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*Corrected version of
1st quarterly Progress
Rpt. dated 8/27/68.
CR 86281*

First Quarterly Progress Report

INVESTIGATION AND DEVELOPMENT OF NEW CONCEPTS
FOR IMPROVEMENT OF
AIRCRAFT ELECTRICAL POWER SYSTEMS

For

NASA Electronics Research Center
Cambridge, Mass.

Contract: NAS 12-659

68-4176(1), Revision 1

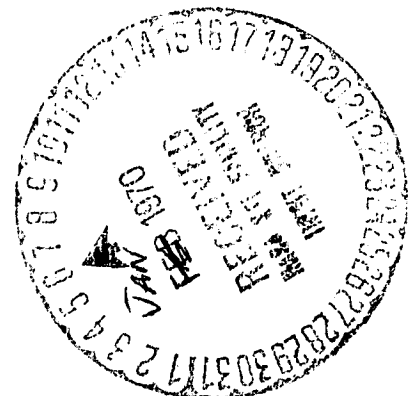
October 4, 1968

FACILITY FORM 602

N70-14347 (ACCESSION NUMBER)	(THRU)
62 (PAGES)	1 (CODE)
CR-86281 (NASA CR OR TMX OR AD NUMBER)	02 (CATEGORY)



AIRESEARCH MANUFACTURING DIVISION
Los Angeles, California



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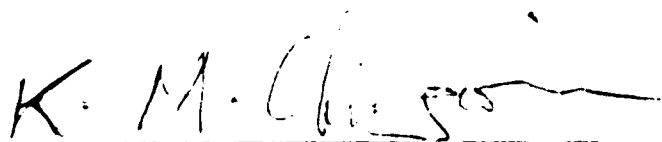
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October 4, 1968

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AIRESEARCH MANUFACTURING DIVISION
Los Angeles, California

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SECTION I

INTRODUCTION AND SUMMARY

This is the first quarterly progress report of a one year study at about a 2 man-year level of effort entitled Investigation and Development of New Concepts for Improvement of Aircraft Power Systems. The study is funded by NASA Electronics Research Center, Cambridge, Massachusetts under Contract No. NAS 12-659. The objective of this study is to formulate a philosophy for devising an optimum electrical power system for advanced aircraft, giving particular consideration to improvements in reliability, weight minimization, efficiency, and cost.

This report covers the reporting period from 15 May 1968 to 15 August 1968. Figure 1 shows the program tasks and gives the projected and actual expenditures for the program. The work covered by this quarterly report is confined to portions of Tasks 1 through 4 which are planning, literature survey and data collection, analysis of the electrical loads on the aircraft, and an examination of methods of power generation.

It has been established that the majority of the power system weight (typical total of about 12,000 lb for large existing transports) is in the distribution (27 percent) and utilization (65 percent) segments of a typical electrical power system. In addition, it appears that these same areas are the ones in which weight reduction efforts will be most profitable. In the utilization sector, the equipment weight can be substantially reduced (about 10 to 20 percent) by using a higher system frequency.

Studies on the generating portion of the system indicate that it will be possible to replace the constant speed drive (CSD) that is presently used with any of several more advanced generating systems. In particular, an attractive alternate is a wild frequency alternator (with wild frequency for the majority of the utilization equipment) with a VSCF system to supply constant voltage-constant frequency power to those loads requiring it. The present CSD units account for about 80 percent of the time and expense involved in servicing all of the generating and distribution equipment. Installation of a VSCF system will eliminate most of this maintenance as well as increasing the reliability of the generating equipment (eventually by as much as a factor of 10).



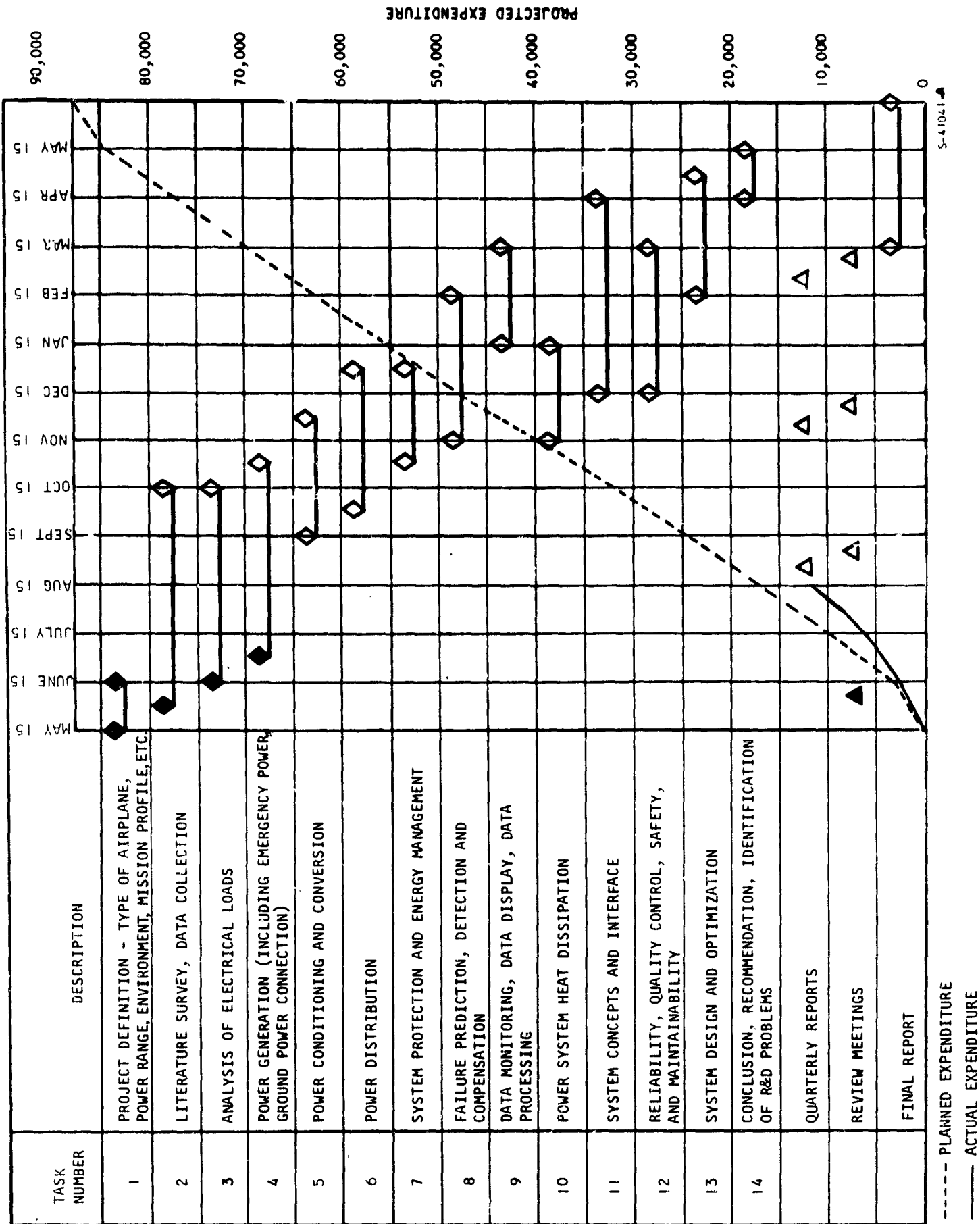


Figure 1-1. Program and Financial Plan - Advanced Aircraft Power Systems Study

SECTION 2

PROJECT DEFINITION - PLANNING

The initial portion of this quarter was devoted to continuing the preliminary program planning presented in the proposal (AiResearch Report 68-3192). For this study, the activities may be broken into four major areas as follows:

1. Background and Planning (Tasks 1 to 3 of Figure 1-1)

This phase of the study examines the current state-of-the-art of aircraft electrical power systems and the probable future trends in their design. This information is then used to establish a typical present-day power system which will serve as a reference point. At the completion of the study, this present power system can be compared with the configuration of an advanced power system using the information generated by this study. Such a comparison will clarify the advantages and disadvantages of changes in the power system.

2. Component Concepts and Design Improvement (Tasks 4 to 10)

The individual components of the electrical power system are each studied to determine what improvements in their design may be anticipated during the time frame considered for this study (an operating power system in the 1980's). In addition, alternate methods of performing the same function are also considered since it is anticipated that many of the components will be superseded by alternate designs. The restraints and requirements to use each method of providing the required function (such as power source; engine-driven generator, fuel cells, batteries, etc; or utilization; hydraulic, pneumatic, electrical, etc) will be tabulated since selection of the optimum component for a specific function is dependent upon the restraints imposed by the remainder of the power system. Consequently, at this component analysis phase of the study no attempt will be made to eliminate possible ways of providing any specific function; only the performance and restraints and requirements of each method will be listed for later use in the system synthesis phase.

3. System Synthesis (Tasks 11 to 13)

The information from the second phase serves as the building blocks that can be used as the basis for a design philosophy for an advanced electrical power system. Various types of systems will be compared to establish the optimum configuration. In addition to the component information, the system selection will consider such system-oriented features as the location of the system within the aircraft, the design for redundancy, selection of energy levels, etc.

The various systems will be analyzed in sufficient depth to allow the selection of the best system for the aircraft. This selection will consider, in addition to the weight of the system, such other performance criteria as reliability, cost, efficiency, maintainability, and predictability (via data monitoring and processing).



It is anticipated that the technological advances in both the components and in the software supporting the system will establish an updated philosophy of design for electrical power systems for aircraft. In particular, such considerations as reliability, system status monitoring, failure prediction capability, and energy management are expected to influence the overall concept.

4. Documentation (Task 14)

This is a continuing part of the study resulting in three quarterly reports and a final report covering all of the program. In addition to documenting the work performed on the study, the final report will identify the areas in which additional research or study would be required to achieve improved performance.

The planning work was primarily concerned with establishing a method of proceeding with the study. To do this, the desired outputs were analyzed to arrive at a sequential arrangement of tasks that would accomplish the work within the desired time. Table 2-1 gives the tentative outputs, listing them approximately in the order in which they will be studied.

TABLE 2-1

OUTLINE OF STUDY COVERAGE

ELECTRICAL SYSTEMS OF PRESENT AIRCRAFT

- Types of components
- Configuration
- Performance parameters (weight, cost, reliability, etc)

ELECTRICAL LOADS

- Loads of present-day subsonic and supersonic aircraft
- Applications of electric power for carrying loads
- Trends of electrical loads in future aircraft
- Power quality requirements of electric and avionic loads
- Load classification (vital and non-vital)
- Application and performance data on various types of electric motors
- Comparison of hydraulic, pneumatic, and electric drives

ELECTRIC POWER GENERATION

- Energy sources and performance
- Characteristics of various generating schemes
- Emergency, auxiliary, and ground power provisions
- Selection of generating system



TABLE 2-1 (CONT)

POWER CONVERSION AND CONDITIONING

Performance and restraints of various types of power converters
Control and regulation of power

POWER DISTRIBUTION

Comparison of various distribution systems
Types of system protection
Use of solid-state devices in power distribution
Methods of energy management
Signal processing for power control
Selection of distribution system

HEAT DISSIPATION OF ELECTRICAL EQUIPMENT

Methods of heat dissipation
Effect of temperature on equipment performance

INTEGRATED DATA SYSTEM

System data display
Method of data acquisition and monitoring
Failure prediction, detection, and compensation
Multiplexing techniques for signals
Utilization of data processing techniques
Selection of integrated data system

RELIABILITY AND MAINTAINABILITY

Areas of potential reliability improvement
Effects of redundancy and degraded operating modes
On-line maintenance concepts

SYSTEM SYNTHESIS

Philosophy for design of electrical power system
Comparison of conceptual power systems
System optimization techniques
Considerations for selection of system voltage, frequency and grounding
Presentation of typical advanced electrical power system diagram
for large supersonic aircraft

FUTURE RESEARCH AND DEVELOPMENT PROBLEMS

Indication of areas of future work
Level of effort of future work



SECTION 3

LITERATURE SURVEY

A literature survey was conducted to determine the present state-of-the-art in aircraft electrical power systems. Also, several of the aircraft manufacturers were contacted so that a better understanding of the performance and design of specific power systems could be obtained. At present over 100 references in recent literature have been collected and categorized in the following manner:

1. Electrical Power System
 - a. Power generation
 - b. Power conversion and conditioning
 - c. Power distribution
 - d. Power utilization
 - e. Miscellaneous
2. Avionics System
3. Hydraulic System
4. SST Aircraft System

Additions to this library will be made on a continuous basis throughout the course of the study. A bibliography of the literature surveyed is given as Appendix A to this quarterly report.

The remainder of this section is a compendium of the literature.

1. Electrical Power System
 - a. Power Generation

Power generation can be classified into two areas, ac and dc power generation.

The conventional method of obtaining constant frequency ac power is from a synchronous generator connected by a constant speed drive (CSD) to the aircraft engine. Since the advent of high-power silicon rectifiers, constant frequency can be obtained through a static frequency changer connected to the generator and the CSD is eliminated. The former method is called constant-speed constant-frequency (CSCF) and the latter method is called variable-speed constant-frequency (VSCF). An advantage of VSCF system is its high reliability because very few moving parts are involved. The meantime between failure (MTBF) is about 50 percent higher for a VSCF system as compared to a CSCF system with CSD (based on operational data). The eventual MTBF of a VSCF system is probably about 10 times that of a CSD system.



There are two main schemes for the VSCF power generation -- dc link and cycloconverter. At the present time they are both heavier than the CSD method if the same conventional generators are used. If the generator speed could be increased, the weight of the VSCF system would be less than that of the CSD system; however, the speed of the generator has to be high (24,000 rpm or higher) before the weight of this system becomes lower. At such a high speed stress problems are encountered. One attractive design solution is to use a solid rotor generator. But some stress problems are still unsolved.

The cycloconverter method is more attractive than the dc link method because of lower system weight and smaller volume. But the cycloconverter has an additional frequency interference problem and a more stringent requirement on the generator subtransient reactance. If the stress and the interference problems are solved, future aircraft will use cycloconverter VSCF systems.

If the operating frequency of the equipment remains at 400 Hz, the input frequency to the cycloconverter will be at least 1300 Hz (input to output frequency ratio should be at least 3 to 1). This high frequency power would have the following benefits:

- Reduce transformer size and weight
- Reduce filter weight and size for dc supply due to high ripple frequency
- Improve frequency regulation, frequency modulation, and transient performances

(Ref: Aircraft Electric Power System - Future Trend by John J. Pierro and Design Approaches for the SST Electric Power System by R. H. Swanberg and W. E. Hyvarinen)

The dc power needed for flight applications is generally obtained by rectification of the available ac power. In an emergency case (ac power supply failure), dc power is obtained from the standby batteries. The conventional battery is a lead-acid type but the sealed nickel-cadmium-batteries are more attractive for advanced applications because of their longer life, higher reliability and safety, and better performance. Another attractive alternative is the silver-zinc type which has the highest energy yield/weight. However, higher voltage, longer life and lighter weight are still demanded from the batteries. (Ref: Nickel-Cadmium Batteries--Commercial Aircraft Application and Maintenance Problems by Harry Wolf and Sealed Nickel-Cadmium Batteries for Aircraft-Electrical Systems by Gerald Miller.)

In emergencies, ac power is obtained from the batteries through static inverters. (Ref: Basic Standby Power Systems by Christ F. Seyer.) If dc power can be generated in large quantity and with lower system weight, the ideal situation is to use dc as the main power supply and whatever ac power needed can be obtained through the lightweight inverters.



Many unconventional techniques to generate dc power have been developed in the space programs. Some of these static or direct methods of electrical power generation offer good prospects for the aircraft application. Aluminum cells have a potential for an energy density of 200 w-hr/lb at the 100-hr discharge rate. Other prospects are thin-film cells, MHD, thermionic-converters and fuel cells. Fuel cells are specially promising if they can use the same fuel as the aircraft engines. (Ref: Space Electrical Power-Quo Vadis by R. I. Vachon, L. H. Wood and J. N. Seitz, Power Systems by George Barna and Study of Electrical Energy Conversion Systems for Future Aircraft by H. Woodson and W. Jackson.)

b. Power Conversion and Conditioning System

Solid-state and integrated circuit devices are being used in power conversion equipment for lightweight and high reliability. Higher rated and better performance items are under development. A manufacturer recently claimed to have successfully developed a high power (10 kva) cycloconverter with fixed-frequency sine-wave output having low harmonic contents so that large and heavy filters are not needed. (Ref: Static Conversion Techniques Tested by Philip Klass.)

Magnetic materials with high saturation flux density such as vanadium permendur have been developed in the space program. The application of these materials in the design of motors or transformers will result in lighter weight and smaller size units. Various developments such as insulators with higher dielectric strength (H-film) and capacitors tantalum applicable in high temperature environments contribute significantly to advance the state-of-the-art of the power conditioning system. (Ref: Application Factors Affecting the Weight of Aerospace Static Inverters by Loren H. Walker and High Temperature Electrical Equipment by J. J. Pierro.)

c. Power Distribution System

Since the engines and generators in the SST are placed at the rear of the aircraft, the transmission line from the generators to the loads will be longer than that of the conventional aircraft having engines at about the midpoint of the fuselage. In addition the SST is about twice as long as other aircraft. Consequently, the weight of the distribution system will be considerably higher than in existing aircraft. Studies should be conducted to obtain the optimum transmission frequency and voltage to reduce the system weight. The estimated optimum frequency is between 0.8 to 2.4 kHz and the voltage, 230 to 575 v/phase. (Ref: Design Approaches for the SST Electric Power System by R. H. Swanberg and W. E. Hyvarinen; and Variable-Speed Constant-Frequency Electric Power Distribution Systems for Aircraft by Edson J. Howard.)

The selection of the type and size of transmission wire is important for the following reasons:

- The transmission line impedance affects the performance of the electric power system, especially in transient conditions.



- Size of wire has considerable effect on the impedance due to the high frequency used in the line.
- Various conducting materials have different conductivity, specific weight and derating due to the severe environmental conditions.
- Losses are proportional to the impedance of the wire.

(Ref: Aircraft Electric Power System Performance as Affected by Transmission Line Impedance by W. E. Hyvarinen; and Cables for Aircraft by P.W.C. Jones.)

Other factors to be considered are the configuration of the transmission lines (whether four-wires with neutral return, three-phase delta or three-wire with ground plane return or other configurations) and the protection of the system. The optimum configuration will give an efficient system and the protection provisions will ensure reliable performance. Since the distribution system extends throughout the entire aircraft an efficient system protection is essential.

The distribution system for the standby power supply should also be studied so that an optimum configuration is obtained. Loads utilizing a standby power supply should be examined to determine if that provision is truly necessary. (Ref: Redundancy and Switching in Standby Power Systems by S. P. Jackson.) The literature mentions problems with switching devices and connectors at high altitudes. (Ref: Performance of Electrical Connectors at High Altitudes by Arlie Coats; and Aircraft AC Electrical Systems Using Changeover Contactors and Rapid Fault Clearance by R. F. Sims and R. L. A. McKenzie.)

d. Power Utilization

Much of the power utilization equipment is motors used for driving fuel pumps or other control devices. Since the motor load is an appreciable percentage of the total electrical consumption of the aircraft, the total weight of the motors is quite significant. To obtain the optimum system, a tradeoff study of the weight vs the operating frequency and voltage should be conducted, taking the load into consideration. (Ref: Effect of Operating Frequency on the Weight and Other Characteristics of Missile Alternators and Transformers by R. Turkington; and Determination of an Optimum Primary Power Frequency and Voltage for Missiles by S. K. Grinnell, R. Warm and R. Turkington.)

The effects of the severe environmental conditions on the motors or rotating machines in general are discussed in the literature. Most of the problems are related to the conductors, insulators, bearings and magnetic materials. (Ref: Rotating Machines for Extreme Environments by D. Irani and C. Smith.)

Some of the loads require a stable power supply, hence a regulating system is necessary. Lightweight and reliable components for switching, sensing and regulating have been developed using solid-state and magnetic devices. (Ref: Magnetic Switching Systems by B. J. O'Neill and Leon Weissman; Static Control of Electrical Generation Systems by P. R. H. Riley and State of the Art of Transducer Application in Germany by Alfred Lang.)



2. Avionic Loads

There are numerous new sophisticated items of avionic equipment that have been developed in the last few years. However, the airlines are reluctant to adopt these advanced airborne instruments for the following reasons:

- (a) Increase maintenance cost: Although the new instruments are more reliable (reducing the frequency of maintenance), this does not offset the increase in cost because greater skill and more time are required to service these more complex items.
- (b) High cost: Since avionic equipment configurations vary considerably between manufacturers, once a certain model is installed in the aircraft, the manufacturer holds a price monopoly of this equipment because it cannot be replaced by other models.

The trend is toward interchangeable avionic equipment. The airlines have pushed this concept for years to stimulate competition and reduce the price. Leading this drive is Aeronautical Radio Inc. (ARIONIC) and its associate, Airlines Electronic Engineering Committee (AEEC).

3. Hydraulic System

Most of the hydraulic devices are used for loads having sudden peak demands that occur mainly in the takeoff and landing phases of the aircraft flight. In some locations both hydraulic (for short high-power bursts) and electric (for lower loadings occurring throughout the flight) motors are provided. A weight and performance tradeoff study should be conducted to determine if it is possible to eliminate one of the motors so that the load is always serviced by the same type of power. In addition, the study should consider localized hydraulic supply centers driven by an electric motor as a possible replacement for the present hydraulic pumps which are usually mounted near the aircraft engines. Such supply centers would eliminate much of the weight penalty attributable to hydraulic line runs throughout the aircraft.

4. SST Aircraft System

The anticipated environment and performance of the SST are well established. (Ref: The 2707 Supersonic Transport by James McKee.) The major differences between the SST and existing commercial aircraft are the SST's high cruising altitude (70,000 ft vs 35,000 ft) and speed (Mach 2.2 vs Mach 0.6) in comparison to conventional aircraft. Thus inside the unregulated SST environment, the pressure will be lower (0.7 psi vs 3.6 psi) and the temperature (-54°C to 260°C vs -54°C to 50°C) will be higher. Since much of the electrical equipment is installed in the unregulated environment, the increase in temperature can cause significant problems. (Ref: Electrical Discharges at Altitudes Between 70,000 and 250,000 Ft by W. G. Dunbar and Voltage Breakdown at Low Air Pressure by E. R. Bunker.)

The safety of an aircraft is of utmost importance. One of the hazards is fire. Fire problems become particularly aggravated at high cruising speeds (Mach 7 or higher) when the environmental temperature is high enough to promote a fire. Hence in the SST electrical system design, considerations are given to



- Prevention of fire
- Prevention of spread of fire
- Fire detection
- Fire extinguishment

(Ref: A Look at Aircraft Fire Precautions and Protections by T. Medgwick.)



SECTION 4

DATA COLLECTION

A series of trips to various aircraft manufacturers (Boeing, Lockheed, and North American Rockwell) was made to obtain information on the performance and design of electrical power systems in their aircraft (in particular, the Boeing Model 2707 (SST), and the North American Rockwell XB-70) and to get their opinions on the probable future trends in power system development. The information on the SST is felt to be particularly useful to this study since this aircraft will be representative of the future generation of supersonic transports.

The Garrett and NASA personnel who attended these meetings are as follows:

Garrett Corporation:

Dr. C. H. Lee, Principal Investigator
J. J. Brandner, Development Engineer
J. E. Minnear, Preliminary Design Engineer
P. Jorgenson, Garrett Sales (Boeing visit only)
D. Hill, Garrett Sales (Lockheed visit only)
H. H. Poulson, Garrett Sales (North American Rockwell visit only)

NASA Electronics Research Center:

Dr. L. F. Tami, Contract Monitor

Visit to Boeing Co., Development Center, Seattle, Washington, June 18

Boeing prepared an 18-page technical folder in response to questions which were transmitted to them prior to the meeting. The meeting was then primarily concerned with a detailed discussion of areas of particular interest. Appendix B contains a summary of this briefing giving the anticipated performance and design details of the Model 2707 electrical power system. The Boeing personnel present at the meeting were Messrs J. Harris, H. L. Ernst, M. Abrams, and M. B. Wall.

Boeing feels that future improvement in aircraft electrical power systems will be confined to the distribution and utilization portions of the system. They would be particularly interested in a programmed control unit that could take on the guardian function of load distribution. Such a unit would sense the load current of the generating channels and would automatically control their output for optimum load distribution, dumping the loads sequentially in order of their priority and switching loads to alternate channels of systems to maintain optimum efficiency.



Visit to Lockheed Company, Burbank, California, June 20

The Lockheed personnel present at this meeting were Messrs M. Cronin, N. C. Clark, and W. W. Cloud.

Lockheed feels that future electrical power systems will maintain the present voltage and frequency levels to avoid costly redesign of utilization equipment and to provide consistent availability. However, they expect future systems to be of a hybrid nature in which most of the loads (70 to 80 percent of the total) would be supplied with crude power and only those loads requiring precise power would be furnished with conditioned power. A VSCF system would probably be used to condition the power for these loads.

To improve the redundancy and reliability of the system, Lockheed is considering a combined hydraulic-electric supply which could operate in any desired mode (as a hydraulic pump driving an electric generator to meet peak electric power demands, or as an electric motor to drive the hydraulic pump for peak hydraulic demands). At present, Lockheed is concerned with the weight penalties attributable to long lengths of high pressure hydraulic lines. They feel that effective load-power-source selection can reduce this weight.

Lockheed is also examining the possibility of replacing circuit breakers with light bulbs. The bulbs, because of their low impedance, would not light unless the circuit is faulty. This gives a positive, easy-to-detect indication of circuit failure as well as a cost reduction.

Multiplexing will be increasingly used on all large aircraft systems. Lockheed is presently considering using multiplexing for the L-1011 entertainment system. It will definitely be considered for eliminating wires which are used for control and other low power signals.

Visit to Edwards Air Force Base, California, June 19

This meeting was held to acquire information relating to the use and testing of a large aircraft electrical power system. NASA (who is operating the XB-70 flight test program) was represented by Messrs J. Love, and R. S. Waite of the Flight Research Center, and North American Rockwell (who manufactured the plane) had Messrs G. F. Pakes, D. C. Silver, and F. W. Munds in attendance. The visit included an inspection tour of the XB-70. Although there have been minor problems in the system during the testing, it appears to have performed well, meeting all design expectations. Information on the system itself obtained during this visit is included with additional material obtained during the visit to North American Rockwell.

Visit to North American Rockwell, Los Angeles, California, June 21

North American Rockwell was represented by Messrs V. N. McLaughlin and J. J. Pierro. Information they presented on the XB-70 electrical power system is given in Appendix C.

North American Rockwell feels that the optimum system frequency on a large aircraft is between 1000 and 2000 Hz. For example, if the total electrical



system weight is 3500 lb, a weight saving of 15 percent can be achieved by using high frequency (1-2 kHz) equipment instead of the standard 400 Hz equipment. If the frequency is further increased to 3200 Hz, the system weight will again approach that of the 400 Hz system. They further feel that the optimum system voltage is about 350 v rms.

NAR agrees with Boeing in saying that cycloconverter VSCF systems should find widespread acceptance in future aircraft.



SECTION 5

TYPICAL PRESENT-DAY AIRCRAFT ELECTRIC POWER SYSTEMS

Existing electric power systems on large transport aircraft typically can supply up to about 160 kva of power. The total loads on the system never exceed about 60 percent of the system capacity; the remaining power is provided for redundancy, degraded operating modes, and to satisfy inrush currents from motors. About 95 percent of the demanded power is used in the ac form with the other 5 percent being supplied as dc power. The total weight of a typical electric power system on a large, existing transport aircraft is about 12,000 lb. This weight can be divided into three major categories: generating equipment, which supplies the power; distribution equipment to control and carry the power to the loads; and utilization equipment that consumes the power. This total weight of 12,000 lb includes the weight of the driven load (fan, blower, pump, etc.) and the weight of the supporting structure in those cases in which the weight of the load itself would change with changes in its driving motor. An analysis has indicated that the 12,000 lb is apportioned within the power system as follows:

- Generating equipment - 8 percent of the total, or about 900 lb
- Distribution equipment - 27 percent of the total, or about 3200 lb
- Utilization equipment - 65 percent of the total, or about 7900 lb

The system has four different modes of operation as follows:

- Normal flight operation - Generators driven by aircraft engines supply all loads in the aircraft
- Ground power operation - Power supplied to the aircraft from a ground power cart or onboard auxiliary power unit used for lighting and passenger comfort loads and equipment warmup
- Degraded flight operation - The system is designed to be dispatchable with a single generator, or power channel inoperative; with two channels inoperative almost all of the loads can still be supplied, however, there may be degraded passenger comfort; with three channels inoperative, the aircraft would descend to a lower altitude, but would still have all of the vital aircraft loads supplied.
- Emergency flight operation - With all channels inoperative, or only a single channel operative, vital aircraft flight controls and navigation equipment are supplied from an emergency inverter and a battery with about 120 amp-hr capacity.

Power is generated on 2 to 4 identical channels (depending on the number of aircraft engines), each about 20 to 60 kva, powered by the aircraft engines



utilizing hydraulic constant speed drive units to accommodate the approximately 2 to 1 output speed ratio of the engine. The generators are brushless, rotating rectifier machines having a weight of about 2.5 (on older, established aircraft) to about 1.0 (on new second generation jets) lb per kva output. Typically, two speeds are used in these units, 6000 rpm on the older design generators using air cooling with auxiliary power for excitation, and 8000 rpm on the newer designs using oil cooling with a permanent magnet generator (PMG) on the same shaft providing the excitation.

The output power from the generators is 120/208 v three phase grounded neutral 400 Hz power conforming to standards of MIL-STD-704. The philosophy is generally to have the quality of all of the power determined by the most exacting of the individual load requirements. This power is typically transmitted over a distance of as much as 150 ft to the main power distribution center located near the flight engineer's station. This center ties together all the generators and an attachment for ground power input when the aircraft engines are not operating. Bus tie breakers and generator circuit breakers are used to allow the generators to be operated together in parallel (as is normally the case) or as independent power sources. The paralleling can be done automatically by sensing the voltage and phase relationship between each channel and the paralleling bus and closing the bus tie breaker when both voltages and frequencies are within prescribed tolerances. Controls and instrumentation are provided on the flight engineer's panel to manually override and control the paralleling or isolated operation of the generators. Appropriate sensing circuits are incorporated in the system to ensure equal real and reactive load division between generators.

Protection incorporated in the electric power system includes differential protection for the generators and feeders, overvoltage, undervoltage, over-frequency, underfrequency, underspeed on the generators, overexcitation and underexcitation for the paralleling operation, and current unbalance on the paralleling bus. The ground power connection incorporates phase sequencing to prevent ground power from being incorrectly connected.

From the paralleling bus, several lines carry the power throughout the aircraft to localized distribution buses that transmit the power to the individual loads. Each of these lines is connected to both the paralleling bus and to one of the generator feeder lines. The connection is between the generator circuit breaker and the bus tie circuit breaker. Consequently, this allows the loads to be serviced from either the paralleling bus or the generator (if it is being operated in isolation from the paralleling bus).



SECTION 6

ANALYSIS OF ELECTRICAL LOADS

This section represents about 25 percent of the material on electrical loads that will be in the final report. The remainder of the loads analysis task will be performed during the next reporting period.

The first objective for this task was to determine the types of electrical loads on the aircraft and their portion of the total power requirement. Future aircraft designs were then investigated to determine the effects of design advances in aircraft on the types of loads. This information was then used to investigate sources of possible weight reduction in the electric load portion of the aircraft electric power system.

The weight reduction investigation indicated that increased system frequency would probably offer weight reductions in the rotating machinery, the lighting, and the rectification equipment. Consequently, a more detailed investigation of the effects of increased frequency on the weight of individual items of equipment was initiated. This section includes material on the effects of increased frequency on motors designed to operate at constant frequency. In addition, because it appears likely that the generating equipment will output wild frequency power in an optimum system, a weight study of wild frequency motors was conducted.

The results of these motor weight studies are applied to a typical aircraft power system to show the approximate relative weights of utilization equipment in constant frequency systems operating at 400 Hz, 1000 Hz, 2000 Hz, and 3200 Hz and in a wild frequency system. The section concludes with a brief discussion of additional work that needs to be performed in this area.

Electrical Load Classification

The loads placed on the electrical power system can be categorized into the following: electronics and controls, heating, lighting, and motors. The approximate distribution of major load classes is shown in Table 6-1.

TABLE 6-1

COMPARISON OF LOAD DIVISION OF SUBSONIC AND SUPERSONIC AIRPLANES

	A Typical Large Subsonic Airplane, Percent	Concorde, Percent	Model 2707 Boeing, Percent
Electronics and Control	13	14	11
Heating	42	47	11
Lighting	10	7	10
Motors	35	32	68



The Boeing Model 2707 does not use electric heating for de-icing but does require large electric power for fuel booster pumps. This explains the low heating and high motor loads for this aircraft in Table 6-1. As the table shows, there is little difference in electrical loads between subsonic and supersonic aircraft.

A more detailed tabulation of loads in the Boeing Model 2707 is given in Tables B-1 and B-2 of Appendix B. Profiles of ac and dc loads are shown in Figures B-1 and B-2.

Trend of Loads in Future Aircraft

Certain aircraft electrical load trends are evident today:

1. There will be a rapid increase in types and utilization of avionics equipment. However, this does not necessarily mean that more electric power will be required for the avionics load, since most new avionics equipment will use integrated circuit components and/or LSI. What will happen is that the power source for the electronics and control devices will require more dc capacity than 400 Hz ac capacity.

Table 6-2 gives representative breakdown of avionics loads power requirements.

TABLE 6-2

CONNECTED AVIONIC LOADS

Normal Operation		Emergency Battery Operation	
Direct Ac Supply	7.3 kva	Dc Standby Power	0.3 kw
Dc Rectification	3.4 kva	Ac Standby Power (inverter)	0.8 kw
Total	10.7 kva	Total	1.1 kw
Percent of total connected = 4.4 % load in the airplane		Percent of total battery = 37 % demand	

To illustrate the increase in avionics expected in advanced transport aircraft, Table 6-3 provides a comparison between the avionics typically provided in a large contemporary aircraft and the avionics recommended for future transports.



TABLE 6-3

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
" 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 Transponder	2	2
Radio Altimeter	2	2
Marker Beacon	1	1
Collision Avoidance System	--	1
Clear Air Turbulence Detection	1	1
Selective Calling System	1	2
Public Address System	1	1



2. The power demand for galley and passenger comfort systems will increase sharply. The galley load for the Boeing Model 2707 is about 20 kw. Boeing engineers are already talking about 100 kw or more for galley and passenger services in future SST's
3. There will also be a major increase in motor loads. There are several reasons for this increase. One is the trend of the changes in the hydraulic system brought about because the air frame manufacturers are inclined toward acceptance of the so-called "fly-by-wire" concept. In present aircraft, the main hydraulic pumps are directly engine-driven. The fluids are then piped to various parts of the aircraft for hydraulic actuation. The possibility of piping leakage and damage reduces the reliability of the system and the weight of the piping is significant. However, if an electric-driven hydraulic pump is placed adjacent to the hydraulic actuator, electric wiring replaces the fluid piping. A "fly-by-wire" system such as this increases reliability, improves maintainability, and can reduce the overall weight. When this system is adopted, there will be more electric motors in the vehicles, and hence, a higher motor load on the aircraft electrical supply.

Further, future aircraft will be equipped with increasingly powerful engines. The pumping power requirement of fuel systems will therefore also be increased. The fuel system represents the bulk of the motor load in an aircraft.

Another reason for increasing motor load is the increased cooling demand due to the increase in avionic equipment, galley load, and the overall more extreme environment.

4. Some unconventional electric loads may be used in future aircraft. One example would be using electrostatic discharge around the airplane to reduce sonic boom and wave drag of supersonic aircraft. Some experiments on this theory were performed with small models in a wind tunnel. According to M. S. Cahn and G. M. Andrew of Northrop Corporation, the model tests fully demonstrated the feasibility of modifying the flow of air by electrostatic fields. Should this become a practical means of reducing sonic boom and air drag, the electrostatic discharge would become a major load on the electrical system. Since this is still in a research stage, and there is no information available on the quantity and voltage requirement of the electrostatic power, this kind of electric load will not be included in the present study.

Sources of Weight Reduction

As indicated previously, the utilization equipment represents the bulk of the airplane electrical system. Any attempt at weight reduction of the electrical system must therefore include a thorough examination of ways to reduce the weight of the utilization equipment.



Motor load constitutes the heaviest part of the utilization equipment. In this context, the motor load is the complete drive package, since when the weight of the motor changes, the load it drives (for example, the pump) and the supporting structure will also change.

Generally, the weight of an electric motor decreases when its design speed increases (for the same horsepower output). Many of the pumps, fans and blowers could be designed to run at speeds up to 60,000 rpm or higher. Therefore, many of the motor loads in the airplane can be made lighter and smaller by using high speed motors. For ac motors, this means a higher operating frequency.

The transformer rectifier unit can also be made lighter and smaller by using higher frequencies.

Fluorescent lights will also be lighter in weight if high frequency is used since the inductive ballast can be dispensed with.

Part of the heating load is represented by fans and blowers which circulate the hot air for de-icing, galley use, etc. In many cases, these fans and blowers can be made lighter if higher speed motors are used.

High percentage weight savings in avionics and control loads can be accomplished by using integrated circuit components. Recent advances in microelectronics technology have made integrated circuit components practical and dependable. It should be possible to say the same of Large-Scale Integration (LSI) avionics components within 5 years.

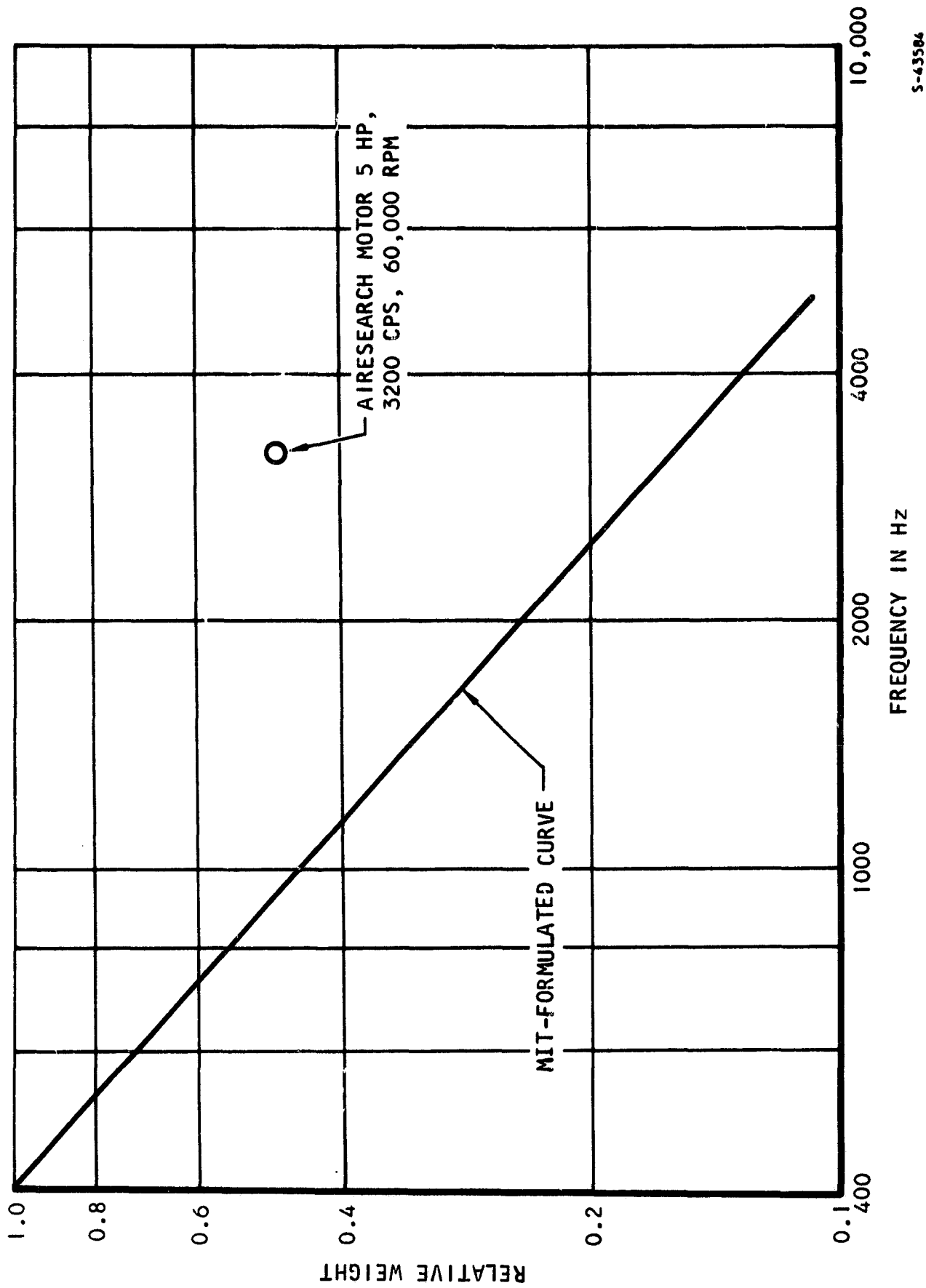
Some loads are sized by the momentary peak power demands. In this case, some energy storage devices may reduce the capacity of the installed load and hence reduce weight. Weight reduction may sometimes be obtained if a different approach is used to perform a certain load function.

Cryogenic cooling of motors may result in overall weight saving. A study on this feasibility will be included in the next quarter's program. It is recognized, however, that the increased servicing required for the cryogenic equipment and the motors may more than offset any potential weight reduction.

Constant Frequency Motors

During the late 1950's MIT performed a study for the Navy on the effect of operating frequency on the weight and other characteristics of missile alternators and transformers. Their result on the relative weight of an induction generator as a function of frequency is shown in Figure 6-1. This curve should be applicable to induction machines in general, including induction motors. However, AiResearch experience in high frequency induction motors does not indicate that the weight reduction of high frequency, high speed induction motors is as optimistic as the MIT study showed. For example, Figure 6-1 shows the test result of an AiResearch 3200 Hz squirrel cage induction motor which has a relative weight of nearly 47% of that of a corresponding 400 Hz motor. (MIT curve shows a relative weight of only 17%).





S-43584

Figure 6-1. Relative Weight of Induction Machines (Silicone Steel Lamination) as a Function of Frequency

This discrepancy can be explained as follows:

1. The MIT curve applies to the "electromagnetic weight" of the motor, while the AiResearch result is for the total weight of the motor, including the frame and supporting structure. The combined weight of the frame, bearings, and supporting structure becomes a larger and larger percentage of the total weight of the motor as the motor speed increases. Therefore, the relative weight of the actual motor is much larger than the "electromagnetic weight" of the motor.
2. In deriving the MIT curve, the assumption was made that there is no heat transfer between the windings and the armature core. This assumption is not true in actual machines.
3. In designing motors, consideration must be given to starting performance, full load slip, etc. This generally results in different shapes of torque-speed curves for low and high frequency motors, affecting the relative weights. This was not taken into consideration in the MIT study.

To derive a complete set of relative weight curves taking into account more practical refinements is a study by itself, and is beyond the scope of the present contract.

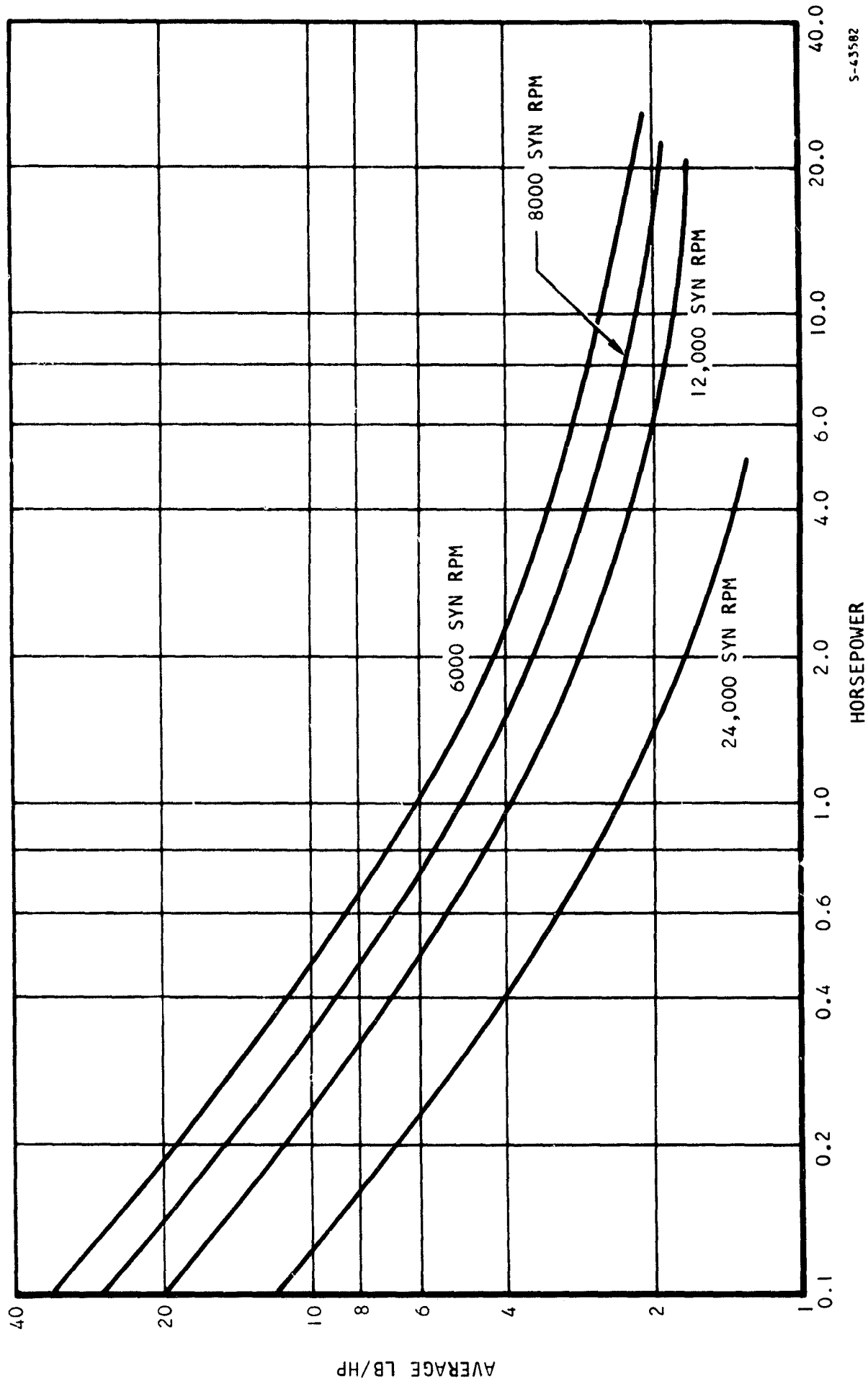
To make a realistic appraisal, weight information on a large number of aircraft electric motors has been taken from General Electric, Westinghouse, Western Gear, and other electric motor catalogs and evaluated together with the AiResearch motor data. The average weight in pounds per horsepower versus horsepower for various speeds for 400 Hz ac and dc aircraft motors is shown in Figures 6-2 and 6-3. The average weight in pounds per horsepower versus speed for various horsepower for 400 Hz a-c motors is shown in Figure 6-4. These curves show the relative weight of motors operating at different speeds, but with the same frequency. If the speed increase is due to an increase in frequency rather than a decrease in the number of poles, the weight reduction is somewhat less than that shown by these figures. This can be explained as follows:

1. At higher frequencies, the working flux density must be reduced to prevent excessive iron losses.
2. The leakage reactances of the machine increase with frequency. To avoid excessive reduction in pullout torque, the machine must be oversized at higher frequencies in order to lower the leakage inductances. The rate of weight decrease in Figure 6-4 will diminish at high speeds as evidenced by the curves for 10 hp and 20 hp motors.

For approximation purposes, the curves of Figure 6-4 can be used as plots of relative weight versus operating frequency (constant number of poles).

The results of the MIT study showing the relationship between transformer weight and frequency are given in Figure 6-5.

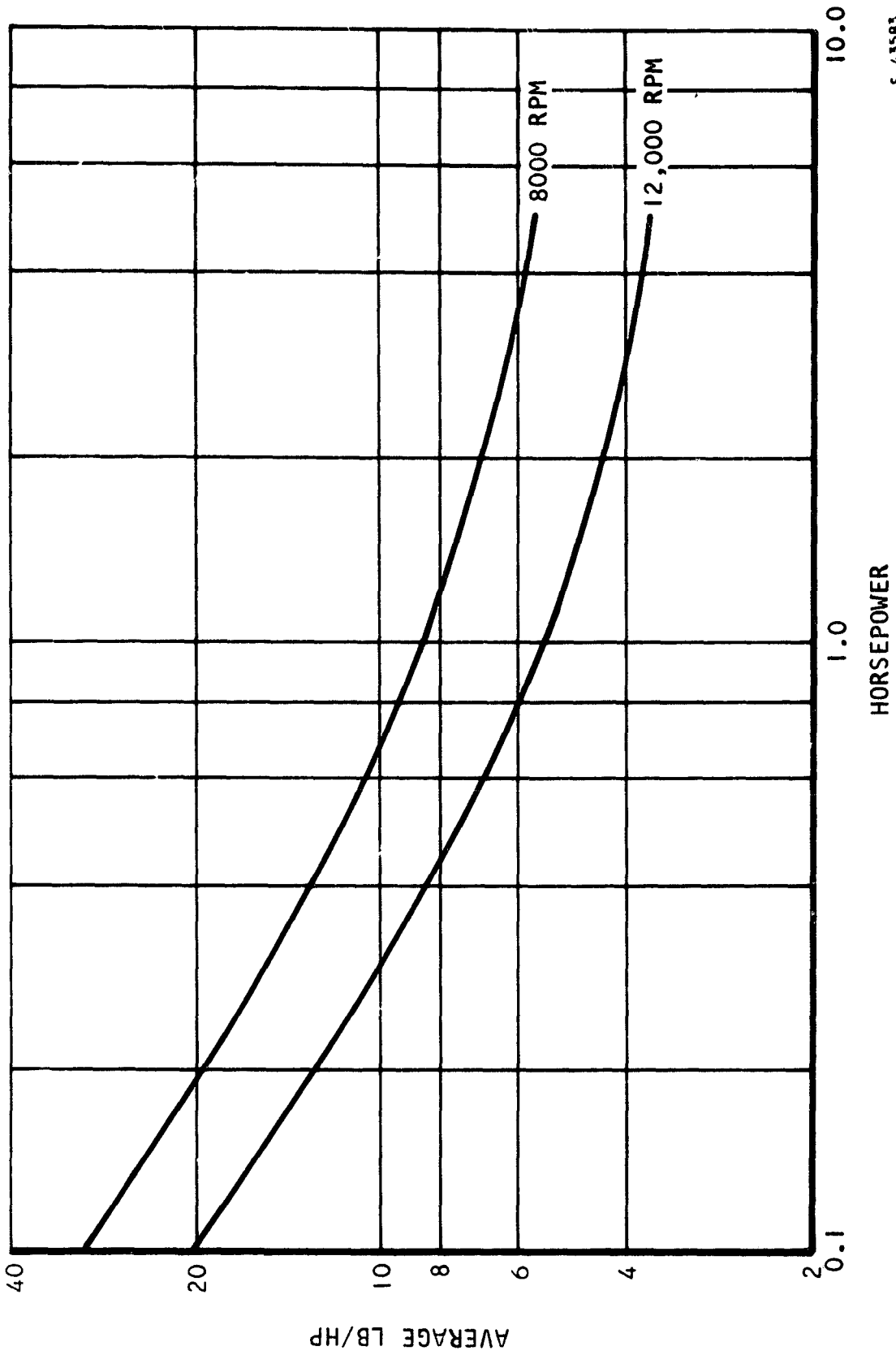




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Figure 6-2. Average lb/hp versus hp, Aircraft Ac Induction Motors, (Silicone Steel Lamination), 400 Hz, 115 v/phase

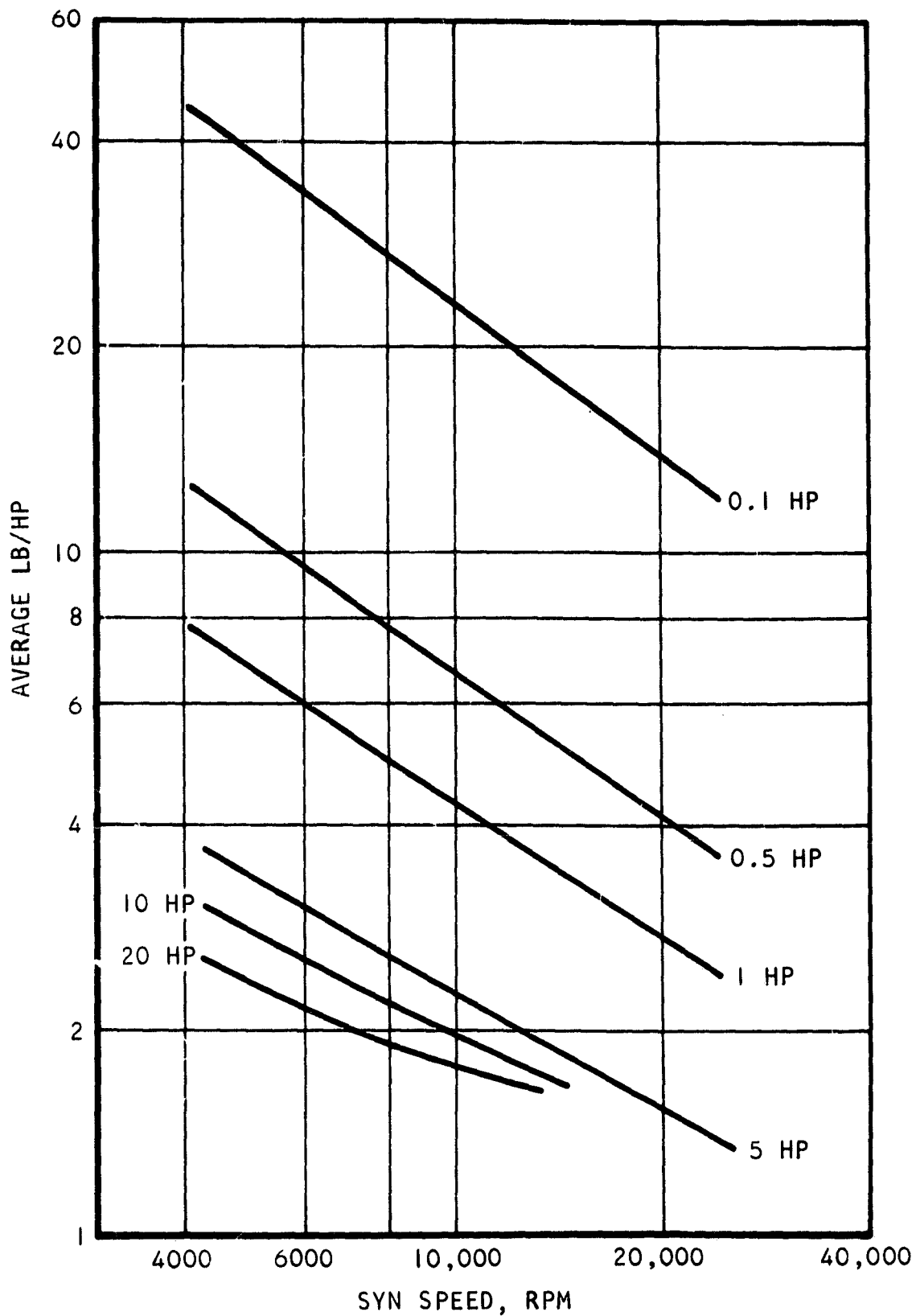




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Figure 6-3. Average lb/hp versus hp, 28 v Aircraft DC Motors
(Silicone Steel Lamination)

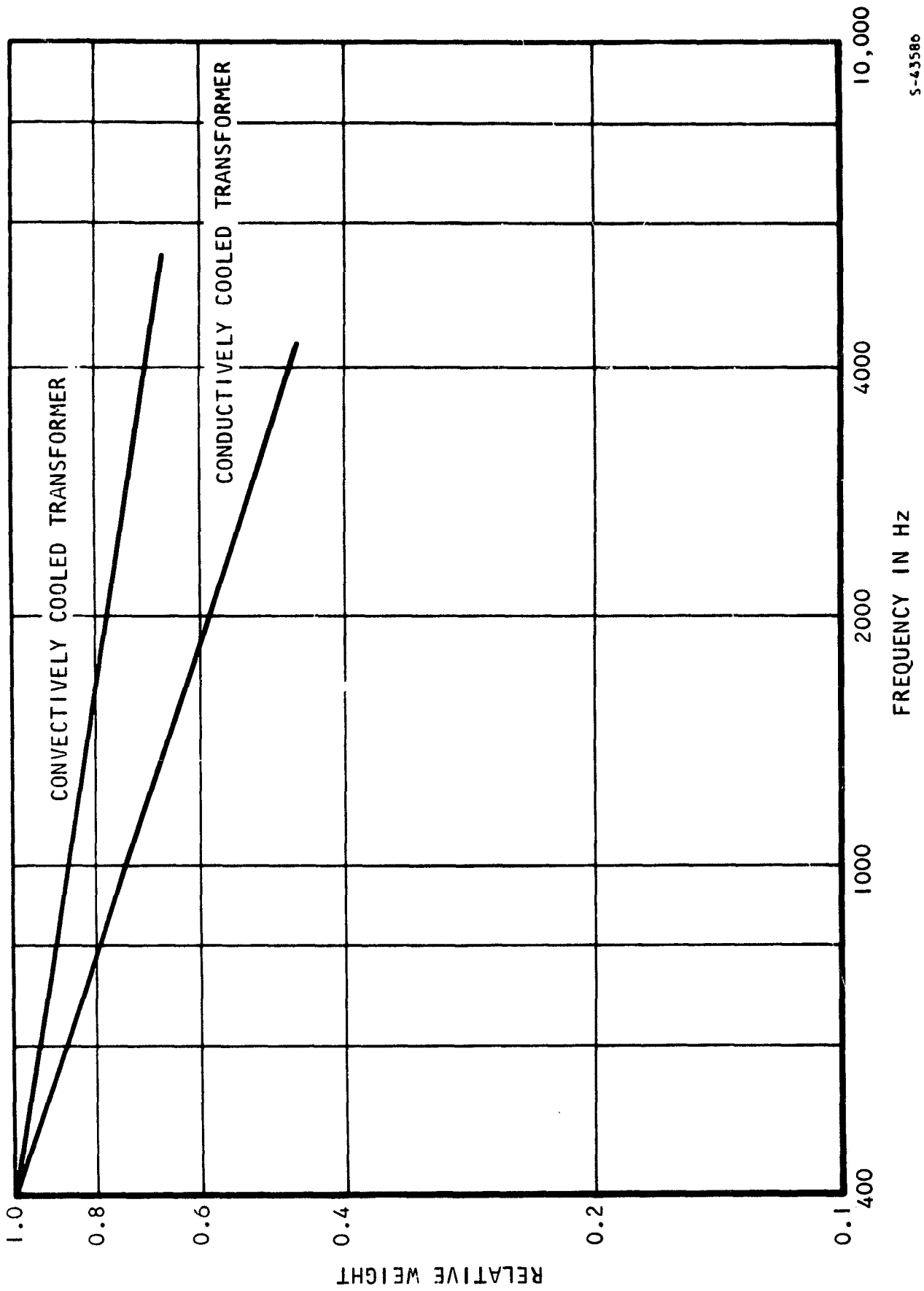




S-43587

Figure 6-4. Average lb/hp versus Synchronous rpm, Aircraft AC Induction Motors (Silicone Steel Lamination), 400 Hz, 115 v/phase





S-43586

Figure 6-5. Relative Weight of Transformers (Silicone Steel Lamination) as a Function of Frequency

Wild Frequency Motors

There is considerable incentive to use a main power supply that would generate wild frequency power. Such a supply would eliminate the constant speed drive used on the present systems. This would result in better maintainability and a higher reliability. If the alternators generate wild frequency, some of the output power would require conditioning to a constant frequency to supply those loads, primarily in the electronics equipment category, that can only operate properly on constant frequency power. The remaining loads, which represent the majority of the power requirement, could operate satisfactorily on wild frequency power. For some of the loads, such as the fuel pumps, wild frequency power in which the frequency varies with the engine rpm would be desirable. Figure 6-6 shows that the fuel requirements vary approximately as the cube of the engine rpm. If the alternators provide wild frequency output, the heating, lighting, rectifier, and other loads would require a constant voltage input. On the other hand, the motor loads could operate properly with either a constant voltage or a constant volts per cycle input power.

This section compares the weight of wild frequency motors of both the constant voltage and the constant volts per cycle type with the weight of motors designed to operate with constant frequency, constant voltage power.

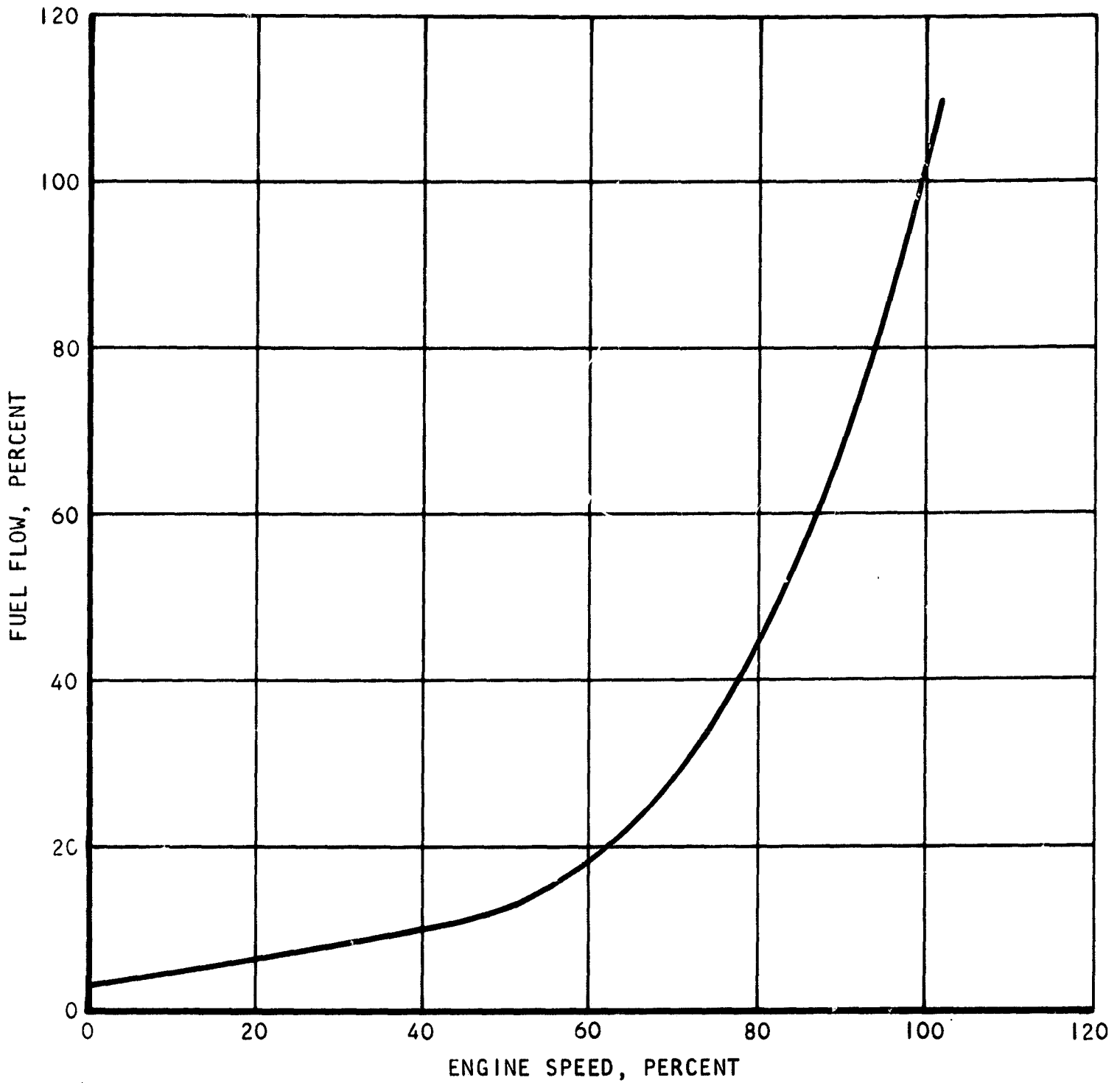
I. Constant Generator Output Voltage

For example, assuming that the frequency variation is two to one, and considering first, the case of constant voltage throughout the frequency range, the flux in the motor at maximum frequency is only half that at minimum frequency. The pullout torque of the motor operated at maximum frequency will only be about 25 percent of the pullout torque of the motor operated at the minimum frequency. Consequently, the weight penalty of the wild frequency motor varies, depending on the type of load the motor drives.

a. Constant horsepower load (a variable displacement hydraulic pump will exhibit the approximate characteristics of a constant horsepower load.)

In this case, the load-torque requirement varies inversely with the speed or frequency. A 400 Hz motor, designed for constant frequency operation, will be an optimum design, with proper electric and magnetic loadings. A wild frequency motor designed for operation from 400 to 800 Hz because of the magnetic flux variation, will be designed with higher magnetic loading and lower electric loading at low speed operation. Let the flux in the constant speed motor be designated as 100%. Normally the pullout torque in this motor is about 200% of the full load torque. If the wild frequency motor is designed with a flux of 60% at high speed and about 120% (neglect saturation) at low speed, the pullout torque at high speed condition is still 145% of the full load torque. The only weight penalty of the wild frequency motor is due to the less favorable distribution between electric and magnetic loadings. From design experience, this penalty would be about 10 to 15 percent. However, if the wild frequency motor is compared with a constant speed motor designed for the higher speed (800 Hz), then the weight penalty will be 45 to 80 percent, depending on the horsepower rating. The penalty is larger for larger horsepower motors.





5-43585

Figure 6-6. Typical Aircraft Engine Fuel Flow Versus Engine Speed



- b. Constant torque load (Fixed displacement hydraulic pumps are an example for such loads).

In this case, the wild frequency motor, under half flux conditions at high speed, needs to put out the same torque as in the low speed condition. The wild frequency motor can tolerate magnetic saturation at low speed operation because the horsepower rating is lower at low speed. If the constant speed motor needs only to supply the horsepower corresponding to the minimum speed condition, the weight penalty of the wild frequency motor will be in the range of 60% (for small motors) to 100% (for large motors). If the constant speed motor (at 400 Hz) has to supply the horsepower corresponding to maximum speed condition, the weight penalty will be only about 30%.

- c. Loads where torque varies as the speed squared (fans, blowers, and centrifugal pumps).

In this case, the horsepower varies as the third power of frequency. The wild frequency motor, with half flux at high speed, has to put out 4 times the torque as at the lowest speed condition. Compared with a constant speed motor rated at the horsepower at minimum speed, the weight of the wild frequency motor will be about 3.5 to 6.0 times the weight of the constant speed motor. If the constant speed motor supplies the maximum horsepower (the load at maximum speed), then the weight of the wild frequency motor will be about 1.8 times the weight of the constant frequency motor.

2. Constant Volts/Cycle Generator Output

If the variable frequency supply is constant volts per cycle, i.e., voltage is proportional to the frequency, there is no weight penalty for the wild frequency motor for the constant horsepower load and constant torque load. The wild frequency motor is actually 35% smaller than the constant frequency motor for the case of constant torque load if the constant frequency motor has to deliver the maximum horsepower at minimum speed.

For the case of load torque varying as speed squared, the weight penalty of the wild frequency motor is about 40% if the constant frequency motor has to put out only minimum power. The weight of the wild frequency motor will be about 15% less if the constant frequency motor has to put out maximum horsepower at minimum speed.

Application to a Typical System

Applying the preceding material on the weight of constant frequency and wild frequency motors to a typical aircraft electric power system, it is possible to tentatively estimate the weights of the utilization equipment in various types of systems. This can be done by breaking the loads into similar types of equipment and then estimating the weights of the equipment for various driving frequencies. A rough estimate of the relative change in the weight of the utilization equipment with a change in frequency is given below.



- 400 Hz constant frequency system (present standard) = 100 percent
- 1000 Hz constant frequency system = 90 percent
- 2000 Hz constant frequency system = 80 percent
- 3000 Hz constant frequency system = 75 percent
- 400 to 800 Hz wild frequency system = 108 percent

Since the utilization system presently represents about 65 percent of the total weight of the electric power system, it can be seen that the potential weight savings from the use of higher frequencies would be a significant portion of the total system weight.

Additional Considerations

Although the preceding material shows that there is incentive to increase the frequency of the electrical system because of the resulting decrease in the weight, there are several additional considerations that may effect the selection of the aircraft frequency. Some of these are as follows:

- Ground equipment - both the servicing equipment and the bench checkout and testing equipment would require redesign or modification if the aircraft frequency were altered
- Redesign cost - extensive analytical and development work would be required before high frequency motor designs comparable to the existing 400 Hz motors could be produced in the quantities and varieties required for advanced aircraft
- Inventory and training - the changeover to a different frequency would increase the parts inventory for the large-scale aircraft operators having several different types of aircraft and would additionally require training of their service personnel.

A detailed analysis of the effects of these and other considerations on the eventual selection of the electrical power system for an advanced aircraft is beyond the scope of this study. However, it would appear worthwhile to investigate the effects on these items also before selecting the operating frequency for each of the aircraft loads.



Work on Electrical Load Analysis for Second Quarter

Remaining work on electrical load analysis, to be done in the second quarter, will include the following:

- Weight, starting performance and other characteristics on gear motors, Rice motors, and brushless d-c motors
- Power quality requirements of electric and electronic loads
- Electrical load classification (vital and non-vital)
- Comparison of hydraulic, pneumatic and electric drives
- Cooling of electric motors (cryogenic) and electronics equipment
- Electromagnetic interference of utilization equipment.



SECTION 7

POWER GENERATION EQUIPMENT

About 15 percent of the planned work on power generation equipment has been completed in this reporting period. The remainder of the work will be done during the second quarter of the study.

The power generation equipment used on today's subsonic transports and that planned for the Boeing Model 2707 supersonic transport will make up about 10 percent of the total weight of the electric power system. Consequently, the areas of major interest in the power generation portion of the system are reliability, cost, and maintainability. In particular, the constant speed drive (CSD) used in the existing aircraft electric power systems limits the reliability, requires a complex overhaul procedure, and has a high initial cost.

An alternate method of performing the same function is to use a variable speed constant frequency (VSCF) system that has become increasingly competitive with the conventional hydraulic constant speed drive. At present, however, the VSCF system is still slightly heavier than the CSD. This disadvantage is compensated for by the higher MTBF (about 50 percent higher) for the VSCF and a better performance with greater installation flexibility.

Generators

If a VSCF cycloconverter system is used, a generator should be a salient pole brushless rotating rectifier machine, based on the information comparing various types of generators given in Table 7-1. The salient pole machine was chosen because of its low weight per output kva and its low internal reactance characteristic which is desirable for cycloconverter loads.

Aircraft in which the generator operates at very high rotational speeds under a severe environment would probably use a solid rotor generator.

The salient pole machine will give a specific weight ratio of 1 kva per lb in the 60 kva rating; this compares with a specific weight ratio of about 0.4 kva per lb on present-day aircraft. Work in the next reporting period will examine the applicability of the salient pole machine for dc-link VSCF systems.

Space-type Energy Sources

A review of the existing space power systems has shown that these systems have energy densities ranging from a few w-hr per lb to 15 w-hr per lb. Some optimistic future estimates of advances in this area indicate that densities as high as 25 w-hr per lb may be obtained. Therefore, space-type power systems will not be suitable as the main electric power source in aircraft in the near future. However, fuel cells may be feasible as an emergency power supply.



TABLE 7-1

COMPARISON OF VARIOUS TYPES OF ALTERNATORS

	WOUND POLE	HOMOPOLAR	LUNDELL SINGLE COIL	LUNDELL RICE	AXIAL AIR GAP - PMG
Maximum Tip Speed Ft/Min	20,000	100,000	35,000	80,000	50,000
Weight Per kva At Constant Speed	Lowest	Highest	High	Low	High, ex- cept in small ratings
Voltage Waveform	Best	Fair	Fair	Good	Fair-Good
Reactance	Lowest	Highest	Medium	Medium	Low
Environ- mental Capability	Poor	Best	Fair	Good	Fair

Chemical Energy Storage

Recent developments in battery research and development programs indicate that battery energy densities compatible with the requirements for the main electric power source may soon be obtainable in production equipment. In particular, the sodium-sulfur battery and the zinc-air battery are both claimed to have densities of up to 150 watts per lb. The zinc-air cell uses a plate of zinc as the anode and air as the cathode. A potassium hydroxide solution is used as the electrolyte. After about 12 hours of operation, the zinc plate is consumed and the battery must have a new zinc plate inserted to restore it to its original power rating.

Table 7-2 compares the energy densities of various types of batteries that will probably be available within the time frame considered by this study. Work for the next reporting period will further investigate the potential of batteries; specifically examining the power conversion requirements, the maintenance and reliability, and the cost of battery usage in the main power supply.



An attractive possibility with a battery-powered generating system is to locate the batteries at several points throughout the aircraft so that much of the distribution system wiring can be eliminated. An additional advantage is that the batteries would not place a demand on the fuel supply as do the present generators. However, these advantages must be traded off against the additional ground servicing that would be needed. This work will be performed during the next reporting period.

TABLE 7-2

COMPARISON OF VARIOUS TYPES OF BATTERIES

	ENERGY DENSITY WATT HR/LB (5-HR DISCHARGE RATE)	TYPE
Lead Acid	10	Secondary cell
Nickel Cadmium	14	Secondary cell
Silver Cadmium	24	Secondary cell
Silver Zinc	50	Secondary cell
Sodium Sulfur	150	Secondary cell
Zinc - Air cell	150	Primary cell

Comparison of Generating Systems

A brief summary of the advantages and disadvantages of the four most feasible generating systems is as follows:

1. Conventional 400 Hz CSD constant frequency system

Advantages: Well developed, off-the-shelf components
Moderate initial cost

Disadvantage: High maintenance cost of CSD unit

2. Variable Frequency System

Advantages: Elimination of CSD
Increased reliability
Higher speed generator



Disadvantages: Problems in paralleling
Beat frequency generation
Increased feeder losses
Undesirable motor operation
Heavier generators
Requires constant frequency converter

3. Constant Frequency System of Higher Frequency

Advantages: Lighter utilization equipment weight
Lighter generators

Disadvantages: Increased feeder losses
Cooling penalties because of smaller equipment size

4. D.C. System

Advantages: Elimination of CSD
Higher speed generator adaptable
Minimum feeder weight
Lightweight voltage transformer (chopper)
Simpler parallel operation

Disadvantages: Heavier motors
Some power conversion to AC is necessary
Heavier switchgear



SECTION 8

WORK TO BE PERFORMED IN NEXT REPORTING PERIOD

The initial tasks to be performed in the second quarter of this study will be the completion of the electrical load analysis and the power generating equipment investigation. Methods of power conditioning and conversion will be examined and completed during this period as well.

The studies on means of distributing the power and of energy management will be commenced, although not completed until the start of the third quarter. The necessary data on components for system synthesis will be about completed at the end of the seventh month; this will then allow the systems study to be started.

Additional visits to airframe and aircraft component manufacturers as well as to an airline company are also planned in the second quarter.



APPENDIX A
LITERATURE SURVEY
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APPENDIX B

BOEING MODEL 2707 ELECTRICAL POWER SYSTEM

This appendix contains a summary of the electrical power system Boeing proposes to use for their Model 2707 aircraft. The information was obtained from Boeing Company on a visit by Garrett personnel on June 18, 1968. The meeting consisted of a question and answer session in which the questions had been earlier provided to Boeing. All of the figures and tables contained in this appendix are identical to or modifications of artwork supplied by Boeing to Garrett.

QUESTION

ANSWER

Loads

- | | |
|---|---|
| 1. Load analysis, AC, DC load profile | See Tables B-1 and B-2, and Figures B-1 and B-2. |
| 2. Priority loads, standby loads, emergency loads | See Figure B-3 and Tables B-3 and B-4. |
| 3. Dispatch philosophy | One generator out |
| 4. Load characteristic, what is largest motor load, is load interlock used? duty cycle? | Largest motor is 10 kva for hydraulic pump to check out ground operation. In-flight largest motor loads are 8 electric fuel pumps each rated 7.3 kva continuous on. No interlock is provided. Total number of fuel pumps (smaller units) is about 30. |
| 5. What types of loads are restricted to 400 Hz at the present time? | Electronic, avionic loads. Most equipment, because of availability. |
| 6. Location of major power consumption. | AC primarily fuel pumps and galleys. DC mainly electronics. |
| 7. Power quality sensitive loads | Uninterrupted power necessary for computers, avionics, and instrumentation. |
| 8. Optimization aspects between hydraulic and electric loads | Hydraulic is preferred for short peak demands of power. This is in general a typical tradeoff study. |

Generation

- | | |
|---------------------------------|--|
| 1. Engine speed range available | 10,000 to 20,000 rpm |
| 2. Generating capacity | Nominally 4 x 60 kva, see Table B-5 for channel ratings. |



TABLE B-1

MODEL 2707 AC LOAD ANALYSIS
LOADS IN KVA

Item	Conn Load	Engine Start	Taxi	Takeoff and Climb	Super-Sonic Cruise	Sub-Sonic Cruise	Holding Pattern and Landing	Roll-out	Taxi
Lighting	25.2	13.3	14.2	15.0	13.0	14.0	15.9	15.9	14.0
Electronics	7.3	3.5	3.6	4.0	4.0	3.0	2.9	2.9	3.5
Trans/Rect Unit	6.4	1.3	2.0	2.1	2.6	2.4	2.1	2.1	2.1
MUX, El, Throttle, Misc	9.5	7.7	6.5	7.1	7.1	6.7	6.5	6.5	6.5
Lavatories	5.2	0.2	0.2	0.2	2.2	2.2	0.4	0.4	0.4
Elec. Equip,									
Racks and ADS Cool	14.3	14.3	14.3	14.3	-	-	14.3	14.3	14.3
Brake Cool	16.0	16.0	-	-	-	-	-	-	-
Windshield Heat	7.7	-	5.8	5.8	-	-	5.8	5.8	5.8
Fuel Pumps	135.6	20.0	50.4	51.2	68.0	51.2	40.0	40.0	40.0
Galleys	20.4	20.0	20.0	20.0	20.0	20.0	5.0	5.0	5.0
Demand on Pwr Sys (kva)	-	92.3	112.4	116.2	112.0	98.1	91.7	91.7	98.2

Sum of connected Loads - 243 kva

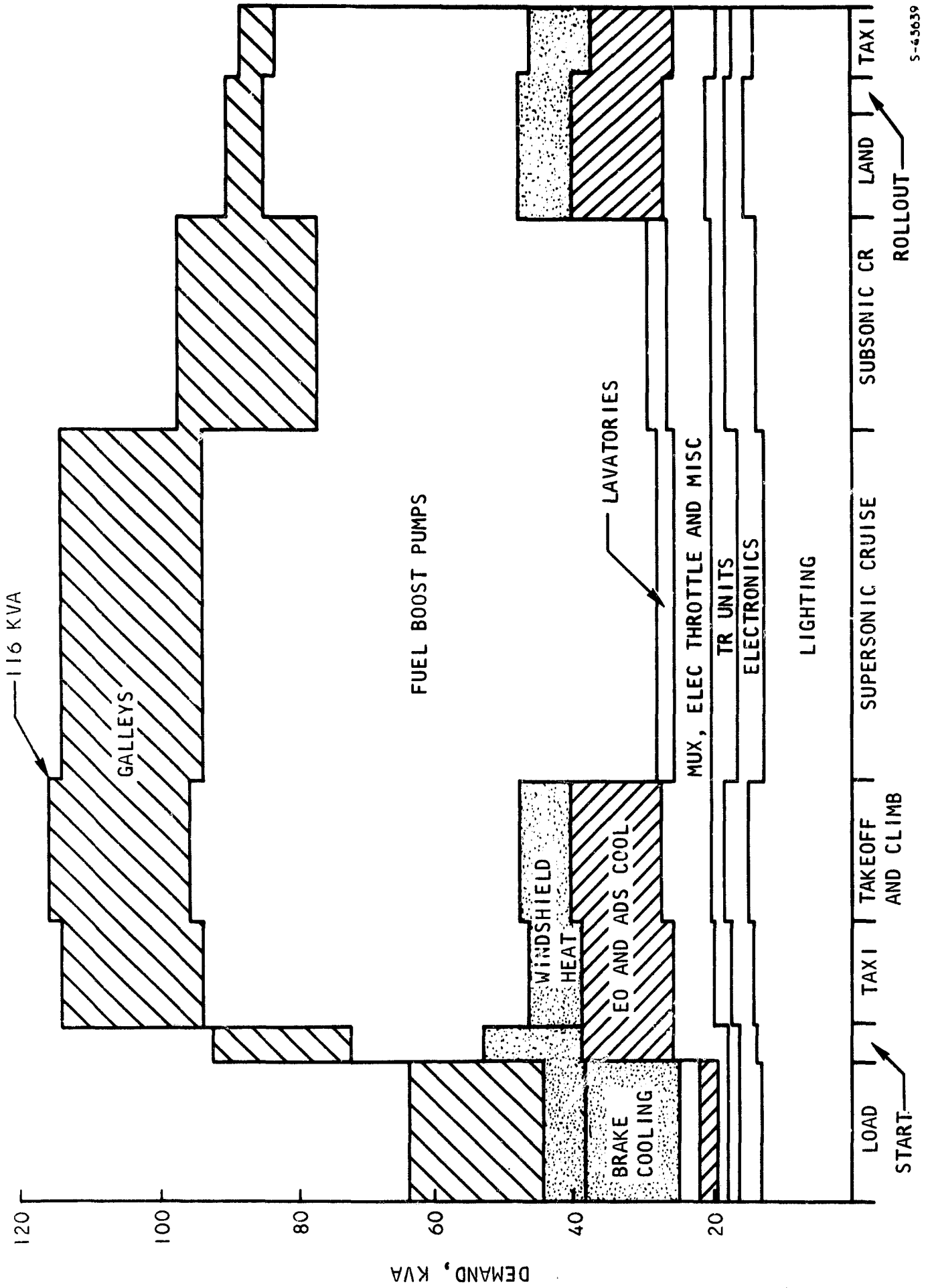


TABLE B-2

MODEL 2707 DC LOAD ANALYSIS

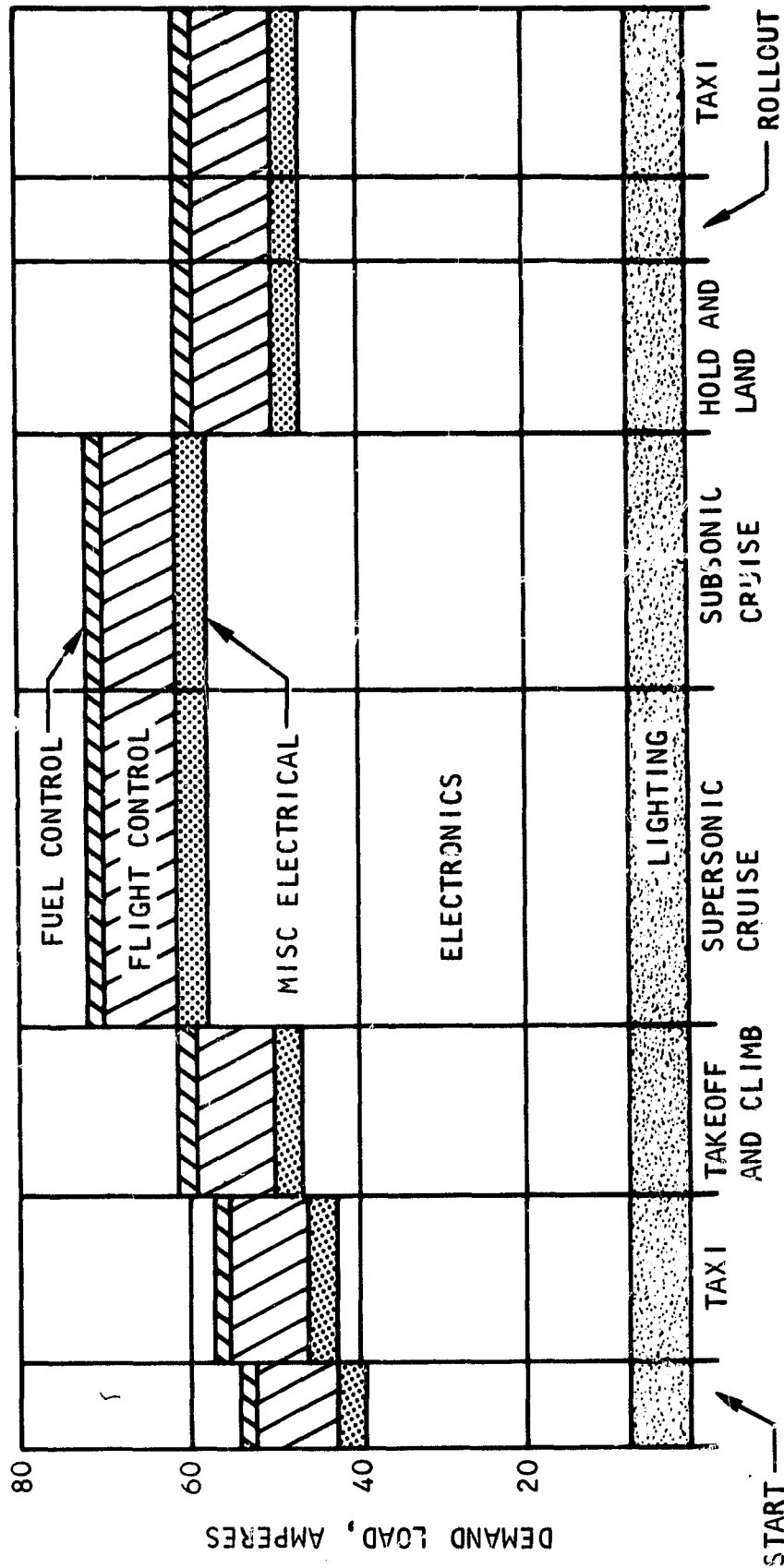
Item	LOAD IN AMPERES									
	Conn Load	Start	Taxi	Takeoff and Climb	Super-sonic Cruise	Sub-sonic Cruise	Hold and Land	Roll-out	Taxi	
Lighting	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
Electronics	90.6	31.4	34.3	38.6	49.3	49.3	38.5	38.5	38.5	38.5
Misc	3.6	3.6	3.8	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Flight Control	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Fuel Indication	58.2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Totals	170.2	54.3	57.2	61.5	72.2	72.2	61.4	61.4	61.4	61.4





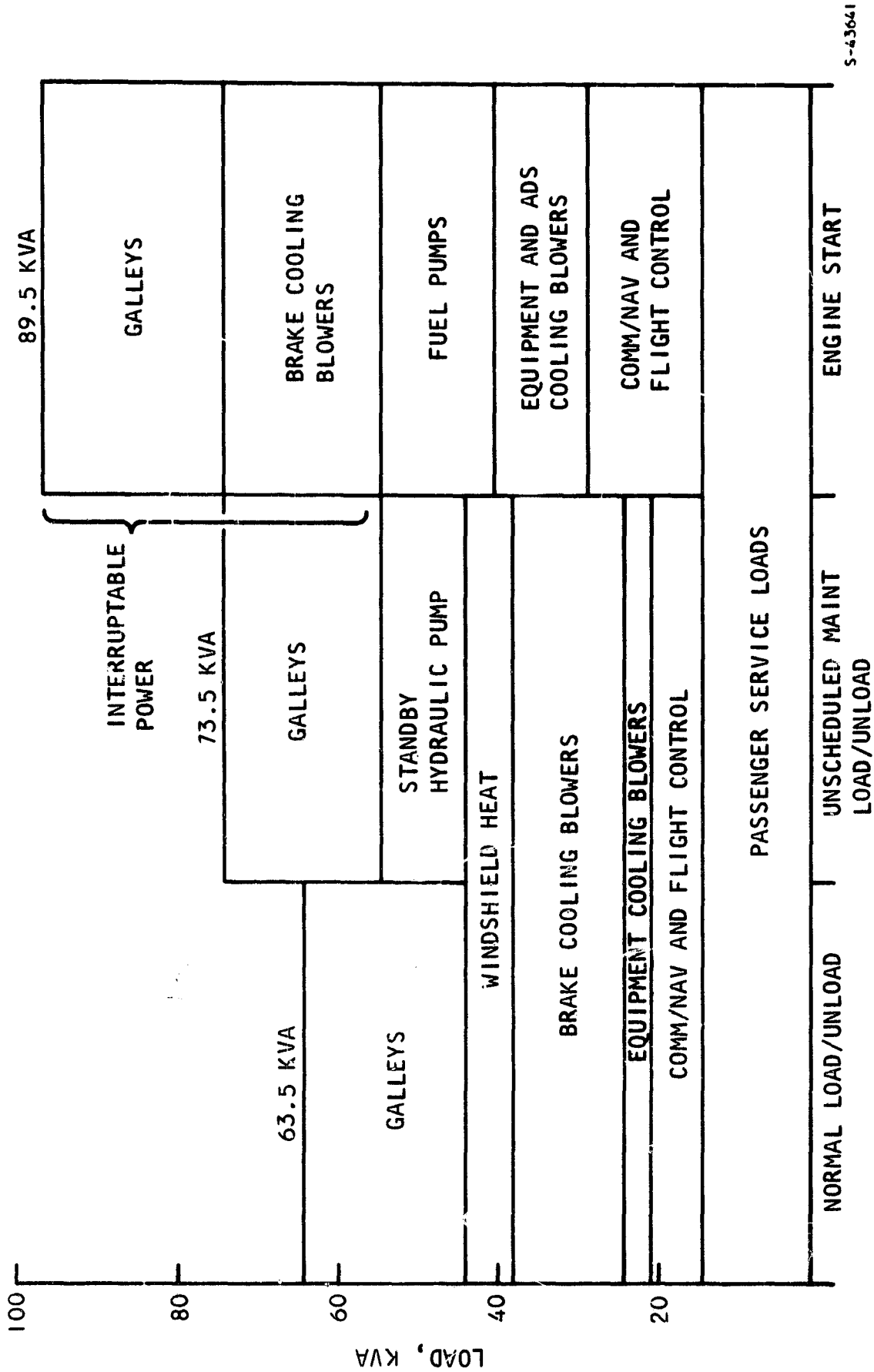
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Figure B-1. Model 2707 AC L ad Profile



S-43660

Figure B-2. Model 2707 DC Load Profile



S-43641

Figure B-3. Model 2707 Ground Power Loads

TABLE B-3

MODEL 2707 STANDBY POWER LOADS

Load	Battery Amperes
Emergency Lighting	4.0
Electronics	6.0
Flight Instrumentation	4.5
Flight Control	7.7
Flight Safety	2.0
DC/AC Inverters	92.0
30-Min Load	116.2



TABLE B-4

STANDBY POWER SYSTEM INVERTER LOADS

Load	Output Volt-Amps
Electronics	310
Flight Instrumentation	285
Flight Control	1,205
Total Output	1,800 va at 0.96 PF

Inverter input at 26 vdc 75% eff - 92 amps



TABLE B-5

MODEL 2707 VSCF CHANNEL RATING

CHANNEL RATING	10,000 to 15,000 rpm	15,000 to 20,000 rpm
Continuous	80 kva	75 kva
10 Minute	75 kva	75 kva
5 Minute	90 kva	90 kva
1 per unit-Base Rating -- 60 kva		



- | | | |
|----|---|--|
| 3. | Source redundancy | Split parallel |
| 4. | Emergency supply | By windmilling the engines, approx. 3 kva emergency power can be obtained from each VSCF channel by special programming the cycloconverter to provide DC output in addition to the airplane battery. |
| 5. | Peculiar VSCF generating characteristic | No peculiarities. Boeing seems happy with GE VSCF. Learverter is also in strong consideration for production type. |

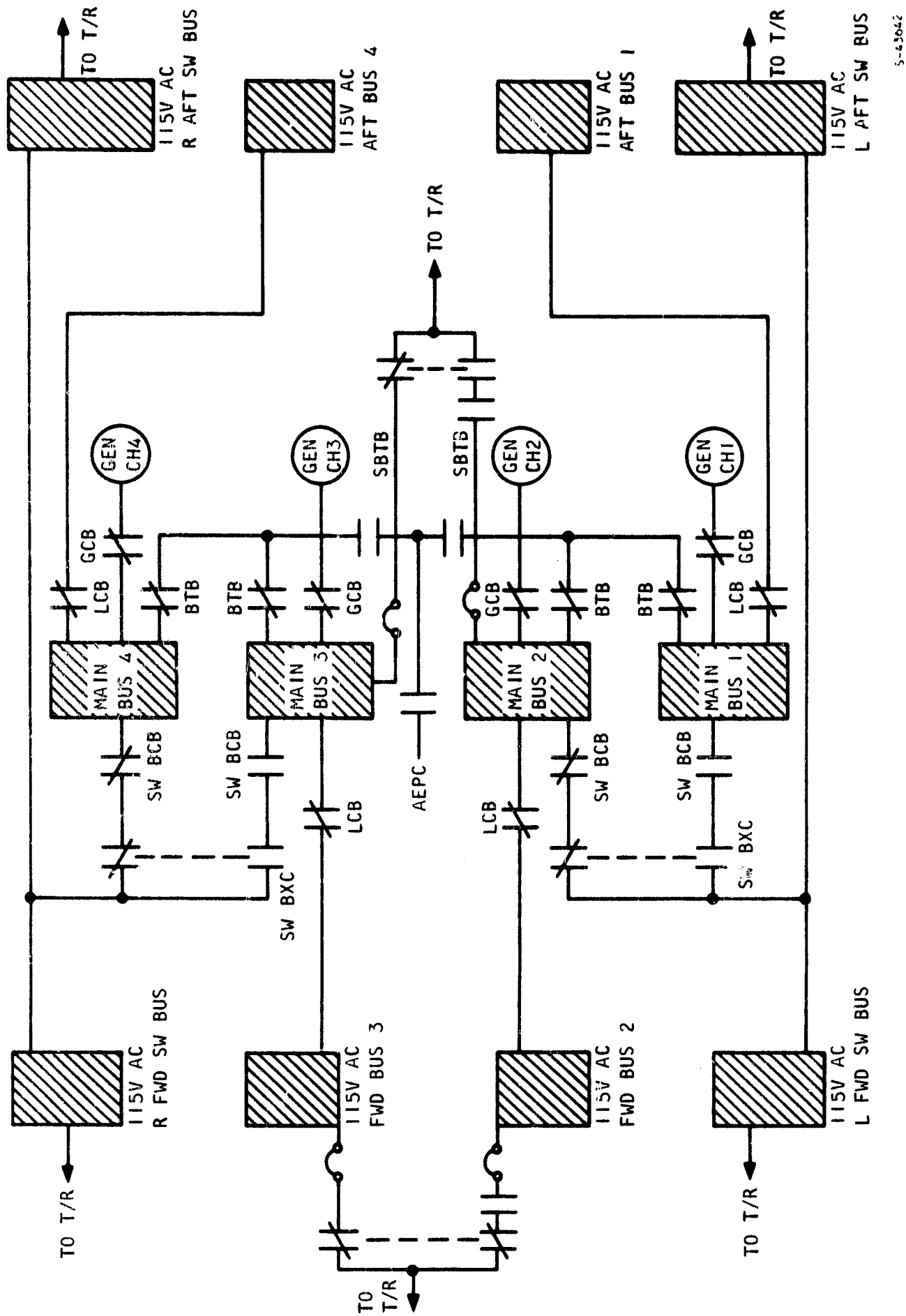
Distribution

- | | | |
|----|---|--|
| 1. | Feeder length | 45 feet outboard run, 25 inboard. 215 feet main distribution to forward distribution center. |
| 2. | Installation configuration | High frequency special feeder cable to cycloconverter. Distribution tree wire equidistant laced group, grounded neutral. |
| 3. | Main distribution center | See Figure B-4 |
| 4. | Source bus, load bus, emergency bus configuration, switching schemes. | See Figure B-4 |
| 5. | Total AC, DC distribution weight | Not yet known estimated to be between 3000 and 6000 lb, depending on extent of multiplexing. |

System

- | | | |
|----|---|--|
| 1. | System voltage, system grounding | Conventional |
| 2. | Protection, protection coordination, system stability | Conventional, no drastic change expected |
| 3. | Annunciation requirements | Boeing announces most abnormalities (such as UV, OV, DP, OF, UF) to the flight engineer. |
| 4. | Anticipated extent of multiplexing (MUX) | Not yet known, Boeing sees no advantage in central MUX. |
| 5. | Extent of power conversion, TR units, inverters | 6 50A TR units, inverters to provide 1.8 kva for emergency. |





5-43042

Figure B-4. Model 2707 AC Power Distribution Schematic



Environment

1. Heat profile, altitude, speed, flight time, uncontrolled, controlled equipment location
Provided by charts. Approx. 40% of electrical equipment in pressurized area, 60% unpressurized.
2. Heat transfer media, heat exchanger, weight penalties
Fuel is not used as heat sink, equipment is cooled by cabin exhaust. Engine environment -40 to 650F, hot spots to 1000F
3. Vibration
See Boeing Spec.
4. Reliability
One VSCF generating channel:

GE predicted	7390 hr MTBF with controls
Boeing calculated	6300 with controls
Sundstrand IDG	5494 with controls
Boeing	4230 with controls
5. Maintainability
Module replacement wherever possible
6. Economics
A rather complex derivation was given leading to an approximate assumption that one pound of weight is equivalent to \$300.



APPENDIX C
NORTH AMERICAN ROCKWELL
XB-70 ELECTRICAL POWER SYSTEM

The information on the XB-70 electrical power system was obtained from North American Rockwell personnel during meetings with Garrett personnel on June 19 and June 21, 1968.

The XB-70 generating system primary power source originally was two 60 kva generators (oil-cooled, nitrogen pressurized with built-in PMG) operating at 8000 rpm. The generators are driven by constant speed drives from the number 3 and 4 engines. The generator output is 240/416 vac. This high voltage (in comparison to the usual aircraft voltage of 120/208 vac) was adopted because it weighs 400 lb less than an equivalent standard voltage system. Normally both generators operate in parallel. The generator output is stepped down to the standard level (120/208 vac) by 3 autotransformers (one for ground power input). Voltage regulation in steady state is ± 0.1 percent.

This primary power source was later modified by installing an additional 60 kva generator on engine number 2. This was added as a safety measure since this channel is capable of being paralleled momentarily with ground power to prevent power interruption to sensitive loads.

A 10 kva hydraulic-driven emergency generator (120/208 vac) feeds the essential bus. The peak ac load occurs during takeoff and climb and is about 78 kva. The largest single load is a 15 kva motor driving a recirculation fan used for equipment cooling.

The distribution system uses 3 No. 8 wires for high voltage feeders. This wiring is 125 ft in length with a teflon-lined conduit having a special safety lining for extra protection. The total wiring is about 150 miles in length.

The protection system uses conventional, differential protection for the generators and feeders with thermal and overcurrent protection provided for the transformers and distribution system. The protection philosophy was aimed primarily at protecting the wiring with little concern about the equipment. For a short circuit case, the source makes three separate attempts to clear a specific fault (load bus). If these attempts fail, the faulted section will be isolated.

The operating environment for the electrical equipment is up to 550°F for a 3-phase motor, 550°F for the generators, and 350°F for the generator feeders.

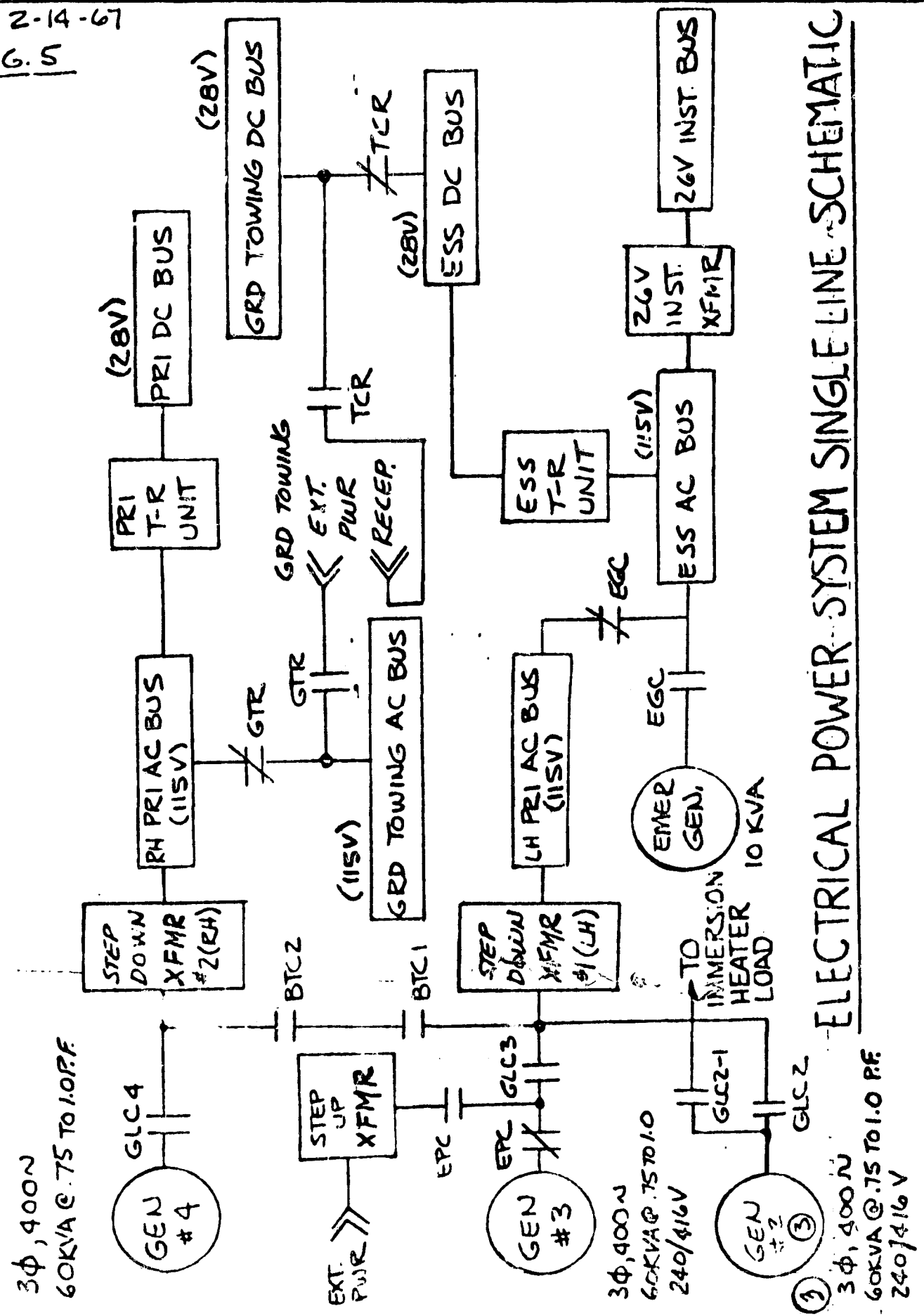
The total operating time for the XB-70 electrical power system is 210 hr (140 hr on No. 1 aircraft, and 70 hr on No. 2).

Figure C-1 shows a schematic of the XB-70 electric power system.



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CHECKED BY:	BLOCK DIAGRAM-XB-70	REPORT NO. LA0203-025K
DATE: 5 FEB 1962	GENERATING & DISTRIBUTION SYS.	MODEL NO. XB-70A

Φ 2-14-67
 FIG. 5



ELECTRICAL POWER SYSTEM SINGLE LINE SCHEMATIC

182-F-4 (FORMERLY RD-118)