, resulting in small operating voltage V. On the other hand, any voltage other than the standard distribution voltage will require voltage transformation equipment. Low operating voltage may also result in large and heavy wiring. A tradeoff between reliability and weight or cost is therefore involved.

Capacitors: The life of capacitors depends on many factors such as operating voltage, current, frequency, temperature, pressure, humidity, shock, and vibration. There are many different types of capacitors. In aircraft, ceramic (high K) and tantalum (solid dielectric) capacitors are the most popular. The failure rate of these two types of capacitors is quite similar, and can be expressed as

$$\lambda = \lambda_b \pi_e + \Sigma_E$$

where λ_b = basic failure rate depending on temperature and stress ratio

π_e = multiplier based on the environmental service

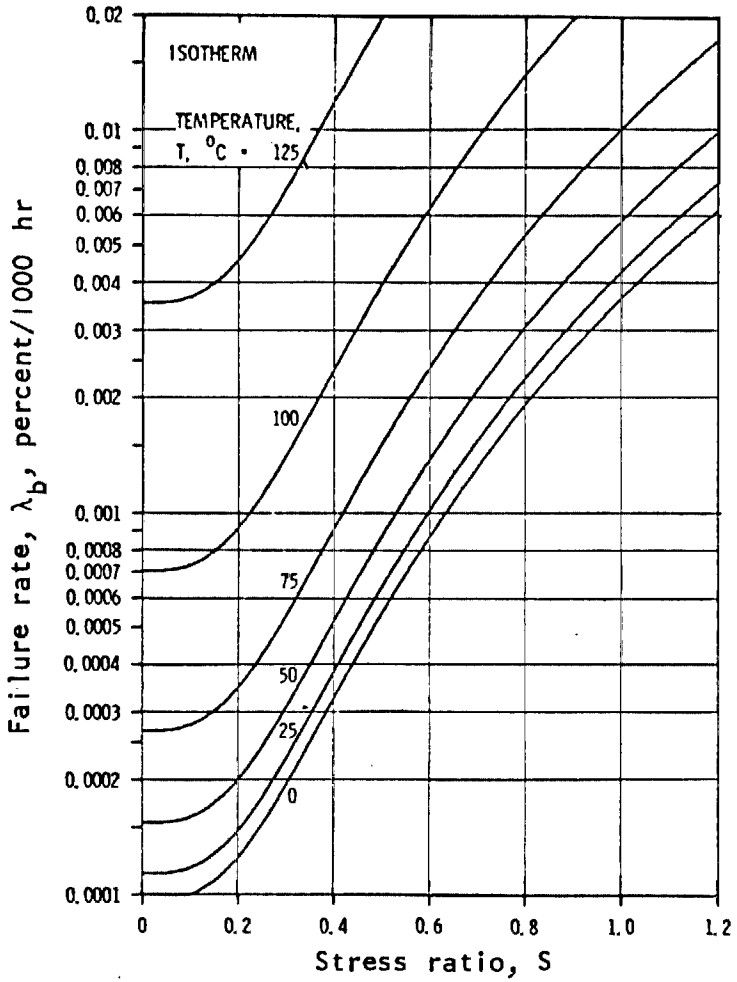
Σ_E = environmental condition modifier

Typical values of basic failure rate for ceramic and tantalum capacitors are shown in figs. 157 and 158, respectively. The stress ratio is defined as

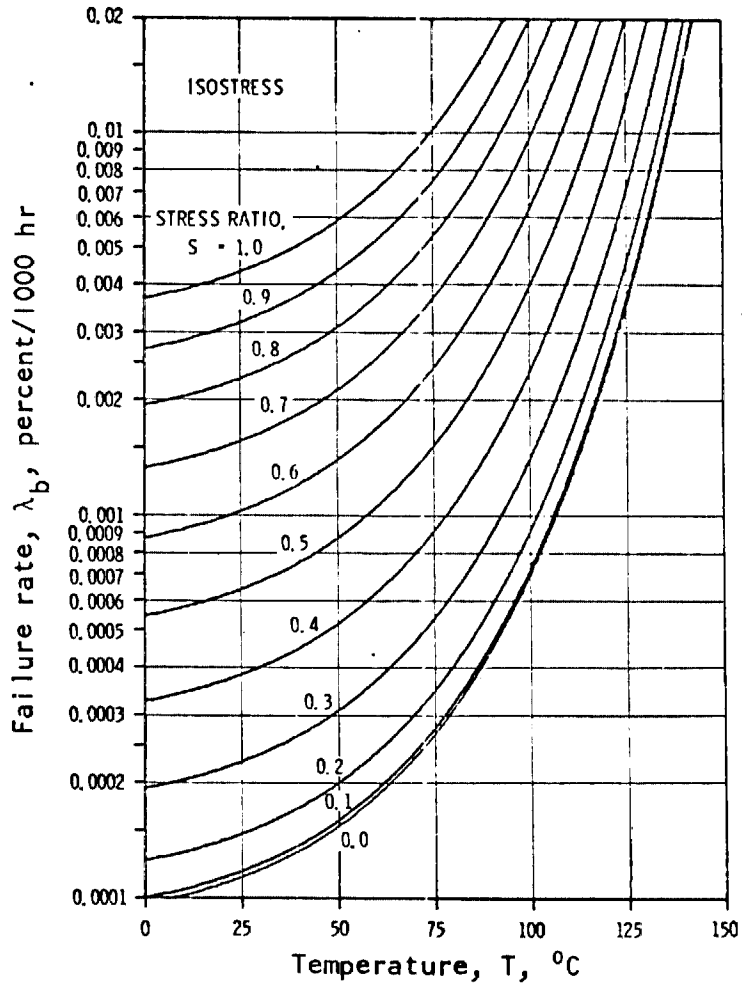
$$S = \frac{\text{operating voltage}}{\text{rated voltage}}$$

The environmental factors π_e and Σ_E for ceramic and tantalum capacitors are shown in table 67.

Data in this section plus the manufacturer's data on capacitor performance, weight, and cost will enable the designers to perform reliability, weight, and cost tradeoff studies.



(a) Failure rate vs stress ratio



(b) Failure rate vs ambient temperature

Figure 157. Basic Failure Rate of Ceramic Capacitors
(from RADC Reliability Notebook)

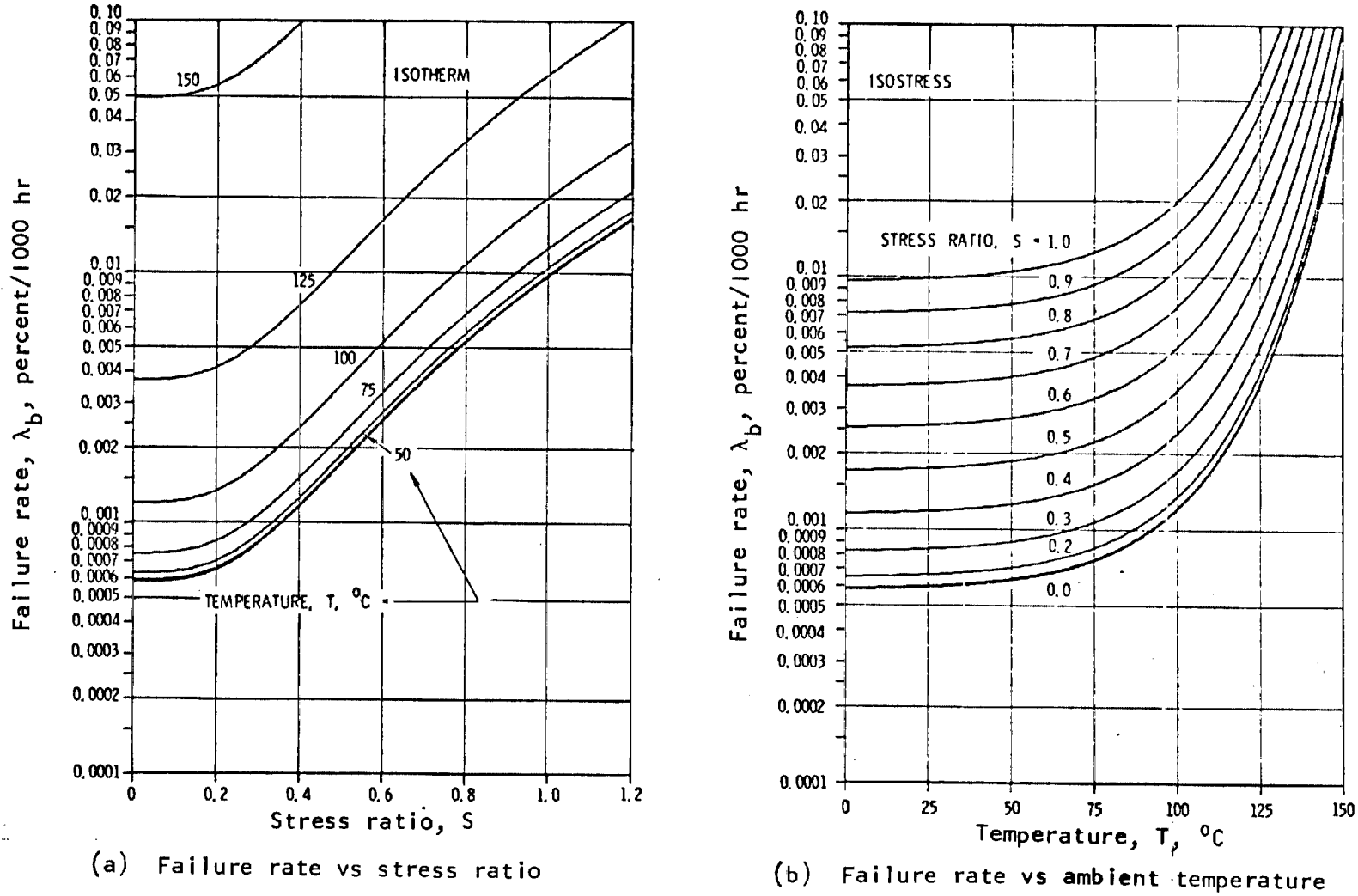


Figure 158. Basic Failure Rate of Tantalum Solid Dielectric Capacitor (from RADC Reliability Notebook)

TABLE 67.--ENVIRONMENTAL FACTORS, π_e AND Σ_E

Capacitor type	Environment	π_e		Σ_E	
		Upper reliability grade	Lower reliability grade	Upper reliability grade	Lower reliability grade
Ceramic (high K)	Airborne inhabited area	4	40	0.0002	0.002
	Airborne uninhabited area	10	100	0.0006	0.005
Tantalium (solid dielectric)	Airborne inhabited area	4	40	0.0002	0.002
	Airborne uninhabited area	15	150	0.0008	0.008

Resistors: The most popular kind of resistor used in aircraft is carbon composition type RC-22. In application where precision values are needed, film resistors are used. The failure rate of resistors can be expressed as

$$\lambda = \lambda_b \pi_R \pi_e + \Sigma_E$$

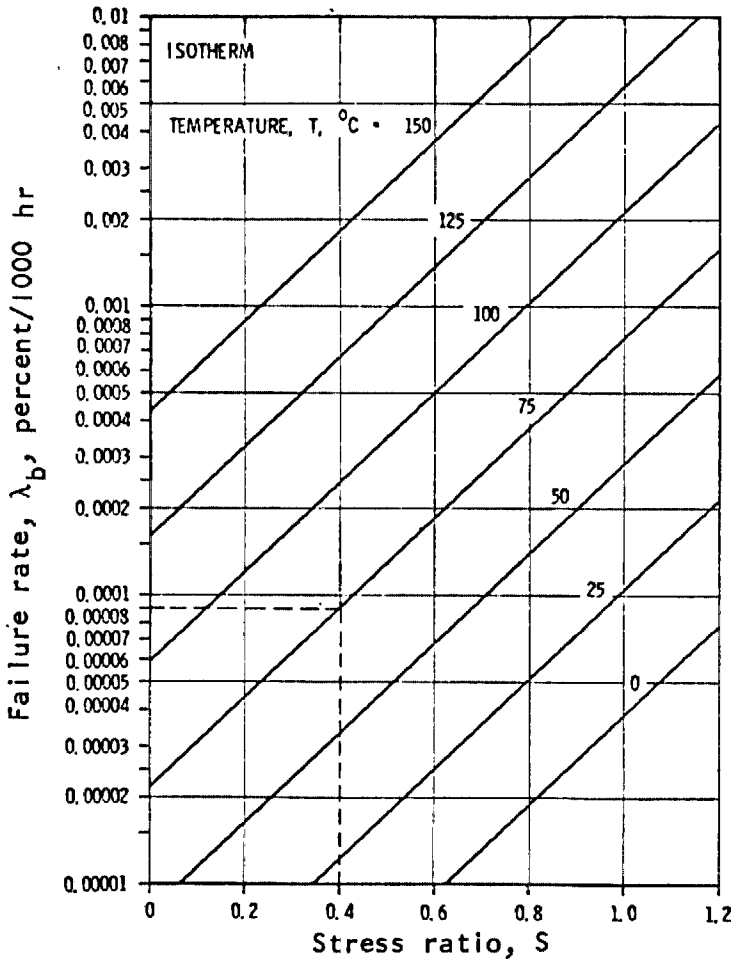
where λ_b = basic failure rate

π_R = resistance factor

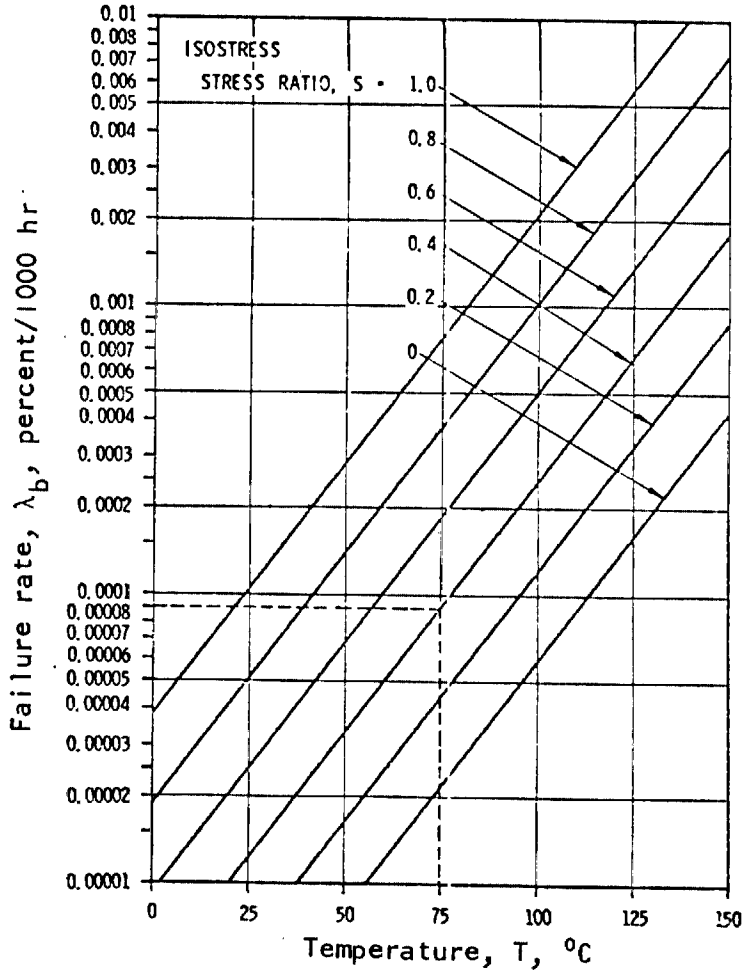
π_e = environmental multiplier

Σ_E = environmental condition modifier

The typical values of the basic failure rate for carbon composition resistors are shown in fig. 159. The stress ratio is the ratio of the operating power to the rated power. The values of π_R are shown in table 68 and the values of π_e and Σ_E are shown in table 69.



(a) Failure rate versus stress ratio



(b) Failure rate vs ambient temperature

Figure 159. Basic Failure Rate of Carbon Composition Resistors, Style RC-22 (from RADC Reliability Notebook)

TABLE 68.--RESISTANCE FACTOR π_R, COMPOSITION RESISTOR

Resistance range (ohms)	π_R
< 100	1.1
100 to 100 K	1.0
> 0.1 meg to 1.0 meg	1.1
> 1.0 meg to 10 meg	1.6
> 10 meg	2.5

TABLE 69.--ENVIRONMENTAL FACTORS, R-22 RESISTORS

Environment	Grade of reliability	π_e	Σ_E
Airborne inhabited	Upper	4	0.0006
	Lower	8	0.003
Airborne uninhabited	Upper	8	0.001
	Lower	20	0.005

These reliability data and the manufacturer's information on weight, cost, etc. will enable the designers to perform reliability and weight, cost tradeoff studies.

Semiconductors: The reliability data useful for the tradeoff studies between reliability, weight, and cost are given below.

Generally the failure rate is expressed as

$$\lambda = \lambda_b \pi_e \pi_a \pi_R + \Sigma_E$$

where λ_b = basic failure rate

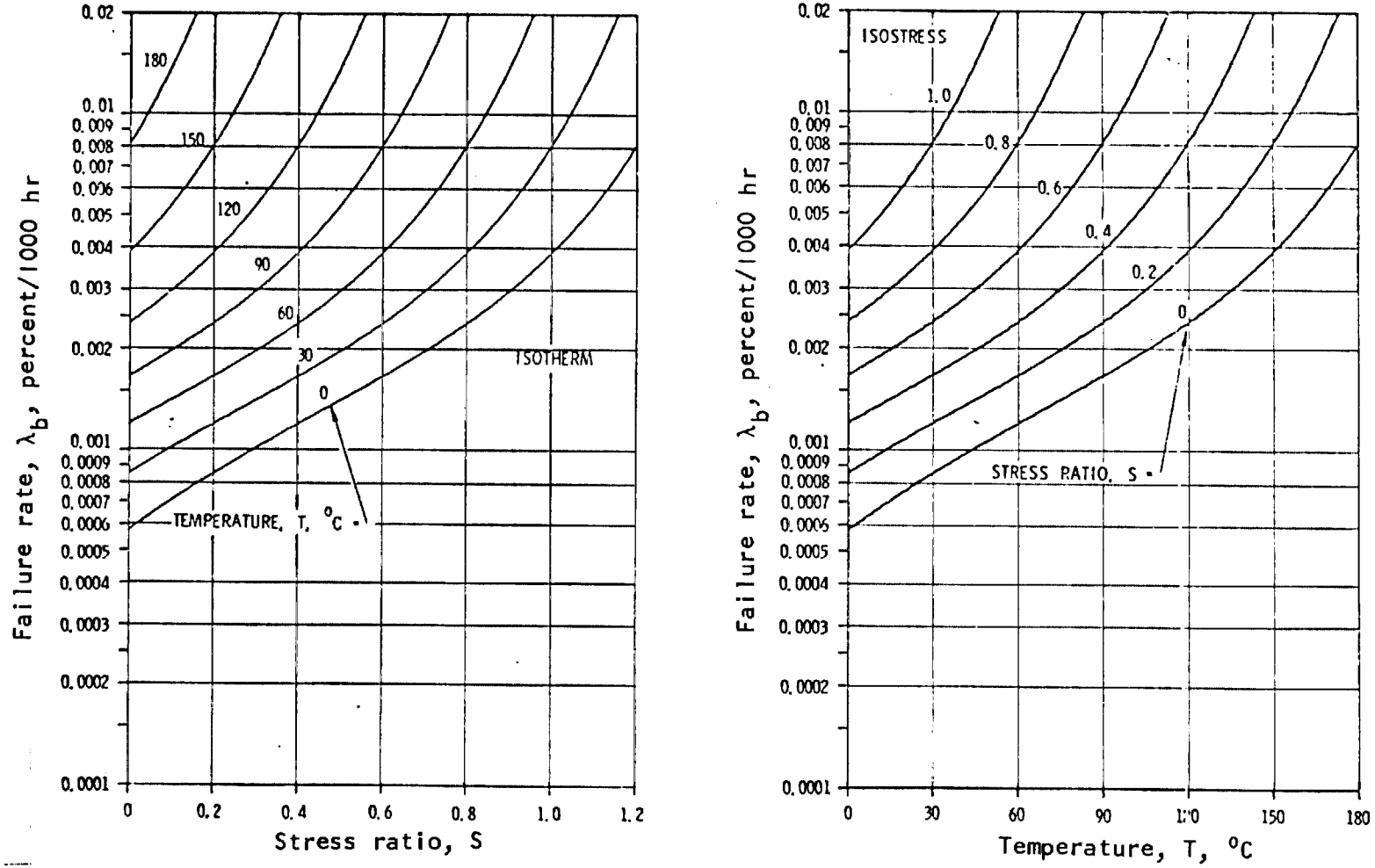
π_e = multiplier based on environmental service

π_a = application factor

π_R = power rating factor for primary stress

Σ_E = environmental condition modifier

Silicon transistor (NPN).--The basic failure rate is given in fig. 160. The environmental factors, application factor, and power rating factor are given in tables 70, 71 and 72, respectively.



(a) Failure rate vs stress ratio

(b) Failure rate vs ambient temperature

Figure 160. Basic Failure Rate of NPN Silicon Transistors (from RADC Reliability Notebook)

TABLE 70.--ENVIRONMENTAL FACTORS VS SEMICONDUCTOR COMPONENTS

Environment	Silicon transistors (NPN)				Silicon diodes and rectifiers				SCR			
	π_e		Σ_E		π_e		Σ_E		π_e		Σ_E	
	UQG	LQG	UQG	LQG	UQG	LQG	UQG	LQG	UQG	LQG	UQG	LQG
Airborne inhabited	30	300	.004	.04	30	180	.002	.02	30	300	.005	.1
Airborne uninhabited	50	500	.005	.05	50	300	.006	.06	50	500	.005	.1

UQG = upper grade of reliability
LQG = lower grade of reliability

TABLE 71.--APPLICATION FACTOR OF SEMICONDUCTOR COMPONENTS

Silicon transistors (NPN)	
Application	π_a
Linear (ac)	1.0
Linear (dc)	2.0
Low noise (audio)	1.5
High frequency (RF)	3.0
Low noise (RF)	4.0
Logic switching	0.5

Silicon diodes and rectifiers	
Application	π_a
Signal (audio)	1.0
Signal (IF, RF)	1.5
Logic switching	0.3
Power rectifier	2.0
Power rectifier $V_{max} > 600$	2.5/junction
Forward reference	0.3

TABLE 72.--RATING FACTORS OF SEMICONDUCTOR COMPONENTS

Silicon transistors (NPN)	
Power rating (watt)	π_R
Up to 1	1.0
> 1 to 5	1.5
> 5 to 20	2.0
> 20	2.5

Silicon diodes and rectifiers	
Current rating I_{max}	π_R
0 to 100 ma	1.2
> 100 to 500 ma	1.0
> 0.5 to 1 a	1.1
> 1 to 3 a	1.5
> 3 to 10 a	2.0
> 10 a	2.5

SCR	
Rated average forward anode current (amp)	π_R
0 to 0.5	1.2
> 0.5 to 1	1.0
> 1 to 10	1.5
> 10	2.0

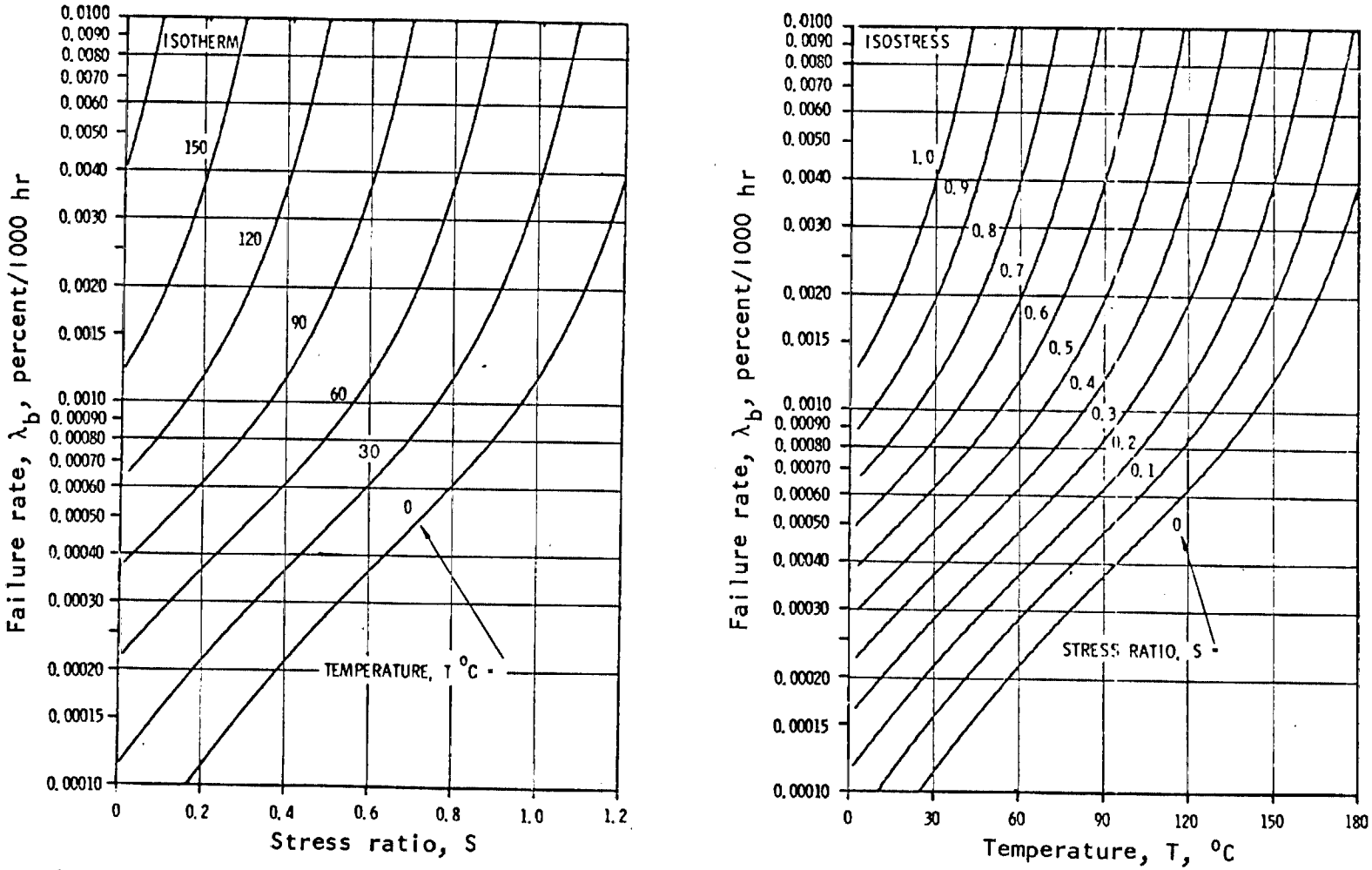
The stress ratio for transistors is defined as

$$S = \text{stress ratio} = \frac{P_{op}}{P_{max}}$$

where P_{op} = actual power dissipated

P_{max} = maximum rated power dissipation at 298°K) for the type of application specified, i.e., in regard to ambient air or heat sink mounted

Silicon diodes and rectifiers.--The basic failure rate is shown in fig. 161. The environmental factors, application factor, and current rating factor were given in tables 70, 71, and 72, respectively.



(a) Failure rate vs stress ratio

(b) Failure rate vs ambient temperature

Figure 161. Basic Failure Rate of Silicon Diodes and Rectifiers (from RADC Reliability Notebook)

The stress ratio for silicon diodes and rectifiers is defined as

$$S = \text{stress ratio} = \frac{I_{op}}{I_{max}}$$

where I_{op} = operating voltage forward current

I_{max} = maximum rated average forward current at ($298^{0}K$)

Silicon control rectifiers: The basic failure rate is given in fig. 162. The environmental factors and rated average forward mode current factor were given in tables 71 and 72, respectively. For this case π_a is 1.0.

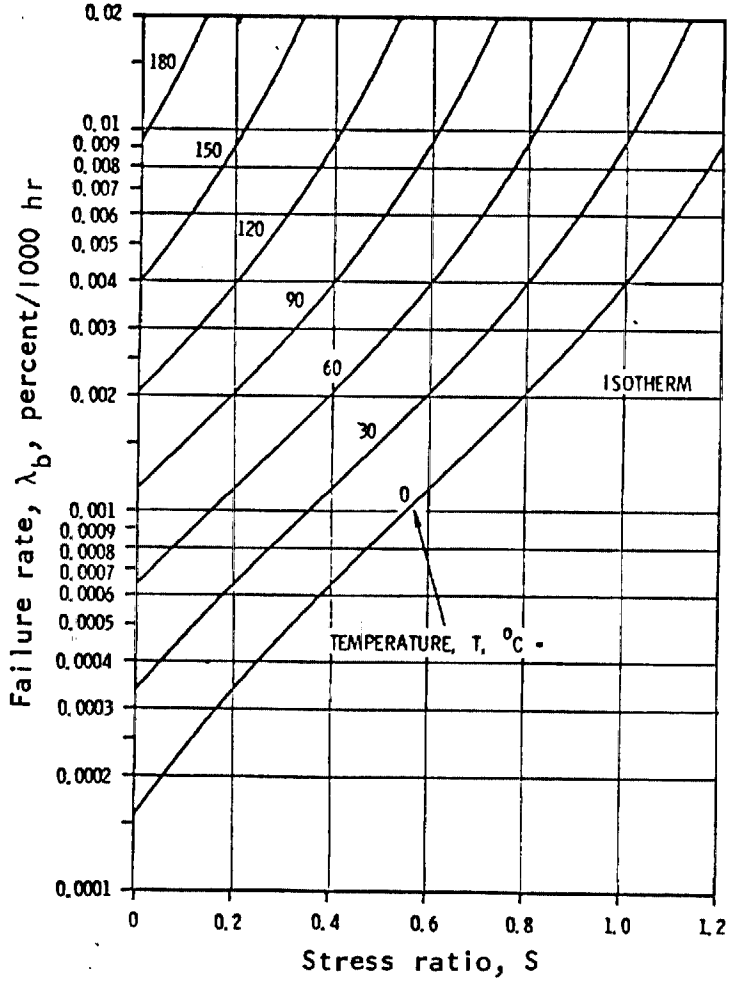
The stress ratio for silicon control rectifiers is the same as that for silicon diodes given in the last paragraph.

Maintainability and its Tradeoffs

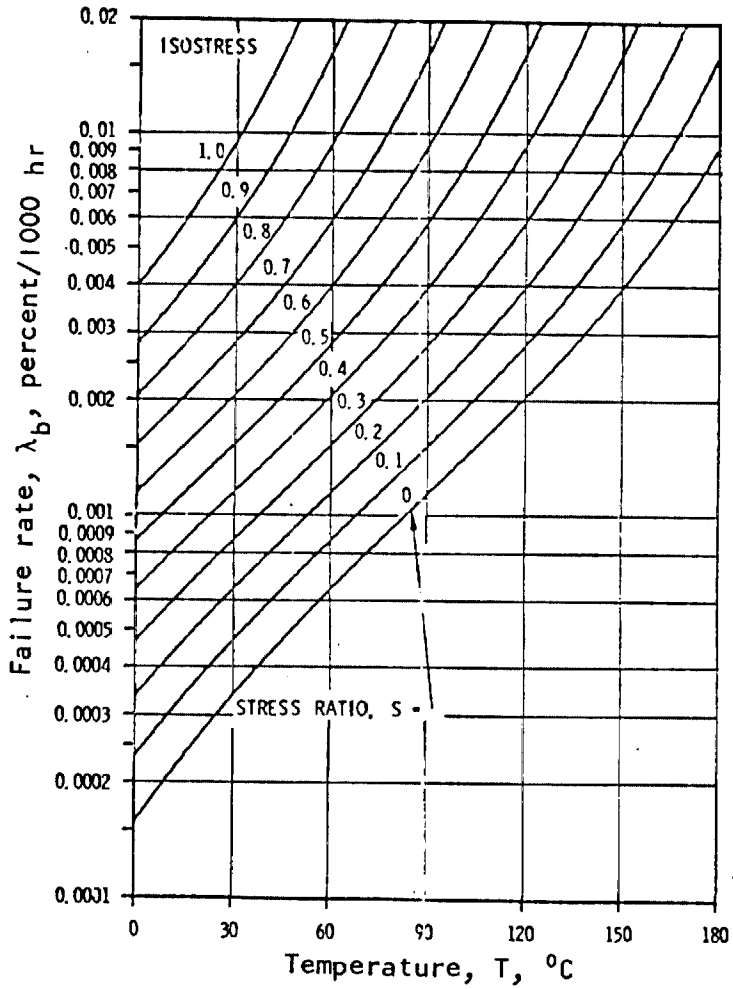
Maintainability is a major element of system effectiveness. It may be defined as those attributes of a design that allow accomplishment of necessary measurements, tests, monitoring, servicing, removal, replacement, and reconditioning with the minimum elapsed time and maintenance effort. The latter includes manpower skills, technical data, support equipment, and facilities.

About ten years ago, maintainability requirements received little attention as compared with other requirements such as reliability. No minimum base criteria were specified, and no measurements were made for design improvement. However, when it was discovered that about 25 percent of the Dept. of Defense budget was spent on maintenance, quantitative maintainability specifications were developed as a standard to govern maintainability requirements for systems and components. Various techniques have been developed since to define maintainability as a system characteristic. Maintainability characteristic definitions are required for incorporating maintainability considerations in new designs.

Most of the airline industry emphasis has been placed upon performance and safety improvements until very recently. Much of the maintenance effort now is concentrated on improving maintenance work effectiveness. Furthermore, many indications revealed that much of the recent aircraft equipment is not as reliable as it could be, and it cannot be tested, adjusted, replaced, or reconditioned as quickly as the airline mission requires. Since airline maintenance bills ranged from 20 to 25 percent of the aircraft direct operating cost, extensive studies and evaluations were conducted. It was concluded that unless significant improvements are made in maintenance concepts, designs, methods, and regulations, a substantial amount of this money will be spent ineffectively. An efficient maintainability program can reduce maintenance cost, and hence increase airline revenue. To achieve this goal, the airline, the FAA, and the manufacturer must work together to provide sufficient information and guidelines for the designer so that the maintainability requirements can be incorporated in the product designs.



(a) Failure rate vs stress ratio



(b) Failure rate vs ambient temperature

Figure 162. Basic Failure Rate of Silicon Control Rectifiers
(from RADC Reliability Notebook)

The numerous factors affecting maintenance cost can be grouped into two categories, factors that directly affect the mean-time-between-failure (MTBF) and factors which affect the maintenance effort.

Factors affecting MTBF.--The factors that directly affect MTBF also affect maintenance cost, since twice the time between failures results in one-half the maintenance time spent in removal and replacement.

Reliability: By increasing reliability of parts or components, the MTBF generally can be increased, thus reducing maintenance cost. In certain cases, however, increase in reliability may increase maintenance requirements. For instance, the use of soldered or welded connections instead of plug-in connections, can increase reliability as well as maintenance requirements.

Self-repair capability: Studies have been conducted to develop a self-repair capability in conductors used in passive elements such as coild, transformers, and resistors. Two noteworthy approaches utilize (1) an indium gallium alloy casting which repairs breaks as a consequence of the I^2R heating generated in the alloy itself and (2) controlled crystalline anisotropy whereby upon failure (break) of the conductor, metallic whiskers are influenced to grow in preferred directions to heal the break. These studies are only a beginning in the self-repair field. Self-repair capability will be extended to more system functions in the future.

Redundancy: Redundancy is a design feature widely used to increase reliability. In some cases however, it can also reduce the maintenance cost if properly employed. Within one piece of equipment or a system, if one component has a short life and is discarded upon failure, redundancy provided for this component will effectively reduce its frequent replacement.

Most redundancy techniques used today are of the simple back-up type in which spare units are provided for rapid replacement of failed ones. However, if man is not available to replace the failed component, or the time taken to locate the malfunction and replace the failed component is considered excessive, the more sophisticated techniques of redundancy will be developed and applied.

Factors affecting maintenance effort.--When equipment must be replaced, repaired, or adjusted, it is always desirable to minimize the maintenance effort to decrease downtime and turnaround time. Some of the factors affecting the maintenance effort are discussed briefly below.

Standardization: Standardization is a design feature that minimizes part or component variety; fewer parts are used to meet the majority of the system hardware requirements. Standardization often results in both physical and functional interchangeability; it is a major consideration of maintainability design since it significantly reduces both the initial and support costs of a system.

Failure prediction and detection: Prediction data systems such as AIDS are capable of predicting impending failures. When the aircraft cannot be dispatched with a component inoperative, the prediction system makes it possible to replace

the component prior to failure during a normal maintenance period, therefore eliminating the delay usually associated with unscheduled repair or replacement. The use of AIDS can also reduce the number of unnecessary removals.

Failure detection equipment automatically isolates and identifies the malfunctioning item to the repair-by-replacement level by means of internal circuitry, thus reducing the troubleshooting time. Furthermore, the use of the failure detection system may allow systems to be maintained by unskilled personnel, which reduces overall system support requirements.

Accessibility: Accessibility is closely related to the configuration of hardware and packaging requirements. For a module discarded at failure, no component accessibility problems will be considered. However, the accessibility of the module itself becomes very important for removal and replacement.

Accessibility should also be considered for testing, adjusting, and troubleshooting purposes. The test points that make signals available to the technician must be readily accessible to minimize service time.

Maintenance facilities: Maintenance facilities include the tools and facilities for removing, replacing, and repairing the parts and components and the test and support equipment for testing, adjusting, and troubleshooting. Although adequate maintenance facilities can ease maintenance work, the amount and complexity of the equipment will significantly increase the support costs. If possible, component and system design should be such that the requirement for maintenance facilities is minimized without sacrificing ease of maintenance. The automatic test equipment for fault isolation can greatly reduce personnel skill requirements. Equipment indicators that identify the faulty subsystem or component can eliminate technician decisions by directing the technician to the next required action.

Skill levels and training requirements: When maintenance requires high-skill levels and special training, the support costs increase. Skill level requirements are usually closely related to the type of support equipment. Use of sophisticated equipment can reduce skill level requirements but will increase equipment cost. A trade-off criterion therefore exists.

Discard-at-failure maintenance: Every system or component has a certain level of repair beyond which total part replacement becomes more practical and economical. Based on this principle, a maintenance policy can be established whereby parts or components of equipment to a given level are discarded at failure rather than repaired.

The level of discard-at-failure for a given design depends upon many factors. An optimum level can only be selected by utilizing trade-off procedures based on cost data and related information.

The increased use of microelectronics would make the repair of many future circuits not only uneconomical, but also impossible. It can be expected that discard-at-failure maintenance will receive more attention in the future.

Human factors: Since man performs maintenance work, psychological limitations of man must be accounted for to establish an effective maintainability program. In general, items that must be considered are (1) the capabilities and limitations of personnel, (2) the equipment, (3) the environment, and (4) safety.

Steps in maintainability program.--Maintainability decisions must be made before or during design of the developmental model. Changes in design after that period are usually very expensive and time consuming. For this reason, a well established maintainability program must be followed to incorporate maintainability requirements into the design. A summary of these steps are listed below:

(1) Prepare realistic maintainability objectives and requirements.

(2) Review the previous equipment (or system) to determine if the experience gained from the previous equipment (or system) are applicable for the new equipment (or system).

(3) Determine maintenance levels and requirements for maintenance supports.

(4) Prepare maintenance procedures.

(5) Establish maintainability prediction techniques.

(6) Evaluate maintainability features and make design modifications as necessary.

(7) Translate design for maintainability into actual equipment and maintenance instructions.

(8) Make tests of maintainability and modify design as necessary.

(9) Evaluate maintainability of the equipment (or system).

(10) Correct deficiencies in maintainability of production equipment.

(11) Review engineering changes and examine their effects on maintainability.

Maintainability prediction.--Maintainability prediction is a technique used to quantitatively predict maintainability characteristics of equipment based on design features. Predictions are normally made during the design and development phase. Depending on the character of a program, maintainability prediction can be initiated after only a brief evaluation of the first production units. This allows necessary design modifications until actual hardware is produced.

There are numerous methods and mathematical models developed for maintainability predictions. For illustration purposes, a prediction technique developed by the RCA Service Company, under sponsorship of the Rome Air Development Center, is described as follows:

The RCA method uses the maintenance time as the criterion of maintainability. The maintenance time is expressed as a function of A, (physical design features B, (support requirements) and C, personnel requirements. Functionally stated, maintenance time = f (design, support, personnel). By using regression analysis of actual maintenance data, an empirical equation relating the maintenance time and the three parameters was developed as follows:

$$M_{ct} = \text{Antilog } (3.54651-0.02512A-0.03055B-0.01093C)$$

where A, B, and C represent measures of the three parameters evaluated for a specific task.

To obtain A, B, and C, a checklist is established for each parameter. Within each checklist, a number of questions are to be answered and a score of 0 to 4 is given to each answer, depending on the condition of the design features for a specific maintenance task. By summing the scores of each checklist, A, B, and C are determined.

To predict the maintainability of a system, a sample of components is selected by reference to existing failure-rate tables. A typical failure of a component will call for a repair task to be performed. By applying the above mentioned technique to each of the components in the sample, the MTTR for the system can be determined.

To facilitate the use of the empirical equation, a nomograph that provides a graphical means of solution is derived and shown in fig. 163. It can be expected that maintainability prediction and analysis procedures for large systems will be very laborious and time consuming, since there are numerous factors involved and the interrelationships among these factors are so complicated. Computer use for maintainability prediction of large systems therefore is undoubtedly the logical solution to this problem. However, much work in identifying and quantifying the factors contributing to maintainability must be completed before the mathematical model can be developed and programmed.

Maintainability demonstration.--A maintainability demonstration is the procedure used to prove to the customer that specified maintainability requirements have been satisfied and to verify the accuracy of the maintainability prediction. Verification of maintainability prediction prior to hardware delivery allows necessary design modifications and maintenance planning adjustments. Maintainability can be demonstrated during product development. However, the demonstration should be scheduled as early as possible to obtain the maximum benefit. There are several types of demonstration, a few of which are described below.

Informal demonstration: Informal demonstration can be initiated with mock-up displays and during manufacturing processes. Design qualities such as accessibility, simplicity, and modularization can be studied, and the principles of human engineering can be evaluated. The manufacturing and test laboratory

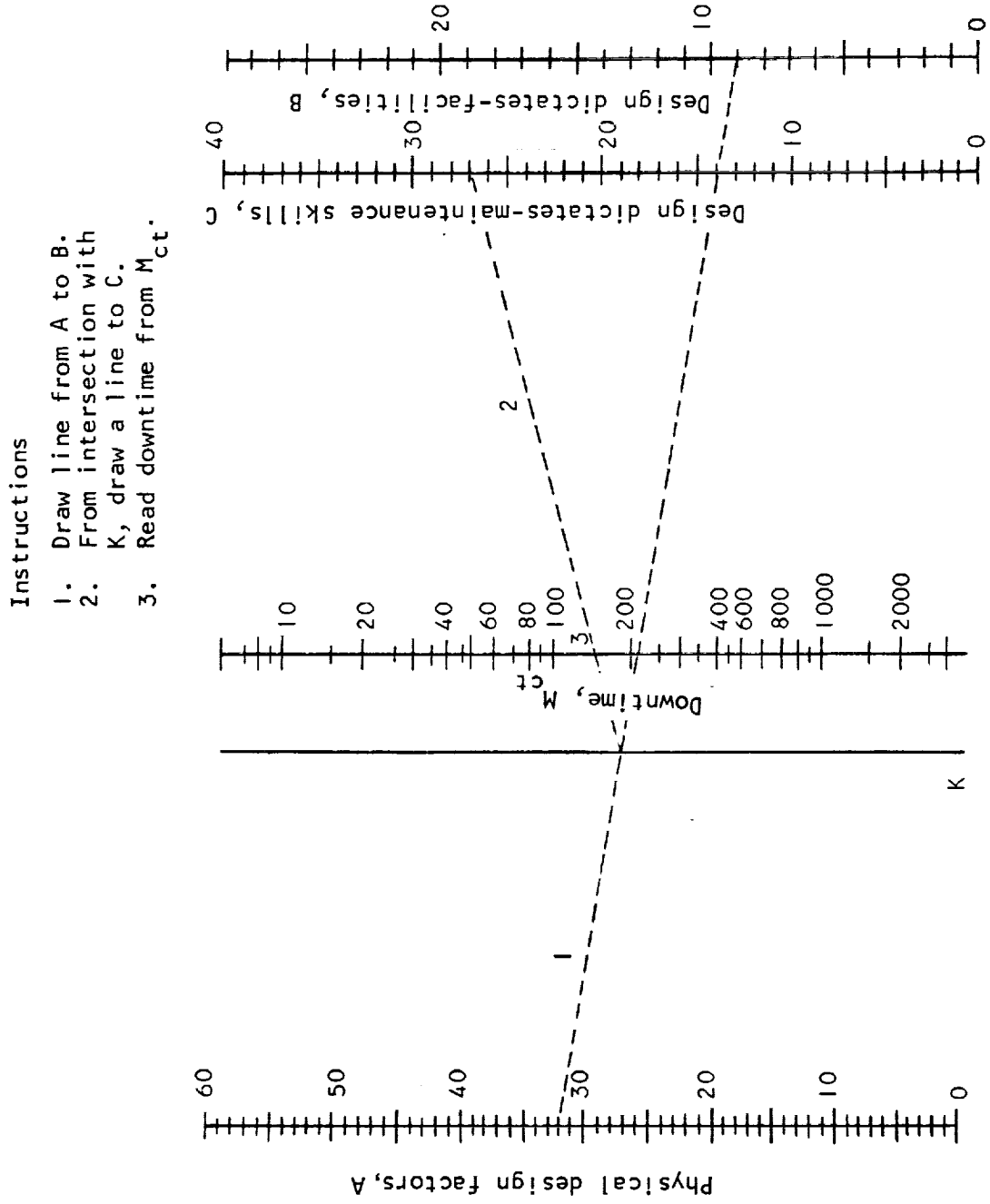


Figure 163. Downtime Nomograph (Ref. 37, P. 60)

personnel can usually provide significant information. For data purposes, notebooks can be placed in convenient locations for problem notation by manufacturing and test laboratory personnel as they are discovered. These notes can be periodically reviewed by maintainability personnel and actions taken accordingly.

Simulation: Computer simulation is a powerful tool for analytical demonstration of system characteristics. To simulate the system under study, the characteristics of the system components are functionally incorporated into the program, from which individual actions can be observed and measured. Then, by analyzing the cumulative effect of all actions, the maintainability of the equipment or system can be evaluated.

Formal demonstation: Two types of demonstration can be employed during the development test activities. One method is direct observation of equipment operating under normal conditions; the other method is based on performing special tests.

Maintainability demonstration for various elements of a system can be accomplished individually. However, demonstration of equipment compatibility and maintenance actions involving more than one item of equipment must be either simulated or delayed until these items are assembled.

Equipment demonstration: When an item of equipment is available for demonstration and all support actions have been identified, the proper procedure is to sequentially perform or simulate all scheduled functions, such as replacement, servicing, adjustment, etc. Then, by selecting a failure, perform or simulate the maintenance steps, such as fault-isolation, troubleshooting, checking, repair, etc. It can be seen that by analyzing the measurements and evaluating the times required for these actions, a demonstration of equipment maintainability in terms of mean-time-to-repair (MTTR) can be accomplished.

To compile an accurate and detailed report during and after maintainability demonstration is an important task since all further work is dependent upon the data in the report. The quality and accuracy of the data, therefore, must be carefully maintained by employing adequate reporting procedures.

Advantages of maintainability demonstration: Maintainability demonstration in general offers the following advantages.

(1) Verifies the accuracy of maintainability prediction and provides data for modification of prediction techniques as necessary.

(2) Provides data for evaluation of equipment downtime, system availability, and modification of maintenance planning.

(3) Reveals deficiencies in maintainability design, support facilities, and personnel.

(4) Provides experience in maintainability demonstration.

(5) Establishes a certain degree of confidence to the customer.

System design planning.--For complex systems, incorporation of maintainability principles into the design to achieve compatibility with the system, the maintenance personnel, and the environment in which the system operates may require development of mathematical models to apportion the overall requirement into various subsystems. Such model development is often based on parameters such as availability and operational readiness to permit maintainability evaluation with respect to other important system characteristics. Operational readiness may be defined as the probability of satisfactory operation at any point in time or readiness for operation on demand when used under stated conditions. Mathematically, it may be expressed as:

$$R_s = P_r \cdot P_s \tag{28}$$

where R_s = operational readiness

P_r = probability that system is operationally available

P_s = probability that system will operate satisfactorily for a time period (t)

P_r and P_s may be related to mean-time-between failure (t_m) and mean-time-to-repair (t_r) as follows

$$P_r = \frac{t_m}{t_m + t_r} \tag{29}$$

where t_m = mean-time-between-failure

t_r = mean-time-to-repair

$$P_s = e^{-\frac{t}{t_m}} \tag{30}$$

where t = mission time

The above relations are based on the following assumptions:

(1) There are no other delay times (e.g. administrative delay time) involved during the repair process.

(2) The probability distribution is exponential.

In a system, if individual equipment is nonredundant and the above mentioned assumptions are met, the system operational readiness can be expressed in terms of the operational readiness of each piece of equipment.

$$R_s = R_1 \cdot R_2 \cdot R_3 \text{----} R_n = \prod_{i=1}^{i=n} R_i \qquad (31)$$

When eq. (31) is used in conjunction with eqs. (28), (29), and (31) individual repair rates can be established for each piece of system equipment through consideration of reliability and overall system operational readiness requirements.

Electric component trade-offs.--To investigate the maintainability trade-off with other parameters such as cost and weight, the factors which affect the maintenance of the components discussed previously must be considered. The factors are grouped into those that directly affect reliability and those that affect the requirements of the maintenance effort. To illustrate possible trade-off areas in the electrical system, several electrical components and subsystems are briefly discussed.

Motors and generators: The generator or motor elements most likely to fail are (1) bearings, (2) spline or coupling, (3) brush-commutator assembly (when used), and (4) electrical windings. One way to reduce the maintenance requirement would be to increase the mean-time-between-failure of these parts. Except for the brush assembly, this can be accomplished by using more materials to reduce mechanical and thermal stress levels. Another way is to increase part life by using better materials or a different design. Therefore, a trade-off between maintenance requirement and cost and/or weight exists. For example, to eliminate the brush-commutator assembly maintenance problem, an electronic commutator can be used instead, which increases both machine weight and cost. The use of a failure detection and prediction device may increase time between scheduled removals and reduce the effort for failure diagnosis, but this again increases the cost and weight of the machine.

Transformers: The life of a transformer depends on the presence of moisture, vibration, corona, heat, etc. Among these factors, the thermal stress is of major importance. In order to reduce the temperature rise of the transformer, more copper and iron must be used, which increases the transformer weight. Curves showing the hot-spot temperature versus failure rate and average temperature rise versus weight are presented earlier in this section.

The development of self-repair conductors indicates another possible trade off between maintenance requirement and cost and weight. The use of a failure detection and prediction device may also result in a new trade off process.

Synchros and resolvers: The majority of failure modes for these slower speed devices are electrical, which include (1) open or shorted stator, (2) open or shorted rotor, and (3) calibration and tolerance. Like transformers, the open or shorted winding can be minimized by using more material to reduce the temperature rise. It is hypothesized that the calibration and tolerance problem due to resistance changes that may result from long term temperature variations. Therefore, reduced temperature rise will also reduce the calibration and tolerance problem. Compensating and anti-drift devices, which can be employed for trimming, would reduce the maintenance problem although cost and weight of the machine will be affected.

Electronic equipment: Like other equipment, the reliability of the components in the electronic equipment directly affects the maintenance requirement. The major factor affecting the failure rate of the components is temperature. By reducing the temperature (which can be accomplished by using adequate heat transfer techniques), component lives can be increased.

Within a module, the components can be arranged such that the components with relatively short lives have better accessibility. Within a piece of equipment, on the other hand, each module must be readily accessible. The level of discard-at-failure to be selected for a given design is dependent upon many factors. The selection of an optimum level depends not only on the cost of initial hardware procurement but also on the user's support cost. To establish a given level, the size of the module must be properly determined. The built-in-test-equipment can eliminate the need of technician participation in fault location. Upon failure of a component, the test equipment can isolate and identify the malfunctioning item to the repair-by-replacement level. It is evident that a trade-off between maintainability and cost and weight exists.

Subsystems: In studying subsystem trade-offs, standardization is an important design feature that cannot be overlooked. By incorporating standardization in a subsystem such that the design of assemblies and components will be physically and functionally interchangeable with other assemblies and components of the subsystem, significant reductions in both the original and the support costs can be realized. However, standardization may result in weight penalties, sacrifices in performance, and other characteristics. Accessibility and redundancy are the other considerations that can be built into the subsystem to enhance maintainability. However, an increase in initial cost and a weight penalty may be introduced; a trade-off study must be performed to determine the optimum configuration of the subsystem.

Trade-off techniques.--When two or more different designs are available for an equipment or system item, and each design has its own maintainability characteristics, it is necessary to determine which design is the more desirable. To accomplish this, trade-off techniques that provide quantitative comparison for different designs must be employed.

It is not intended to discuss the various techniques developed for trade-off studies. For illustration purposes, however, the NSIA trade-off technique is summarized. This trade-off technique, developed by the National Security Industrial Association, is a well known one that enables the designer to determine with reasonable accuracy which of several maintainability considerations should be adopted. To apply this technique, the following steps are taken:

(1) List all the designs and obtain or prepare all materials that clearly define each.

(2) For each design, prepare a data sheet similar to the one shown in fig. 164.

(3) Determine all the parameters that could be affected by the given design. These include reliability, safety, fabrication cost, etc. Then enter these parameters in the appropriate column of the data sheet.

(4) Assign a proper weighting value that represents the relative significance for each characteristic entered in the parameter column. A value of unity should be given to the least important characteristics with adequate integers (or fractions in some cases) given to other characteristics according to their relative importance.

(5) Evaluate the design and its affect on each system characteristic or other parameter. Care must be taken that each characteristic associated with a design is evaluated in isolation and never influenced by other characteristics. The evalutation should be made by a qualified individual or group, and from the evaluation finding, the evaluator assigns a positive or negative number to represent value for desirability (or undesirability) as shown in fig. 165.

(6) Multiply the assigned value in the basic rating column by its corresponding weighting value, and enter the product in the adjusted value column.

(7) After the adjusted values for all the parameters have been obtained, add algebraically all the values in the adjusted value column to obtain the total net value for the design.

(8) By adding all the weighting values, obtain a total weighting factor for design.

(9) Obtain the average net value for the design by dividing the total net value by the total weighting factor. This final result serves as the figure of merit for this particular design. Its algebraic sign and its absolute value will indicate the degree of desirability or undesirability.

Data Sheet

Design Failure _____ Date _____ Evaluator _____

No.	Parameters	Considerations	Relative weighting	Basic rating		Adjusted values	
				Undesir	Desir	Undesir	Desir
Totals							

1. Calculations:
   A. Net value (Algebraic sum):
   B. Average net value:
      (Net value/total relative weighting)

2. Results:
   A. Desirable _____
   B. Undesirable _____

Figure 164. Data Sheet for NSIA Trade-off Technique

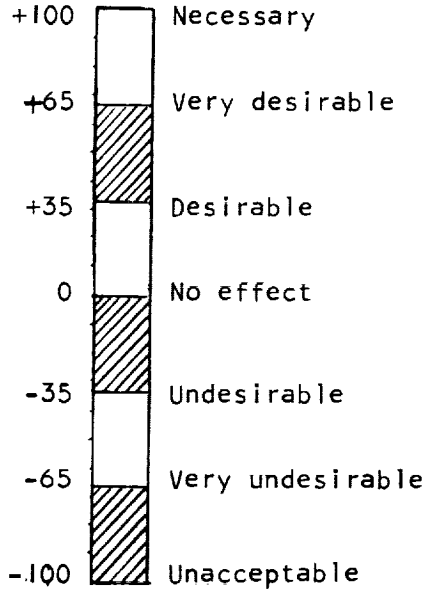


Figure 165. Basic Rating Scale

Summary of Component Improvements

General.--All the previously discussed components were examined for areas of potential improvement both in the immediate future of the 1970's and for possible 1980-1985 realization. The major areas for improvement are weight, reliability, cost and performance, not necessarily in that order. Often an improvement in weight or reliability is foreseen to have an increased cost tradeoff. However, a prediction of the overall cost impact of given improvements is out of the scope of this study. The factors are very complex and not very well known. For example, it may very well turn out to be the case that an initially increased component cost (to increase reliability) will result in a decrease in overall system cost due to lower maintenance charges.

The following is a summary of suggested and expected improvements taken in order of the previous discussion:

Electric motors.--Weight may be improved by using:

(1) High permeability magnetic materials such as Hyperco alloys, Supermendur, etc.

(2) A high frequency system (ac) or high speed motors (dc).

Reliability may be improved by:

(1) Use of continuous wire instead of separate coils for ac motors. This increases cost.

(2) Design of ac motors for operation when one phase is lost by an open circuit. There is some weight penalty.

(3) Shrink fitting the ac motor stator to the frame to improve heat transfer.

(4) Use of melted epoxy resin for slot linear insulation to improve heat transfer.

(5) Use of preloaded bearings.

Performance and control may be improved by advances in future material technology for Brushless dc motors (BDCM). With future (1985) materials technology, the BDCM could also be lighter than induction machines at ratings below 3 kW (4 hp).

Electric generators.--Weight, size, performance and efficiency of ac generators are improved by use of a sleeved salient-pole rotating-rectifier alternator. A new manufacturing technique for this alternature has been developed by Garrett/AiResearch.

For a dc system, brushless (and therefore more reliable) operation can be achieved by use of a variable speed alternator and generator field regulation to keep the output voltage constant.

Power conversion equipment.--Weight can be reduced significantly (as much as 50 percent) and efficiency improved by use of:

(1) Solid state EMI suppression techniques

(2) Insulated copper-clad aluminum wiring

(3) Integrated circuits for all logic, control and instrumentation.

(4) Provision of adequate cooling and use of dc electrolytic capacitors

(5) Bulk dc power conversion, even for close-tolerance wide-range power sources.

(6) Improved commutation circuits for high power choppers. This depends mostly on future development of solid-state circuitry.

Distribution equipment.--Weight of wires can be reduced by:

(1) Future development of insulation enamels.

(2) Use of insulation materials like Kapton Type HF film.

(3) Use of Micro Miniature wiring concepts (MIMI). This promises to reduce wire weight by 40 to 60 percent.

(4) Use of aluminum foil construction with interleaved Kapton or Nomex high temperature insulation.

Circuit breaker weight and performance characteristics can generally be improved by use of solid-state components such as gate-turn-off thyristors and self-healing switches. However, these components are presently costly as compared with more conventional components. Future demand and techniques should improve this situation.

Avionic loads.--For late generation transports such as the L-1011 and 747, the power demand of avionic loads represents as much as 8 percent of all power consumption. Future aircraft requirements are for increased numbers of avionics. Their efficiency, weight and cost is therefore significant.

A considerable improvement can be made by drastically reducing the number of acceptable dc voltage levels. The voltage levels recommended are: +5 Vdc for digital circuits and ±15 Vdc for analog circuits.

More attention should be paid to reducing output impedance by shortening cable lengths to the minimum and to employing tradeoffs of weight versus efficiency in future design.

New materials.--Materials discussed here are soft magnetic, permanent magnet, and structural.

Soft magnetic: The use of cubex steel in aircraft generators at a nominal cost increase is expected to reduce machine weight and volume by 10 percent or more. The use of Hiperco 50 alloy in generators and motors can reduce electromagnetic weight by up to 24 percent. In addition, frame and shaft weight can be reduced because of smaller size. The cost penalty of Hiperco 50 at present is prohibitively high (10 to 20 times silicon steel). However, increased demand and improved production techniques are expected to lower the cost by 1980 to competitive levels.

By use of supermander in power transformers, depending on the copper/core loss ratio the transformer weight can be greatly reduced. For example, at a loss rate of 1.0 the weight reduction is approximately 33 percent. At 0.5 it is 55 percent.

Permanent magnetic materials.--Samarium cobalt is by far the most promising material for future permanent magnetic application. As compared with platinum cobalt, the cost reduction factor is approximately 80:1. It also is four times as strong (magnetically) as most Alnicos. If used in brushless dc motors and generators, considerable savings in weight, volume and cost are expected to be realized.

Structural Materials.--Graphite filament can effect great weight savings as the material is 40 percent lighter than aluminum and can withstand temperature of 533°K (260°C). The price, however is high ($135 per kg) and will have to come down to the region of < $40 per kg to be acceptable. This is expected to occur with increased production.

Fans, blowers and hydraulic pumps.--Weight can be improved by greater use of high speed centrifugal pumps instead of displacement pumps. Typically a 36 percent weight saving (pump weight) can be achieved. However, improved weight is traded off versus a lower efficiency.

The potential reliability of centrifugal pumps is also greater than standard displacement pumps which have built-in limitation at higher speeds.

A high frequency power source (> 400 Hz) would improve efficiency for emergency high head-pressure, > 690 N/cm^2, (1000 psi). For lighter weight fan and blower motors and lighter overall fan weight, the trend is towards less efficient fans of small impeller tip diameter.

Component heat transfer techniques.--There are a number of component heat transfer techniques available. Some, such as thermoelectric cooling, have been available for a long time. Their capability is limited by materials technology state-of-the-art.

The highest potential improvement is expected to arise as a result of incorporating optimizing techniques into existing performance predicting thermal analysis computer programs.

CONCLUSIONS

General

The subject matter of the foregoing study is the electrical power system which serves aircraft, its present day characteristics and possible improvements for implementation in the 1980s. Both conventional (subsonic commercial and military) and unconventional (VTOL, V/STOL) aircraft were examined.

A major part of the study was concerned with a detailed examination of the subsystems comprising the electrical power system and the subsystem components.

Each of the above study areas produced results and conclusions. The major conclusions are restated here without comment and are for the purpose of review. They are given in the order of their presentation in the report and not necessarily in order of importance.

Conclusions: Power Systems for Conventional Aircraft

(1) A high voltage dc system (300 vdc) is the optimum system for implementation in the 1980-1985 time period. The HV dc system is the lowest in weight, highest in reliability and lowest in projected operating and maintenance cost. The second and third best are the VSCF cycloconverter system and the dc/ac hybrid.

(2) The optimum system should incorporate the most advanced methods of solid state and hybrid switching techniques, multiplexing of control and status signals and an efficient data management system.

(3) The use of a negative structural return for the high voltage dc system is within present day ratings. An 'electrical reinforcement' may be required for the nacelle and engine areas. This could be done using a small amount of cabling for structure bonding.

(4) The main power shield should be placed at the load center of aircraft to minimize power cabling.

(5) All remote power controllers (RPCs) should be grouped in substations or distributed power centers. This will minimize power supply weights, minimize transmitter, receiver and logic requirements and simplify load distribution.

(6) A controller processor (CP) is required for automatic load management. Associated load management requirements require a control/display panel (CDP) and a central bus control (CBC).

(7) Heavy motor loads particularly for a HV dc system, should be powered by the hydraulic or pneumatic subsystem and not by the electrical system. This will avoid weight and design capacity penalties levied on

the electrical power system due to high inrush currents on motor starting.

(8) Significant research and technology problems need to be resolved before the high voltage dc system can be implemented. The research and technology areas are:

- High voltage, high current dc switchgear
- High efficiency power converters
- Brushless dc motors up to 15 kW (20 hp)
- An integrated management subsystem
- Electrical power system static and dynamic characteristics and interactions.

(9) Reliability was considered to be the most important factor in system evaluation followed by cost, weight and maintainability. The last three are about equal in importance. As long as performance met or exceeded certain minimum standards, it was concluded to have little impact on system merit evaluation.

(10) The major gains expected in future aircraft electrical power systems will be in the important cost effective areas of maintainability and reliability rather than in overall performance. Weight will also be reduced significantly as a result of development in high voltage dc system components and utilization of high voltage dc power transmission.

Conclusions: Power Systems for VTOL, V/STOL Aircraft and Air-Space Vehicles

VTOL, V/STOL aircraft.--

(1) For short range aircraft (up to 1300 km), ac power systems are the best choice. When the engine speed ratio (maximum to idle) is less than 1.25:1, a wild frequency generation approach is recommended. Above this ratio, a constant frequency scheme is recommended.

(2) For medium and long range aircraft (1300 to 4800 km), variable frequency generation and high voltage dc distribution with square-wave ac power for motor loads is recommended.

Air-space vehicles.--

(1) The booster electrical system should use ac power transmission. This eliminates the need for much power conversion equipment. Likewise, the orbiter system should use dc transmission.

(2) For control and protection, an advanced data bus system utilizing multiplexing of signals and solid state switching is recommended.

(3) Dc centralized power conditioning should be used since the increase in payload capability is offset by an increase in complexity and system power losses.

(4) High voltage (>115 vdc) power transmission cables can be used to achieve considerable weight savings.

Conclusions: Aircraft Electrical Power Subsystems

Generation subsystems.--The constant speed constant frequency system (CSCF) remains the standard approach for obtaining constant frequency. It has been much improved in recent years and is used on most present day aircraft. Major conclusions on other considered generation subsystems are as presented below:

(1) The variable-speed constant-frequency (VSCF) system performs better than the CSCF. It has a) precise frequency control, b) good voltage regulation and phase balance, c) much shorter transient response time, d) lower transient amplitudes and better paralleling capabilities.

(2) The VSCF of the future can be significantly reduced in weight and size by using a) higher generator rotational speeds, b) direct mounting of equipment on engine and accessory pads, c) improved converter and filter designs, and d) integrated circuits for converter and control circuits.

(3) Both the cycloconverter VSCF and dc-link VSCF systems have better maintainability than the conventional CSCF generation systems. This is largely due to their modular construction, permitting localization of defective components and ease of replacement.

(4) The synchronous inverter (rotating inverter system) requires considerable advances in technology, producing a weight decrease in order to make it attractive for aircraft use. A major disadvantage is that it requires brushes. Reliability and maintainability are slightly better than for the CSCF generation subsystem.

(5) The line-commutated inverter (rotating inverter system) combines the best features of rotating machine and solid-state technology. The system output is a nearly pure sine wave. The addition of a flywheel should greatly improve short circuit current capability. System construction is simple and relatively easy to maintain. It has a great drawback of requiring a special start-up circuit. Except for the start-up question, the subsystem is one of the most adaptable generation schemes reviewed.

(6) For the Super Auxivar system reliability and maintainability are improved at the cost of 2 to 1 increase in weight. Transient response

is relatively slow. The induction machine in the Super Auxivar can be used for engine starting if ac power is available.

(7) The wild-frequency generation scheme is the simplest, least expensive, most reliable, lightest weight and least in volume among the generation schemes. It has, however, limited utility for aircraft because a) it is not adaptable for emergency parallel operation, b) output is variable frequency, and c) voltage regulation has to accommodate load and speed changes. The system is attractive for engine speed ratios of less than 2 to 1.

(8) The dc generation scheme is the next best to the wild frequency system in the categories of reliability maintainability, weight and initial cost. It can be easily paralleled when necessary. Direct mounted rectifier losses lower the generator efficiency by an average of only 2 percent. Some radio noise suppression is required due to diode switching.

(9) For performance only, the line-commutated rotary inverter is the best choice because it does not have the limitations of either the dc or wild frequency schemes. Where low maintainability cost and weight are the most important, either the dc generation scheme or the wild-frequency schemes are recommended.

(10) An internal engine generator (IEG) concept promises considerable advantages in drag reduction and improved reliability. Its implementation in a dc generation subsystem would - if practical - increase its attractiveness. Further investigation is recommended, particularly in the area of dc system compatibility.

Distribution subsystems.--The conclusions presented are taken from the subsections on: (1) power and signal transmission, (2) power switching and control, and (3) provision for backup power and protection.

Power transmission:

(1) A split-parallel system, where the generators are divided into groups separated by normally open tie-breakers, provides the highest reliability arrangement. This is because faults in one group can not propagate to others and fail the complete system.

(2) Dc power transmission has several advantages over ac transmission. They are (a) the cable has no reactance drop; (b) power factor is unity; (c) the aircraft frame can be used as a return wire (excluding titanium); (d) no skin effect; (e) corona onset voltage is higher for dc; (f) dc is safer to personnel than ac at the same voltage.

(3) Dc power transmission also has some disadvantages: They are (a) dc is more difficult to interrupt; (b) dc voltages are more difficult to insulate.

(4) By using highvoltage dc transmission (e.g. 300 v) power cable weight can be reduced by 50 percent or more depending on feeder length. Single wire transmission is practicable.

(5) If 115/200 volt ac is acceptable for personnel safety, then a dc level of 300 volts should be acceptable.

(6) The corona-safe voltage level is 300 volts dc in unpressurized areas at altitudes up to 30 km. For pressurized areas it is higher.

(7) When the dc voltage of power transmission cable is doubled, the maximum conductor weight reduction attainable will be a factor of 4, while the minimum weight reduction is a factor of 2.92, depending on whether the cable is voltage drop or current density limited.

(8) Power should be transmitted at or near the current rating of the minimum size wire providing adequate mechanical strength.

(9) For high voltage ac (230/400 v, 345/600 v), no significant weight savings are obtained over low voltage if the installation length is less than 32m (100 ft). For a definite weight-savings, cable lengths should exceed: 50m (150 ft) for a 40 kVA channel, 40m (120 ft) for 60 kVA and 30m (100 ft) for a 90 kVA channel.

(10) For ac transmission line voltages higher than triple standard, isolation transformers should be used for step down operation.

(11) At double standard ac voltage (based on given assumptions) a 60 kVA channel feeder (plus autotransformers) weighs the minimum at a frequency of 900 Hz. The minimum weight for a triple standard voltage channel occurs at 2 kHz.

(12) For long feeder runs, high voltage transmission is unavoidable to keep feeder weights within tolerable limits.

Solid state power switching and control:

(13) Solid state devices require only low signal level control. These control signals can be multiplexed. The requirements of automatic load management can not be met by conventional electromechanical switches, but can be met by solid state devices.

(14) Solid state switches are generally much lighter and smaller than equivalent rating remotely controlled electromechanical circuit breakers. Weight savings are at least 50 percent.

(15) For immediate and near future high power circuit applications requiring series relays, solid state switching is not practical because of excessive voltage drops.

(16) Production of EMI is reduced. There is no 'contact bounce' in solid state switches.

Signal multiplexing:

(17) Weight savings, as compared with a hardwired scheme, are significant when multiplexing is used for systems with large numbers of signals (>150).

(18) Time division multiplexing (TDM) is recommended as being generally less complex than frequency division multiplexing (FDM). Both analog and digital information can be handled by the TDM system. The recommended encoding scheme for analog data is a cyclic progressive code. This is a result of majority voting and redundancy considerations.

(19) To minimize hardware at individual substations, redundant time-shared analog-to-digital converters (ADC) should be used.

Uninterruptible power:

(20) An uninterruptible power system arrangement is recommended for future aircraft. For high power ratings, the recommended configuration uses a battery blocked by an SCR switch. The SCR switch operates to connect the battery to inverters when output voltage drops below a predetermined value.

Utilization subsystems.--These subsystems are powered by either electrical, hydraulic or pneumatic means.

Electrically powered loads:

(1) Motor and heating loads represent the largest quantity of the electrical loads.

(2) Recently developed high performance servomotors, particularly the Minertia motor and Hyper-Servomotor, exhibit the desirable, high torque-to-inertia ratios needed for future fast response servosystems.

(3) Fluorescent lighting should use square wave ac power at frequencies between 400 and 1000 Hz for maximum life and lighting output. High voltage operation (up to 800 vac) improves circuit efficiency.

(4) For electronic loads, separate modular interface units are recommended. These units will provide closely regulated steady state voltage, a clean dynamic output free of noise and transients, low surge impedance and a means of attenuating disturbances. This will largely eliminate the present need for separate conditioning circuits in each avionics box. The modular interface units would be dc-dc converters.

Hydraulic and pneumatic powered loads:

(5) Hydraulic power sources are preferred when:

- Very high power amplification is required

- Very high force-to-inertia ratios are required
- High stiffness is required
- Transmission distance is relatively low
- Radiation environment is minimal or protected

(6) Pneumatic power sources are preferred when:

- Environmental conditions are severe (e.g., thermal and radiation)
- Transmission distance is relatively long
- Contamination may be a problem
- High pressure compressed air is available

(7) Emergency hydraulic power can be supplied by pumps driven by electric motors. Otherwise, the use of electric motors for normally powered hydraulic loads should be minimized.

Conclusions: Aircraft Electrical Components

The conclusions are stated for the following categories:

(1) Electric motors

(2) Electric generators

(3) Power conversion equipment

(4) Distribution equipment

(5) Avionic loads

(6) New materials

(7) Fans, blowers and hydraulic pumps

(8) Component heat transfer techniques

(9) Maintainability

Electric motors.--In the immediate future, the constant-frequency ac squirrel cage induction motor is the best choice. For the 1980s, the brushless dc motor (BDCM) will be preferable since it provides an adjustable speed drive, draws moderate starting current and has better overall performance.

With future (1985) materials technology, the BDCM could also be made lighter than induction machines for ratings below 3 kW (4 hp). Other conclusions for electric motors are as given below.

(1) For a specific motor drive, a weight saving can be obtained by increasing the motor speed even if additional gears are required.

(2) The use of a wild-frequency generation system will increase required motor weight by ratios varying from 1.2 to 5.2.

(3) Reliability of electric motors can be improved by:

(a) Using continuous wire instead of separate coils for ac motor windings

(b) Design of ac motors for operation when one phase is lost by an open circuit.

(c) Shrink fitting the ac motor stator to the frame to improve heat transfer.

(d) Use of melted epoxy resin for slot linear insulation to improve heat transfer.

(e) Use of preloaded bearings.

(4) Motor weight can be substantially reduced by use of high permeability magnetic materials such as Hyperco alloys and Supermendur.

(5) The majority of brushless dc motor weight is in its electronic package. Using a Samarium-cobalt permanent magnet and motor speeds of 48 000 rpm the motor specific weight can be lowered to 1 kg/kW at a rating of 24 kVA. However, development of high powered solid state switching is required.

Electric generators.--Weight, size, performance and efficiency of ac generators are improved by use of a sleeved salient-pole rotating-rectifier alternator.

(1) For a dc system, brushless (and therefore more reliable) operation can be achieved by use of a variable speed alternator and generator field regulation to keep the output voltage constant.

(2) The use of a new manufacturing technique (developed by AiResearch Mfg. Co.) promises to (a) double present allowable sleeved salient-pole alternator tip-speeds,(b) reduce magnetic leakage and windage loss,(c) reduce construction costs, and(d) reduce weight significantly.

(3) Internal engine generator (IEG) concept promises advantages in drag reduction and improved reliability. Further development on this concept is well justified.

Power conversion equipment.--Weight can be reduced significantly (as much as 50 percent) and efficiency improved by use of:

- Solid state EMI suppression techniques
- Insulated copper-clad aluminum wiring
- Integrated circuits for all logic, control and instrumentation.
- Provision of adequate cooling and use of dc electrolytic capacitors
- Bulk dc power conversion, even for close-tolerance wide-range power sources.
- Improved commutation circuits for high power choppers. This depends mostly on future development of solid-state circuitry.

(1) For the highest system efficiencies it is desirable to convert power at the highest possible system voltage compatible with safety.

(2) It is beneficial to use complex switching circuitry only if the desired output waveform is then most closely approximated.

(3) Direct ac-to-ac conversion techniques, although complex can, with advances in semiconductor technology, provide a lower weight and more efficient system than a dc-link concept. Internal stress problems exist when the input/output frequency is high.

(4) For general purpose dc-to-dc conversion utilization, chopper systems provide efficiencies in excess of 90 percent and excellent weight-per-unit-power ratios when operated at reasonably high frequencies.

(5) When electrical isolation is required between the source and the output, dc-ac-dc power conversion techniques should be used. Either an auto-transformer or a multi-wound transformer can be used.

Distribution equipment.--This includes cabling, busses, switchgear and transformers.

(1) Aluminum alloy cables are the most attractive for future aircraft use; however, termination problems have to be overcome.

(2) The weight of wiring and cable insulation can be significantly reduced by:

(a) Future development of insulation enamels such as polyamide-imide.

(b) Use of insulation materials like Kapton Type HF film.

(c) Use of Micro Miniature wiring concepts (MIMI). This promises to reduce wire weight by 40 to 60 percent.

(3) An evaluation of the feasibility of sodium conductors found that it's use creates many new problems (such as poor flexibility, fire hazard and special terminations) and may not offer substantial weight savings. It is not recommended for use.

(4) The use of aluminum foil for transformers has a number of advantages over conventional copper wires such as: higher conductivity-to-weight, relative ease of winding, elimination of hot spots and a low turn-to-turn voltage stress. The most difficult problem is turn-to-turn insulating; however, the future use of interleaved Kapton or Nomex high temperature insulation promises successful light-weight low-cost transformers.

(5) Gate-turn-off tyristors and self-healing fuses are very promising developments for future aircraft applications. These are, however, costly as compared with conventional circuit breakers.

Avionic loads.--Future aircraft requirements indicate increased numbers of avionic loads and increase above the present maximum of 8 percent of all power consumption.

(1) Switching regulators are recommended for most low voltage supplies (e.g., 5 V) rather than series pass regulators to reduce power dissipation. A high (50 kHz to 150 kHz) chopping frequency should be selected to keep filter choke and capacitor weight down.

(2) A considerable improvement can be made by drastically reducing the number of acceptable dc voltage levels. The voltage levels recommended are: +5 Vdc for digital circuits and ±15 Vdc or ±12 Vdc for analog circuits.

New materials.--Materials studied were soft magnetic, permanent magnetic and structural.

Soft magnetic:

(1) The silicon-iron alloy Cubex steel offers high weight reduction potential for generators. Compared with conventional silicon steel, for a given magnetic field the flux density of Cubex is approximately 10 percent higher.

(2) Hiperco 27, because of high saturation induction and high Curie temperature, is suitable for use in aircraft generators and motors. It can reduce electromagnetic weight by up to 15 percent. Hiperco 50 can produce even greater weight savings of 24 percent or more. Complicated processing makes them relatively costly.

(3) When supermendur is used to replace silicon steel in transformer cores, approximately 30 percent more power output can be realized, or a size reduction can be made. Depending on the acceptable copper/core loss ratio the transformer weights may be reduced by as much as 55 percent.

Permanent magnetic materials: Samarium cobalt is by far the most promising material for future permanent magnetic application. As compared with platinum cobalt it is twice as strong and the cost reduction factor is approximately 80:1. It also is four times as strong (magnetically) as most Alnicos. If used in brushless dc motors and generators, considerable savings in weight, volume and cost are expected to be realized. For example, even with use of an Inconel rotor-support sleeve, the estimated savings over an Alnico 9 material is more than 30 percent for a brushless dc motor.

Structural materials: Graphite filament is 40 percent lighter than aluminum and can withstand high temperatures (e.g., 533°K). It's price, although high, is expected to come down with increased production.

Fans, blowers and hydraulic pumps.--

(1) High speed centrifugal pumps are much lighter than displacement pumps. The 36 percent or so weight savings is traded off versus lower efficiency

(2) Reliability of centrifugal pumps is higher than displacement pumps-particularly at high speeds.

(3) Because of the weight savings, a less efficient fan of small impeller tip diameter is probably preferable to a more efficient, but larger diameter, machine.

(4) A high frequency power source (>400 Hz) would improve efficiency for emergency high head-pressure requirements; e.g., >690 N/cm^2 (1000 psi). This could also eliminate the need for step-up gear trains.

Component heat transfer techniques.--

(1) An attractive method of cooling components is the Vortex (or Hilsch) tube. A temperature differential of 55°C (100°F) is obtainable. It is small in size, has no moving parts, and can be located in inaccessible places.

(2) Convective cooling can be effectively applied to both power cables and rotating machinery. The cables would be cooled by forced convection utilizing a coolant flowing in a conduit which contains the cables. Rotating machinery such as alternators can use their centrifugal force for either air cooling or liquid cooling.

(3) The use of cryogenic fluids for cooling on aircraft is not recommended except in cases where the fluid is expendable, and refrigeration plant is therefore not required.

(4) Forced convection pin-fin and plate-fin air cooled heat sinks are 4 to 9 times better than extruded conduction heat sinks. Liquid cooled heat sinks are 3 to 12 times more effective than air cooled heat sinks (for aluminum extrusions).

(5) Thermal network synthesis should be used where possible to optimize thermal design.

(6) Thermoelectric refrigeration can be effectively used in many applications. It requires a dc power source. Modules come in a great variety of sizes, shapes, ranges and materials. They are highly recommended-particularly where spot cooling or fine temperature control is required.

Maintainability.--

(1) Some reliability improvements such as soldered or welded connections, instead of plug-in connections actually increase maintenance time. Each design should be examined and plug-in connections used where increased maintenance would otherwise occur.

(2) Self-repair capability is an encouraging new development for components. Studies in this area are just beginning and should be supported.

(3) Failure prediction data systems such as AIDS should be used on large, complex aircraft systems to predict impending failures and reduce the number of unnecessary removals of components.

(4) Maintenance equipment should be designed so as to decrease required personnel skill level without excessive equipment cost.

(5) The increased use of microelectronics is expected to increase the discard-at-failure occurrence. Repair is often uneconomical.

(6) Maintainability decisions should be made before or during design of the developmental power system. This is because later changes are usually expensive and time consuming. It is recommended that maintainability requirements be incorporated into the design.

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APPENDIX A

METHOD OF COMPUTATION OF SYSTEM FLIGHT WEIGHT

Introduction

The electrical system flight weight includes all additional weights that are connected with system installation and operation. Included are all additional aircraft engine and airframe weights as well as fuel and lubricant resulting from loading the engine with the generator.

This extra weight depends on (1) the characteristic of the engine as to fuel and oil consumption, (2) the aerodynamic characteristic of lift versus drag, and (3) the average flight duration. To obtain the system flight weight, the following must be known:

(1) The engine specific fuel consumption for weight SFC_W kg/h/kg (kg of fuel necessary to carry 1 kg of aircraft weight for 1 hr).

(2) The engine specific fuel consumption for energy SFC_E kg/kWH (kg of fuel necessary to obtain 1kWh output of the main generator).

(3) The aircraft lift-to-drag ratio L/D (dimensionless).

(4) Equipment efficiency η in percent.

(5) Average flight duration t in hr.

(6) The total energy demand for the mission in kWh.

It should be recognized that these parameters are by themselves dependent variables. They vary with aircraft speed, altitude thrust setting, air density, temperature, etc. Also, the equipment efficiency is usually stated for full-rated load; efficiency is considerably lower for light loading or idle. Since generators rarely are used continuously to full capacity during a flight mission, an additional source of error is present. Because of the oversimplification, the calculated absolute equipment flight weight will not yield accurate data. The usefulness of this approach, however, becomes more apparent when a comparison between candidate systems is made and only relative quantities are considered.

The formula and an example calculation are given below.

Example Calculation

The formula for the flight weight is (the portion of weight for fuel is at take-off):

$$W_F = W_I + \frac{W_I SFC_W t}{L/D} + \frac{kWh\ SFC_E}{\eta} + \left[\frac{W_I SFC_W t}{L/D} + \frac{kWh\ SFC_E}{\eta}\right] \frac{SFC_W t}{L/D\ 2} \qquad (A\text{-}1)$$

The expression in the bracket is a fuel penalty of the required fuel. Assuming specific representative values, then

Total installed weight W_I = 4 536 kg (10 000 lb)

Specific fuel consumption weight SFC_W = 0.8 kg/h/kg

Specific fuel consumption energy SFC_E = 0.136 kg/kWH (0.3 lb/kWH)

Lift-to-drag ratio L/D = 10

Equipment efficiency η = 0.8

Total energy demand kWh = 400

Average flight duration t = 4 hr

$$W_F = 4\,536 + \frac{4\,536 \times 0.8 \times 4}{10} + \frac{400 \times 0.136}{0.8} +$$

$$\left[\frac{4\,536 \times 0.8 \times 4}{10} + \frac{400 \times 0.136}{0.8}\right] \times \frac{2 \times 0.8}{10} = 6\,280 \text{ kg}$$

If efficiency is to be expressed in equipment flight weight, eq. (A-1) may be rearranged with total energy demand and flight duration held constant.

$$W_F = W_I \left[1 + \frac{SFC_W t}{L/D} + \frac{SFC_W t^2}{2(L/D)^2}\right] + \frac{1}{\eta}\left[kWh\ SFC_E + \frac{kWh\ SFC_E SFC_W \cdot t}{2\ L/D}\right]$$

$$W_F = W_I K_1 + \frac{K_2}{\eta} \qquad \text{(A-2)}$$

In eq. (A-2), $W_I K_1$ represents the weight term and $\frac{K_2}{\eta}$ is the energy term.

Using the previous numerical example, K_1 = 1.3712 and K_2 = 63.1

The energy term slightly exceeds 1 percent of the weight term, and efficiency improvements of the equipment have negligible affect for the flight weight derivation. Efficiency, even though it does not influence equipment flight weight appreciably, has yet a secondary affect on weight. If efficiency is low, losses are high. Losses appear in the form of heat, and additional heat exchanger or cooling equipment may become necessary, depending on environmental conditions. Approximately 0.15 to 0.45 kg of heat exchanger weight is required for removal of 1 kW heat. Considering this projected weight penalty, the overall affect of system efficiency on equipment flight weight still is negligible.

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APPENDIX B

SYSTEM WORTH AND THE COST BASIS METHOD

Introduction

The engineer's objective is to maximize some parameters of system worth of his design. System worth is a function of the differences between benefits and cost. Absolute differences by themselves, however, provide no true criterion of worth. They must be related in some way to the scale of the particular value.

A design activity or decision may result in a gain in benefit over cost for one component of the value at the expense of a loss for some other; thus, a trade-off situation exists. In order to conclude the worth of the one value in terms of the other, there must be a value scale for relating them. In the most general sense the objective is to maximize system worth or utility. Therefore,

$$\text{maximize } U = f(X_2 \ldots\ldots X_n)$$

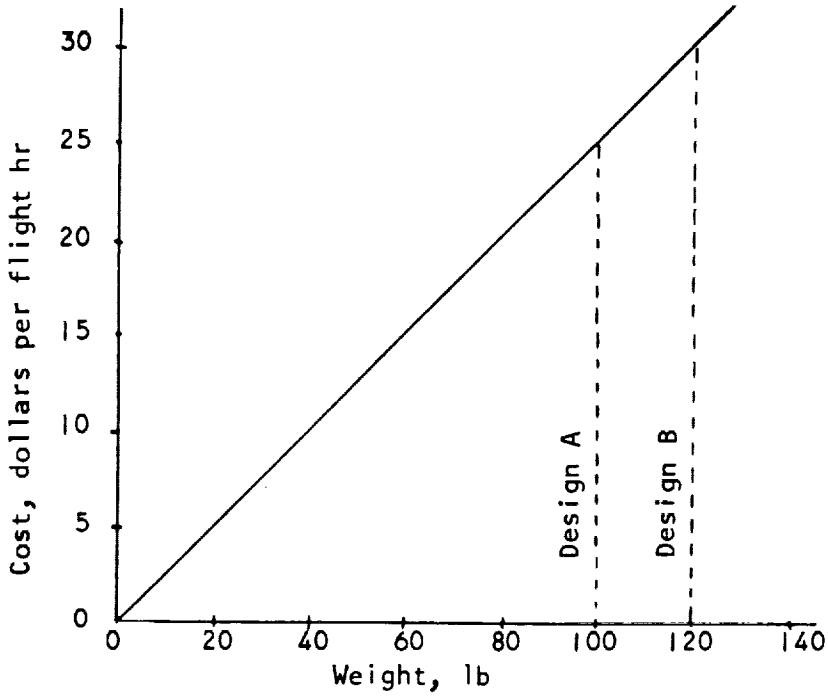
Where X's are the value variables, some are positive (benefits) and others negative (const). It would be very useful if all, or most parameters could be related directly to cost. These relationships, however, are often indirect and have to be defined. The cost basis method which is now presented is an example of one possible approach.

Cost Basis Method

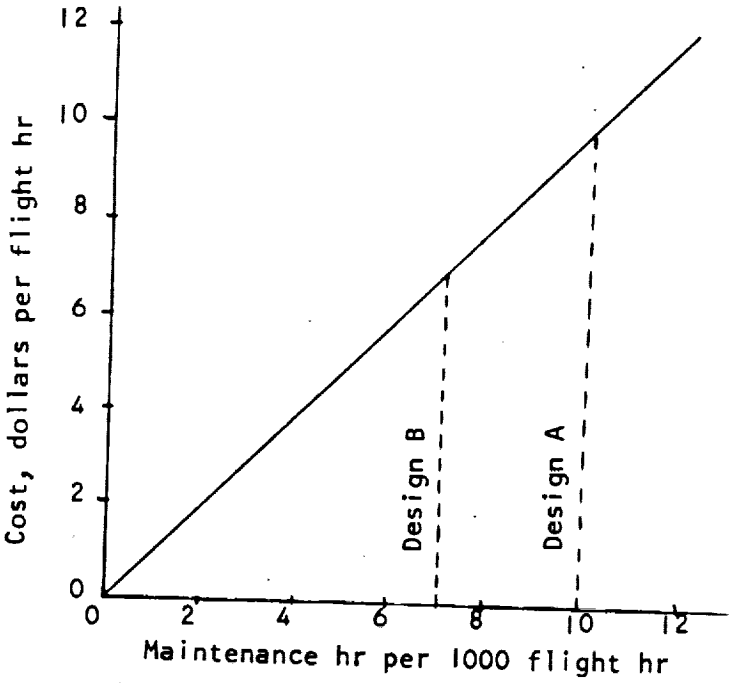
It is assumed that all the parameters in question are related directly or indirectly to cost. Therefore, theoretically, through data reduction and analysis, the relation between any parameter and cost can be established, and from this the relative weighted factors can be determined. To illustrate this method, two parameters, the maintainability and the weight of a certain component are employed and the relations between the cost and the two parameters are assumed to be as shown in Figure B-1 (a) and (b) in which the relations are assumed to be linear and the cost is expressed in dollars per flight hour.

Assuming there are two designs, A and B, in order to compare their relative merit, one straightforward method would be to calculate the total cost. Thus the following result is obtained:

Total cost of A = 25 + 10 = \$35/hr
Total cost of B = 30 + 7 = \$37/hr



(a) Cost versus Component Weight



(b) Cost versus Maintenance Hr

Figure B-1. Example of Relationship Between Cost and Parameter for Optimization

Therefore the ratio of their relative merits is

$$\frac{M_a}{M_b} = \frac{37}{35} = 1.057$$

The same result, however, can be obtained by using the method of "weighted factors". When design A is used as a basis, it can be seen that 1 p.u. of weight is equivalent to 2.5 p.u. of maintenance time ($25/flt.hr. for weight and $10/flt.hr. for maintenance). Therefore, if a weighted factor of 1 is assigned to maintainability, the relative weighted factor of weight should be 2.5. The equation for calculating the relative merit is:

$$\text{Relative Merit} = \frac{1}{\Sigma(\text{Parameter value in P.U. x weighted factor})} \qquad \text{(B-1)}$$

The parameter values in this example are, from Figure B-1:

	Parameter values in P.U.	
	Weight	Maintenance
Design A	1	1
Design B	1.2	0.7

The relative merits of the two designs, A and B, can then be calculated:

$$M_a = \frac{1}{1 \times 2.5 + 1 \times 1} = 0.286$$

$$M_b = \frac{1}{1.2 \times 2.5 + 0.7 \times 1} = 0.27$$

$$M_a/M_b = 0.286/0.27 = 1.057$$

The above is a simplified example that shows how the relative weighted factors can be determined and how the method of weighted factors enables us to evaluate the figure of merit of various designs (components or systems) without knowing their absolute values of cost. However, even to determine the parameter values (which are related to cost), an extensive cost effectiveness analysis must be performed and considerable difficulties should be expected.

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APPENDIX C

CALCULATION OF CABLE WEIGHT AS A FUNCTION OF VOLTAGE AND FREQUENCY

Assumptions

A method of using approximated equations for determining the cable weight is employed for evaluating the system weight as a function of voltage and frequency. To make the process simple and manageable, two assumptions are made.

(1) For one generating channel, three equilateral groups are always used, i.e., three conductors are used for each phase.

(2) There is an infinite number of wire sizes. This means when the cable is not limited by voltage drop, it is assumed that there is always a cable size that can carry the current to its maximum allowable current density.

Since the purpose of calculating the cable weight is to determine the practical range of system voltage and frequency. It is felt that the method based on the above assumptions is satisfactory.

Example Calculation

The independent variables on which the weight of the cable depends are

C = capacity in kVA

V = system voltage in volts

F = system frequency in kHz

L = cable length in m

The procedures for calculating the cable weight are as follows:

(1) Calculate the current per phase

$$I = \frac{C \times 1000}{3 \times \frac{V}{115} \times 120}$$

(2) Calculate current per conductor

$$C_c = I/3 \qquad (C\text{-}2)$$

(3) Calculate the impedance of conductor

$$Z = 787\ C_c^{-1.38} + 8.55\ F\ C_c^{-0.145} \qquad (C\text{-}3)$$

where Z = impedance per km

(4) Calculate the maximum cable length based on an allowable voltage drop of 4.35 percent (5 V for 115 V system)

$$L_{MAX} = \frac{\frac{5}{115}\ V}{C_c \times Z} \times 1000 \qquad (C\text{-}4)$$

(5) Compare the desired cable length L with L_{MAX}. If L is less than L_{MAX}, it means the cable being calculated is current capacity limited, in which case the cable weight can be calculated by using the following approximated equation

$$W_{cable} = 0.694 \times 10^{-3}\ L\ C_c^{1.4}\ kg \qquad (C\text{-}5)$$

(6) If L is greater than L_{MAX}, it means the cable is voltage drop limited. In this case, the maximum allowable impedance (in ohms/km) is calculated

$$Z_m = \frac{\frac{5}{115}\ V}{L \times C_c} \qquad (C\text{-}6)$$

(7) Calculate the size of the cable (represented by its current carrying capacity) which has an impedance of Z_m. This can be done by solving C_c from eq. C-3 shown in step 3. Since it cannot be solved analytically, an iterative method should be used. After the required current carrying capacity C_c is obtained, the weight of the cable can be calculated similarly by using eq. C-5 shown in step 5.

It should be noted that an approximated equation for calculating C_c' directly from Z_m and F has been determined as follows

$$C_c' = 53.2\ (3.28Z)^{-(1.43 + 0.535\ F)}\ e^{1.787\ F} \qquad (C\text{-}7)$$

where e is the base of natural logarithm.

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However, since this equation is not accurate as eq. C-3, it is not used when a computer program is employed for the weight calculation. Nevertheless, this approximated equation does provide a quick answer whenever necessary. A flow diagram illustrating the calculation procedure is shown in fig. C-1.

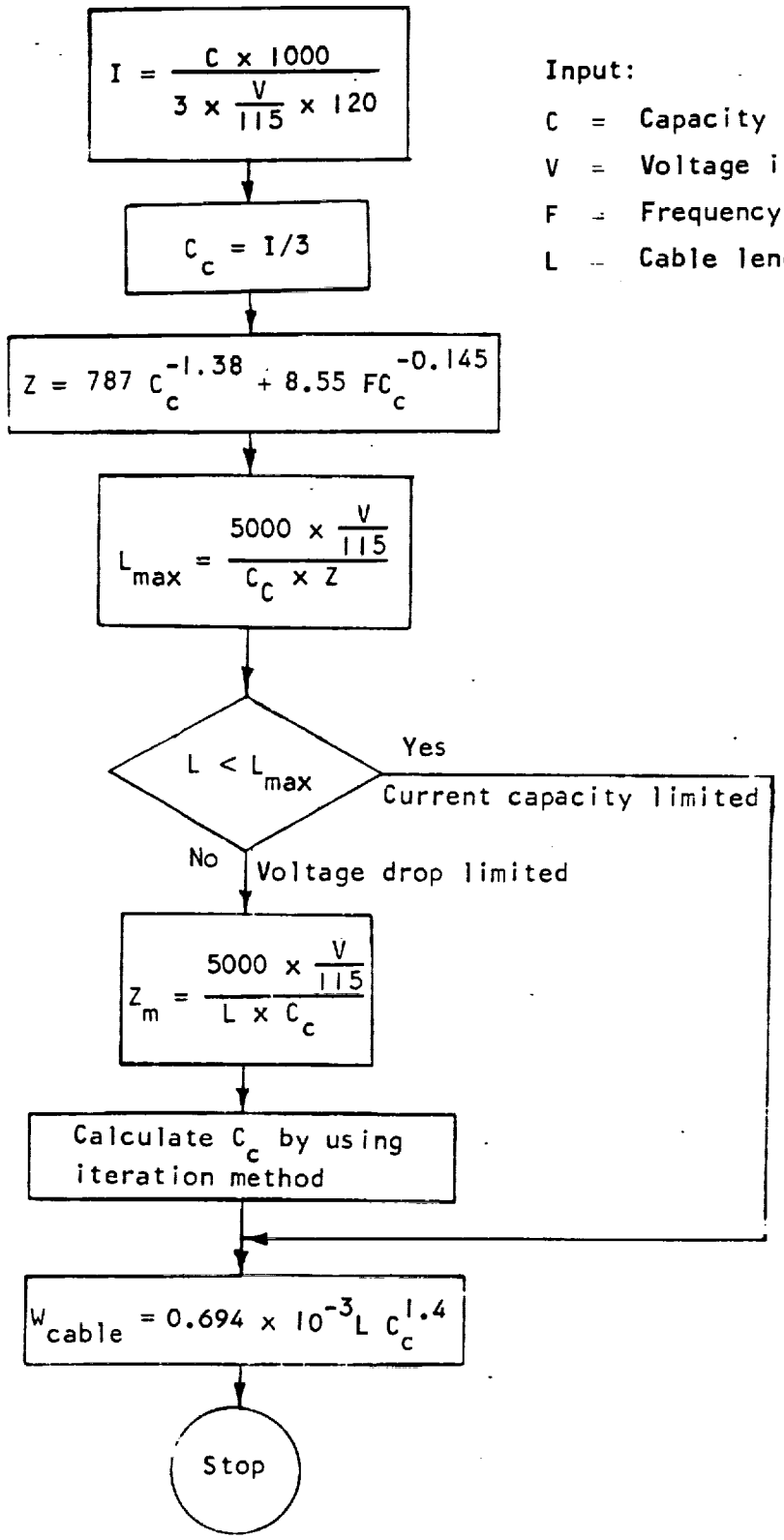


Figure C-1. Block Diagram--Cable Weight Calculation

APPENDIX D

FEEDER WEIGHT DATA

Introduction

The results of computations of feeder weights for ac and dc power transmission lines are presented. The ac tables are for 40 KVA, 60 KVA and 90 KVa power levels and are presented for single, double and triple standard line voltage at a frequency of 400 Hz.

The dc tables are for 40 kW, 60 kW and 90 kW power levels and are for 200 and 400 Vdc line voltages.

AC Feeder Weights

1. 40 KVA, 115/200 V, 400 Hz, 111A line current
   Maximum impedance 0.045 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at Max. Length, kg	
			One Phase	3 Phase
3 #12	123	24	2.8	8.4
3 #10	165	33.5	6.5	19.6
3 #8	219	44.2	13.8	41.5
3 #6	303	55.7	27.4	82.5
3 #4	405	> 61	44.8*	135*

2. 40 KVA, 230/400 V, 400 Hz, 55A line current
   Maximum impedance 0.180 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at Max. Length, kg	
			One Phase	3 Phase
3 #16	66	36.5	1.97	5.9
2 #14	64	41.5	2.22	6.7
1 #10	55	44.5	2.90	8.7
3 #14	96	> 61	5.0*	14.9*

*Feeder weights are for 61 m (200 ft) length

3. 40 KVA, 345/600 V, 400 Hz, 37A line current
Maximum impedance 0.405 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at Max. Length, kg One Phase	3 Phase
2 #16	44	55	1.94	5.8
1 #12	41	> 61	2.36*	7.1*

4. 60 KVA 115/200 V, 400 Hz, 166A line current
Maximum impedance 0.030 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at Max. Length, kg One Phase	3 Phase
3 #10	165	23	4.5	13.4
3 #8	219	39.5	9.2	27.7
3 #6	303	37.2	18.2	54.8
3 #4	405	43.9	32.2	96.5
3 #2	543	> 45.8	51.2**	154**

5. 60 KVA, 230/400 V, 400 Hz, 83A line current
Maximum impedance 0.12 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at Max. Length, kg One Phase	3 Phase
2 #12	82	43	3.3	9.9
3 #12	123	> 45.8	5.3**	15.9**

*Feeder weights are for 61 m (200 ft) length
**Feeder weights are for 45.8 m (150 ft) length

6. 60 KVA, 345/600 V, 400 Hz, 55A line current
Maximum impedance 0.282 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at 150 ft length, kg One Phase	3 Phase
3 #16	66	> 46	2.4	7.2

7. 90 KVA, 115/200 V, 400 Hz, 250A line current
Maximum impedance 0.020 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at Max. Length, kg One Phase	3 Phase
3 #6	303	25	12.1	36.4
3 #4	405	29	21.4	63.9
3 #2	543	>30	34.0*	102*

8. 90 KVA, 230/400 V, 400 Hz, 125A line current
Maximum impedance 0.080 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at Max. Length, kg One Phase	3 Phase
3 #10	165	59.5	11.7	35.0

9. 90 KVA, 345/600 V, 400 Hz, 83 A line current
Maximum impedance 0.181 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight at Max. Length, kg One Phase	3 Phase
2 #12	82	64	4.9	14.8

*Feeder weight is for 61 m (200 ft) length

DC Feeder Weights

The feeder weight in a dc transmission system with frame as return is presented as follows:

(1) 40 kW, 200 Vdc, single line structure return, 200A, maximum resistance 0.0415 ohm

Feeder	Current Carrying Capacity A	Max. Feeder Length, m (Voltage Drop Limit)	Feeder Weight for Maximum Length, kg (Single Line)
3#8	219	54.3	17.0
2#6	202	58	19
1#1	211	> 61	28*

(2) 40 kW, 400 Vdc, single line structure return, 100A, maximum resistance 0.166 ohm

Feeder	3#12
Current carrying capacity, A	123
Maximum length, voltage drop limit, m	> 61
Feeder weight for (200 ft), kg	7.1

(3) 60 kW, 200 Vdc, single line structure return, 300A, maximum resistance 0.0277 ohm

Feeder	3#6
Current carrying capacity, A	303
Maximum length, voltage drop limit, m	58
Feeder weight for maximum length, kg	28.4

(4) 60 kW, 400 Vdc, single line structure return, 150A, maximum resistance 0.1106 ohm

Feeder	2#8
Current carrying capacity, A	146
Maximum length, voltage drop limit, m	> 61
Feeder weight for 61 m, kg	13

*Feeder weight is for 61 m (200 ft) length

(5) 90 kW, 200 Vdc, single line structure return, 450A, maximum resistance 0.0184 ohm

Feeder	3#3
Current carrying capacity, A	465
Maximum length, voltage drop limit, m	49.4
Feeder weight for maximum length, kg	46.7

(6) 90 kW, 400 Vdc, single line structure return, 225A, maximum resistance 0.0738 ohm

Feeder	3#8
Current carrying capacity, A	220
Maximum length, voltage drop limit, m	> 61
Feeder weight for 61 m (200 ft) length, kg	42

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APPENDIX E

SERVOMOTORS

Summary

The general types of servomotors are: (1) two-phase ac, (b) brushless dc and (c) brush-type dc. These types are briefly discussed. New, high performance servomotors with significant future potential are described and discussed in some detail. Their performance, in particular their frequency response, is also compared.

General Motor Types

Two-phase motor.--The two-phase ac motor is equipped with two stationary windings in the stator and a squirrel cage armature in the rotor. One stationary field winding is the reference field, which is constantly excited with an alternating voltage of fixed magnitude and frequency; the other winding is the control field to which the variable magnitude control signal is applied. The control voltage is of the same frequency as the reference field but is displaced 90-deg in time phase. The currents in the two-90-deg mechanically-spaced field windings generate a rotating field that produces a torque in the rotor by inducing current in the armature conductors. The magnitude of the rotor torque is proportional to the magnitude of the control signal, and the direction of rotation is dependent on whether the control signal is 90 deg leading or lagging with respect to the reference excitation. The two-phase motors are often filled with velocity generator to control the loop damping equivalents of acceleration and velocity feedbacks, respectively. Fig. E-1 shows the speed-control voltage characteristics of a typical small two-phase motor for a number of constant values of load torque. High-performance two-phase motors generally use 400- to 1600-Hz power.

Brushless dc motors.--The brushless dc motor has a revolving field configuration in which the rotor is the dc field and the stator is the armature. The stator winding is wound for a desired number of poles energized in sequence to generate a rotating flux that leads the rotor's position. It is therefore necessary to provide some type of commutation, which is usually done by sensing the rotor position via optical or Hall-effect devices. Solid-state devices are generally used for switching. For simplicity the rotor is usually a permanent magnet in low-power machines, but it also can be the pole structure used in Lundell and Rice machines. The brushless motor, due to the peripheral electronics, is heavier and more expensive than the conventional dc motor. However, since the brushes are eliminated, it has a longer life and does not require frequent maintenance. Also, for certain applications the brush-type machine is entirely unsuitable. In these cases, the brushless motor is greatly preferred, if not the only choice.

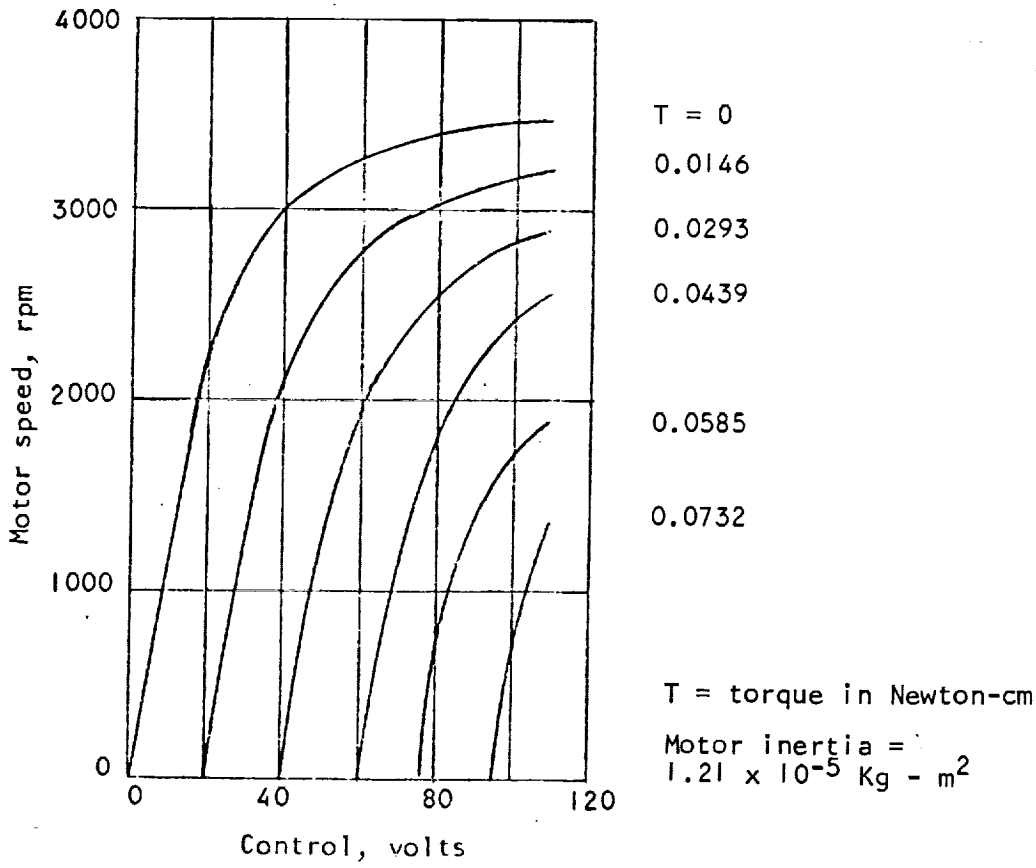


Figure E-1. Typical Two-Phase Servomotor Speed-Voltage Curves for Constant Torque Loads

Brush-type dc motors.--The conventional brush-type dc motors include (1) the shunt motor, (2) the series motor, (3) the compound motor, and (4) the permanent magnet motor. The field of the shunt motor is proportional to the terminal voltage. It can also be excited by a separate source to increase torque at low control voltages. The field of the series motor is proportional to the motor current. Since the field flux increases with increasing current, the speed of the series motor must decrease rapidly with increasing load. Theoretically, the speed of the series motor at no load would be infinite. Practically, however, friction losses increase rapidly with speed; therefore, small motors do not overspeed. There are two types of compound motors. If the shunt and series windings are connected such that the magnetizing effects are cumulative, the motor is a cumulative compound motor, and its characteristics are intermediate between those of the shunt and series types. If the two fields oppose each other, the motor is a differential compound motor, the characteristics of which are similar to those of the shunt motor with an exaggerated armature demagnetizing effect. The permanent magnet motor is similar to the separately excited motor except that the field is constant and cannot be varied. These types of motors are widely used, especially in small units.

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High Performance Servomotors

High performance servomotors for servosystem applications require very high torque-to-inertia ratios. To reduce the electrical and mechanical time constants, special design techniques are generally utilized, and unconventional motor configurations are often incorporated. A few high-performance servomotors developed by various manufacturers are discussed below.

Printed dc servomotor.--The printed motor uses a permanent magnet field and a nonmagnetic disc-type armature on which the conductors are deposited or printed. Since the armature contains no iron, the rotor inertia is reduced to a minumum, and the armature inductance is almost negligible. The uninsulated conductor pattern of the flat armature provides greater exposed surfaces for cooling. As a result, higher current pulses can be applied so that very high-pulse torque can be obtained.

The printed motor does not need a special commutator. Commutation is accomplished directly on the conductors. The absence of iron in the armature plus the large number of commutator bars practically eliminate preferred armature position and cogging. In addition, because of the relatively large rotor diameter, extraordinary smooth torque over the entire speed range is obtainable. The torque is so smooth that in some applications gearless drives become possible. Table E-I shows the motor characteristics of three different models.

Minertia motor.--The Minertia motor is a high-performance power servomotor developed by Yaskawa Electric Manufacturing Company in Japan. The Minertia motor name is deduced from its minimized inertia.

The Minertia motor armature is of a slotless construction in which the coils are mounted on the periphery of the armature core. To sustain mechanical forces and thermal stress, the coils are secured properly on the core by special mounting techniques.

The rotor conductors are wrapped on the slotless core with glass tape. Then the assembly is placed in a vacuum tank and impregnated with a high-polymer epoxy resin. To obtain better bonding, the armature core, conductor, glass tape, etc. are subjected to special treatment before assembly. Owing to the high resistance to heating and the great bonding strength of the epoxy resin, this fabrication technique is found to be highly successful in the manufacture of high-performance servomotors.

To reduce inertia, the rotor is made long and slender. The rotor core is built of silicon steel sheets, and the shaft is made of special steel since greater magnetic pull in the radial direction would be exerted on the shaft from its higher magnetic flux density. As the coils are mounted on the core periphery, the effective air gap is relatively larger than in an ordinary dc motor. Consequently, more magnetomotive force is required which results in a stator that looks comparatively large in size. The stator of the Minertia motor can be

TABLE E-1.--PRINTED SERVOMOTOR CHARACTERISTICS

Characteristics	Units	Model 368	Model 488	Model 668
Rated torque	Nm	0.085	0.300	0.99
Maximum pulse torque capability	Nm	1.1	2.65	8.3
Armature inertia (including hub and shaft)	NmS^2	0.00003	0.00013	0.00062
Mechanical time constant	sec	0.028	0.030	0.0295
Equivalent series mechanical impedance (at constant terminal voltage)	Hz/Nm	158	36.3	7.5
Armature inductance	μH	<100	<100	<100
Rated speed	rpm	3300	3300	2700
Rated current for 70°C rise	amp	7.0	7.5	10
Maximum stall current	amp	5.	6.	8
Rated voltage	volt	12	24	36
Power output @ rated speed	watt	30	105	280
Magnetic field		8-pole	8-pole	8-pole
Number of commutation segments		97	121	145
Armature resistance	ohm	0.63	0.6	0.4
Maximum friction torque	Nm	0.011	0.014	0.056
Back EMF per 1000 rpm	volt	2.22	5.55	10
Average torque per ampere	Nm	0.02	0.053	0.095
Weight	kg	1.4	2.9	5.9

either a field winding type or a permanent magnet type. Although the laminated pole shoe is not required because of the slotless construction, it is employed in large-size units to reduce manufacturing cost. Also, in larger size motors the commutating pole is still useful for improving the commutation. According to the manufacturer, the Minertia motor furnishes the following features.

(1) Its inertia (GD^2) is reduced to one-tenth the conventional value.

(2) The electrical time constant of the armature circuit is reduced to one tenth or one twentieth the conventional value.

(3) Its maximum torque can be made ten times larger than its rated torque.

(4) It can operate smoothly at extremely low speed and has no clogging problem.

(5) There is excellent linearity over a large loaded range.

Table E-2 shows the motor characteristics of several Minertia motors. Fig. E-2 illustrates the maximum acceleration of various types of motors.

Hyper-servomotor.--The hyper-servomotors are a new line of high performance dc servomotors developed at Speciality Motor Department of General Electric, Fort Wayne, Indiana. Similar to the Minertia motor, the design of the hyper-servomotors is based on the principle that for fast response, minimize armature inertia by making the armature long and slender. In addition, the armature conductors are distributed around the periphery of the armature instead of being set in slots as in conventional dc machines. This is a prime reason for the fast response and high torques of the motor. This configuration produces significantly greater torque-to-inertia ratios since it has a higher flux per unit of inertia and can operate at higher current densities due to better heat transfer characteristics from the conductor. The hyper-servomotor utilizes either a wound field or a permanent magnet field. Either wound or transient compensation can be supplied. The wound compensating winding decreases the armature circuit's electrical time constant. But, due to the added armature resistance, the mechanical time constant of the rotor is also increased. The transient compensation does not affect response time. The compensating winding, a squirrel cage set into the stator poles, generates flux only during a change in armature current. It helps to linearize acceleration characteristics, and by minimizing armature inductance better commutation characteristics can be achieved during transient current conditions.

Typical motor characteristics of a series of hyper-servomotors in listed in table E-3. Large units with ratings in excess of 4 hp are being developed. Fig. E-3 shows the frequency response of a 4 hp servomotor, the characteristics of which compare favorably with hydraulic motors.

The newly developed high-performance servomotors discussed above might not have been used for aerospace applications. However, they offer significant potential for future aerospace usage.

TABLE E-2.--RATINGS OF SERVO-SERIES MINERTIA MOTOR (Ref. E-1)

Frame No. MM	3 EM	6 EM	13 EM	25 EM	25 SM	50 EM	50 SM	50 SR	100 SR	200 SR
Cooling method	Totally enclosed self-cooled	Totally enclosed self-cooled	Totally enclosed self-cooled	Totally enclosed self-cooled	Separately-ventilated	Totally enclosed self-cooled	Separately ventilated	Separately ventilated	Separately ventilated	Separately ventilated
Rated torque, kg cm	3	6	13	20	25	30	50	50	100	200
Max torque, kg cm	30	60	130	250	250	500	500	500	1000	2000
Rated current, A	5.7	7.1	7.8	8.9	10.8	7.6	11.8	11.8	31.8	49.0
Max. current, A	57	71	78	108	108	118	118	118	318	490
Rated speed, rpm	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Terminal voltage,* V	25	34.5	63	82	83	142	146.5	146.5	106.5	134
Rated output*, V	90	180	390	600	750	900	1500	1500	3000	6000
L/R, msec	0.15	0.25	0.48	0.52	0.52	1.0	1.0	1.0	2.1	3.6
GD^2, kg cm	0.98	2.5	6.4	12.4	12.4	30.5	30.5	30.5	68.5	294.0
Mechanical time constant, msec	4.9	4.4	4.6	4.0	4.0	4.4	4.4	4.4	4.4	5.0
Max. acceleration, rad/s^2	12.0×10^4	9.5×10^4	8.0×10^4	7.9×10^4	7.9×10^4	6.4×10^4	6.4×10^4	6.4×10^4	5.7×10^4	2.7×10^4
Armature thermal time constant, min	7.0	9.0	11.0	13.0	9.0	16.0	10.0	10.0	11.5	13.5
Field current, A	Permanent magnet	Permanent magnet	Permanent magnet	Permanent magnet	Permanent magnet	Permanent magnet	Permanent magnet	2.28	3.80	5.7
Field resistance, ohm (75°C)	-	-	-	-	-	-	-	38.6	19.9	14.2

NOTES: 1. * Values given are in case of 3000 rpm

2. Max. torque, max. speed, and max. current are 1-sec. rating

3. Drop in brush voltage is about 2 V

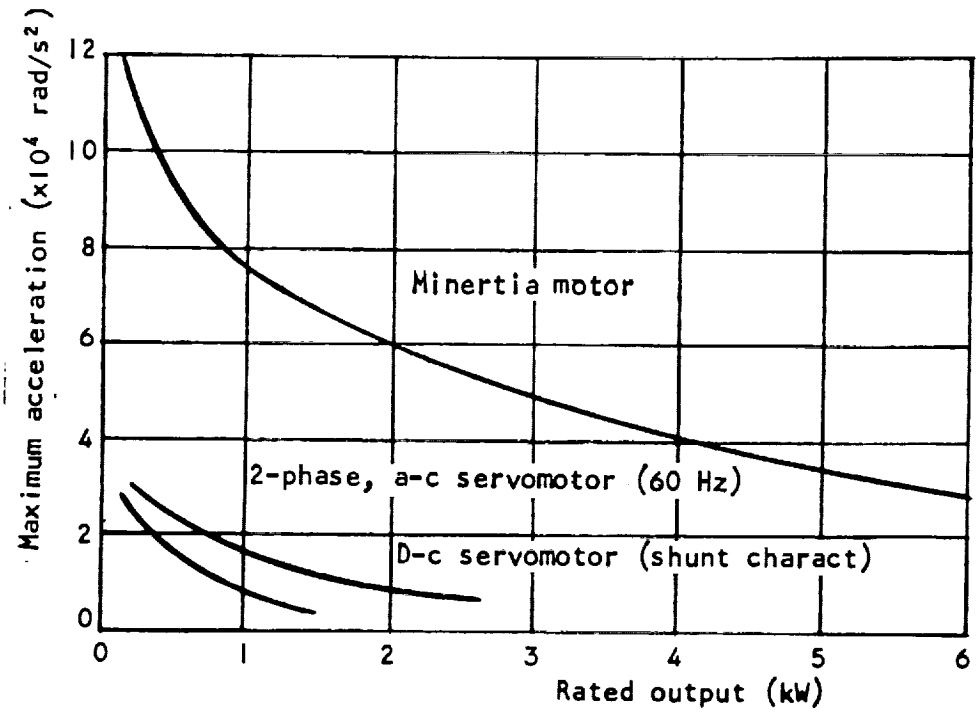


Figure E-2. Maximum Acceleration (ref. E-2)

TABLE E-3.--HYPER-SERVOMOTOR CHARACTERISTICS

(From ref. E-2)

Parameter	Symbol	Units	Model No. 5BLG32HA1	5BLG32NA1	5BLG32SA1	(2) 5BLG46HA1	5BLG46HA4	5BLG46HA5	(2) 5BLC48PA2	5BLC48PA3
Motor diameter		cm	8.6	8.6	8.6	11.7	11.7	11.7	12	12
Rated armature voltage		volts	12	24	36	12	12	12	30	30
Rated armature current		amps	8	8	7	8	8	13	26.5 (3)	18.0 (3)
Rated torque		Nm	0.23	0.45	0.70	0.35	0.35	0.57	2.30	1.57
Rated speed		rpm	2700	3000	2800	2250	2250	1850	2800	2100
Rated output		watts	64	143	204	81	81	110	675	346
Shunt field		shunt	PM	PM	PM	PM	PM	PM	Wound	Wound
Inductance, armature circuit	LA	Micro Henries	82	115	164	67	62	70	100	100
Resistance, armature circuit	RA	ohms	.43	.60	.84	.325	.325	.24	.26	.55
Voltage constant	KV	Volt-sec/rad	.0291	.058	.100	.0447	.0447	.044	.085	.085
Torque constant	KT	Nm/amp	.028	.057	.100	.0435	.0435	.0438	.0870	.0870
Armature inertia	JA	μ NmS^2	20	35	58	21	20	25	31	25
Pulse torque, 50 msec		Nm	2.3	4.6	8.0	4.35	4.35	4.8	17.4	9.55
Pulse current, 50 msec		amps	80	80	80	100	100	110	200	110
Inertial time constant by test (1)		Milliseconds	9.0	6.7	5.6	4.3	4.3	4.0	1.47	1.9
Inductive time constant		Milliseconds	.19	.19	.20	.20	.2	.29	.43	.18
Torque/inertia at rated voltage		Rad/Sec^2	40,000	65,000	73,125	78,300	82,500	88,000	330,000	191,000
Continuous rms current rating		amps	8	8	7	8	8	13	26.5 (3)	18.0 (3)
Motor length		inches	10.9	15.3	21.6	16.5	11.8	11.8	22.6	18.5
Motor weight		kg	2.3	4.0	6.12	6.57	5.75	5.75	12	11
Enclosure and cooling			Tenv	Tenv	Tenv	Tenv	Tenv	Tenv	FV	FV
Cooling air required		m^3/s at N/cm^2	-	-	-	-	-	-	0.0236 at 0.92	0.0236 at 0.75

(1) = $\frac{JA}{JA + JLoad}$

(2) Equipped with digital tachometer (3) at 0.0236 m^3/S (50 cfm)

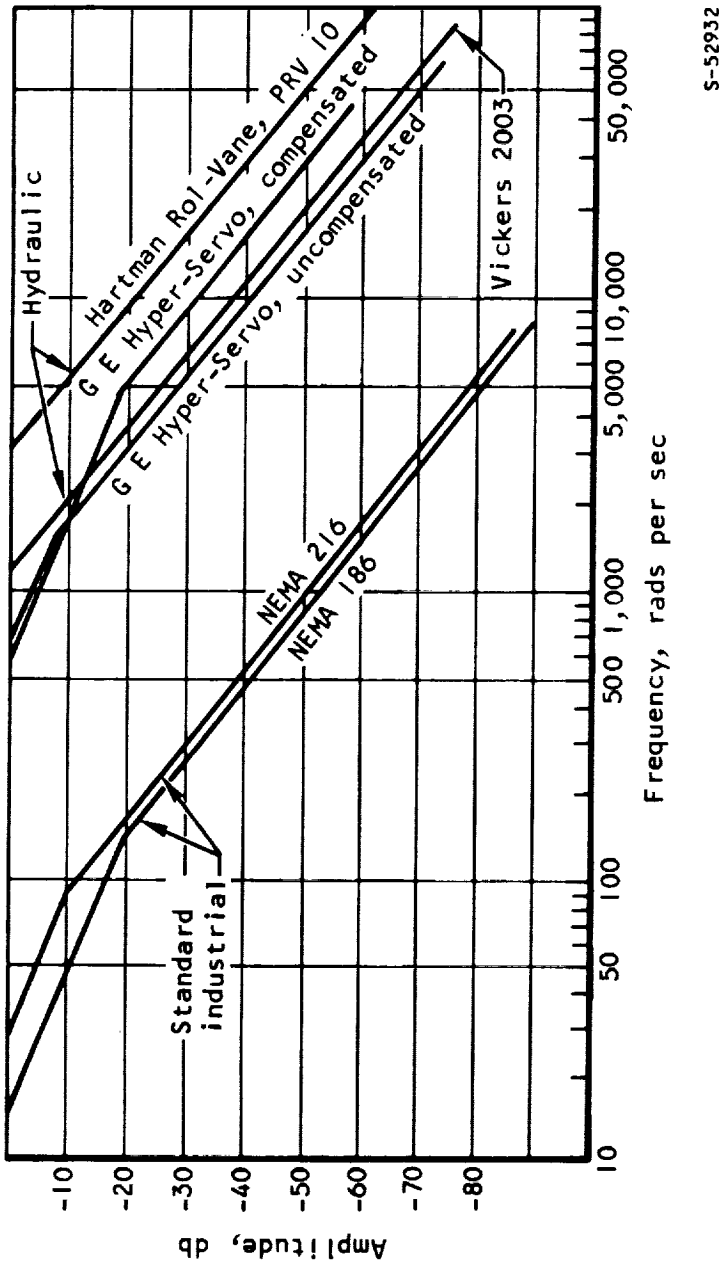


Figure E-3. Frequency Response of New G.E. 4-hp Servomotor (ref. E-2)

Electric Motor Performance

The motor performance is usually illustrated by a set of plots including the torque vs speed, input and output power, the armature current, and efficiency. For various types of small servomotors, the curves are similar. Fig. E-4 shows a set of typical performance curves. The speed and current curves are linear except for the series motor. The nonlinearity is introduced because of the varying field. Efficiency of the dc motors ranges approximately from 40 to 60 percent. For the two-phase ac motor, the efficiency is only 10 to 20 percent if the total input power is used as a basis.

For comparing motor performance several parameters are significant. These include (1) the torque constant which specifies torque produced per armature current, (2) the voltage constant which states rotational speed attained per applied armature voltage, (3) rotor inertia, (4) continuous rated torque, (5) short-term maximum torque at over-voltage, and (6) stall torque at rated voltage.

Acceleration capability.--When a stepped voltage is applied across the armature of a shunt motor previously excited, the motor speed will change according to certain governing factors. First, the armature current builds up with a time delay that is dependent on the inductance to resistance ratio (L/R) of the armature circuit. The interaction between this current and the magnetic field produces motor torque. Secondly, the torque accelerates the rotor, and the speed builds up with a time delay that depends on the armature inertia. These two delay factors are caused by the electrical and mechanical time constants, respectively. Therefore, to improve the servomotor performance, these two constants must be minimized. The mechanical time constant is proportional to the rotor inertia. In considering the response of a servosystem, however, the load inertia must also be considered, even though the motor inertia usually takes up the major portion. If the electrical time constant of the motor is relatively high and the inertia minimized, the response cannot be significantly improved.

The response of a motor can be improved by supplying a stepped voltage larger than the set value. This gives the desired motor speed at steady state. In this case, the motor starts with a larger current and hence, a larger starting torque. During the acceleration, the desired motor speed can be reached more quickly by changing the initial voltage to the set value. This technique is usually done by employing a speed feedback loop.

The maximum torque of a motor is limited by its commutation, heating, and other factors. The ratio of the maximum torque to the motor inertia is known as the torque-to-inertia ratio or maximum acceleration; this is an appropriate criterion of the motor response.

Duty cycle.--The duty cycle is a major consideration for applying the servomotors since it is closely related to motor heating. During any one cycle, the armature current can vary widely. Fig. E-5 illustrates a typical duty cycle with peak current during start and stop, but low current level during the running period. Periodic pulse currents far in excess of rated current are permitted without danger of overheating, provided that the peak current time is within the limit and the rms current of the duty cycle is below the rated current.

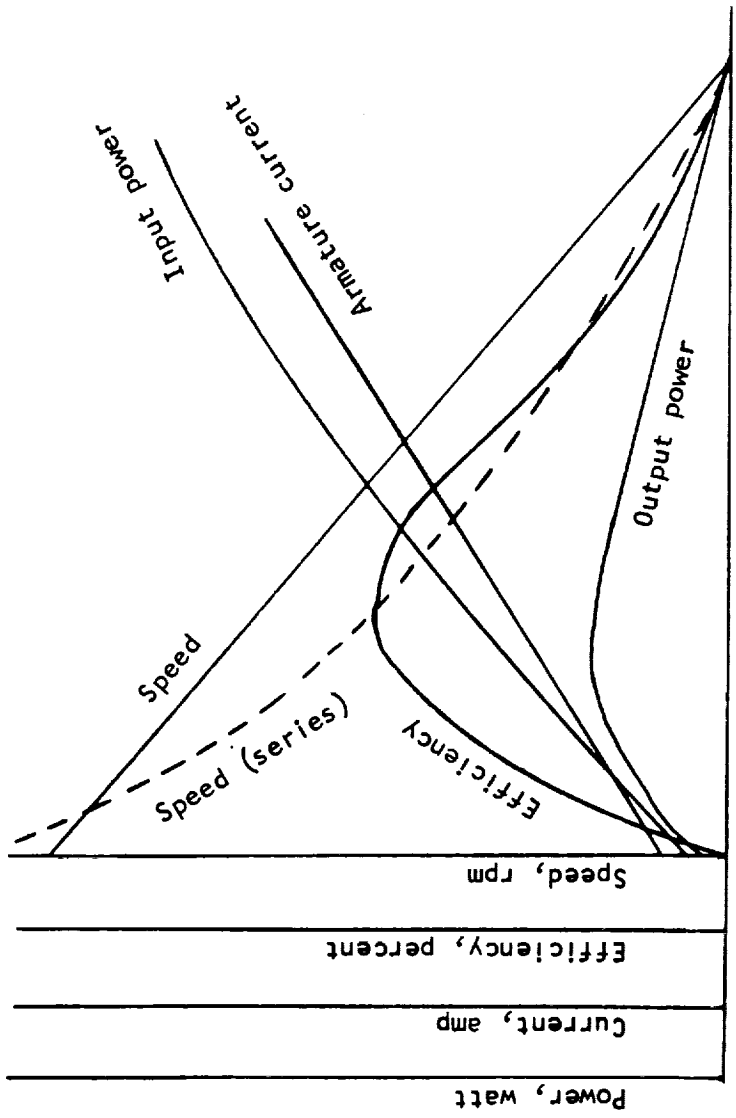
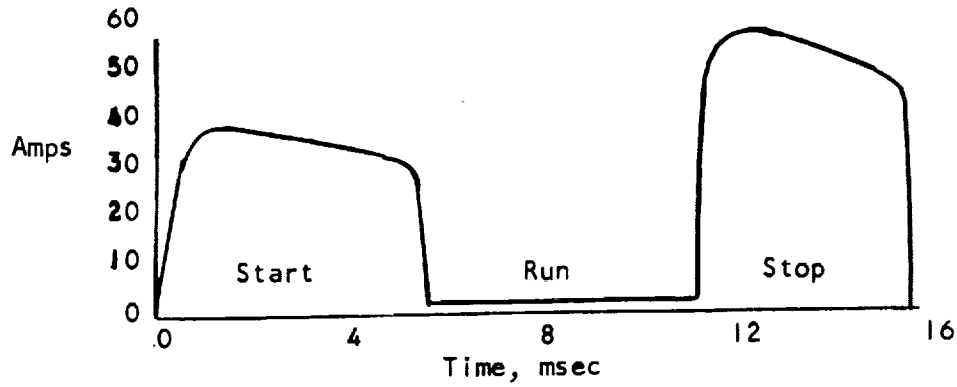


Figure E-4. Typical Torque Motor Performance Curves



$$I_{rms} \sqrt{\frac{1}{T}\int^{T} j^2 \, t \, dI}$$

(ref. E-3)

Figure E-5. Typical Hyper-Servomotor rms Duty Cycle

References in Appendix E

Ref. E-1 "Minertia Motor Bulletin" Publication No. ES-1081, Yaskawa Electric Mfg. Co.

Ref. E-2 "Bulletin on Hyper-Servo for Computer Peripheral Equipment" Publication No. GEA-8251, General Electric Co.

Ref. E-3 "Meet a Brand-New Servomotor with Startling Performance" B.M. Blake, Control Engineering, May 1966, pp. 81-85.

APPENDIX F

FAILURE PREDICTION, DETECTION AND COMPENSATION

Introduction

This presentation discusses the theoretical means only by which failures may be predicted. The many parameters which may need to be monitored can only be determined once the given electrical power system configuration is selected. The discussion includes: a) Trend analysis, b) Failure detection techniques, c) Types of Integrated systems (such as AIDS), and d) Sensor developments.

Trend Analysis

The objective of trend analysis is to predict the future behavior of the trended parameter, or more specifically, to predict the future point in time at which the trended parameter will exceed a certain limit. For meaningful trend and prediction analysis, the failure mode to which the trended parameter is sensitive must be of the gradual type. Also, the deviation in the parameter due to deterioration must be large enough to offset the normal data scatter. Since trend analysis is a long-term prediction method, periodical data recording is required. By using simple data processing techniques, significant trends can be defected, and failure prediction information can be obtained. Two such processing techniques are described below.

Least squares curve fitting.--In the curve fitting method, a polynomial is fitted to a given number of the most recent data points by the least squares method. The intersection of the polynomial with the trended parameter limit is then determined so that the remaining time before the parameter will exceed its limit can be estimated. This method is illustrated in fig. F-1, where a second-order curve is fitted. In addition, the variance of the data can be used to provide a measure of the estimated confidence level. Using the data variance, a band enclosing the extrapolated curve can be determined, which provides limits for the estimated remaining time for a 95-percent confidence level. In applying the curve fitting technique, several variables exist, which are (1) the order of the polynomial chosen for fitting, (2) the number of current data points used in the fitting process, and (3) the amount by which the various data points are weighted. In general, the more recent data are more heavily weighted in the calculation.

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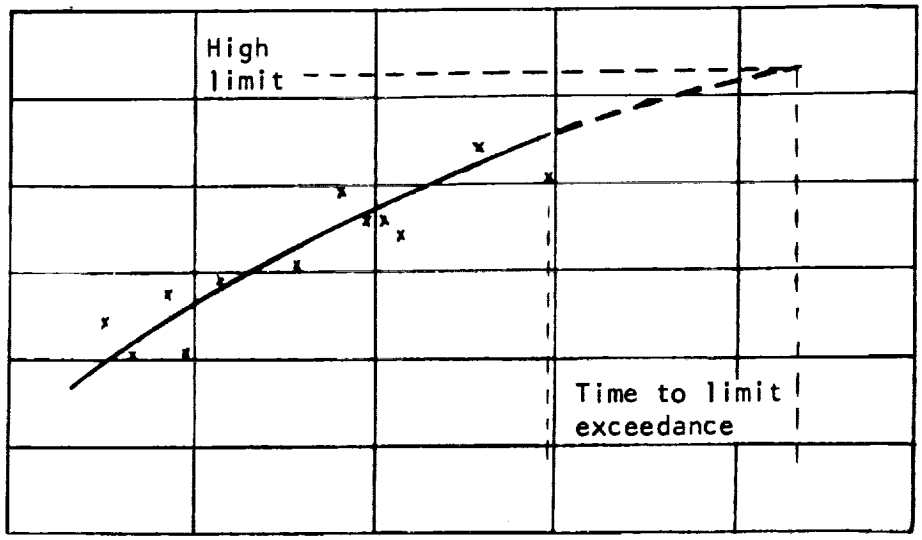


Figure F-1. Least Squares Curve Fitting

Exponential smoothing.--Exponential smoothing is the manipulation whereby data are smoothed by adding a fraction of the difference between the previous smoothed value and the current observed value. Expressed mathematically,

$$\bar{X}_t = \bar{X}_{t-1} + \alpha \left[X_t - \bar{X}_{t-1} \right] \qquad \text{(F-1)}$$

where $\bar{X}_t$ = the smoothed value of X at time index t

$\bar{X}_{t-1}$ = the smoothed value of X at time index t-1

α = the smoothing constant, $0 < \alpha < 1$

X_t = the observed value of X at time index t

This equation can be rewritten as

$$\bar{X}_t = \alpha X_t + (1-\alpha) \bar{X}_{t-1}$$

since $\bar{X}_{t-1} = \alpha X_{t-1} + (1-\alpha) \bar{X}_{t-2}$

It can be seen that the above equation can be expanded as

$$\bar{X}_t = \alpha \sum_{i=0}^{t-1} (1-\alpha)^i X_{t-i} + \alpha (1-\alpha)^t X_o \qquad \text{(F-2)}$$

which shows why the process is called exponential smoothing.

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Exponential smoothing may be represented by an operator as follows:

$$S_t\ (X) \equiv \bar{X}_t = \alpha\ X_t + (1-\alpha)\ S_{t-1}\ (X) \tag{F-3}$$

For higher degrees of smoothing, the nth order operator is defined

$$S_t^n\ (X) = S\ \left[S_t^{n-1}\ (X)\right] = \alpha\ S_t^{n-1}\ (X) + (1-\alpha)\ S_{t-1}^n\ (X) \tag{F-4}$$

In addition to the obvious use of exponential smoothing, the smothing operations can be used to estimate the coefficients of any order polynomial curve model for trend data. One method involves smoothing the differences between successive smoothed data points to determine estimated coefficients of higher order terms in the polynomial model. In the case of the linear model, for example.

$$\bar{X}_{t+\tau} = a_t + b_t\ \tau \tag{F-5}$$

where $\bar{X}_{t+\tau}$ is the estimate of the smoothed value of X at the future time index $t+\tau$ (the current time index is t).

The coefficients are estimated as follows

$$a_t = S_t\ (X) = \bar{X}_t = \alpha\ X_t + (1-\alpha)\ S_{t-1}\ (X) \tag{F-6}$$

$$b_t = S_t\ (\Delta X) = \dot{\bar{X}}_t = \beta\ (\bar{X}_t - \bar{X}_{t-1}) + (1-\beta)\ S_{t-1}\ (\Delta X) \tag{F-7}$$

since $\bar{X}_t - \bar{X}_{t-1} = \alpha\ (X_t - \bar{X}_{t-1})$

$$b_t = \dot{\bar{X}}_t = \beta\ \alpha\ (X_t - \bar{X}_{t-1}) + (1-\beta)\ \dot{\bar{X}}_{t-1} \tag{F-8}$$

where $\dot{\bar{X}}_t$ is the smoothed value of the rate of change per unit time at time index t. It is noted that a second smoothing constant β is introduced in this case. Coefficients of higher order terms may be determined similarly.

The sample points are assumed to be at equally spaced intervals (hours, flights, etc.). To predict the time remaining before the parameter will exceed its limit by using the linear model, substitute $\bar{X}_{t+\tau}$ in eq. (F-5) by the limit of parameter L and solve for τ; therefore

$$\tau_L = \frac{L - a_t}{b_t} \tag{F-9}$$

where τ_L = time remaining (hours, flights, etc.) to reach limit L

L = limit for the parameter

a_t and b_t are the coefficients determined by the above mentioned method. Fig. F-2 illustrates the exponential smoothing technique.

Out-of-Tolerance Test

In failure detection and prediction, the most commonly used technique is the out-of-tolerance test, in which the performance parameters or failure sensitive parameters are tested against prescribed limits. If the parameter is within the tolerance, there is high probability that the component or subsystem will complete the mission. If the parameter exceeds the limit, it shows that a defect or failure exists in the system, and maintenance service or a replacement of the component is required. Since this technique does not need any information associated with the previous behavior of the tested parameter, no complicated data processing is required. The selection of the effective tolerance limit should be properly performed since it affects system cost effectiveness. In general, it should be based on

(1) the statistical behavior of the parameter, and

(2) the acceptable variation in the parameter values, i.e., the actual tolerance limits imposed on the values of the parameter for acceptable system or component performance.

Typical Failure Prediction Requirements

Failure prediction generally requires data recording and processing. For relatively small components, such as control and instrumentation devices, it is doubtful that any provision for failure prediction will be cost effective. The rotating devices, such as synchros and resolvers, have failure modes similar to those of the motor. However, the majority of failure modes for these devices are electrical rather than mechanical since they are operating at relatively low speed. The electrical failures include (1) open or shorted stator, (2) open or shorted rotor, and (3) calibration and tolerance problems. For calibration and tolerance problems, it is believed that resistance changes may be largely responsible for drift in output voltage and phase shift, and that those changes may result from the long-term influence of temperature variations. This type of failure can be predicted by monitoring the output performance of the device.

The electronic equipment consists of numerous elements, most of which fail instantaneously. Therefore, it is very difficult to predict the failure of the electronic equipment. However, when one (or more) element fails, in some cases, it may cause a deviation in equipment performance but not a total failure. By monitoring the performance, this type of failure can be detected. The current trends for failure detection of electronic equipment are toward the built-in self-test, which can perform support functions such as stimulating, loading,

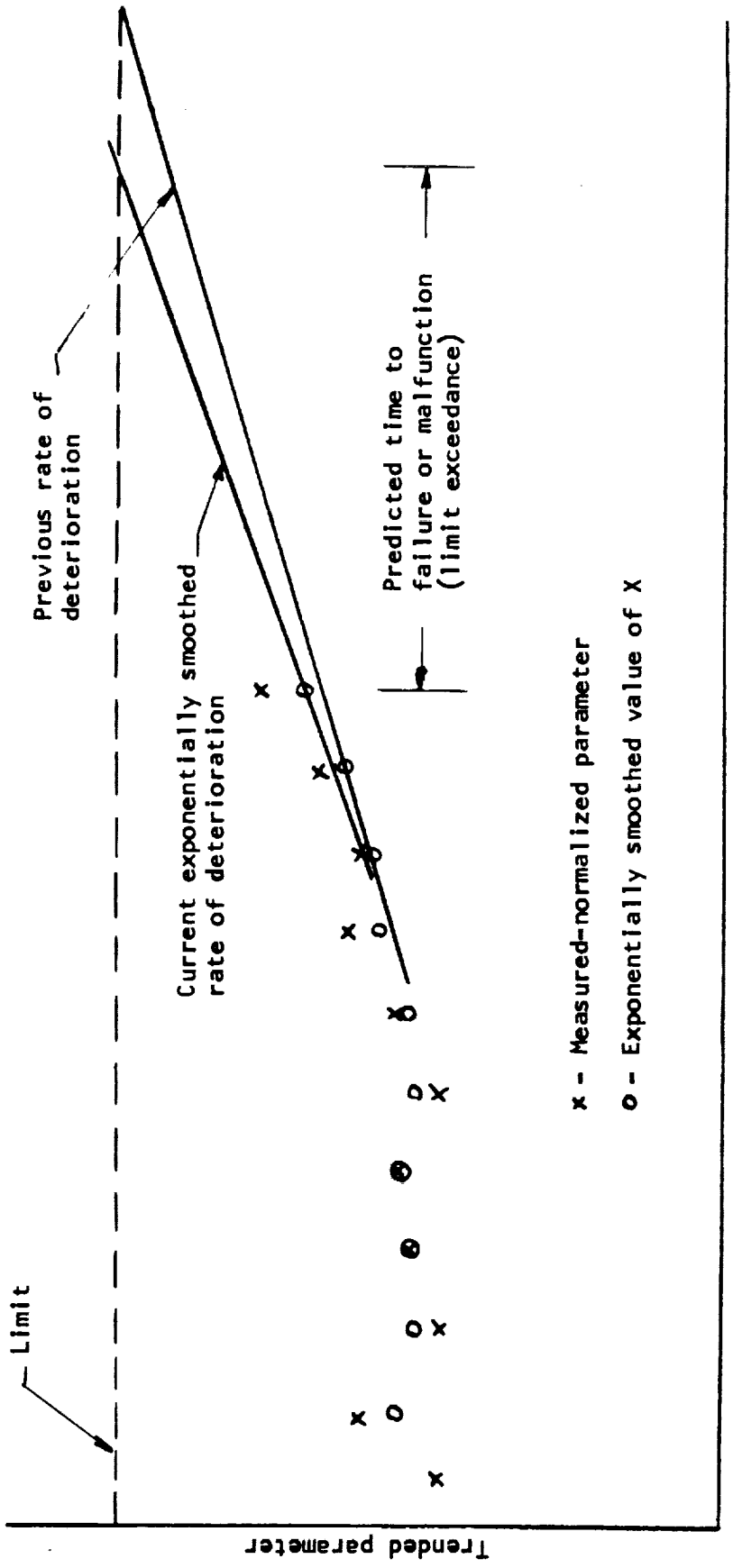


Figure F-2. Exponential Smoothing Technique for Trend Analysis

monitoring, recording, and controlling during the test. Several concepts of built-in-test are used in today's avionics. These concepts can be classified into the categories of (1) unit built-in-test, (2) subsystem level built-in-test, and (3) total integrated self-test system.

Failure Detection Techniques

Failure detection techniques which can be applied to electrical equipment include the measurement of (1) insulation temperature and resistance (2) bearing temperature, (3) vibration, (4) CSD parameters such as oil flow, oil temperature, output speed, and trim head current, and (5) output performance.

Insulation temperature and resistance.--It is recognized generally that the relationship between the insulation life and the insulation temperature can be expressed as:

$$\ln t = \frac{b}{T} - a \qquad \text{(F-10)}$$

where t = the insulation life

T = the absolute temperature of insulation

b = the slope of the insulation life curve,

and a = a constant.

If logarithms of insulation life are plotted on the ordinate, and the reciprocals of absolute aging temperature are plotted on the abscissa, the insulation life curve becomes a straight line.

For comparison of various loading cycles in regard to their effect on the insulation aging of apparatus, it is convenient to use the concept of relative aging. In this method, the maximum temperature allowed for normal life is used as a reference (a relative aging of unity assigned to it). Aging at any other temperature is either a fraction or a multiple of the reference aging temperature, depending upon whether the temperature is lower or higher than the reference. To express the relation analytically

$$\ln R = b\left[\frac{1}{T_o} - \frac{1}{T}\right] \qquad \text{(F-11)}$$

where R = the relative aging,

b = the slope of relative aging curve,

T_o = the absolute reference insulation temperature,

and T = the absolute insulation temperature.

By comparing eq. F-11 to eq. F-10, it can be derived that the relative aging is

$$R = \frac{t_o}{t} \tag{F-12}$$

where t_o and t are the insulation lives at temperatures T_o and T, respectively. Fig. F-3 shows some relative aging curves with typical reference temperatures and various aging rates.

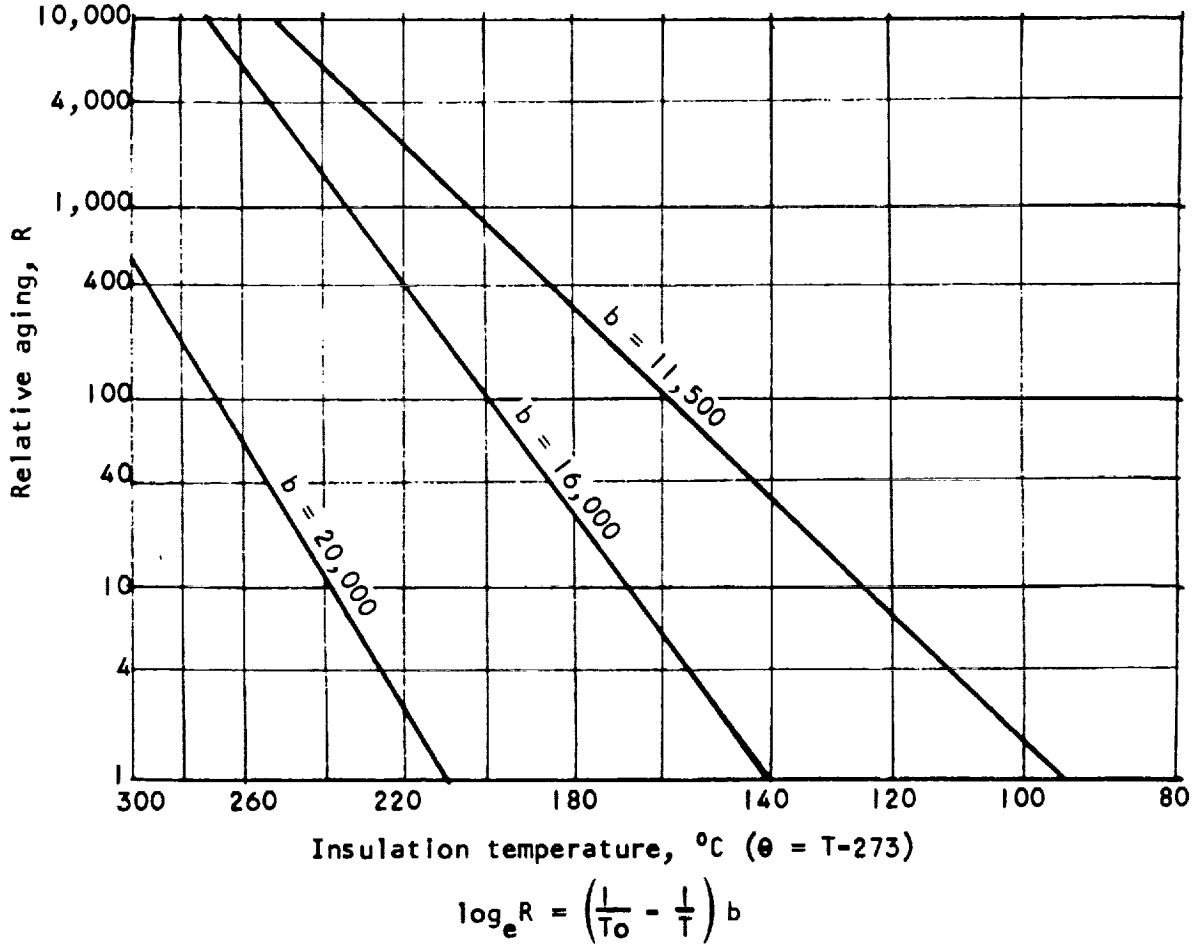
In a practical case, the temperature of the insulation fluctuates. If the temperature value is sampled periodically, however, the temperature variation can be determined as a function of time. Since the insulation relative aging curve is known, a curve relating relative aging and time can be created. By integrating this curve, the relative aging (in hours) during this time period can be determined.

If this technique is utilized for predicting the insulation failure, the remaining life of the insulation can be determined after each flight. When the remaining life falls below a prescribed value, the component will be removed for maintenance service.

The insulating capability of the insulation is closely related to its electrical resistance; the higher the resistance, the higher the insulating capability. When the insulation deteriorates, the resistance decreases. Therefore, monitoring the insulation resistance is a direct method for insulation failure prediction. Either the out-of-tolerance or the trending method can be incorporated for the insulation resistance monitoring.

Bearing temperature.--In a normally operating bearing, the temperature should be constant for a given ambient. When irregularities are present, such as spalling on the races or rollers, the temperature will increase because of the increased friction loss. By monitoring the bearing temperature, therefore, the condition of the bearing can be determined. The correlation between the bearing condition and the temperature depends on many factors, such as the rotational speed, the bearing configuration, the ambient temperature, the heat transfer characteristics, and the type of lubricant. Detailed information can be obtained through experimentation.

Vibration.--Vibration monitoring has the greatest potential capability among all monitoring techniques for supplying mechanical condition information. The mechanical integrity of rotor elements and components with mechanical failure could be detected through the rotor movements. Although a more complicated circuitry will be required to provide this extended capability, recent developments in the field of microelectronic linear I.C's and the L.S.I's ensures its feasibility.



$$\log_e R = \left(\frac{1}{To} - \frac{1}{T}\right) b$$

Figure F-3. Examples of Relative Aging Curves with Representative Reference Temperatures and Various Aging Rates (Values of b)

Experience in propulsion engine vibration monitoring has shown that individual mechanical components possess unique vibration frequency characteristics. For example, when a bearing is operating under normal conditions, random vibrations (noise) are produced. If spalling on the races or rollers are present, discrete frequencies are produced. From the dimensions of the bearing and the shaft speed, these frequencies can be determined, depending upon whether the spall is on the inner or outer race or on the rolling elements. The amplitude of the signal serves as the indicator of the bearing condition. In general, the rotational characteristics of bearings produce a spectral rise in amplitude over a band of frequencies rather than a single discrete rise. Fig. F-4 shows the spectral rise centered at the outer-race frequency. To diagnose the machine condition with respect to vibration and noise, some kind of data analysis must be performed. At present two distinct approaches are being used. The first method is called the deterministic correlation approach in which the reference pattern is represented by a set of frequency components. The establishment of such a reference is based heavily on the designer's priori knowledge of mechanical details. In establishing a reference for a bearing, for instance, the bearing structure, modulation effects, and the frequency components at corresponding speed must be known. The second approach, known as the statistical learning approach, adopts an updating learning process to recognize healthy reference patterns and malfunctioning patterns based on statistics. Digital data processing techniques are used to distinguish the signal from the noise.

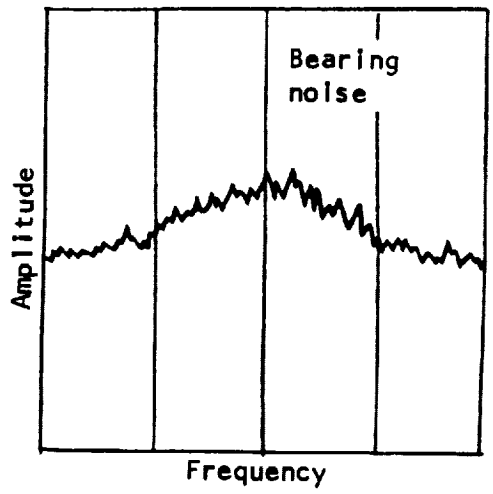


Figure F-4. A Malfunctioning Bearing Noise

The direct adoption of such techniques for vibration monitoring of electrical components presents a difficult problem because of weight, size, reliability, and cost-effectiveness limitations of the hardware equipment required on the aircraft to implement the technique. The problem might be solved by using a bank of parallel bandpass filters to completely cover the important vibration frequency range. If 1/1 octave bandpass filters are used for a frequency range from 30 Hz to 16,000 Hz, only 10 such filters are needed. In case special attention is needed for a particular band of frequencies, the bandpass filters covering that frequency range can be narrowed, and the number could be increased to achieve a better frequency resolution.

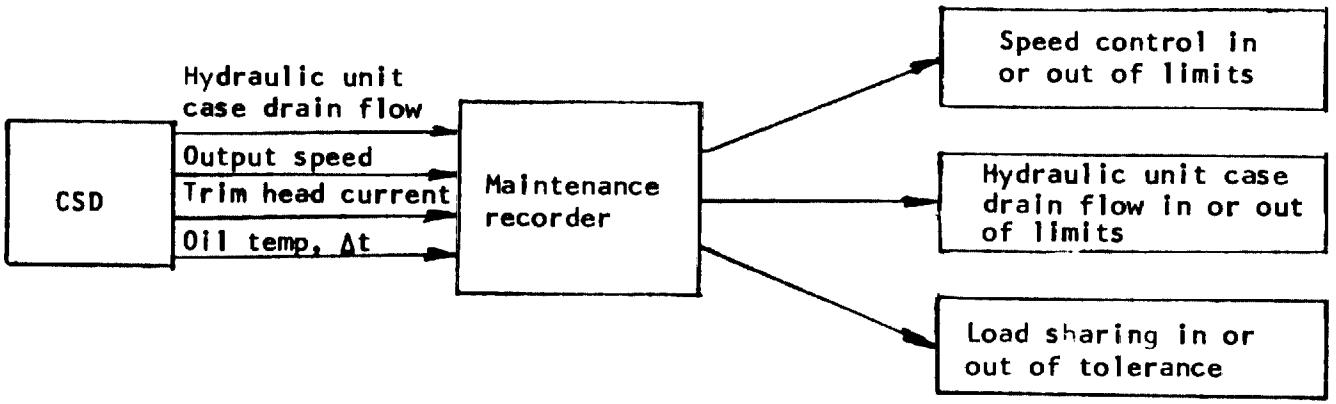
CSD parameters.--CSD hydraulic unit wear is best measured by the case drain flow. The case drain flow information is fed into a computer to compare with a preset limit that is a function of generator load. Limits will be programmed for cruise and for idle engine input speeds to accommodate inflight and ground checkout measurements, respectively. Measurement of CSD output speed (with a pickup on the output gear) and generator frequency allows distinction between a drive failure and a generator PMG failure. Reactive power sharing may be desired to find voltage regulator drift during parallel generator operation.

Measurement of trim head current serves as an indication of drift of the CSD speed during parallel operation. This measurement could be omitted if each unit's steady-state output speed is checked while nonparalleled at suitable intervals. Oil temperature rise comparisons of the several CSD drives will reveal the trouble of any one unit if the temperature rise in that unit is higher than that of all other units. One scheme for CSD failure prediction is shown in fig. F-5.

The unscheduled maintenance actions for the CSD with the above measurement scheme are shown in table F-1.

Performance and other failure-sensitive parameters.--Monitoring output performance parameters can aid in analyzing malfunctions and in detecting system defects. Since most of the parameters are in electrical form, little signal conditioning usually is required. The hardware circuitry for monitoring these parameters is, therefore, relatively simple. In the power generation system, monitoring the phase voltages, frequencies, and excitation voltages of the generators can aid in detecting malfunctions of the regulators, splines or couplings, and excitation systems. The current values of the transformer-rectifier units can serve as an indicator for faults in the transformer-rectifier systems.

Performance monitoring also can be used for many other electrical components. However, output performance parameters, in many cases, are not particularly sensitive to failures. Failure-sensitive parameters which are sensitive to many faults or to important or high-probability failures therefore must be used.



Built-in test equipment

Flight engineers panel	Drive visual indicator
CSD oil Δt gage	Oil filter ΔP
Low change pressure light	Decomplex position indicator
Generator frequency	Magnetic drain plug
	Oil level sight glass

Figure F-5. CSD Failure Prediction, Maintenance Scheme

TABLE F-I.--UNSCHEDULED MAINTENANCE ACTIONS

Discrepancy	Indication	Maintenance Action
(1) Excessive wear of hydraulic unit or units	High CSD ΔT and high case drain flow	Replace hydraulic units
(2) Bearing failing in differential gear system	High CSD ΔT and check of drain plug shows chips (case drain flow in tolerance)	Replace drive (return hydraulic units and control module to stores)
(3) Speed control drift	(a) if paralleled - High Trim Head Current	Replace control module
	(b) if not paralleled - Generator frequency out of tolerance	Replace control module
(4) Load sharing control drift	Load sharing out of tolerance	Replace load controller
(5) High charge or scavenge pump wear	Hign CSD ΔT (due to low oil flow and/or high churning losses) - No chips on drain plug and case drain flow in tolerance	Replace pump module
(6) Charge relief valve drift	Low charge pressure	Replace charge relief valve
(7) Dirty oil filter	High filter ΔP	Replace filter

Types of Integrated Data Systems

Depending upon the intended application, the integrated data system can range from a simple system monitoring a few parameters to a complicated onboard data processing system covering several aircraft subsystems. Generally, however, an integrated data system consists of equipment that monitors various parameters during the aircraft operation and provides some capability for recording specific parameters either periodically or continuously. Although a detailed description of system configuration and operation is not provided, several different recording systems are discussed below to indicate the versatility that the AIDS can provide.

Simple AIDS system.--In a simple system, the selected parameters are monitored and recorded during the flight for failure detection purposes. The recorded data are processed by ground facilities at the end of each flight to detect malfunctions by using the out-of-tolerance tests and/or the trend analysis. A slightly modified system monitors the various parameters during its entire flight, but records only those data which deviate from previous measurements. This approach is advantageous because the amount of recorded data is largely reduced, which results in reduced data processing time and costs.

Expanded AIDS system.--When the first recording system is expanded by adding data on aerodynamic performance, control settings, and other parameters indicative of pilot performance, the recorded data can then be used to evaluate the proficiency of the pilot or used as an aid for training new pilots. American Airlines is using this in its BAC-111 aircraft, in which two recording systems are installed, one for maintenance purposes and the other for performance evaluation.

Continuous recording.--To meet FAA's requirements for long-term storage of flight information, a recording system capable of continuous recording during the entire flight can be incorporated with the accident flight data system. Preferrably, the two systems are separate but supplied from the same data sources. The short-term data recorder, which is physically protected, is used for accident investigation, while the long-term recorder can provide complete storage records that also can be used for trend analysis.

Airborne data processing.--The most expensive and sophisticated system, preferred by overseas airlines, provides facilities for airborne data processing. The recorded data are processed not only on ground after each flight but also during the flight so that information regarding aircraft condition is continuously available to the flight crew. The airborne computer must have a memory large enough for storing the normal parameter measurements and the selected tolerance limits against which the measured data are compared. To provide information of the aircraft condition that can be interpreted properly and quickly by the flight crew, adequate facilities for information display are also required.

Sensor Developments

One of the problem areas in implementing the aircraft integrated data system involves the sensor. The location of the sensing device is frequently under a severe environment with temperature variations, changes in altitude, excessive vibration, etc. Therefore, the sensing devices must be well designed and fabricated to possess the high-reliability requirements. To make sensible failure predictions, the repeatability of the sensor is very important. This requirement becomes difficult to meet when the sensor output is low and electrical noise in the aircraft is usually high.

Most of the presently used sensors are active sensors joined physically to the primary equipment under test. This is highly undesirable because (1) failure of the sensor might affect the consequence of the mission, (2) insertion of the sensor into the circuit might introduce system defects due to insufficient care during installation, and (3) the insertion of the sensor becomes more and more difficult due to the increased use of microcircuitry. New types of sensors under development to overcome these problems are briefly discussed below.

Infrared sensors.--Infrared sensors are used for detecting temperature variations in electronic equipment. To obtain line-of-sight access into packaged equipment, fiber optic bundles are being used for infrared transmission. The problems encountered in this approach include (1) the transmission distance, for reliable result, is limited to approximately 1 meter, and (2) the emissivity variations of the various components affect the temperature readings.

Acoustic sensors.--The army has been developing acoustical monitoring techniques for detecting failures in tank engines. A computer is used to diagnose the acoustical energy input from which the required repair can be determined. The problems encountered in acoustical techniques include (1) isolation of the useful signal from the noise, and (2) recognition of the various patterns representing various characteristics. Since the acoustic techniques are applicable for moving part devices, it might become useful in detecting mechanical failures deemed too difficult to monitor presently.

Electromagnetic sensors.--Several sensing devices using electromagnetic coupling are being investigated. The use of solid-state Hall-effect devices has been developed to an extent that satisfactory output signals of almost constant level in a frequency range from about 5 Hz to 5 MHz have been obtained. Another electromagnetic device capable of indicating dc current flow in electronic circuits has been developed by the Illinois Institute of Technology Research. This device, known as the ferrite core indicator, consists of a ferrite core on which a primary winding and a secondary winding are wound. When an ac signal is applied to the primary, an output signal appears across the secondary winding, which varies according to the magnitude of the dc current in the conductor passing through the center of the core. By monitoring the output of the secondary winding, the amount of dc current in a circuit can be determined.

Other sensors.--Other sensor techniques being investigated include the use of light, radio-frequency interference, radioactive isotope tracers, etc. By using a light-emitting diode that switches on when a signal is present, bilevel

(on-off type) conditions can be sensed. The Boeing Company has been developing a mathematical computer model for predicting sources of radio frequency interference and susceptibility. Honeywell has found that by stimulating certain electronic devices mechanically, a predictable range of noise around 27 MHz can be obtained. Radioactive tracers have been used for detecting existing leaks in hermetically sealed electronic components. Future development in this area may make this technique applicable for detecting leaks in pneumatic systems and liquid systems.

APPENDIX G

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PRELIMINARY DESIGNS OF FANS AND COMPRESSORS

Axial Flow Fans

The graphical method for obtaining the size of axial flow fans has developed for conservatively rated designs. It was not intended to give an absolute and final answer on what size fan is needed to meet a given requirement, but rather to give a size that is most likely feasible. It is still necessary to do a detailed analysis of the air velocity vector triangles across the blade span to determine whether a design is really practical, particularly at low hub/tip ratios.

Assumptions.--An axial flow fan with the following parameters is assumed (see Nomenclature I p. 465).

(1) Aerodynamic efficiency, η = 60 percent

(2) Pressure rise coefficient, ψ = 65 percent = $2\Delta u/u$

(3) Blade tip air inlet angle, $\alpha = 21.8^0$; i.e., $V_x/u_t = 0.4$

(4) Axial stage inlet and outlet air velocities

(5) Constant axial velocity

(6) Free vortex design

(7) No inlet guide vanes

(8) One rotor and one stator stage

(9) Five percent motor slip

Graphs.--Fig. G-1 shows airflow per unit area, Q/a, plotted against pressure rise, $\Delta P/\sigma$.

From fan laws

$$u_t \Delta u = \frac{0.816}{\eta} \frac{\Delta P}{\sigma} = u_t^2 \frac{\Delta u}{u_t}$$

Substituting assumption (2) into the above equation:

$$u_t^2 \frac{\Delta u}{u_t} = u_t^2 \frac{\psi}{2}$$

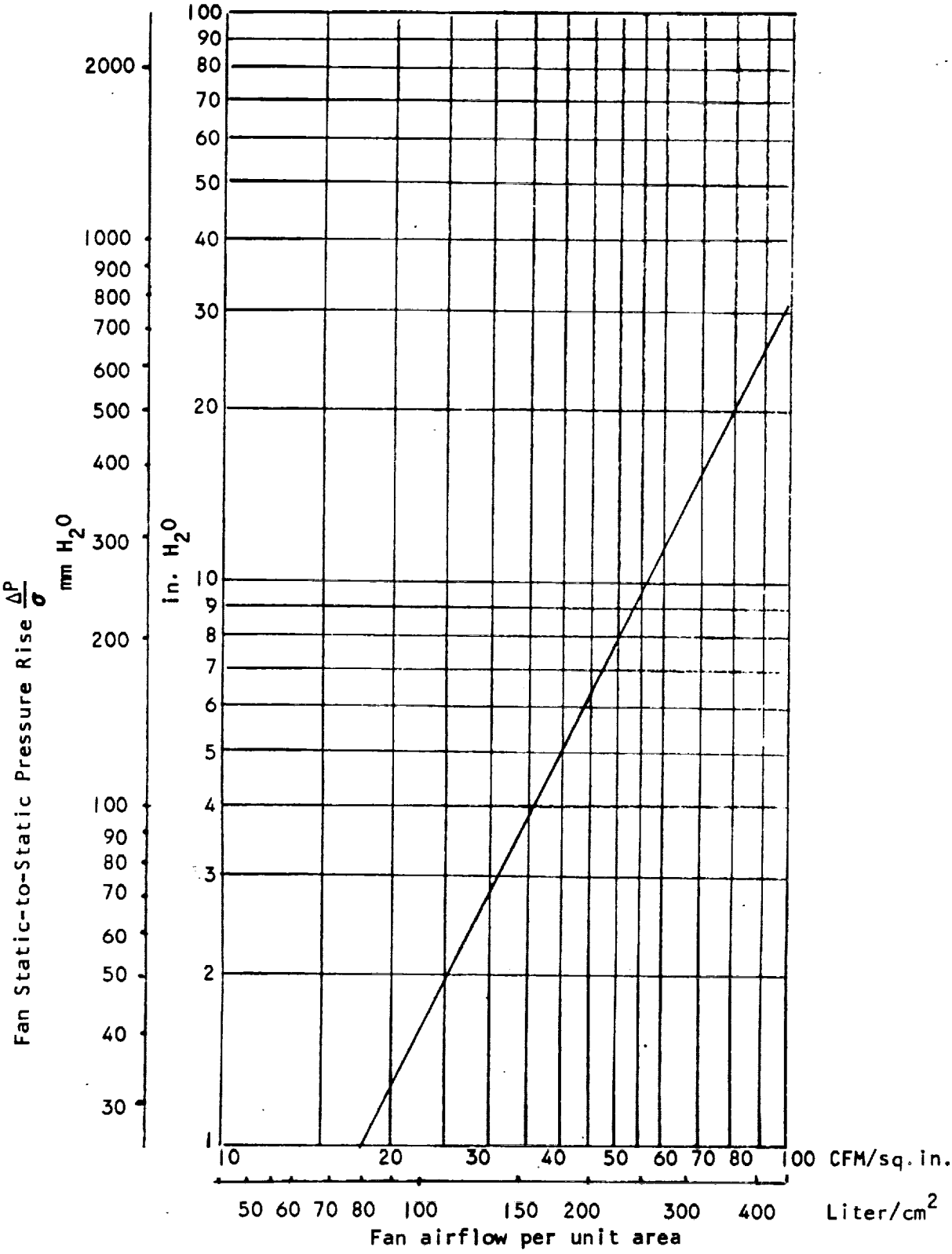


Figure G-1. Fan Airflow vs Pressure Rise

Therefore,

$$\psi = \frac{1.632}{u_t^2 \eta} \frac{\Delta P}{\sigma}$$

Substituting assumptions (1) and (2) into the above equation:

$$\frac{\Delta P}{\sigma} = 0.239 \quad u_t^2 \qquad \text{(G-1)}$$

Substituting assumption (3) into eq (G-1):

$$\frac{\Delta P}{\sigma} = 1.5 \quad V_x^2 \qquad \text{(G-2)}$$

since $V_x = \frac{Q}{a}$

therefore $\frac{\Delta P}{\sigma} = 1.5 \left(\frac{Q}{a}\right)^2$ (G-3)

Fig. G-1 is a plot of eq. (G-3). Fig. G-2 is a plot of eq. (G-1).

The fan tip speed is given by:

$$u_t = \frac{\pi D N}{720} \qquad \text{(G-4)}$$

For ac electric motors, with slip (s) of 5 percent

$$N = \frac{120f(1 - s)}{N_p} = \frac{114f}{N_p} \qquad \text{(G-5)}$$

Fig. G-3 is a plot of eqs. (A-4) and (G-5).

The annulus flow area is given by

$$a = 0.785 \, (D^2 - d^2) = 0.785 \, D^2 \, (1 - h^2) \qquad \text{(G-6)}$$

Fig. G-4 is a plot of eq. (G-6).

Figs. G-5 and G-6 represent

$$\text{Specific speed} = \frac{N Q^{0.5}}{\Delta P^{0.75}} \qquad \text{(G-7)}$$

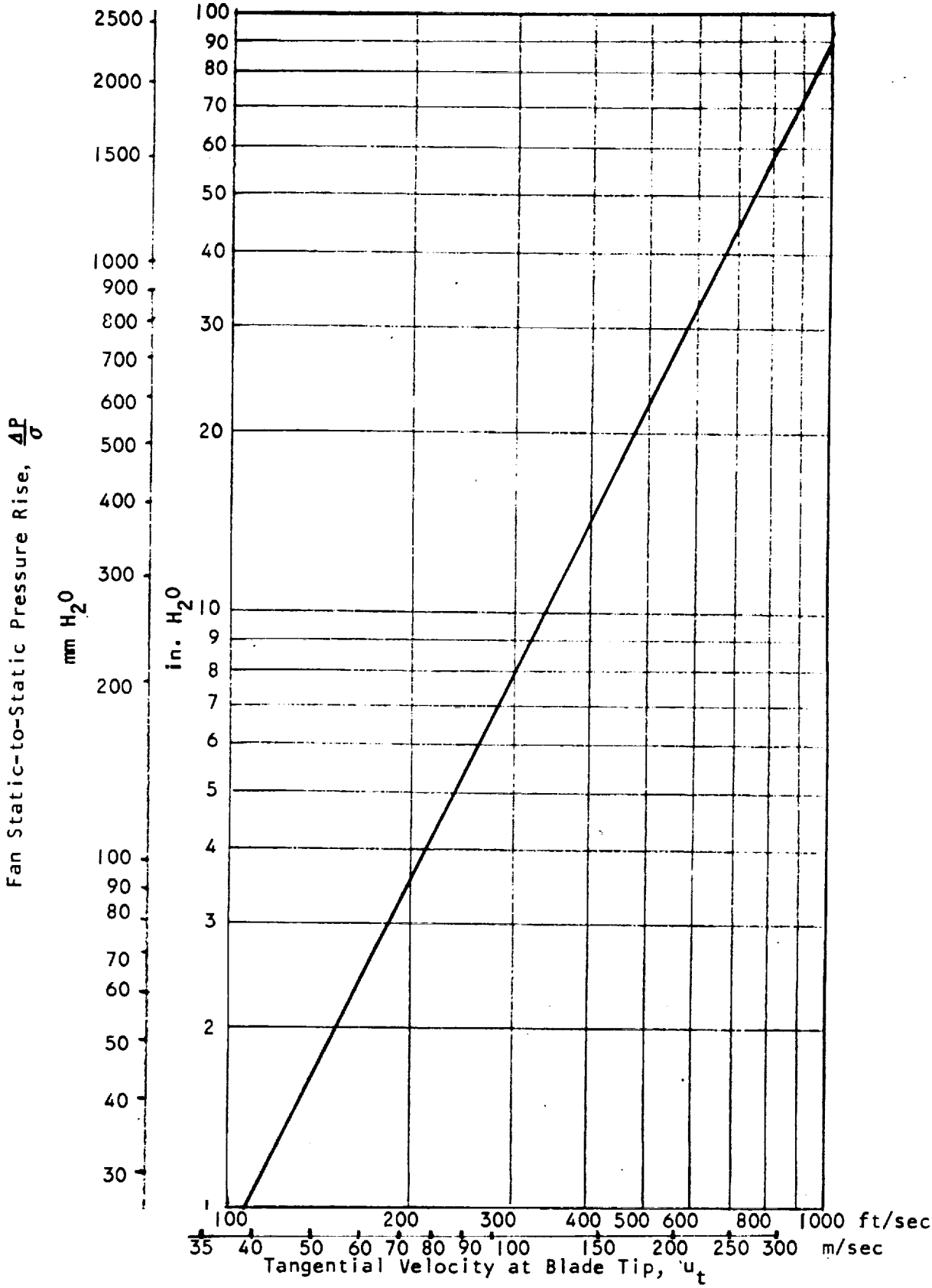


Figure G-2. Velocity vs Static Pressure Drive

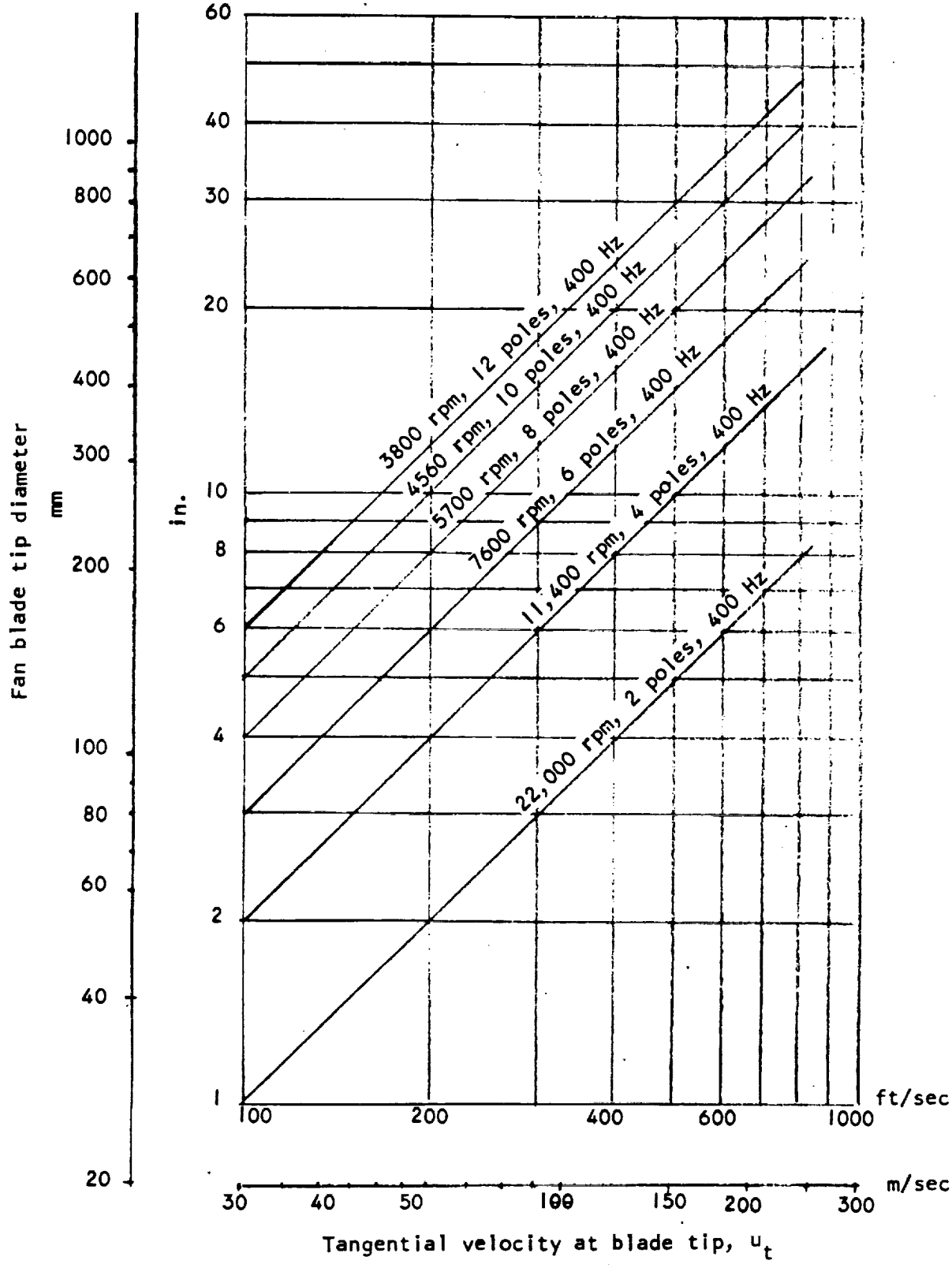


Figure G-3. Velocity vs Fan Variables

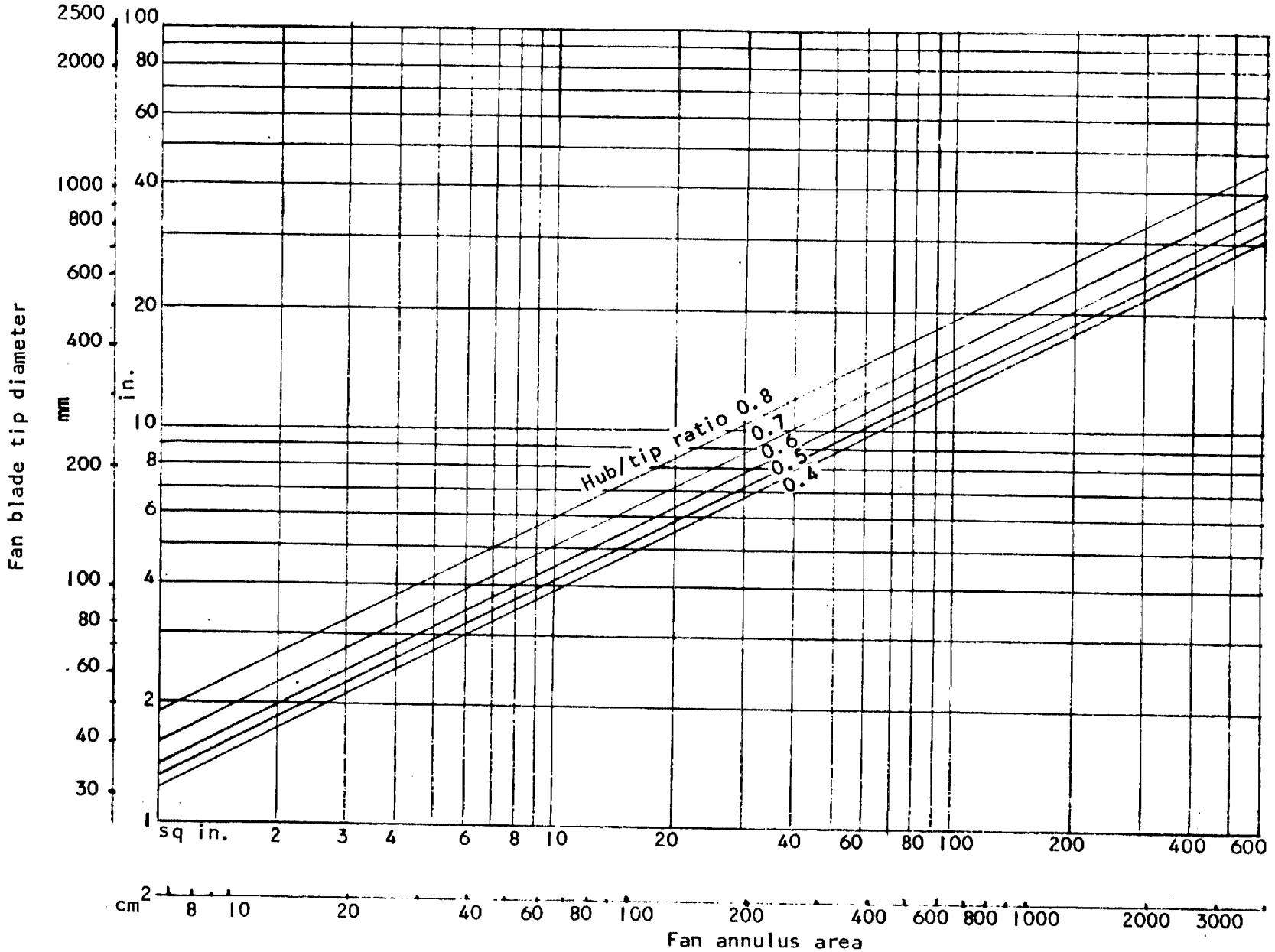


Figure G-4. Fan Annulus Area vs Fan Variables

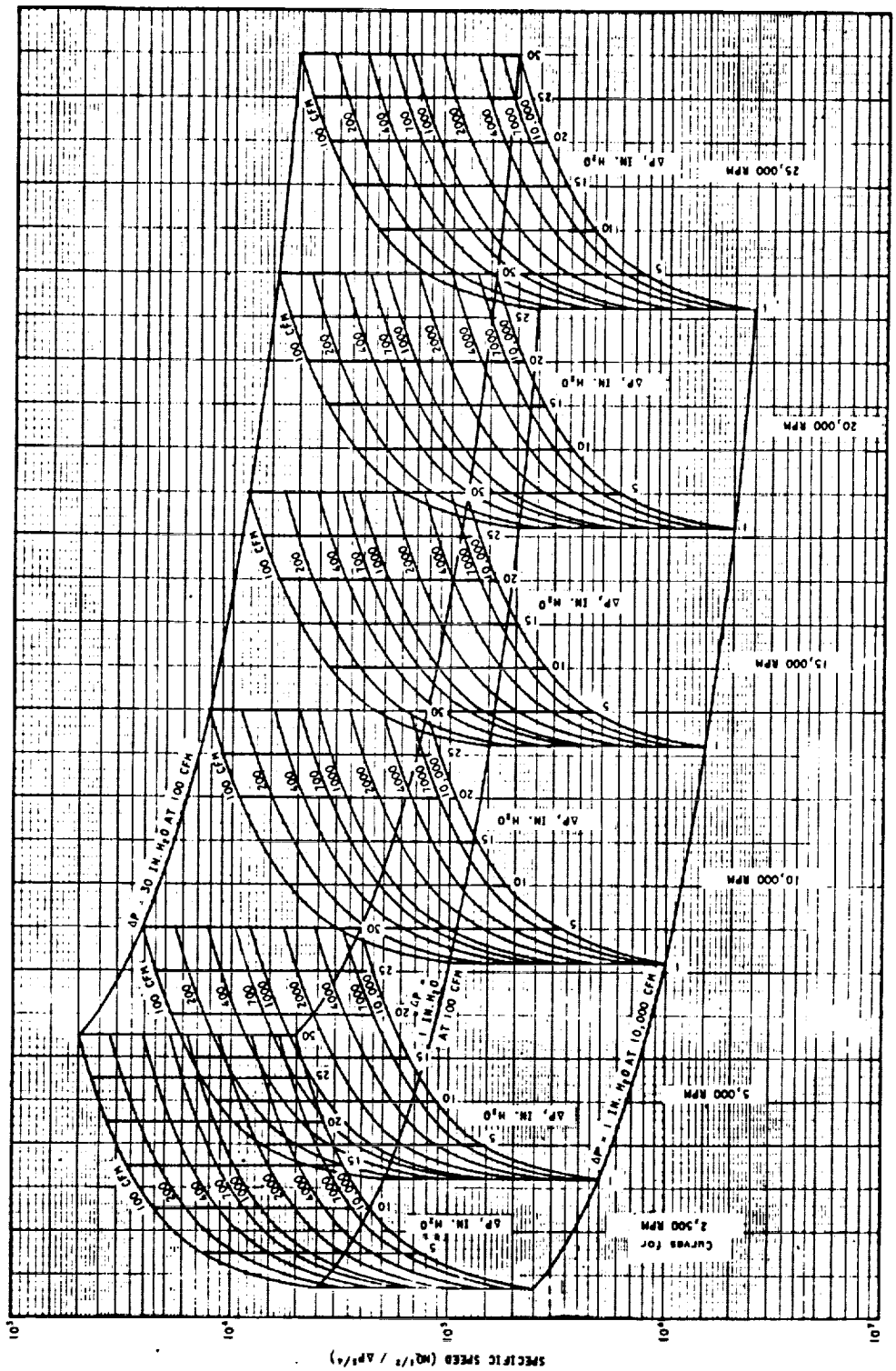


Figure A-5. Specific Speed Curves for Fans

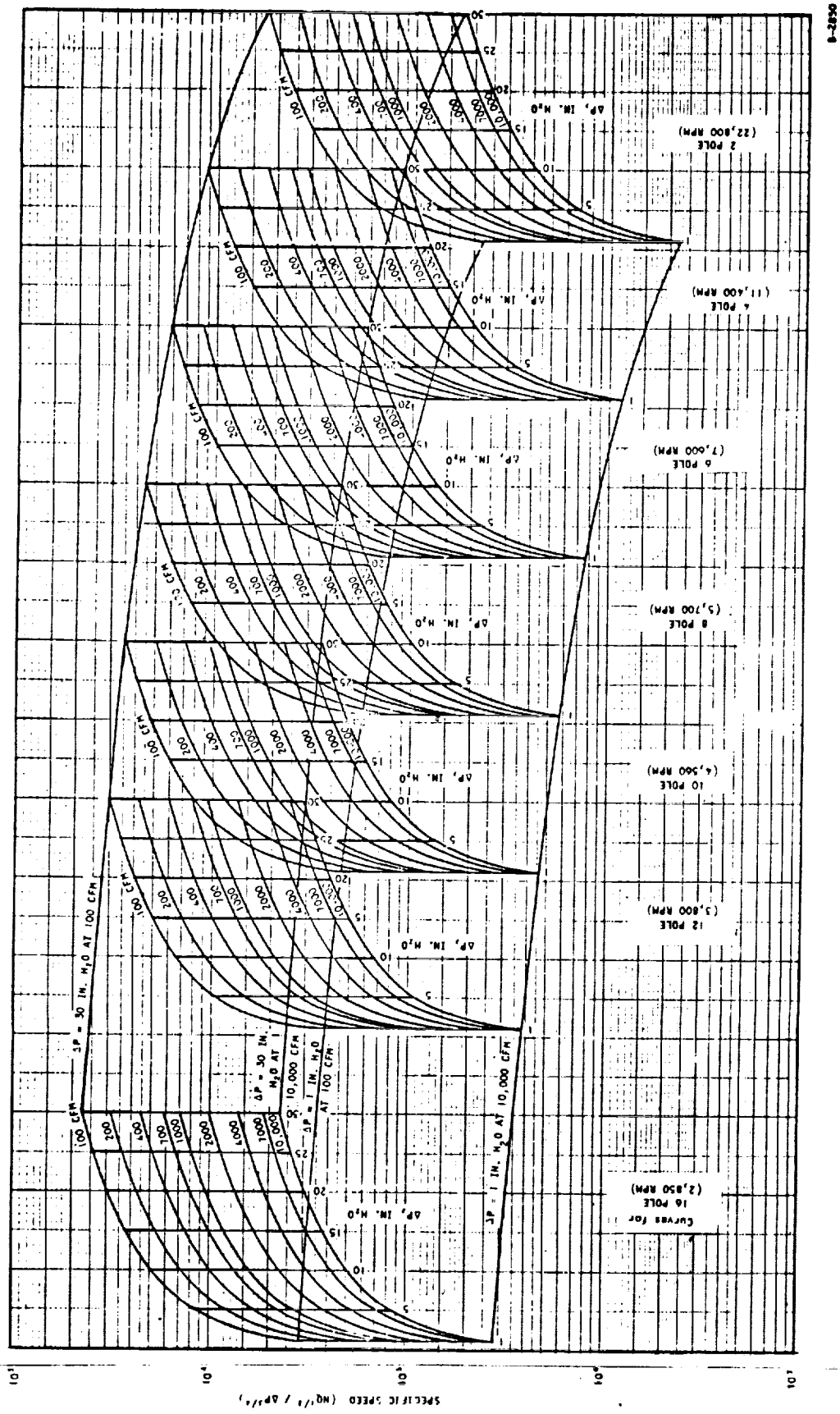


Figure A-6. Specific Speed Curves for 400-Hz, AC Motor Driven Fans

Figs. G-5 and A-6 are carpet plots of pressure rise vs specific speed with flow as a parameter, with separate plots for various speeds. On Fig. G-5 these plots are spaced out proportionally to the speed, thereby permitting accurate interpolation for speeds not shown. However, as the majority of motor driven fans are driven by 400-Hz induction motors, fig. G-6 is plotted to show the most common speeds directly. In this case the plots are spaced proportionally to the number of poles.

Fig. G-7 is an empirical plot of aerodynamic efficiency vs specific speed.

Technique for using graphs to find size of axial flow fan.--The following technique should be followed to find the axial flow fan size:

(1) From fig. G-1, pick off Q/a for the $\Delta P/\sigma$ as required.

(2) From fig. G-2, pick off u_t for the $\Delta P/\sigma$ required.

(3) From fig. G-3, with this value of u_t, choose a tip diameter D and speed compatible with the speed and size limitations of the installation.

(4) From the value Q/a found in (1), and the required flow, Q, calculate a. With this value of a and D from (3) obtain h from fig. G-4. If the values of a and D do not correspond to a value of h given, i.e., from 0.4 to 0.8, then a new choice of D and N in (3) has to be made and repeated until a solution is reached.

(5) Using the value obtained for N, determine the specific speed from figs. G-5 and G-6.

If the aerodynamic efficiency for the specific speed obtained in (5) is less than 60 percent, a new speed must be selected from fig. G-5. The problem must then be reworked from (3).

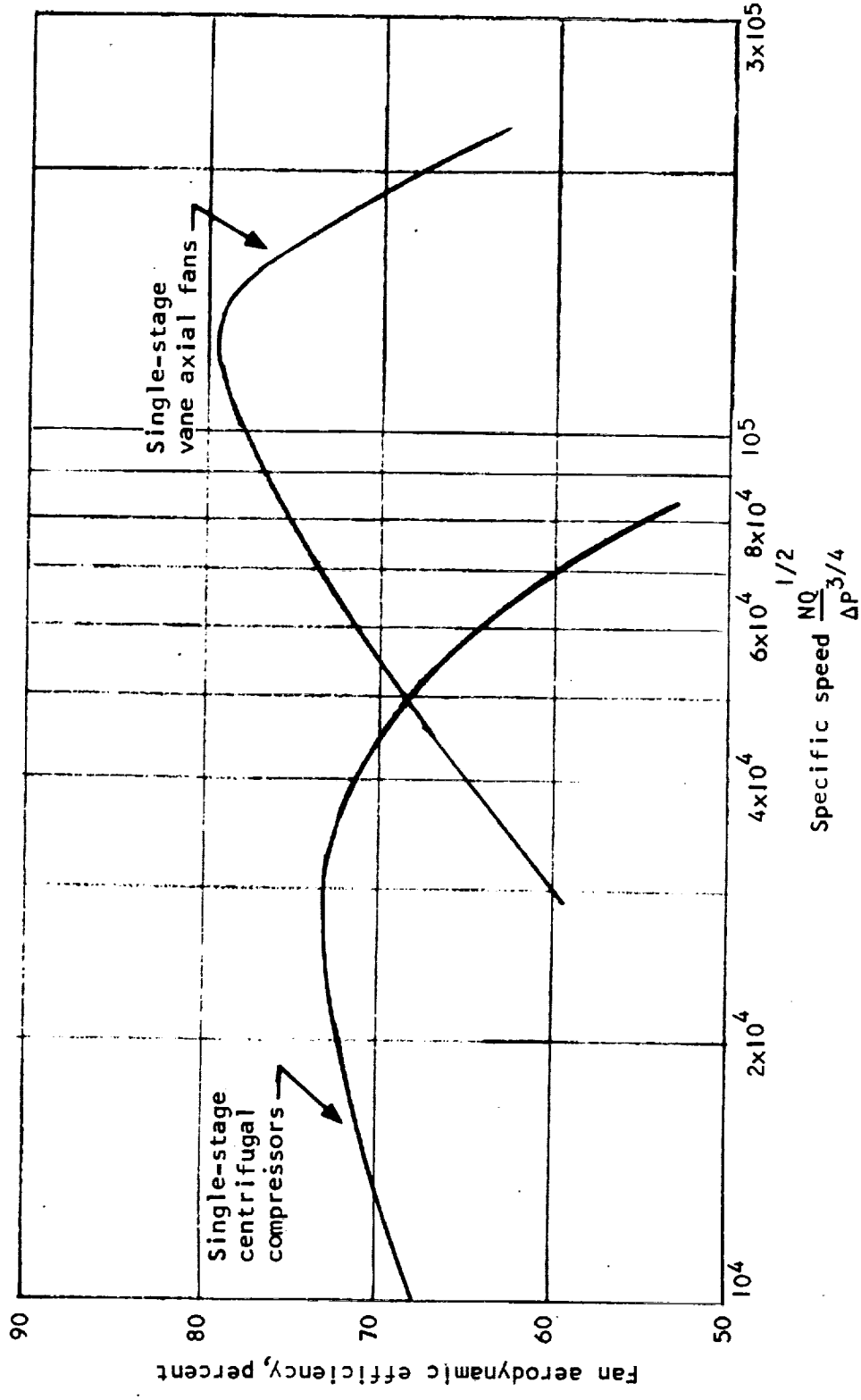


Figure A-7. Specific Speed vs Efficiency

Nomenclature I
For Axial Flow Fans

a	Annulus through flow area, m^2
d	Diameter of root of blades, m
D	Diameter of tip of blades, m
f	Electrical supply frequency, Hz
h	Hub/tip ratio = d/D
N	RPM
N_p	Number of poles in motor stator
P_i	Inlet absolute pressure, N/m^2
ΔP	Static pressure rise across fan, N/m^2
Q	Airflow rate, m^3/s
S	Motor slip factor
T_i	Inlet absolute temperature, ^0K
u_t	Tangential velocity at blade tip, m/s
Δu	Change in whirl velocity of air at blade tip, m/s
V_x	Air axial velocity, m/s
α	Air inlet angle from tangential, rad.
η	Aerodynamic efficiency, percent
σ	Air relative density
ψ	Pressure rise coefficient, percent

Centrifugal Compressors

The graphical method for sizing contrifugal compressors described here is limited to low pressure rise compressors (less than 25000 N/m^2 (100 in. of H_2O), using vaneless diffusers and rotor blades swept back 45 degrees at the tip. Unlike the axial flow fan sizing graphs, these can be used for design purposes, because the centrifugal compressor is essentially a simple machine, and detailed flow analyses are not necessary for these low pressure rise compressors.

Assumptions.--A centrifugal compressor with the following parameters is assumed (see Nomenclature II, p. 470):

(1) Overall aerodynamic efficiency, $\eta_o = \eta_i = 70$ percent

(2) Aerodynamic slip, $S = \frac{V_{u3}}{V_{ub}} = 0.71$

(3) $\beta_2 = 0.785$ rad (45^0)

(4) $V_x = V_r$

(5) $d_1 = 0.45D_1$

(6) Zero prewhirl

(7) $\Delta P_i = 0.87\ \Delta P_o$

(8) $\Delta P_d = 0.13\ \Delta P_o$

(9) $V_{xi} = 15.2$ m/s (50 fps)

Graphs.--Fig. G-8 shows the compressor volume flow vs the inlet duct diameter. This is merely a plot of the equation:

$$Q = V_x a_1$$

where $$a_1 = \frac{\pi}{4}(D_1^2 - d_1^2)$$

Substituting assumptions (5) and (9) into the above equation:

$$Q = 9.52\ D_1^2\ m^3/s$$

Fig. G-9 gives the compressor total-to-total pressure rise vs impeller tip tangential velocity. From the fan laws:

$$u^2\ \Delta u^2 = \frac{.0626\left(\frac{\Delta P}{\sigma}\right)\rho}{\eta_{ip}\,0.0765} = \frac{0.816}{\eta_i}\frac{\Delta P_i}{\sigma} = u_2 V_{u3} = u_2 S V_{ub} \qquad (G\text{-}8)$$

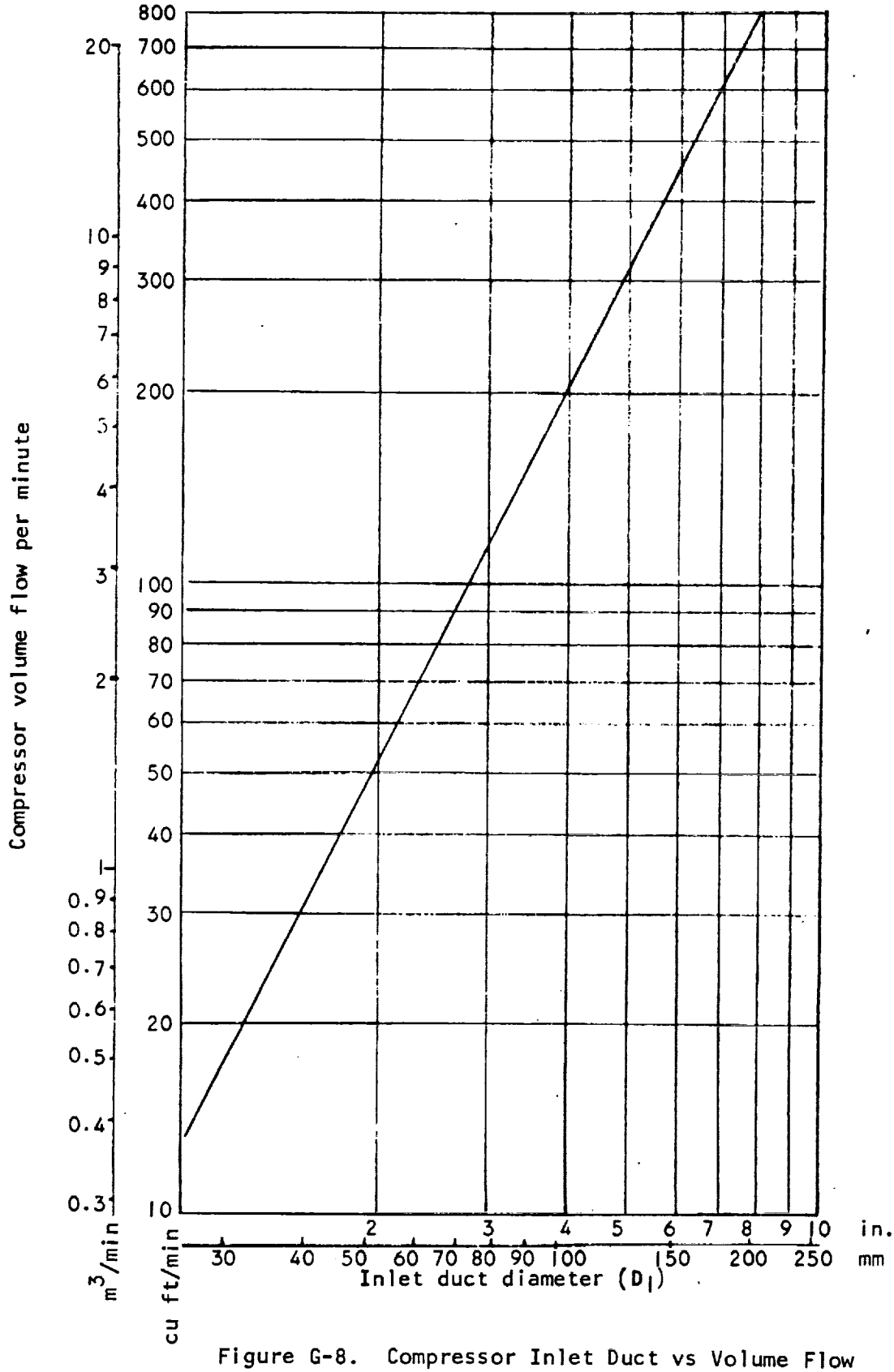


Figure G-8. Compressor Inlet Duct vs Volume Flow

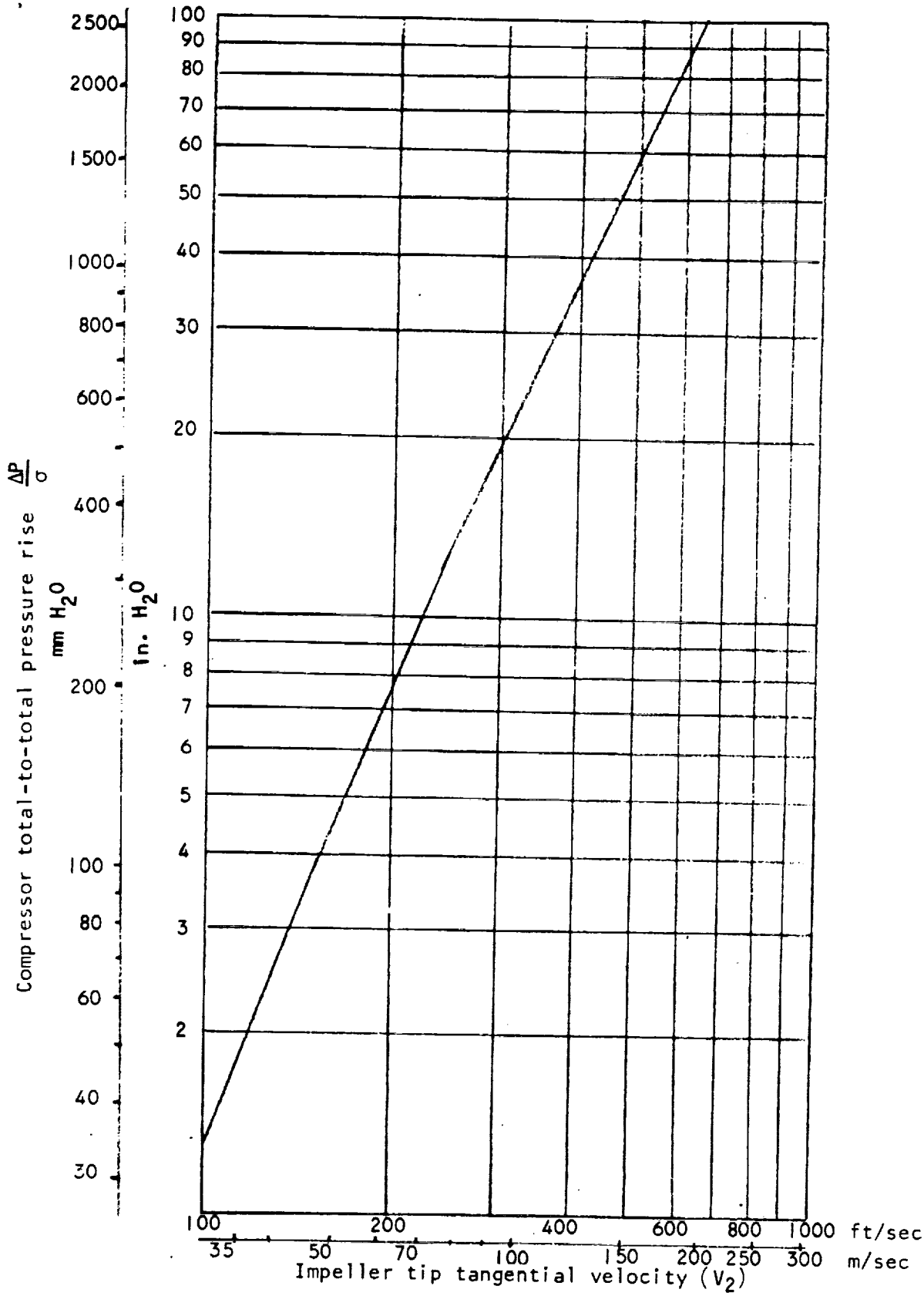


Figure G-9. Compressor Impeller Velocity vs Total-To-Total Pressure Rise

But, because $\beta_2 = 0.785$ rad (45°), $V_{ub} + V_r = u_2$

Therefore

$$u_2^2 \cdot \Delta u_2 = S\,(u_2^2 - V_r u_2) = S\,(u_2^2 - V_x u_2)$$

Substituting assumption (9) and eq. (A-8) into the above equation:

$$\frac{0.816}{\eta_i}\,\frac{\Delta P_i}{\sigma} = S\,(u_2^2 - 15.2\,u_2)$$

Substituting assumptions (1), (2), and (7) into the above equation:

$$\frac{\Delta P_o}{\sigma} = 0.705\,(u_2^2 - 15.2\,u_2) \qquad \text{(G-9)}$$

This equation is plotted on fig. A-9.

Technique of using graphs to find the size of a centrifugal compressor.-- Pick off the inlet diameter D, from fig. G-8 for the volume flow, Q, required.

Pick off the impeller tip tangential velocity from fig. G-9 for the pressure rise, $\Delta P/\sigma$, as required.

Select impeller tip diameter D, from fig. G-3 compatible with the speed desired. Higher rpm results in smaller and lighter compressors at the expense of cost and life. Also, the tip diameter should be at least 1.5 times the inlet duct diameter.

With the chosen speed, N, rpm, determine the specific speed from figs. G-5 and G-6, and refer to fig. A-7. The specific speed should be within the range where the aerodynamic efficiency is at least 70 percent.

The overall diameter of the centrifugal housing will be about 1.7 times the impeller tip diameter for compressors with axial discharge. Those with radial discharge will have a volute casing superimposed on this diameter.

Nomenclature for compressors is given in Nomenclature II, p. 470 and figure G-10.

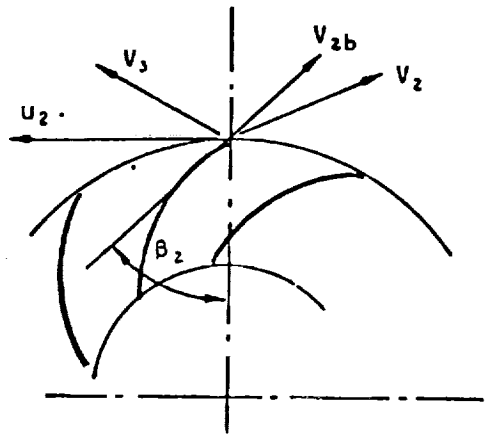
Nomenclature II
(Reference fig. G-10)
For Centrifugal Compressors

a_1	Impeller inlet annulus area, m^2
d_1	Impeller inlet inner diameter, m
D_1	Impeller inlet outer diameter, m
D_2	Impeller outlet tip diameter, m
ΔP	Pressure rise, in. N/m^2
Q	Volume flow rate, m^3/s
S	Slip = Vu_3/Vub
u	Tangential velocity
Δu	Change in tangential velocity, m/s
V	Gas velocity, m/s
Vu	Tangential component of gas velocity, m/s
α	Air angle, rad.
β	Blade angle, rad.
η	Efficiency
ρ	Density of gas, kg/m^3
σ	Relative density of gas

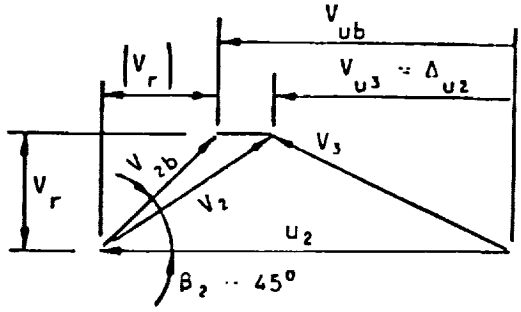
Subscripts

b	Blade	r	Radial
d	Diffuser	x	Axial
i	Impeller	1	Inlet, relative to impeller
o	Overall	2	Outlet, relative to impeller
		3	Outlet, absolute

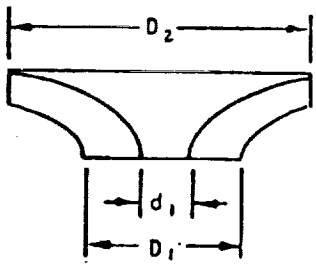
View in blade-to-blade plane



Outlet velocity triangle



View in meridional plane



Inlet velocity triangles and view of blade inlet

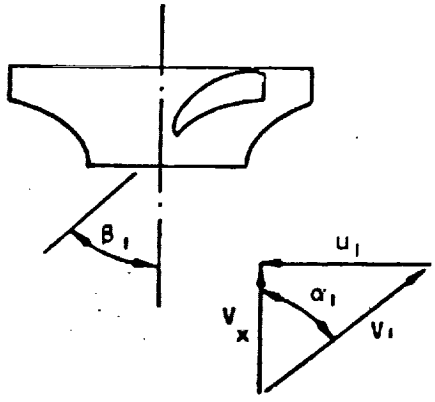


Figure G-10. Nomenclature for Centrifugal Compressors