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Sixth Quarterly Progress Report

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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(6)

January 23, 1970

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GARRETT

AIRESEARCH MANUFACTURING DIVISION
Los Angeles, California

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SECTION I

INTRODUCTION AND SUMMARY

This is the sixth quarterly progress report on a study entitled "Investigation and Development of New Concepts for Improvement of Aircraft Electrical Power Systems" funded by NASA Electronics Research Center, Cambridge, Massachusetts, Contract No. NAS12-659. Work under this contract was initiated on May 14, 1968 and will last to July 14, 1970 with a total effort of approximately four and three-quarter man-years.

Objective and Method of Approach

The study objective is to formulate a philosophy for devising optimum electrical power systems for advanced aircraft. The philosophy recommended will consider improvements in reliability, safety, weight, size, and other factors that would result in increased revenue for transport aircraft; it will apply and extend advances in space power technology and related fields to aircraft electrical power systems. This study will review the entire aircraft electrical power system, including generation, conversion, distribution, and utilization equipment, in accordance with the above objective, independent of traditional 400-Hz aircraft power technology.

Obtaining aircraft economy and reliability are complicated and involved tasks. The following factors have been considered in the search for improvements in the aircraft electrical systems:

(1) Simplicity--A simpler system will be more reliable and more economical

(2) Automation--Additional automation will facilitate system manageability and increase aircraft safety

(3) Weight--A reduction in the weight of the electrical system will increase revenue. For example, consider a typical large subsonic aircraft with payload capacity of 43,000 lb and electrical system weight of 11,000 lb. A 30-percent reduction in electrical system weight will increase the payload capacity appreciably by 8 percent.

(4) Protection--Better system protection will increase system safety

(5) Information display--Better information display will also increase system safety

(6) Fault prediction, detection, and isolation--These will reduce maintenance cost and increase reliability

(7) Performance--Improved performance will result in higher efficiency and increased system capability

(8) Components--Use of better components will result in higher system reliability and less maintenance

The present aircraft electrical system (115/200-V, 3-phase, 400 Hz constant frequency ac) was developed about 25 years ago. This system concept was based on the relatively small aircraft needs at that time. Many of the future aircraft will be much larger in size and will demand much more electrical power, part of which must be at very precise quality. Future advanced aircraft operating at progressively greater speeds and higher altitudes will, of course, involve environmental conditions markedly different from those of 25 years ago. Recent technical advances may also outdate some of the equipment and concepts presently used in aircraft. This study therefore is advisable to determine whether the long established electrical system configuration is still suitable for use in the future advanced aircraft.

The study is oriented primarily toward the relative merits of various power system concepts. To accomplish this it is necessary to establish the approximate performance capabilities of the individual components so that they can be used collectively to indicate system performance. Consequently, the performance data in this report are representative rather than detailed component performance predictions.

The study information has been divided into three categories:

(1) Equipment in use whose performance primarily reflects technology existing at the time of its design (present large subsonic transports were designed in the late 1950's; small subsonic transports in the early 1960's)

(2) Equipment that can be designed with current technology and has not yet been used in aircraft

(3) Equipment that can be predicted with technology anticipated for 1980 to 1985

Meaningful presentation of information from this study requires that anticipated component performance data be applied to the various system configurations to arrive at relative system performance. A baseline system configuration typical of existing large subsonic aircraft will be used as a reference point with which to compare the candidate systems.

The anticipated output of this study program will be the documentation of a philosophy for devising optimum aircraft electrical systems and the selection and description of candidate configurations for future aircraft electrical power systems. The performance (weight, reliability, size, maintainability, safety, etc.) of the candidate systems will be compared. In addition, significant technological problems applicable to selection of the most promising candidate system will be discussed.

Scope of Investigation

The scope of investigation is defined by the following study tasks·

(1) Conduct an industry and literature survey on present day practice and state of the art in aircraft electric power generation, transformation, distribution, and utilization including present and projected electric loads on aircraft.

(2) Optimize the methods to supply electric power to the various loads to suit their inherent functional mechanism.

(3) Compile the necessary parametric information for the power system components on physical size, weight, and performance for the given power levels vs power system configuration, voltage, and frequency. This information will be based on the present state of the art of system component technology.

(4) Investigate application of new materials such as exotic magnetic materials, new insulation materials, unconventional conductor materials, etc., for critical electrical system components.

(5) Investigate new system component concepts for application to aircraft with respect to the objectives of this program.

(6) Review and analyze the preferable power system heat transfer technique.

(7) Specify the techniques and displays required for the acquisition and characterization of the electric power system, such as: failure prediction; detection and compensation; efficient energy management; and data monitoring.

(8) Investigate power system component reliability and its tradeoff against component cost and weight.

(9) Investigate component maintainability and its tradeoff against component cost and weight.

(10) Survey and determine the static and dynamic power requirements for present hydraulic and pneumatic powered loads, and establish the trade-off criteria in the selection and application of electric or combined electric-hydraulic and electric-pneumatic power subsystems for that purpose.

(11) Determine the relative weight of factors that determine the effectiveness of the electric power system with respect to program objectives.

(12) Formulate an electric power system design philosophy consistent with the above objectives.

(13) Devise and analyze power system candidates including system design and optimization concepts, provide complete power system diagrams and descriptions.

(14) Identify significant research and technology problems associated with achieving the most promising candidate electric power systems.

Progress To Date

First year work.--During the first year, existing literature was surveyed to establish the state of the art and trends in system design. A bibliography on aircraft electrical power systems and components was compiled. Trips were made to major aircraft manufacturerers, users, hardware suppliers, and government agencies to obtain data and operating experience on the electric power systems of existing and planned aircraft. These data were needed to establish configuration and design requirements and to evaluate typical current electrical power systems.

Over 60 people in responsible positions in various organizations were visited, all having considerable experience and background in the engineering discipline of aircraft electrical systems. Generally, persons contacted recognized the need for and timing of the study, and appreciated the farsightedness of NASA in initiating such a program. Hope was expressed that the result of this program should be fruitful and beneficial to the aircraft electrical industry.

The following activities were performed during the first year:

(1) The work on electrical load analysis began with (1) classification of the electrical loads, and (2) a weight analysis of the constant and wild frequency ac motors and brushless dc motors. The parametric data of aircraft utilization components were divided into groups of (1) components in existing aircraft, (2) current technology components to be applied to aircraft, and (3) components with future technology. The utilization weights were compared as a function of system frequency (including dc).

(2) In the area of power distribution, design considerations on safety, corona, voltage, and frequency levels were investigated. Characteristics and performance data on cables, relays, circuit breakers, contactors, and transformer-rectifier units were collected. Data for voltage and frequency effects on wiring weight were prepared.

(3) Power conversion techniques were considered and compared. Parametric weight data were obtained for the various possible techniques. Selection of an optimum conversion system cannot be made without system optimization since the conversion equipment used is dependent upon the load location and type and the generating equipment output.

(4) Possible methods of generating electric power were examined. The established existing generation system is the constant speed, constant frequency (CSCF) system. Current technology systems under development are variable speed, constant frequency (VSCF); rotating inverter (which uses two rotating machines to provide the required power); and high-voltage dc systems. Analysis indicates that the more advanced generating concepts offer performance advantages over the present CSCF systems while still remaining weight competitive. The cycloconverter VSCF system, tentatively selected for use on the SST, appears to be particularly attractive; another possibility is the Learverter system, although information on it is limited. Parametric information on emergency power sources was also collected.

(5) Design criteria and performance capabilities of both the hydraulic and pneumatic systems were surveyed because so many aircraft loads are presently serviced by hydraulic or pneumatic power. The survey indicated that the major hydraulic loads are flight controls, landing gear, brakes, and thrust reversers. It also indicated that for reasonable distances between the power source and the load, a hydraulic system can provide the load power for a lower weight than can the electric system.

(6) System control and protection methods in existing aircraft were reviewed and various protection schemes for single and parallel system operations were analyzed.

(7) Present techniques of cooling aircraft electrical components and heat transfer systems were studied; possible improvements in heat transfer methods utilizing state-of-the-art technology were considered.

(8) The objectives and criteria of aircraft electrical system reliability were outlined, and the level of reliability currently achieved by various aircraft components and subsystem was tabulated.

Fifth quarter work.--Study of optimum methods for supplying electric power to the loads was begun in this quarter. Graphical methods of optimizing electric drives for axial flow fans and centrifugal compressors was established. The possibility of applying new materials for aircraft electrical power components were investigated. Trade offs between component reliability and weight were studied. Specific weight penalties resulting from improvements in reliability for some components were determined. Trips were made to visit General Electric and Westinghouse to obtain their views on aircraft electrical power systems.

Sixth quarter work.--The study on optimum methods of applying electric power to loads was concluded in this quarter. The loads considered were electric drives for hydraulic pumps and secondary flight controls, electronic loads, lighting loads, and thermoelectric refrigeration loads.

The three types of actuation systems--hydraulic, pneumatic, and electric--are further compared; the dynamic capability of each system is briefly discussed in this report. Some of the component characteristics of the various systems are investigated since the development of components directly affects system capability.

The factors which affect the maintenance cost are presented. Maintainability prediction and demonstration techniques are discussed with maintainability design steps to be taken during the design and development period. For the electrical equipment, possible trade-off areas between maintainability and cost and weight are investigated and illustrated.

An approach to define relative weighted factors that determine system effectiveness also is presented in this report, as well as the aircraft electrical equipment weight criteria. More work on system optimization techniques will be performed during the next reporting period.

The advantages of using failure prediction and detection for electrical equipment are presented. The failure mode of the system components and the possible techniques of detecting and predicting these failures are evaluated. Different types of recording systems, display techniques, and sensors are also briefly discussed.

WORK PLAN FOR THE NEXT REPORTING PERIOD

The work for the next reporting period will include the following:

(1) Continue the task of determining the relative weight of factors that determine electric power system effectiveness with respect to program objectives.

(2) Investigate new system component concepts for application to aircraft with respect to the objectives of this program.

(3) Select conceptual electrical power candidate systems for future aircraft application.

(4) Formulate an electric power system design philosophy consistent with program objectives.

SECTION 2

INDUSTRY SURVEY

Visit to Sundstrand Corporation, Rockford, Illinois
(May 16, 1969)

A meeting was arranged with Sundstrand in Rockford, Illinois to obtain first-hand, updated information on recent development improvement in their hydraulic constant-speed-drive product line.

Background.--Sundstrand is recognized as one of the main contributing pioneers in the development and evolution of aircraft electrical ac constant frequency systems. The need for obtaining ac constant frequency on aircraft spurred the development of constant speed drives to the extent that significant improvements have been made during the past two decades. Drive specific weights have been reduced and drive reliability improved drastically. The most remarkable improvement, the integral drive generator (IDG) concept, however, did not occur until fairly recently, when parallel development effort for the solid-state electrical power conversion and the variable-speed constant frequency approach (VSCF) gained momentum.

Status.--The Sundstrand integral drive generator is a service-proven axial geared differential (AGD) unit built into the same housing with a newly developed generator. The IDG resulted from a combined effort by several generator manufacturers with Sundstrand. The weight reduction was achieved by integrating the two units and by adopting a new oil spray cooling system for the generator.

The system weights and overall dimensions given by Sundstrand are listed in table 2-1. Sundstrand projected unit reliability figures are 20,000 hr for the CSP portion and 30,000 hr for the generator. The resultant IDG package reliability therefore will be a 12,000 hr MTBF. The IDG time-between-overhaul (TBO) is on condition. The 60-kVA IDG generator weighs less than 45 lb (generator operates at 12,000 rpm). This yields a specific weight of less than

TABLE 2-1

SYSTEM WEIGHTS AND DIMENSIONS

Rating, kW	Weight, lb	Length, in.	Diameter in.
60	107	20.5	11
90	144	22.8	11.2
120	190	26.1	12.4

3/4 lb/kVA. Sundstrand predicts that its competitor (VSCF system supplier) will not be able to reduce the generating equipment weight beyond the IDG weight. A variable speed generator is required to provide full rated output (including overload) at the low speed end, which is presently about 10,000 rpm. Therefore, it has to be of heavier design. Also, the weight advantage of saving a bearing and an end bell as done for the IDG is not likely to be applied for the VSCF generator.

Sundstrand deemphasizes the significant influence of power quality, the area in which the VSCF system has demonstrated superior characteristics (particularly dynamic response) over the constant speed scheme. Sundstrand did not agree that the closer tolerance and better quality power produced by the VSCF system compensates well for slightly heavier generating equipment when considering the weight saving on an overall system basis. Some significant figures, such as drive efficiency, were not revealed, but they will be furnished at a later date. The data has not yet been received.

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SECTION 3

OPTIMUM SUPPLY TO AIRCRAFT ELECTRICALLY OPERATED EQUIPMENT

In the fifth quarterly progress report, design and performances predictions for fans and blowers were investigated. To complete the load group "mechanical motion", two more motor loads should be investigated, which are hydraulic pumps and actuators.

Hydraulic Pumps

Centrifugal versus 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 3-1.

Weight comparison: A weight comparison of centrifugal and reciprocating hydraulic pumps of optimum design is shown in fig. 3-1 as a function of flow-capacity at a 3000-psi design pressure. Typically, a 20-lb saving, or 36 percent of the total weight, can be achieved if a 100-gpm, 3000-psi centrifugal pump weighing 36 lb is used instead of a 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. 3-2 gives a comparison of efficiency for centrifugal pumps and reciprocating pumps plotted as a function of flow capacity. Fig. 3-3 shows a comparison of pump input power for centrifugal pumps and reciprocating pumps as a function of flow capacity for a 3000-psi system. The somewhat higher power required by the centrifugal pump reflects the lower efficiency.

TABLE 3-1

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

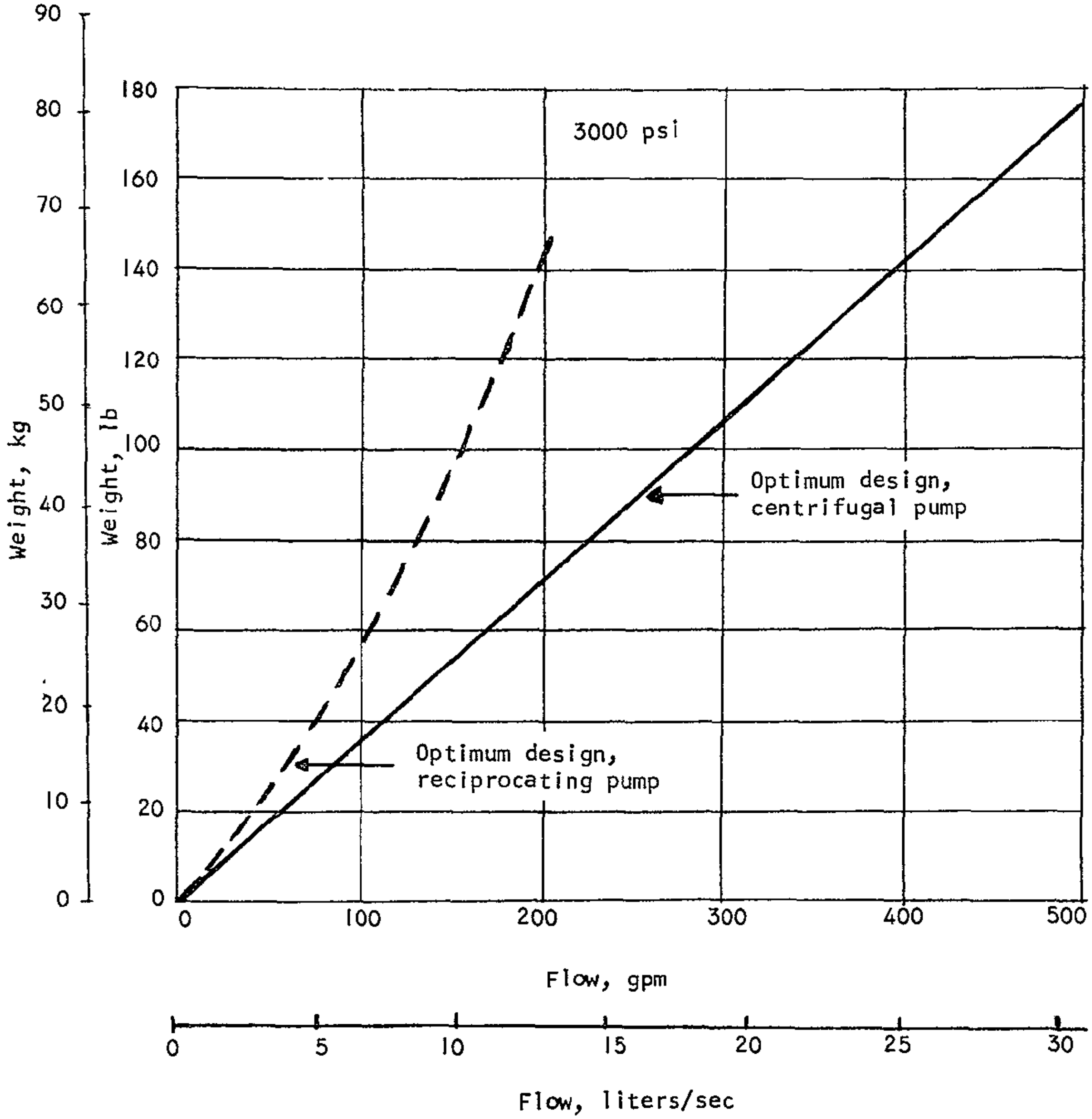


Figure 3-1. Weight Comparison, Centrifugal Pump vs Reciprocating Pump

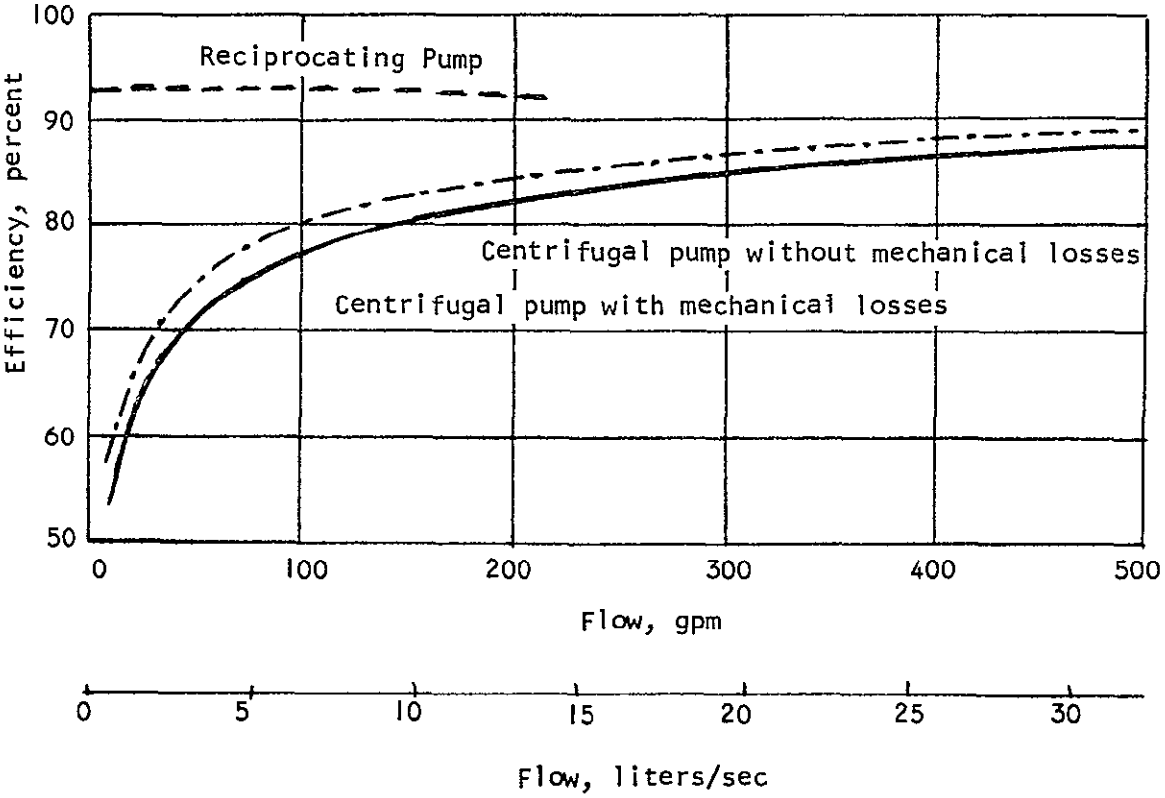


Figure 3-2. Efficiency Comparison, Centrifugal Pump vs Reciprocating Pump

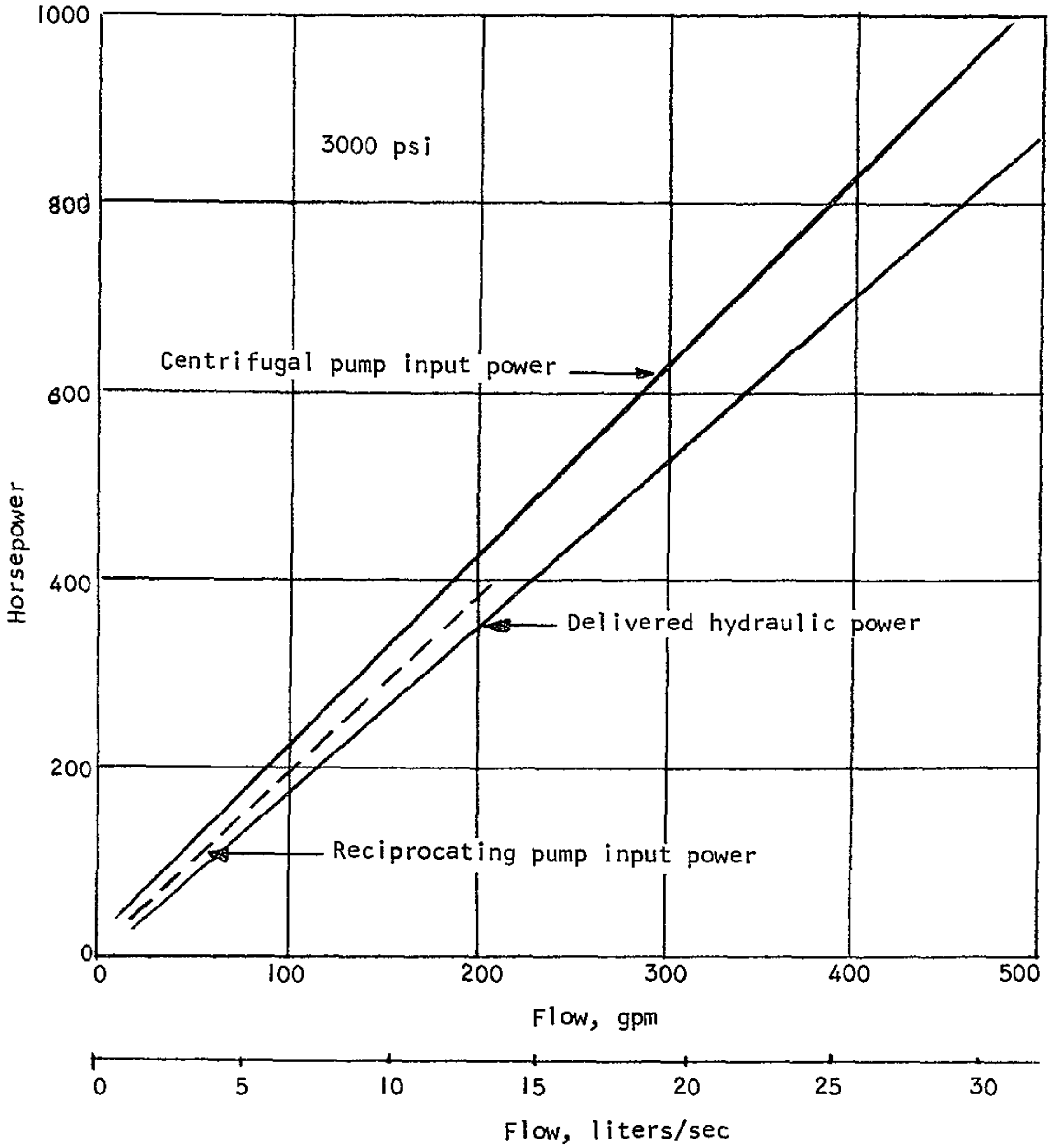


Figure 3-3. Power Comparison, Centrifugal Pump vs Reciprocating Pump

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. 3-4 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 100 gpm. There is a definite similarity between the operating characteristics of the two designs. The reciprocating machine operates along a flatter pressure curve and provides better efficiency, but its maximum flow is limited by its speed-displacement capacity.

<u>Pump drives</u>.--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. 1-1 through 1-4 is for very large-capacity engine driven pumps. Electrically driven pumps for contemporary large transport airplanes rarely exceed the 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 8-hp shaft input from an electric motor. However, when the head pressure is typically between 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 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. 3-5. 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.

Actuators

There are a large variety of different size actuators that perform numerous duties on aircraft. Usually, they are used as controlling members of flight surfaces. Actuators may be powered hydraulically, pneumatically, electrically, or may receive power from a hybrid source included for redundancy. Parametric data and characteristics for various types of actuators were discussed in the second quarterly progress report, AiResearch Report No. 68-4176(2). A brief summary of electric driven actuators and an updated comparison of pneumatic, hydraulic, and electric motors are discussed below under the two basic types of actuator, the linear and the rotary.

<u>Linear actuators</u>.--The basic linear actuator form is a conventional screw jack extended or retracted by a motor through a geared drive. The motor direction is reversible, and limit switches at the extremes of travel interrupt the

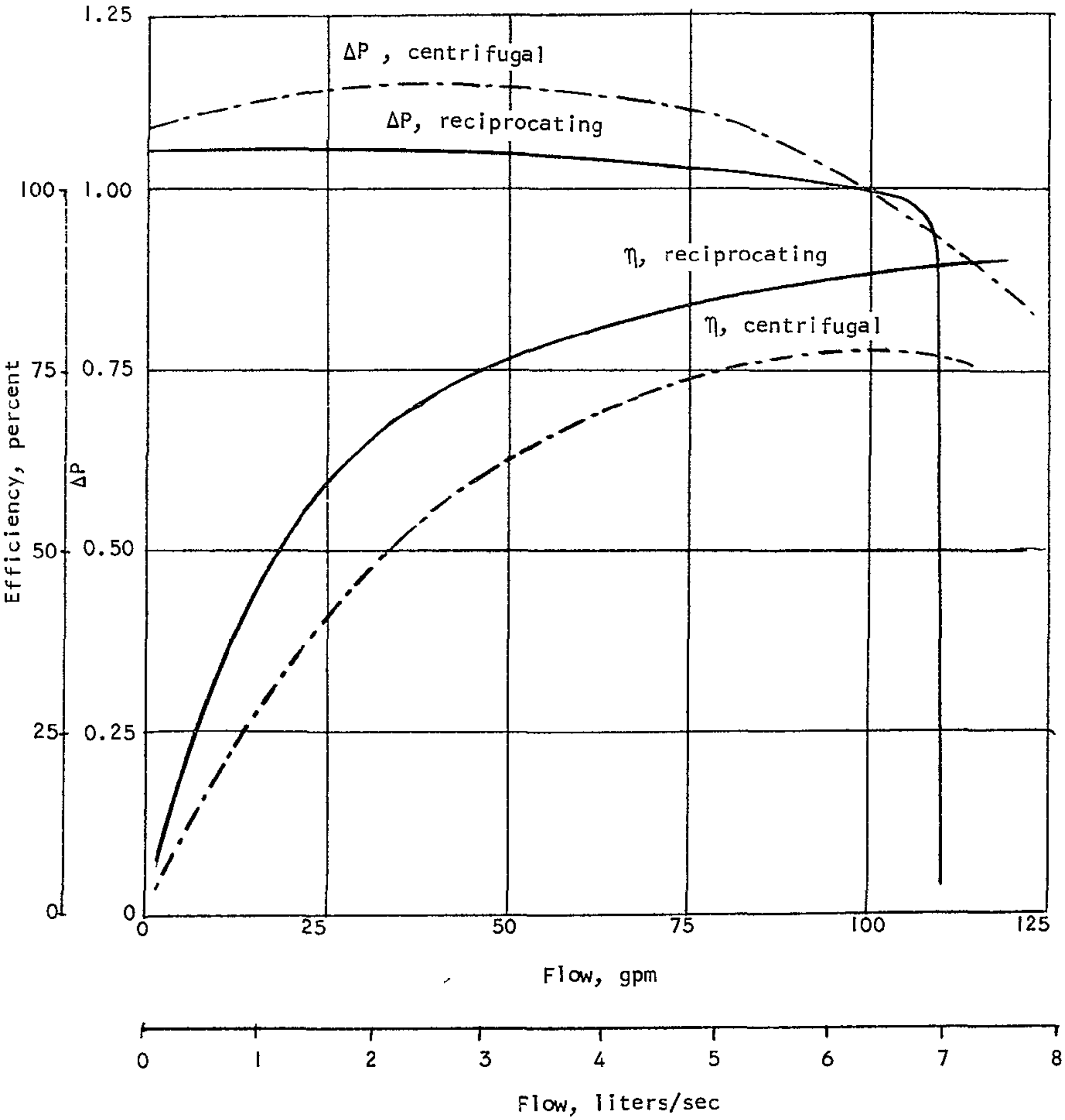


Figure 3-4. Pressure vs Flow for Centrifugal and Reciprocating Pumps at Constant Speed

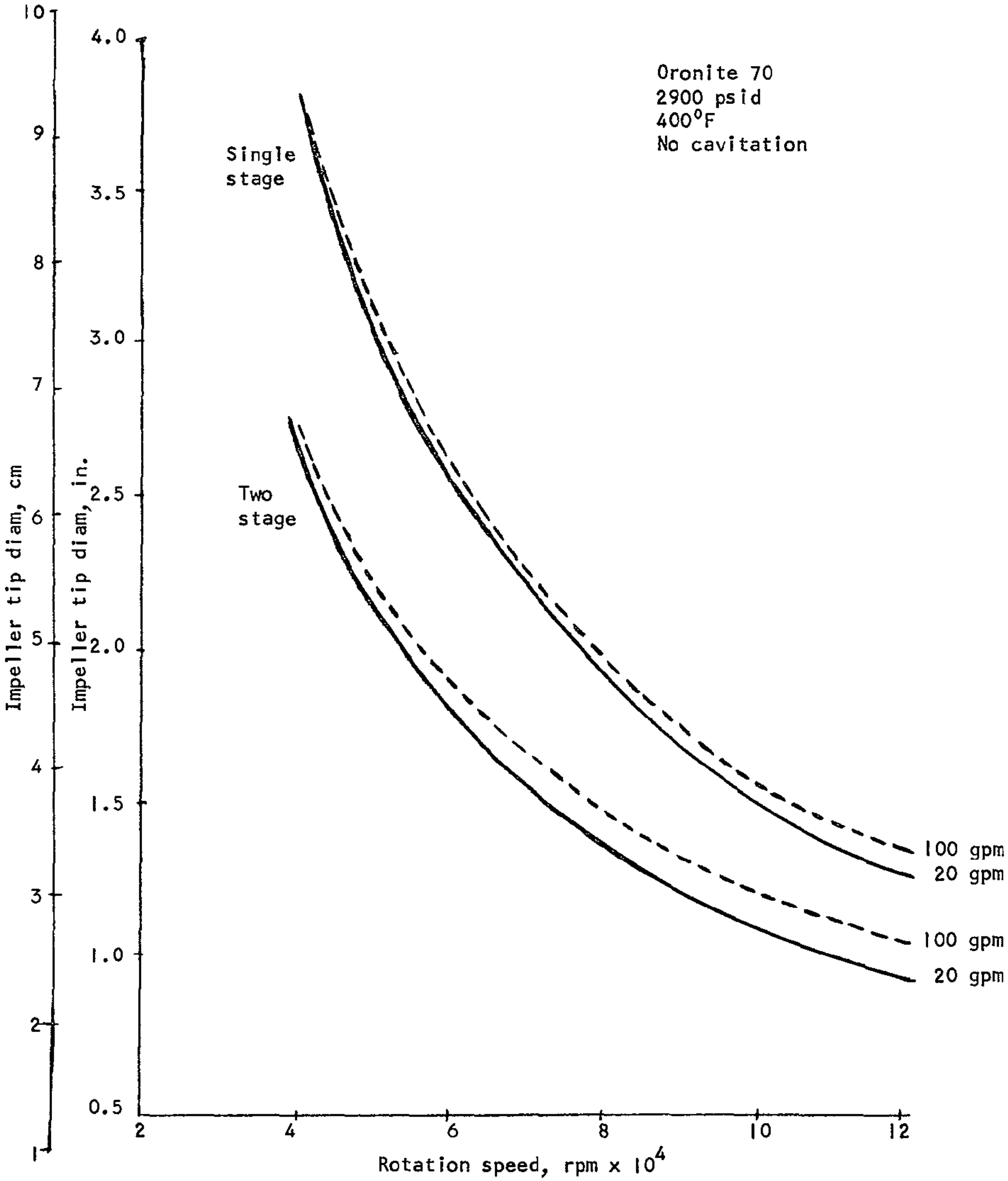


Figure 3-5. Impeller Tip Diameter vs Rotational Speed

supply that drives the motor in that particular direction. An actuator must limit the momentum of the motor and/or overdrive of the load to a minimum. To accomplish this, a solenoid-operated brake is arranged with the motor such that the brake is released whenever the motor is energized. The actuator also must have a clutch-type friction drive incorporated between the screw drive and the gear train to prevent damage to the gears or motor if the actuator movement should be obstructed.

Larger actuators may employ two motors, one for main operation and the other for emergency. However, additional limit switches, brakes, and clutches required for the second motor complicates the arrangement.

Rotary actuators.--Rotary actuators are generally smaller devices that operate fuel cocks, butterfly valves, and similar equipment performing light duty functions on aircraft. Travel of less than 360 deg is obtained through intermediate gear trains with limit switches at the extremes. As with linear actuators, brakes and clutch-protected drives are incorporated in all standard rotary actuators.

Actuator brakes.--Since shunt brakes might not be energized when the motor is running and vice versa, brakes in series with the driving motor are preferred. One of the main disadvantages of ac-type actuators is the braking problem. For example, failure of one phase on a three-phase motor during operation would still permit the actuator to run. However, if the failed phase controlled the braking circuit, serious equipment damage could result. For actuators with duplicate motors driving tandem through a differential gear, if one motor fails the brake holds one gear stationary while the other motor maintains the drive. Also, stopping one motor might be an intended feature of a two-speed drive, since one motor running under these conditions results in one half the driven shaft speed obtained when both motors are running.

Temperature environment.--Since actuators that operate control surfaces are fully exposed to ambient temperature variations as low as -70°C, permanently energized built-in heaters are provided to prevent lubricant gelling and bearing clearance contractions.

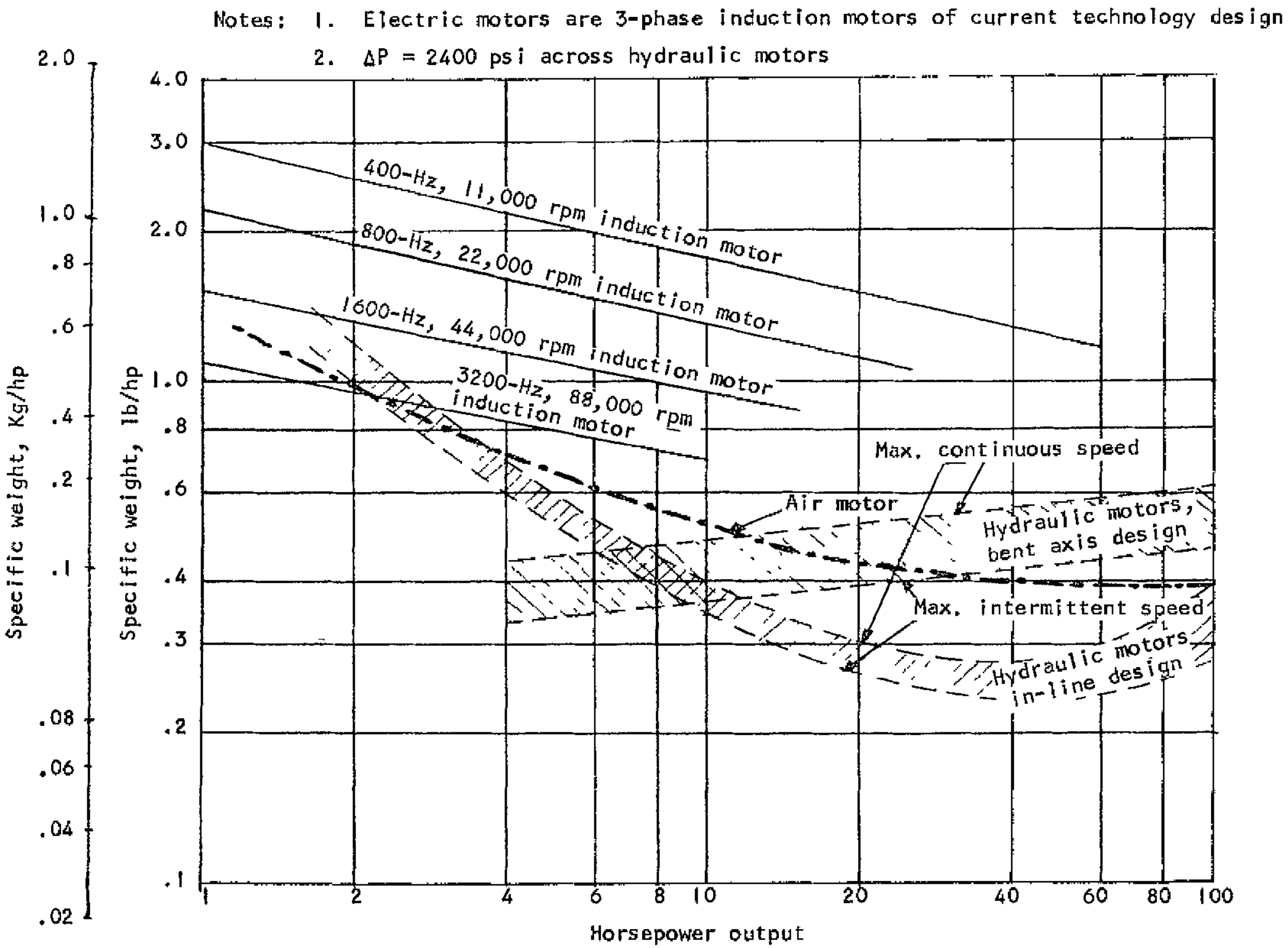
Electric power for actuators.--Electric power is required for the three different loads listed below:

(1) Actuator driving element load (a control load)

(2) Solenoid-operated clutch load (a control load)

(3) Actuator heater load

Specific weights of driving motors.--The weight trend curves for electric (ac), pneumatic, and hydraulic drive motors are shown in fig. 3-6. Hydraulic motors were arbitrarily selected for a differential pressure of 2400 psi. The hydraulic in-line motor design is clearly advantageous for the 10- to 100-hp range. Three design points of air motors show them competitive with both the in-line and bent-axis hydraulic designs. Electric induction motors exhibit the



Notes: 1. Electric motors are 3-phase induction motors of current technology design

2. ΔP = 2400 psi across hydraulic motors

Figure 3-6. Comparison of Specific Weights of Hydraulic, Pneumatic, and Electric Motors heaviest specific weight. Speed curves from 6000 to 100,000 rpm were plotted assuming a supply frequency high enough to permit use of a 4-pole machine. The weight of internal control mechanisms and power supply lines was not considered in the graph. Depending on system location in the aircraft, the ac-induction motors, which definitely require the lowest transmission line weight for all power ratings (see second quarterly progress report), could be the optimum system from a weight consideration.

Electronic and Avionic Loads

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. 1) 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 3-2. 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.

For equipment that cannot tolerate short primary power interruptions, as is the case for digital devices, to prevent loss of memory, a scheme may be adopted as shown in fig. 3-7. Here, the 3-phase 400 Hz is transformed, rectified, and filtered to provide 28 Vdc to a dc-to-dc converter. The input to the converter is backed by the airplane battery bus, the bus is slightly lower in the dc level. In case of short power outings on the ac side, the battery supplies the converter instantly. Uninterruptible supply to all the sensitive loads is thereby maintained.

For energy gaps of lower magnitude and up to 1 msec duration, capacitor storage is frequently employed.

The requirement of several voltage sources with different levels, dual polarities, and precise regulation characteristics for the various digital and analog applications has called for individual transformation and conditioning devices within the equipment.

Future standardization of voltage levels, particularly for MSI circuitry, will hopefully reduce the variety of voltage levels in use today. The requirements for the electrical power system interface with the electronic/avionic load are listed below:

(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 uniform to effectively attenuate disturbances and minimize propagation.

TABLE 3-2

THE MORE COMMONLY USED VOLTAGE LEVELS IN AIRCRAFT AVIONIC SYSTEMS (ref. 1)

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	-

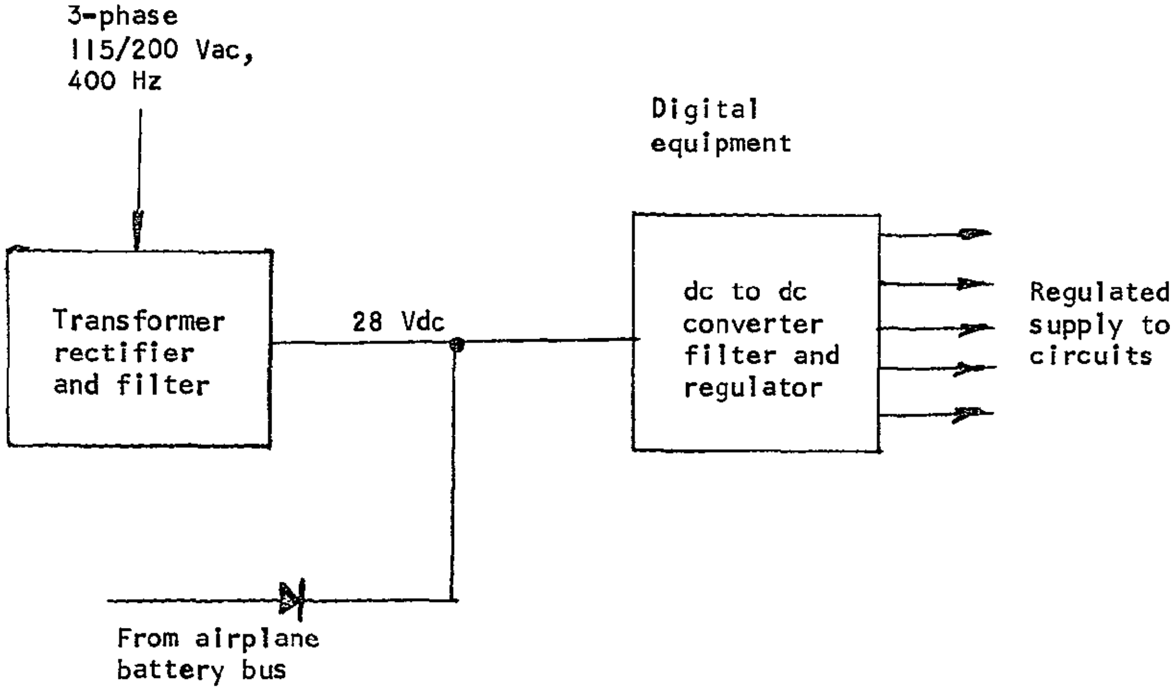


Figure 3-7. Uninterruptable Power for Vital Electronic/Avionic Loads

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. 3-8 shows efficiency versus input power frequency for two fluorescent lamps (ref. 2). Fig. 3-9 shows the effect of type of ballast and frequency on fluorescent lamp efficiency (ref. 2). The effect of input voltage wave form on light output with the same rms lamp current is shown in fig. 3-10 (ref. 3). 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 to 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. 4) 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.

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.

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 thermoelectric coolers.

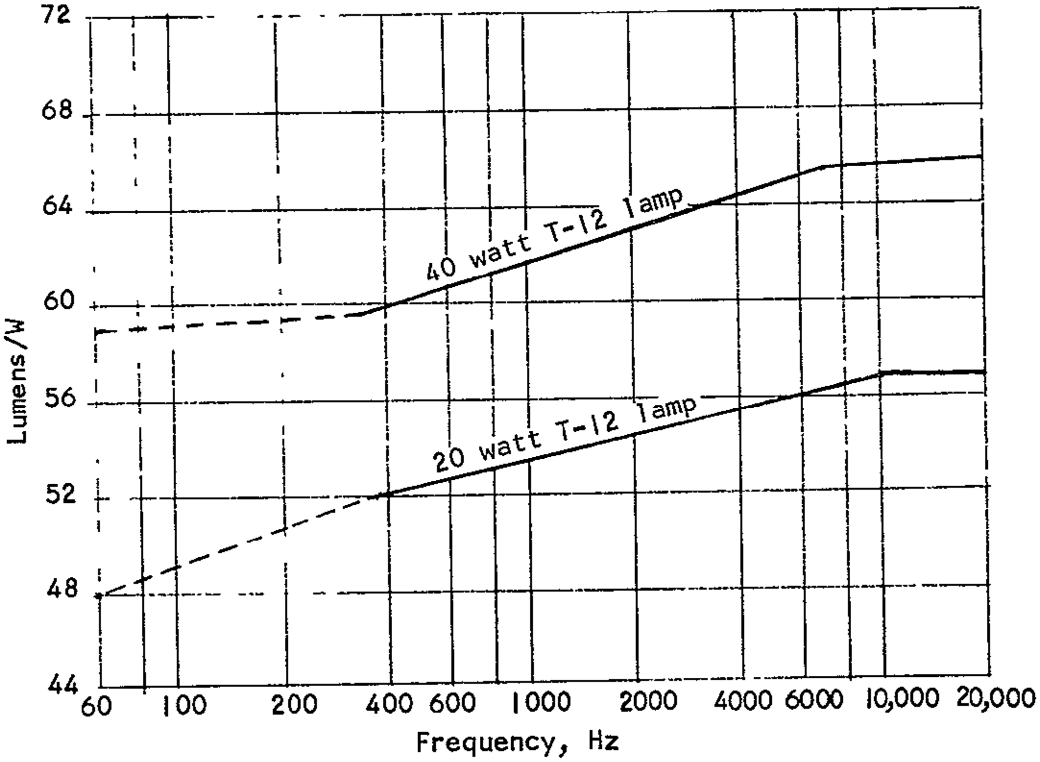


Figure 3-8. Lamp Efficiency vs Frequency (T-12 lamp) (Ref. 2)

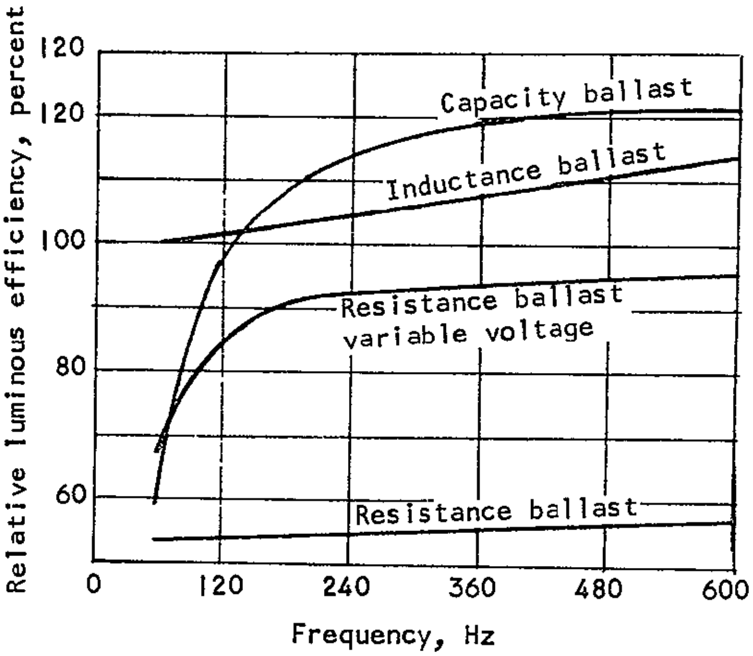


Figure 3-9. Relative Over-all Luminous Efficiency with Various Ballasts (Ref. 2)

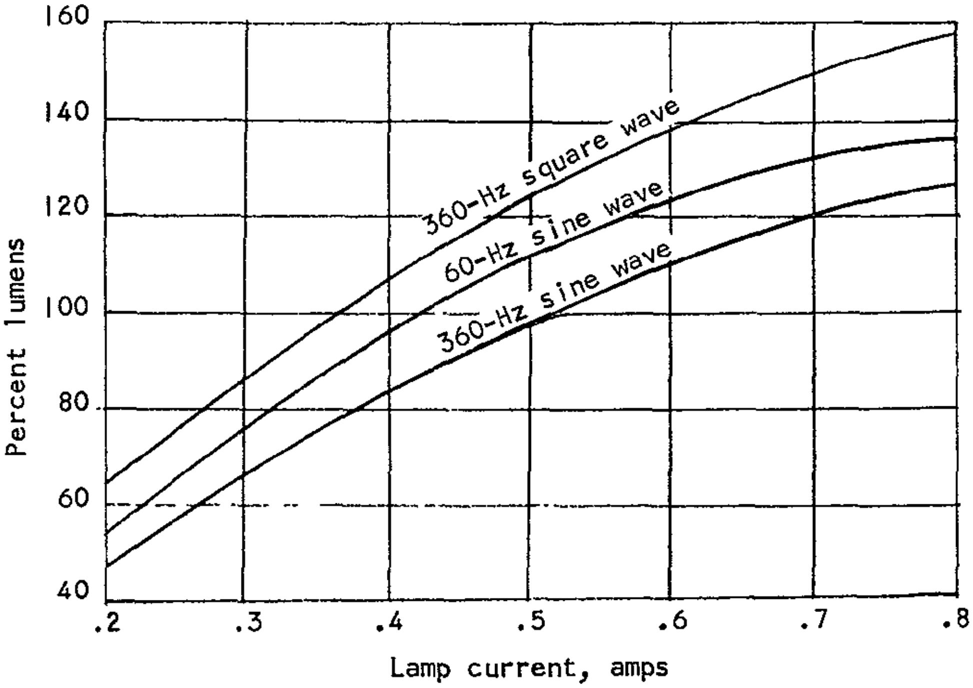


Figure 3-10. Relative Lumen Output vs Lamp Current for T-12 Lamp, Comparison of Square and Sine Wave Current Input (Ref. 3)

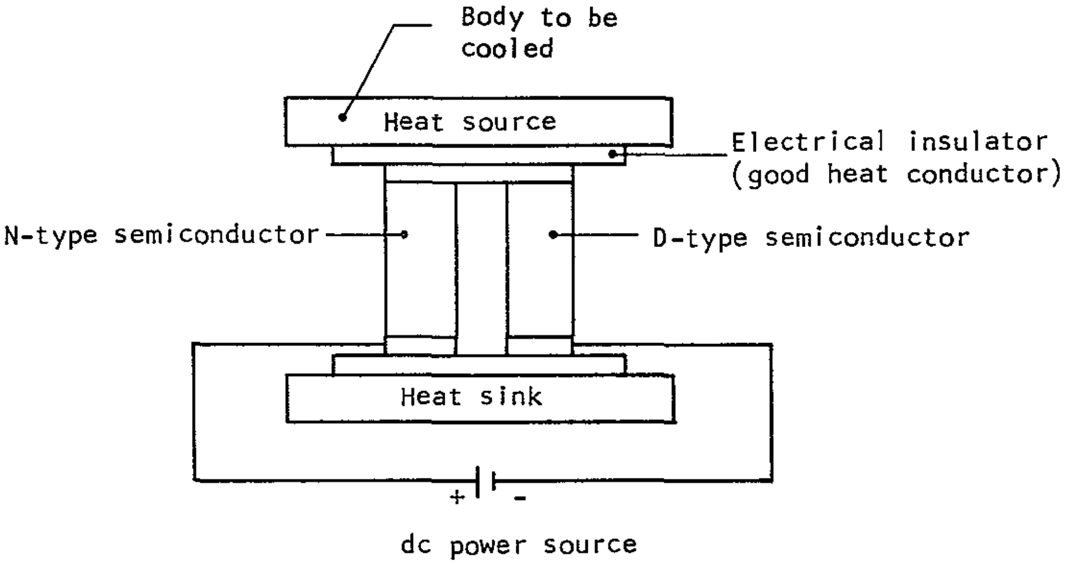
Principle of operation.--Thermoelectric cooling follows the same basic laws of thermodynamics, and the principles are essentially the same as in conventional refrigeration. The refrigerant in both liquid and vapor form is replaced by two dissimilar conductors. The freezer surface becomes cold through 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 shown in fig. 3-11a.

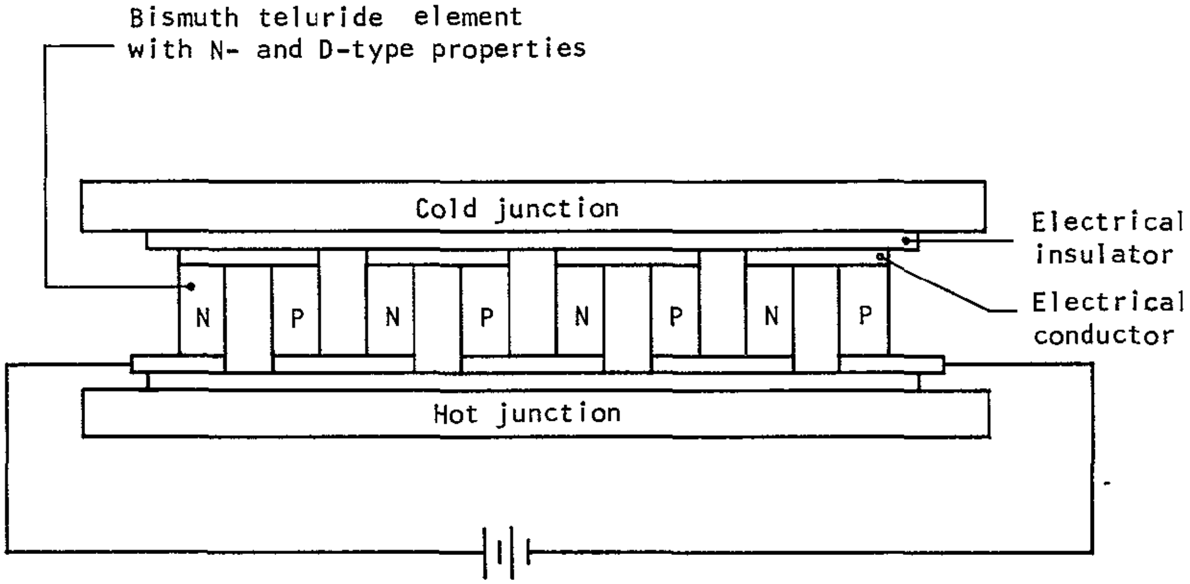
Semiconductor materials with dissimilar characteristics are connected electrically in series and thermally in parallel, resulting in two junctions. Heat absorbed at the cold junction is pumped to the hot junction at a rate proportional to carrier current passing through the circuit and the number of semiconductor elements.

Good thermoelectric semiconductor materials, such as Bismuth Telluride, greatly impede conventional heat conduction from hot to cold areas, but provide an easy flow for the carriers. In practical use couples, such as those shown in fig. 3-11a, are combined in a module where they are connected electrically in series and thermally in parallel as shown in fig. 3-11b. 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 70°C or less. For applications requiring greater temperature differences, the modules can be cascaded. Practical limits of temperature differences up to 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 (Q_c) 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.



(a) Single Element



(b) Assembly of Elements

S-52931

Figure 3-11. Thermoelectric Cooler Module Assembly

The relationship of these parameters is shown in fig. 3-12. The thermoelectric module is the Borg-Warner model number 920 designed for a heat sink temperature of 27°C. To illustrate the utility of these curves, the following example is considered: the desired operating temperature of a diode is -8°C and the hot junction temperature can be maintained at +27°C. The cooler is required to pump a total heat load of 6 W from the diode and surrounding environment. In fig. 3-12a, a vertical line is drawn from the point $Q_c = 6$ W. The total temperature difference $(\Delta t) = 8 + 27 = 35°C$. Now a horizontal line is drawn at the point $\Delta t = 35°C$. At the point of intersection, COP = 0.5 and current I = 5 A. The power supply voltage may be selected by using fig. 3-12b. A vertical line is drawn from the point I = 5 A to a point halfway between Δt max (70°C from fig. 3-8a) and $\Delta t = 0$. Then, a horizontal line is projected to the voltage axis, which yields 2.35 V. A heat load of 60 W at $\Delta t = 35°C$ and I = 5 A could be cooled by using 10 modules thermally in parallel and electrically in series with a power supply of 23.5 V.

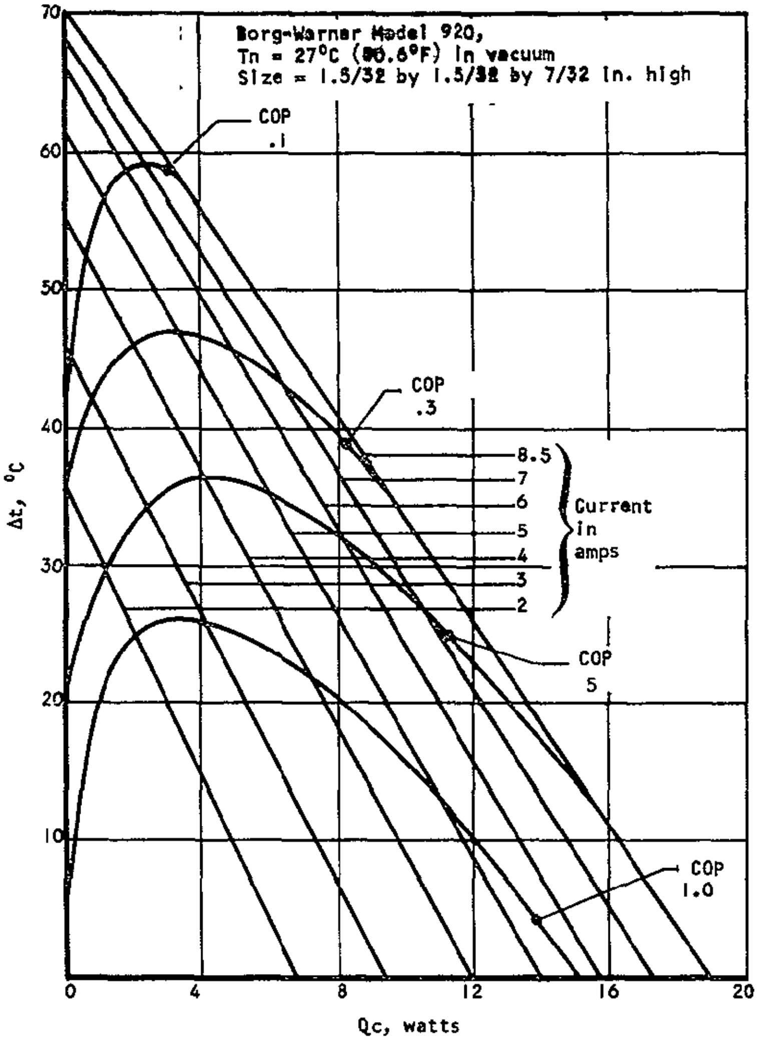
Where desired temperature differences cannot be obtained with a single-stage module, cascaded modules are used. Since the cold-surface temperature is much colder than the ambient temperature,caution should be used to adequately insulate the cold surface from extraneous heat loads (generally, radiation 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. 3-13).

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. 3-14 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:

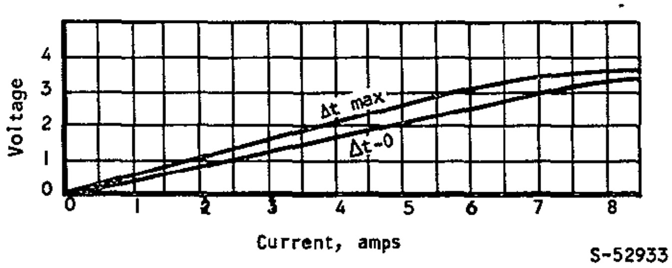
$$\frac{\Delta t}{\Delta t \text{ max}} = \frac{1}{1 + N^2}$$

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 3-10, the effect of ripple to junction temperature difference is negligible if the ripple content is less than 10 percent.



(a) Module ΔT vs heat pumping capacity



(b) Module Voltage

Figure 3-12. Thermoelectric Cooler Characteristics*

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* Taken from The Where and the Why of Thermoelectric Cooling. Borg-Warner, Thermoelectrics Department, Des Plaines, Illinois, 1967.

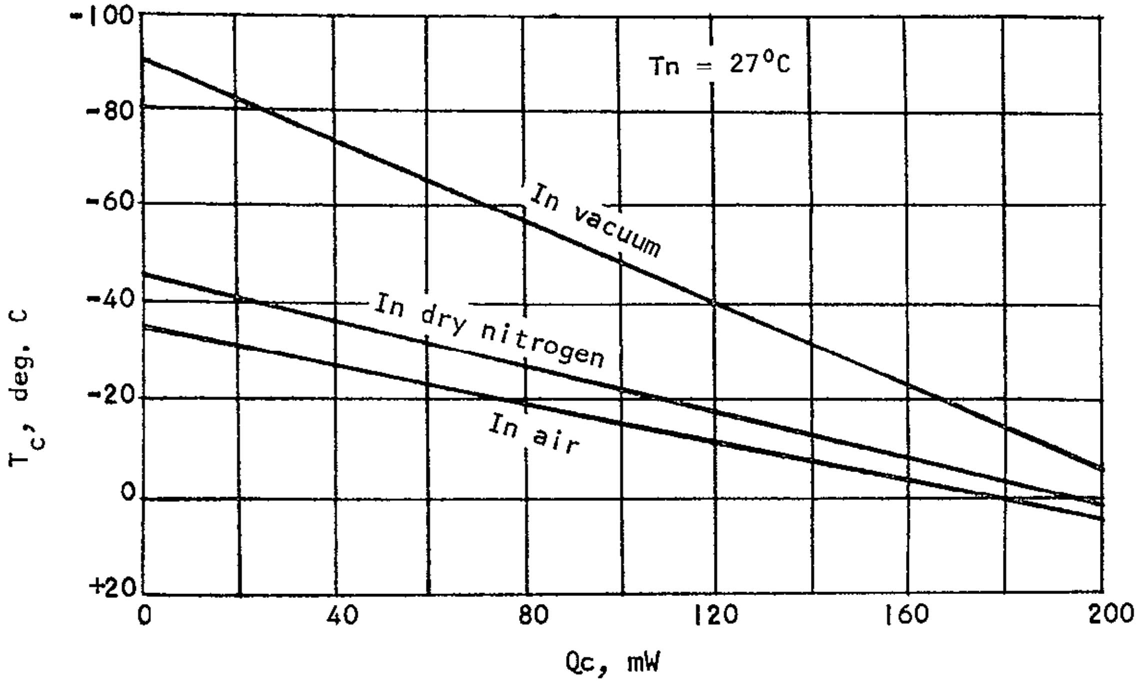

Figure 3-13. Performance of Borg-Warner Model 670*

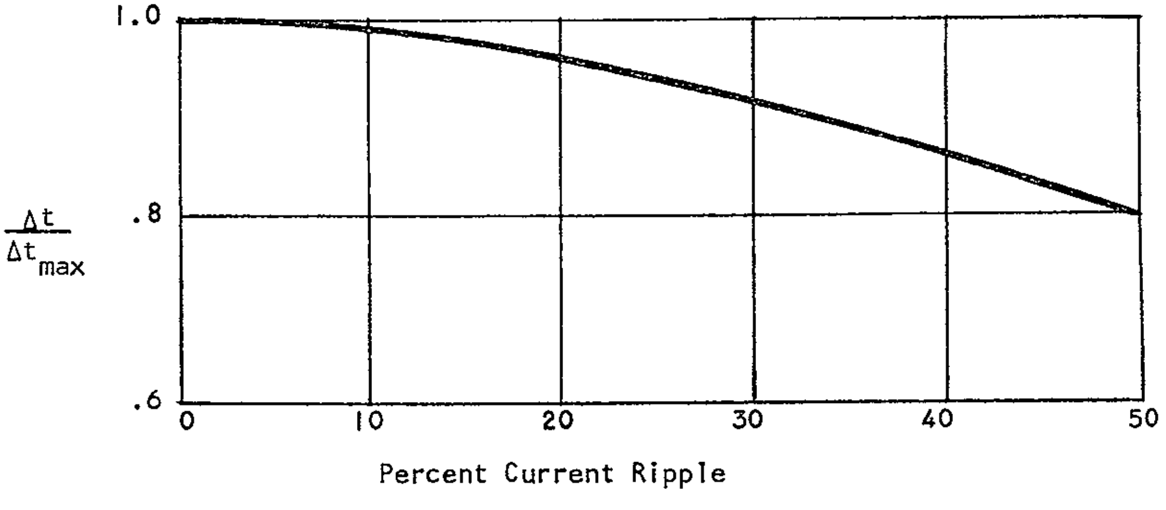

Figure 3-14. Effect of dc Ripple on Temperature Difference of Junction*

* Taken from The Where and Why of Termoelectric Cooling. Borg-Warner, Thermoelectric Department, Des Plaines, Illinois, 1967.

SECTION 4

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COMPARISON OF HYDRAULIC, PNEUMATIC, AND ELECTRIC POWER FOR AIRCRAFT ACTUATION SYSTEMS

In the second quarterly progress report some comparison was made on the hydraulic, pneumatic, and electric actuation systems. The comparison of these systems is further discussed in this section.

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 System

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 pressure up to 5000 psi with flow response from approximately 2 to 5 msec. The most commonly used pressure level of the aircraft hydraulic system is 3000 psi. However, Lockheed selected a 4000 psi system for their SST design. It has been found that the main weight saving attainable with the higher pressure system results from the reduced volume of hydraulic fluid in the system.

Servovalves.--In constant pressure sytems, the servovalve controls the position of the power actuator piston. By using good design techniques, the servovalve 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 although 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.

Hydraulic actuators.--The hydraulic power output devices include motors and actuators. For flight control systems, the primary interest is in power actuators, some of which are briefly discussed below.

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.

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.

Other 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 Caravelle 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.

To improve reliability, the dual tandem linear actuator is widely used. 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 of hydraulic actuation system.--When hydraulic power is used for servo actuation, the following advantages are generally observed.

(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 approximately between 0.2 and 0.4 lb/hp.

Disadvantages of hydraulic actuation system.--The hydraulic actuation system has the following disadvantages:

(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 System

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 system are similar to those of the hydraulic system, 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 the power source 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.

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.

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.

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.

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.

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.

Rotary vane motor: This is a high-rotational-speed, low-stall torque device. The sliding vanes create wear leakage and friction problems.

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 of pneumatic actuation system.--The pneumatic actuation system is primarily used for low-load, 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 of pneumatic actuation system.--The pneumatic system has the following disadvantages.

(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.

Electrical Actuation System

An electrical actuation system uses electric current to deliver power to the load through electromechanical power conversion devices. The components used in an electrical system include generator drives, generators, actuators, clutches, gear trains, and control amplifiers. The drive system is usually a constant-speed drive powered from the accessory pad mounted on the main engine of an aircraft. For other applications, the constant speed drive system is often driven by an accessory turbine. The generator supplies constant frequency, 3-phase ac power. The frequency is usually 400 Hz and voltage is 115/208 V. Although the electrical power system, the generators, amplifiers, etc. will not be discussed, several types of motors are briefly discussed below because the motor is the most critical component whose characteristics directly affect the choice of the electrical actuation system for a certain application.

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 and are occasionally provided with inertia or viscous dampers for mechanical equivalents of acceleration and velocity feedbacks, respectively. Fig. 4-1 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.

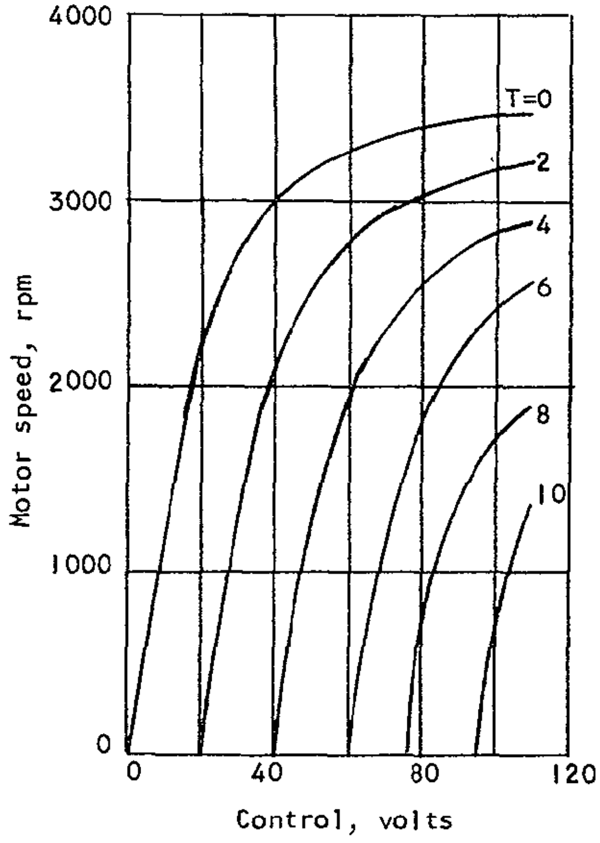

Figure 4-1.

Typical Two-Phase Servomotor Speed-Voltage Curves for Constant Torque Loads

T = torque in oz-in.

I = motor inertia = 0.66 oz-in.^{2}

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 is greatly preferred, if not the only choice.

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.

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 4-1 shows the motor characteristics of three different models.

TABLE 4-1

PRINTED SERVOMOTOR CHARACTERISTICS

Characteristics	Units	Model 368	Model 488	Model 668
Rated torque	oz-in.	12	42.5	140
Maximum pulse torque capability	oz-in.	150	375	1175
Armature inertia (including hub and shaft)	oz-in.sec^2	0.004	0.018	0.088
Mechanical time constant	sec	0.028	0.030	0.0295
Equivalent series mechanical impedance (at constant terminal voltage)	rpm/oz-in.	66.7	15.37	3.2
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	oz-in.	1.5	2.0	8
Back EMF per 1000 rpm	volt	2.22	5.55	10
Average torque per ampere	oz-in.	3	7.5	13.5
Weight	lb	3	6.5	13

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 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 4-2 shows the motor characteristics of several Minertia motors. Fig. 4-2 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 Specialty 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

TABLE 4-2

RATINGS OF SERVO-SERIES MINERTIA MOTOR (REF. 7)

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

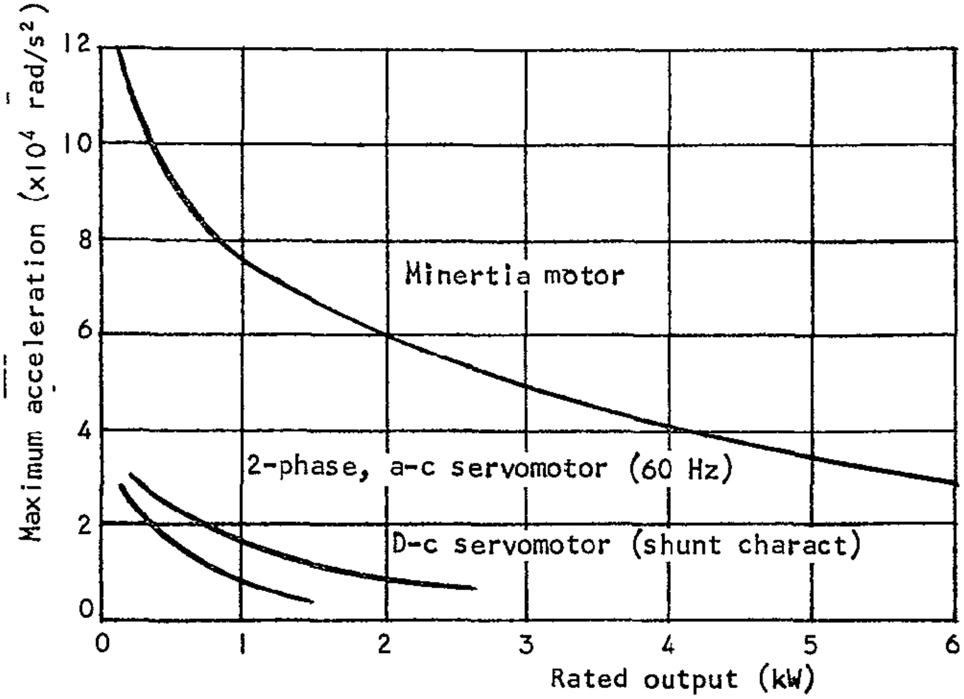

Figure 4-2. Maximum acceleration (Ref. 7)

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 is listed in table 4-3. Large units with ratings in excess of 4 hp are being developed. Fig. 4-3 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.

<u>Electric motor performance</u>.--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. 4-4 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

TABLE 4-3

HYPER-SERVOMOTOR CHARACTERISTICS

[From ref. 8]

Parameter	Symbol	Units	Model No. 5BLG32HA1	5BLG32NA1	5BLG32SA1	(2) 5BLG46HA1	5BLG46HA4	5BLG46HA5	(2) 5BLC48PA2	5BLC48PA3
Motor diameter		inches	3.4	3.4	3.4	4.6	4.6	4.6	4.8	4.8
Rated armature voltage		volts	12	24	36	12	12	12	30	30
Rated armature current		amps	8	8	7	8	8	13	26.5 at 50 cfm	18.0 at 50 cfm
Rated torque		oz-in.	32	64	99	49	49	80	326	222
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	Oz-in./amp	4.0	8.1	14.1	6.15	6.15	6.20	12.3	12.3
Armature inertia	JA	Oz-in. Sec^2	.0028	.005	.0082	.003	.0028	.0035	.0044	.0035
Pulse torque, 50 msec		Oz-in.	320	650	1130	615	615	680	2460	1350
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 at 50 cfm	18.0 at 50 cfm
Motor length		inches	4.28	6.03	8.53	6.50	4.64	4.64	8.90	7.3
Motor weight		pounds	5.1	8.9	13.5	14.5	12.7	12.7	26	24
Enclosure and cooling			Tenv	Tenv	Tenv	Tenv	Tenv	Tenv	FV	FV
Cooling air required		cfm at in. H^2O	-	-	-	-	-	-	50 at 37	50 at 30

(1) = $\frac{JA}{JA + JLoad}$

(2) Equipped with digital tachometer

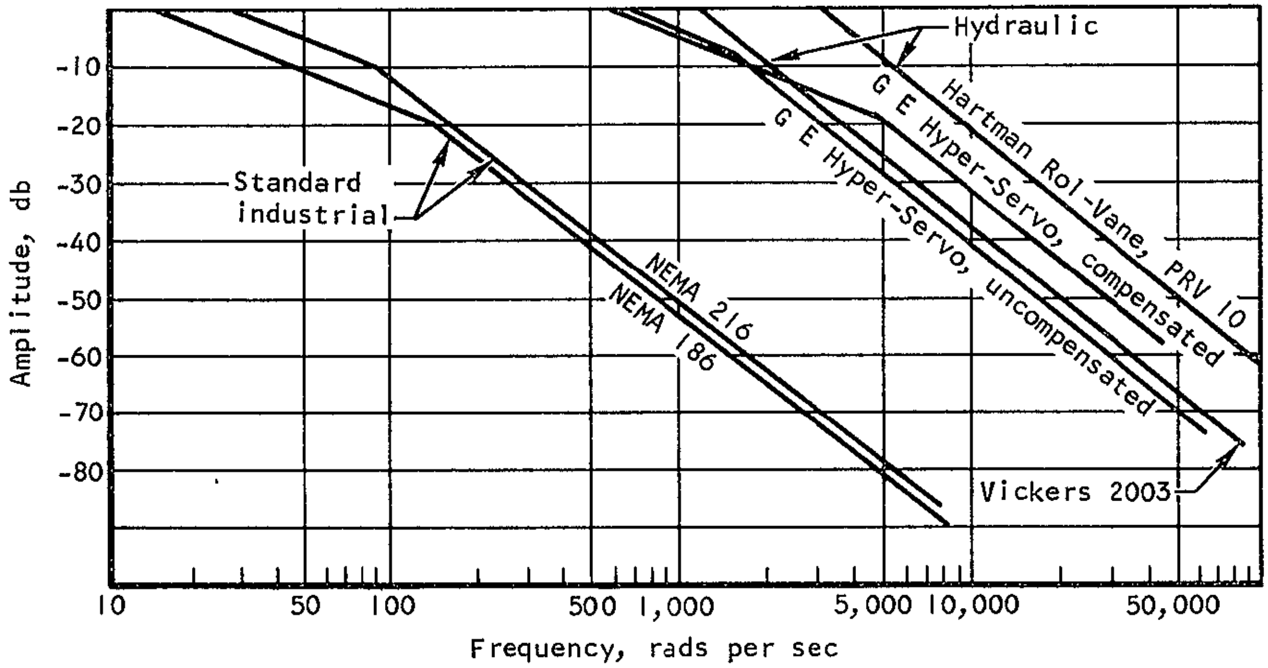

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Figure 4-3. Frequency Response of New G.E. 4-hp Servomotor (Ref. 8)

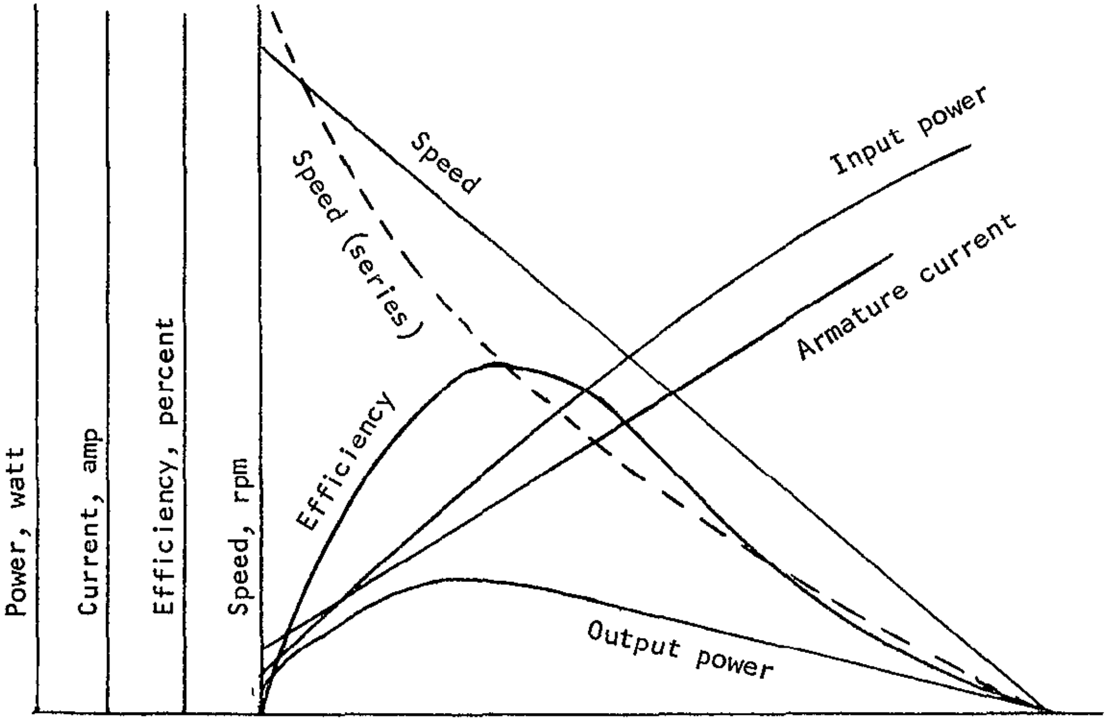


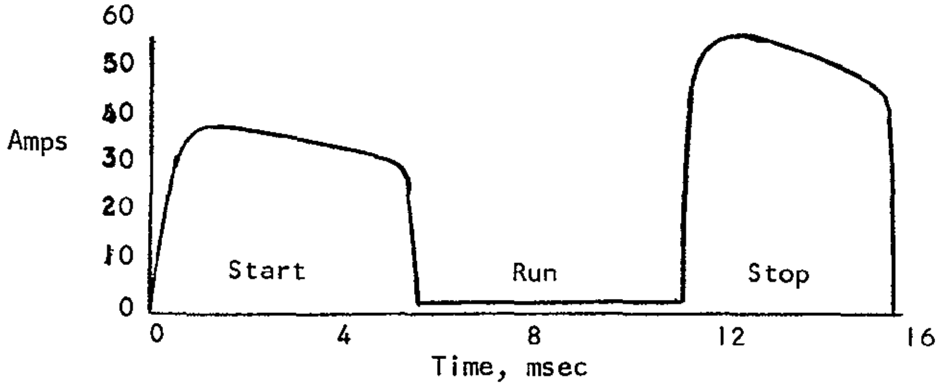
Figure 4-4. Typical Torque Motor Performance Curves

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. 4-5 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.



$$I_{rms} \sqrt{\frac{1}{T}\int^{T} j^{2}\, t \, dI}$$

(Ref. 9)

Figure 4-5. Typical Hyper-Servomotor rms Duty Cycle

Advantages of electrical actuation system.--The electrical actuation system, although not widely used for aircraft flight controls, offers the following advantages:

(1) The electrical system offers good maintainability. The electrical components, in general, do not need frequent maintenance and some components need no maintenance service during their operating life. Therefore, maintenance cost is relatively low.

(2) The electrical system is easy to install, and thereby reduces the initial cost.

(3) Superior power transmission capability is offered. The electrical power transmission is simple and efficient.

(4) The electrical system is highly reliable. Also, significant knowledge and experience have been gained with electrical components.

Disadvantages of electrical actuation system.--The following are the disadvantages of the electrical system. These have been the major drawbacks for flight control applications.

(1) Due to the inherent flux density saturation characteristics, power density of electrical devices are limited.

(2) The system has relatively low-power amplification. Weight and size penalties are usually unavoidable in many applications.

(3) The electrical system has relatively low torque-to-inertia ratios, which limits the dynamic performance.

(4) The frequency response attainable with the electrical system is inferior compared with that of the hydraulic system. Furthermore, load holding is a problem due to its low stiffness factors.

(5) The system is inapplicable at high temperatures since the insulation and the magnetic properties of the core material breakdown.

High Temperature Actuation System

The future advanced aircraft flying at supersonic and hypersonic speeds will undoubtedly result in extremely high temperature requirements for system components. In addition to the higher environmental temperature, the self-generated heat in the system may raise the operating temperature to an even higher level considerably beyond the capabilities of present day hydraulic systems. Several approaches to the temperature problem have been under development. These approaches use either a high-pressure pneumatic system or a redesigned hydraulic system. The pneumatic system, due to the temperature capability of the gases, is very attractive for high-temperature applications. To improve the temperature capability of the hydraulic system, the following approaches are being investigated.

Cooled hydraulic system.--One method to overcome the temperature problem is to incorporate cooling systems into the hydraulic system. By extracting heat from the working fluid, the fluid temperature can be maintained at a low level for which the present components, fluids, and associated techniques are applicable. Obvious disadvantages of this configuration result from the added cooling system provisions. These include (1) severe penalty in overall weight, (2) additional space requirements, and (3) reduced system reliability.

Hydraulic systems using high temperature working fluids.--Programs have been conducted to develop new working fluids, components, and system techniques that are suitable for high-temperature applications. Table 4-4 lists several types of working fluids along with their temperature capabilities.

TABLE 4-4

HIGH TEMPERATURE HYDRAULIC FLUIDS

Fluid	Temperature range, ^{0}F	Viscosity	Specific Gravity
MIL-H-5606A hydrocarbon	-75 to 275	14.2(100^{0}F)	0.847
Synthetic hydrocarbon	-65 to 650	4.5(210^{0}F)	.85
Chlorophenyl silicones	-100 to 650	17.7(210^{0}F)	1.04
MLO-7277 napthenil	-30 to 700	8.4(210^{0}F)	.88
MLO-62-294 paraffinil deep dewaxed	-70 to 700	4.18(210^{0}F)	.88
Silicones	-15 to 700	12.1(210^{0}F)	
5-P polyphenyl ether	-40 to 900	13.3(210^{0}F)	1.2
Sodium potassium cesium	-95 to 1300	.19(1300^{0}F)	1.49
Nak 77	10 to 1400	.14(1200^{0}F)	.87

Development of new components that are adaptable for the new work fluids has also been in progress. Among the new high-temperature components are (1) the vane pumps for chlorinated silicon fluid, (2) the high-temperature scoop pump and integrated actuator, (3) the centrifugal pump and the electromagnetic pump for continuous-flow liquid metal systems, (4) the jet pipe servo valve, and (5) the accumulator for the continuous flow liquid metal system.

General Electric Company has developed a system that uses Năk 77 as the working fluid and studied its feasibility for high-temperature flight control applications. The system uses the conventional continuous flow techniques; individual system components have been developed and successfully operated.

Pulsating hydraulic system.--Republic Aviation has worked on a new system approach where pulsating hydraulic power is generated and used. The system consists of two fluid systems, one using Nak 77 fluid for high-temperature environment only and the other using conventional fluid as a low-temperature system throughout the rest of the vehicle. Power is transmitted between the two systems by hydraulic transformers. The advantage of this over the conventional liquid metal system is that the liquid metal system is restricted in the high-temperature environment, and liquid metal does not have to be pumped through all areas of the vehicle. The disadvantages of the pulsating system include the complexity of the system and the low overall efficiency.

Choice of Actuation System

Three different types of actuation systems, the hydraulic, pneumatic, and electric, have been briefly discussed. The choice of the actuation system for a specific application depends on many factors and considerations. Without thorough evaluation and trade-off studies, it is very difficult to determine which is the best system, although for certain applications the selection seems to be rather easy and straightforward.

The most important factor for selecting an actuation system for flight control application are dynamic performance characteristics such as frequency response, stiffness factor, etc. The hydraulic system offers the best dynamic characteristics, while the pneumatic and electrical systems have relatively inferior performances. When high-speed response is required, hydraulic system may be the only type that can satisfy the requirement. For applications where more than one system is feasible, the choice of the system should be determined through trade-off studies. The factors which are generally considered are listed below:

(1) Weight and size

(2) System reliability

(3) Component maintainability

(4) Installation requirement

(5) Cost

To evaluate and compare the various systems on the basis of the above characteristics, a simple method using various weighting factors for various rating categories can be used. A maximum score may be given for the best system in each rating category and other system scores normalized with respect to the best system. The total score of the system can be obtained by summing the scores in each category and used as an indication of system effectiveness.

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SECTION 5

MAINTAINABILITY AND ITS TRADEOFFS WITH EQUIPMENT COST AND WEIGHT

Introduction

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.

Factors Affecting Maintenance Cost

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 coils, transformers, and resistors. The conductor study concentrated on (1) an indium gallium alloy coating 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. This study is only a beginning of development 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 many future circuits not only uneconomical, but also impossible to repair. 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.

Design for Maintainability

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 physical design features (A), support requirements (B), and personnel requirements (C). 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.

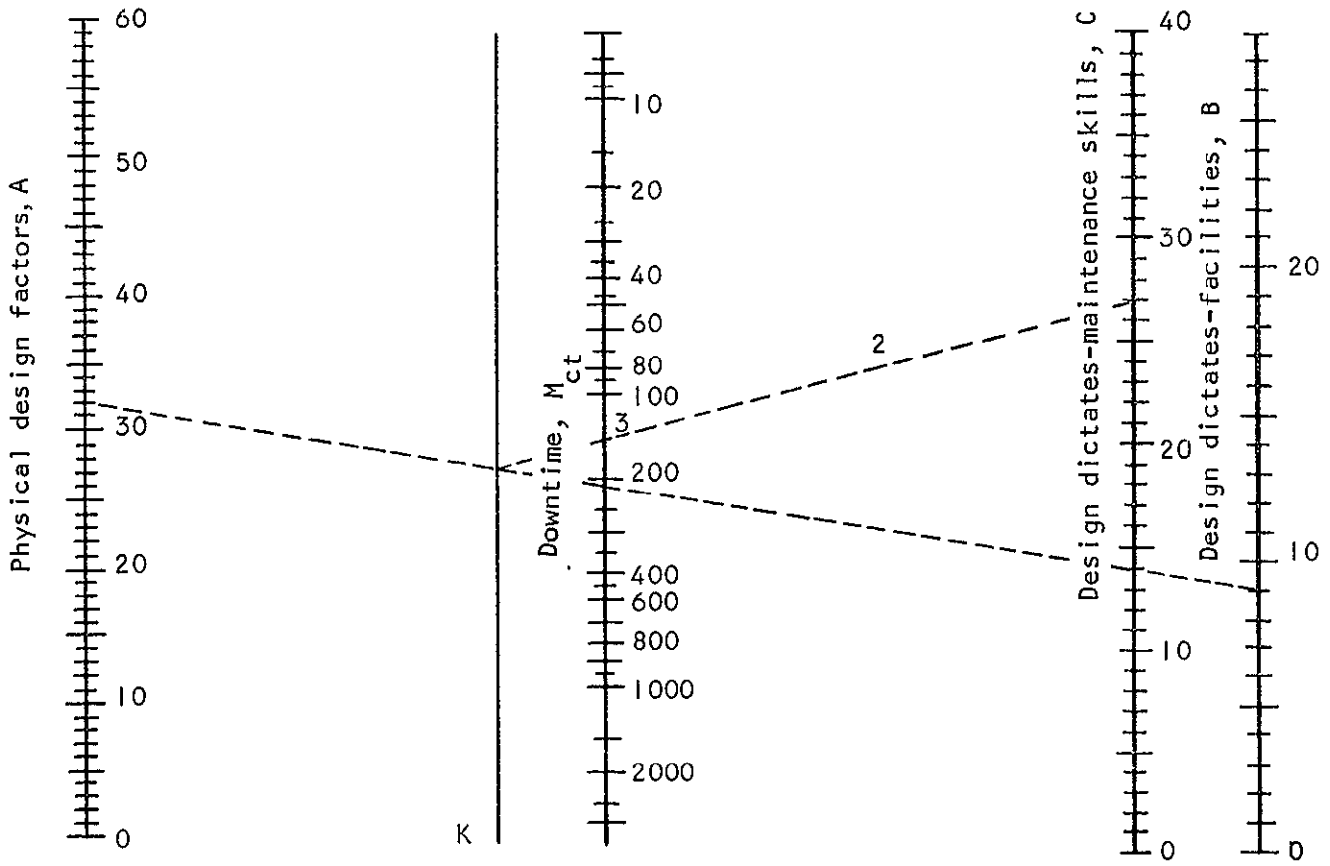
To obtain A, B, and C, a checklist is established for each parameter. Within each checklist, a number of questions are to be answered and a score of 0 to 4 is given to each answer, depending on the condition of the design features for a specific maintenance task. By summing the scores of each checklist, 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. 5-1. 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



Instructions

1. Draw line from A to B.
2. From intersection with K, draw a line to C.
3. Read downtime from M_{ct}.

Figure 5-1. Downtime Nomograph (Ref. 10, 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:

$$R_s = P_r \cdot P_s \qquad (5\text{-}1)$$

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

$$P_r = \frac{t_m}{t_m + t_r} \qquad (5\text{-}2)$$

where t_m = mean-time-between-failure

t_r = mean-time-to-repair

$$P_s = e^{-\frac{t}{t_m}} \qquad (5\text{-}3)$$

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.

$$R_s = R_1 \cdot R_2 \cdot R_3 ---- R_n = \prod_{i=1}^{i=n} R_i \qquad (5\text{-}4)$$

When eq. (5-4) is used in conjunction with eqs. (5-1), (5-2), and (5-3), individual repair rates can be established for each piece of system equipment through consideration of reliability and overall system operational readiness requirements.

TRADE OFFS

The term trade off denotes a procedure used as an aid in decision making. In general, the procedure includes comparing two or more parameters to determine their relative significance and quantitative relationship, and using the data so gained to select the optimum combination of the parameters so that the most advantageous action can be taken.

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 in the reliability section of the fifth quarterly progress report.

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. 5-2.

(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.

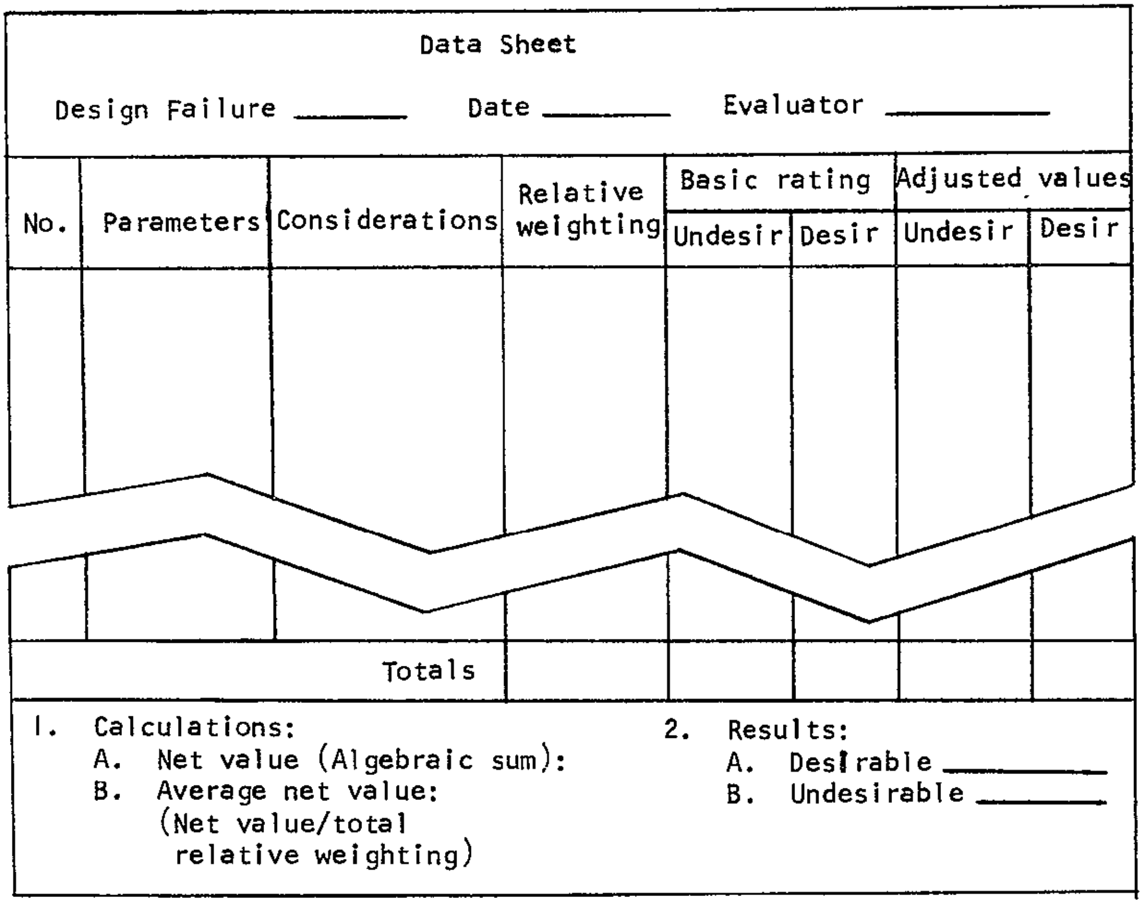
(5) Evaluate the design and its affect on each system characteristic or other parameter. Care must be taken that each characteristic associated with a design is evaluated in isolation and never influenced by other characteristics. The evalutation should be made by a qualified individual or group, and from the evaluation finding, the evaluator assigns a positive or negative number to represent value for desirability (or undesirability) as shown in fig. 5-3.

(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 5-2. Data Sheet for NSIA Trade-off Technique

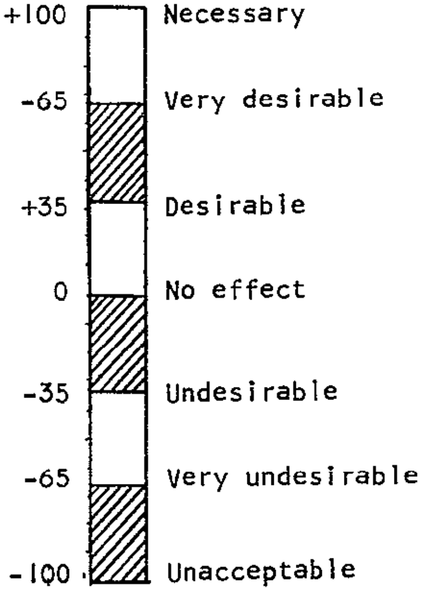


Figure 5-3. Basic Rating Scale

SECTION 6

APPROACH TO DEFINE RELATIVE WEIGHTED FACTORS WHICH DETERMINE SYSTEM EFFECTIVENESS

This section describes part of the material on relative significance of factors which determine system effectiveness. The remainder of the material will be presented in the next quarterly progress report.

General Considerations

When the term effectiveness is used in connection with relative weighted factors, it implies cost effectiveness. There is a growing awareness of a need for measures of system effectiveness in relationship to their cost.

Cost-effectiveness, more simply engineering economics, is concerned with estimation of costs and the evaluation of the worth or effectiveness of systems, to which the time element may be added. To place cost-effectiveness in a proper perspective, the systems engineering process must clearly be understood. In system design, many different requirements must be taken into consideration. These requirements are illustrated in fig. 6-1. In addition to the more familiar requirments of performance, safety, reliability, and packaging, 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 trade offs among these parameters. The methodology for combining each of these parameters into the optimized system, as well as for handling each one separately within its own discipline, is called the design process.

Design of a system is essentially a decision process. Decisions involve the future; this, in turn, requires prediction and prediction is, by its nature, uncertain. The realm of uncertainty is probabilistics. In large measure, the probabilities that must be employed are subjective. They are based on experience and knowledge of the physical phenomena that govern performance. Also, probabilities are influenced by new information. Therefore, it is important to understand how information influences the decision process.

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. Effectiveness, in contrast to cost, connotes the desirable effects or benefits gained by reason of the expenditure or incurring of a cost. Effectiveness also connotes some measure of performance or level of output of the benefit producing system.

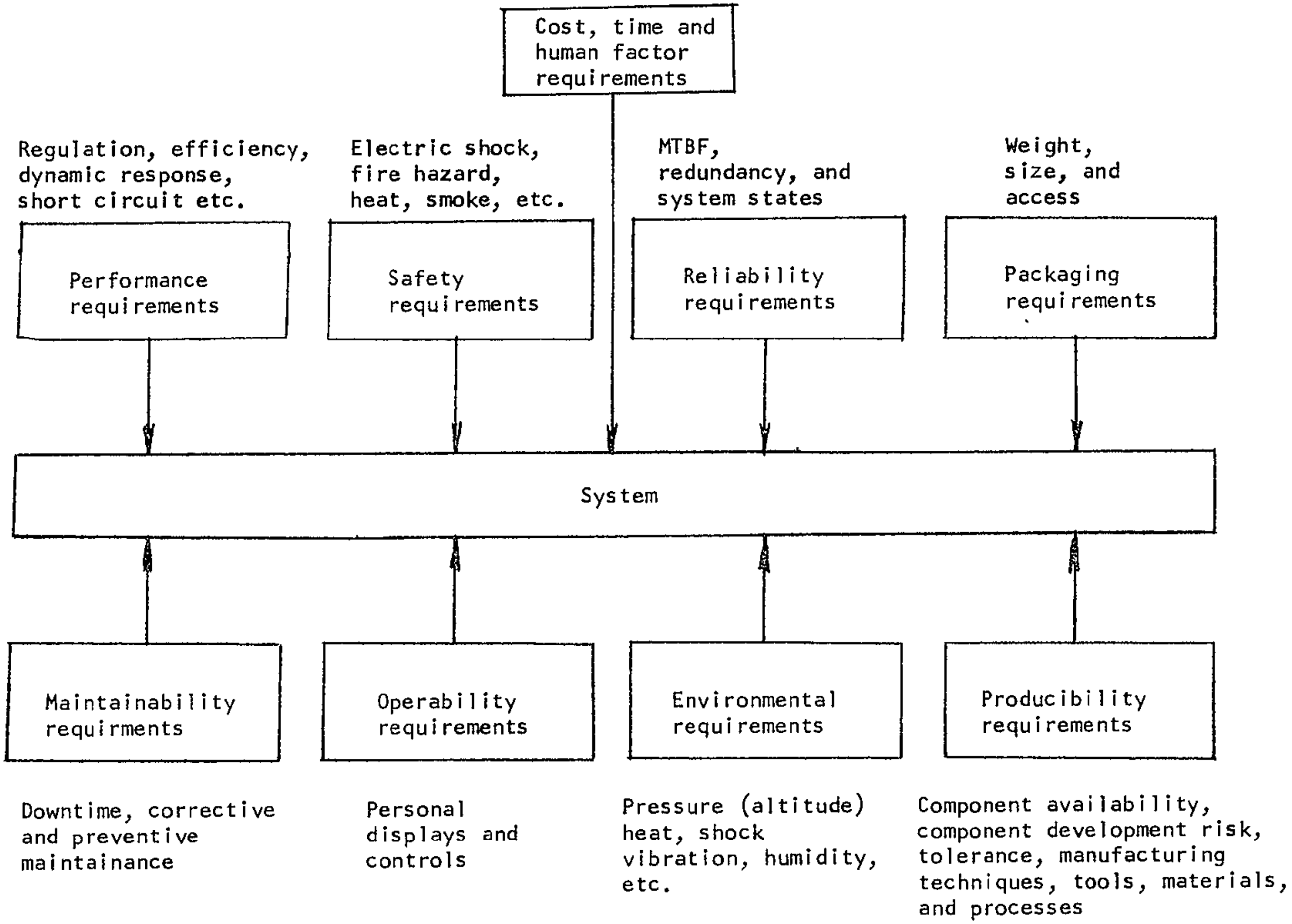


Figure 6-1. Framework of System Design

System worth.--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,

$$\text{maximize } U = f\ (X_1, X_2 \ldots\ldots\ldots X_n)$$

Where X's are the value variables, some are positive (benefits) and others negative (costs).

Identification of Trade Off Criteria for the Aircraft Electrical System

Referring again to fig. 6-1, there are eight basic needs imposed on the system. By closer examination of these requirements, the environmental requirements are misplaced because they represent a fixed set of external conditions over which the designer has no control. The environmental requirements, however, are shown as a separate block because of their significant influence on system design. They should, therefore, not enter in the trade-off evaluation; instead, they should serve as input requirements for system performance. Further, some of the demanding functions on the system are more significant than others; the level of importance is different from one requirement to another. A qualitative analysis should be made to assign each set of requirements a priority number. A quantitative analysis should follow to establish the relative weighted factors to obtain a measure for meaningful trade-off criteria.

Safety requirements.--Safety is one of the most difficult criteria to identify 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 center 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.

Safety concerns are related to system reliability. 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 of primary importance in the decision process. For this reason, safety itself should not be subject to a trade-off evaluation. Safety may reflect its requirements under reliability, maintainability, or operability categories. It is estimated that the effectiveness could be distributed as follows:

(1) Reliability ------ 60 percent

(2) Maintainability -- 30 percent

(3) Operability ------ 10 percent

Producibility requirements.--Producibility concerns (1) whether a system component is a shelf item, and if it is not, what is the development risk involved, and (2) the manufacturing processes, tolerances, materials, and tools used in producing system components.

For a new system, evaluation of the development risks of the new components in that system is an important criterion, since the practicality of that system depends on the success of component development.

The manufacturing processes, tolerances, tools, etc. determine the initial as well as maintenance costs of components. Aside from the requirements of manufacturing techniques, particular attention also should be given to system installation. This is especially true for the electrical distribution subsystem. Here a careful choice of installation configuration and optimum utilization of space with consideration to access and maintenance ease could leave a marked influence on maintainability.

Performance requirements.--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 characteristic of one system in any particular area can be readily compared to the corresponding characteristic of the other system.

Important characteristics of the ac power system are.

(1) Steady-state voltage and frequency

(2) Transient voltage and frequency

(3) Overload characteristic

(4) Short-circuit characteristic

(5) Efficiency

(6) Phase unbalance

(7) Phase displacement

(8) Wave form

(9) Harmonic content

(10) Dc content

(11) Amplitude modulation

(12) Frequency modulation

(13) Radio noise

(14) Real and reactive load division (parallel operation only)

Important characteristics of the dc-power system are:

(1) Steady-state voltage

(2) Transient voltage

(3) Ripple

(4) Ripple frequency

Also, the quality of the electrical power is allowed to degrade from normal to abnormal, and abnormal to the emergency operation mode. For grading total system performance, the following evaluation procedure may be considered.

If a system meets the required minimum performance level as stipulated by the procuring agency (this might be entirely different from present established standards), the system may be graded as 100 percent conforming. Any upgraded performance capability that can be demonstrated by the system will increase its value in proportion to the required minimum. For example, if the steady-state voltage variations are allowed within the tolerance band of ±2 percent and the system in evaluation demonstrates a capability of regulating to ±1 percent, the figure of merit in this particular area is 50 percent. The system exceeding specifications does not always result in increased benefits. For some areas, it is important that minimum requirements are met since superior characteristics beyond and above these are of little significance. The above mentioned figure of merit must be adjusted accordingly. For contempory aircraft electrical power systems, the areas most desirable to improve are listed in the order of importance below.

Dc power

(1) Duration of transient voltage to a minimum

(2) Excursion of transient voltage to a minimum

(3) Ripple reduction

(4) Higher efficiency for conversion

Ac power

(1) Transient voltage duration to minimum

(2) Transient voltage excursion to minimum

(3) Maximum efficiency

(4) Closer steady-state frequency regulation

(5) Minimum radio noise

(6) Minimum total harmonic content

(7) Minimum amplitude modulation

(8) Least parallel power losses

Operability requirements.--The increased complexity of modern aircraft systems demands more and more operation skill and training. As one authority recently stated, "it requires almost an electrical engineer for effective and swift manipulation of the electrical system". It is, therefore, highly desirable to simplify operational requirements by adopting automated operational schemes. This is not so much beneficial from a cost-savings viewpoint for training professional personnel as it is from a safety aspect.

If system operation is automated to the extent that decision making is taken away from the operator, human factor requirements are reduced and the possibility of mismanagement eliminated. Also, instrumentation and displays will be minimized, easing the continued effort to relax cockpit congestion.

The near future will see fully automated operation of the electrical system. Proposed schemes like automatic load management have been studied and are under evaluation. Meanwhile, the operability requirements may be valued as follows:

(1) Is mismanagement which could lead to a temporary total power loss possible?

(2) What is the probability of the above happening?

(3) Do check-out and operating procedures require decision making?

(4) Is information display and instrumentation such that, if required, corrective action by the operator could be initiated?

Evaluation of the above points, for which some statistical data are necessary, enables the designer to affix a coefficient of merit to each of the requirements.

Discussions of packaging, reliability, and maintainability requirements will be included in the next quarterly progress report.

Equipment Weight Criteria

One of the most important factors for all airborne application is equipment weight. Experience shows that each additional pound of equipment requires 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 pound of equipment weight 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 to obtain the highest economy or yield maximum profit. While it is extremely difficult to apportion fixed relative values to each and all of the cost effecting variables, a few system parameters can be more readily compared and evaluated for their individual contribution toward cost effectiveness. These parameters are equipment (system) performance, weight, and size.

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.).

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

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

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

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

(4) 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).

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. This 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 lb/h/lb (lbs of fuel necessary to carry 1 lb of aircraft weight for 1 hr).

(2) The engine specific fuel consumption for energy SFC_E lb/kWh (lbs of fuel necessary to obtain 1kWh output of the main propulsion engine).

(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 for the flight weight then is (the portion of weight for fuel is at take-off):

$$W_F = W_I + \frac{W_I\, SFC_{W.}\, t}{L/D} + \frac{\text{kWh}\ SFC_E}{\eta} + \left[\frac{W_I\, SFC_W \cdot t}{L/D} + \frac{\text{kWh}\ SFC_E}{\eta}\right] \frac{SFC_{w.}\, t}{L/D\ 2} \qquad (6\text{-}1)$$

The expression in the bracket is a fuel penalty of the required fuel. Assuming specific representative values, then

Total installed weight W_I = 10,000 lb

Specific fuel consumption weight SFC_W = 0.8 lb/h/lb

Specific fuel consumption energy SFC_E = 0.3 lb/kWh

Lift-to-drag ratio $L/D = 10$

Equipment efficiency $\eta = 0.8$

Total energy demand $\text{kWh} = 400$

Average flight duration $t = 4$ hr

$$W_F = 10{,}000 + \frac{10{,}000 \text{ X } 0.8 \text{ X } 4}{10} + \frac{400 \text{ X } 0.3}{0.8} +$$

$$\left[\frac{10{,}000 \text{ X } 0.8 \text{ X } 4}{10} + \frac{400 \text{ X } 0.3}{0.8}\right] \text{ X } \frac{2 \text{ X } 0.8}{10} = 13{,}885 \text{ lb}$$

If efficiency is to be expressed in equipment flight weight, eq. (6-1) may be rearranged with total energy demand and flight duration held constant.

$$W_F = W_1 \left[1 + \frac{SFC_W t}{L/D} + \frac{SFC_W t^2}{2(L/D)^2}\right] + \frac{1}{\eta}\left[\text{kWh } SFC_E + \frac{\text{kWh } SFC_E SFC_W \cdot t}{2 \; L/D}\right]$$

$$W_F = W_1 K_1 + \frac{K_2}{\eta} \tag{6-2}$$

In eq. (6-2), $W_1 K_1$ represents the weight term and $\frac{K_2}{\eta}$ is the energy term.

Using the previous numerical example, $K_1 = 1.3712$ and $K_2 = 139.2$.

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 0.3 to 1 lb 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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SECTION 7

FAILURE PREDICTION, DETECTION, AND COMPENSATION

Introduction

Increasing complexity and sophistication in various types of aircraft equipment and systems has resulted in increased maintenance problems, stringent requirements for safety and reliability, and emphasis on cost reduction, which have necessitated the development of various equipment and systems that can detect, predict, and compensate component and system failures. In general, failure detection and prediction systems include (1) automatic test equipment (ATE), (2) built-in test equipment (BITE), and (3) aircraft integrated data systems (AIDS). The following discussion is limited, however, to airborne equipment; any discussion on automatic test equipment or similar types of ground support equipment is therefore excluded.

Advantages of AIDS

AIDS have been employed for both military and commercial aircraft. The advantages of the AIDS system, which generally has the capability of predicting impending failures, are discussed below. Generally, AIDS measures many parameters related to various subsystems. Since this study program is devoted to improvement of the aircraft electrical system, only failure detection, prediction, and compensation aspects related to this particular system are discussed.

Improved overhaul life.--Component overhaul life has been traditionally based on flying hours. With the proper monitoring system provided by AIDS, the condition of the component is known flight by flight. Therefore, any maintenance service can be scheduled at the proper time, thus preventing waste of manpower and component useful life.

Reduction of secondary damage.--For systems utilizing out-of-tolerance checking and long term trending techniques, an impending failure will be detected in its incipient stage. Extensive and expensive secondary damages therefore can be avoided, and due to the early detection of a failure, optimum maintenance scheduling for required repairs can minimize aircraft downtime.

Improved aircraft operation and utilization.--As a broad generalization, aircraft operation is a function of reliability and maintenance efficiency. By using AIDS, dispatch reliability can be improved, turnaround time can be minimized, and enroute maintenance can be performed correctly to avoid repetition.

Increased flight safety.--Excluding those caused by instantaneous failures, aircraft accidents and failures generally result from unnoticed performance deterioration. Accelerated deterioration can occur between formal inspections and go unnoticed, or it can take place at locations not visible by normal techniques or not properly monitored by current instrumentation. The continuous monitoring capability of AIDS ensures constant surveillance of selected parameters and a warning of any deviation from predetermined limits.

Improved crew proficiency analysis.--Aerodynamic performance and control setting data can be recorded and used to assess aircrew proficiency or pilot trainee progress.

Reduced operating cost.--The use of AIDS will (1) reduce maintenance and turnaround time, (2) increase dispatch reliability and safety, (3) reduce the amount of support equipment required for inventory and maintenance purposes, and (4) reduce the skill level required for maintenance personnel. These factors reduce operating cost and increase revenue.

Deterioration Modes

Most subsystem and component failures can be grouped under the categories of gradual deterioration, accelerated deterioration, and instantaneous deterioration (fig. 7-1).

Gradual deterioration.--The deterioration of the electrical insulation operating at the design temperature can be classified as gradual. Under constant temperature, insulation resistance decreases as time increases. Since the deterioration rate is gradual, the insulation failure is therefore relatively predictable. However, in practice predictive accuracy is significantly reduced by variables that may accelerate or decelerate the deterioration rate. For electrical insulation, temperature is one of these variables.

Accelerated deterioration.--Accelerated deterioration occurs in a relatively short time interval as compared with gradual deterioration (fig. 7-1). A well-lubricated bearing operating at relatively low stress levels would belong to this category. A well-lubricated bearing will operate for an indefinite period of time without perceptible deterioration. However, when the lubricant is contaminated, it can deteriorate rapidly. Since the time between an acceptable standard of condition and a standard of malfunction may be quite short, the failure associated with the accelerated deterioration is difficult to predict.

Instantaneous deterioration.--In instantaneous deterioration, the failure occurs with practically no deterioration or malfunctions before the event. Most light bulbs fall into this category. It is difficult, if not impossible, to predict this type of failure.

Parameter Selection

Since AIDS cost and cost savings resulted from AIDS use increase with the number of system parameters monitored, and since an abundance of parameters is not necessarily more cost-effective than a smaller subset, the selection of AIDS parameters becomes very important. Many factors must be carefully considered. By establishing a suitable evaluation criterion, such as converting all AIDS benefits (savings in downtime, availability, dispatch reliability, labor man-hours, skill levels, spares and logistics support, etc.) into a common unit (e.g., dollars), and by applying this criterion to various aircraft subsystems, an optimal selection of AIDS parameters can be obtained.

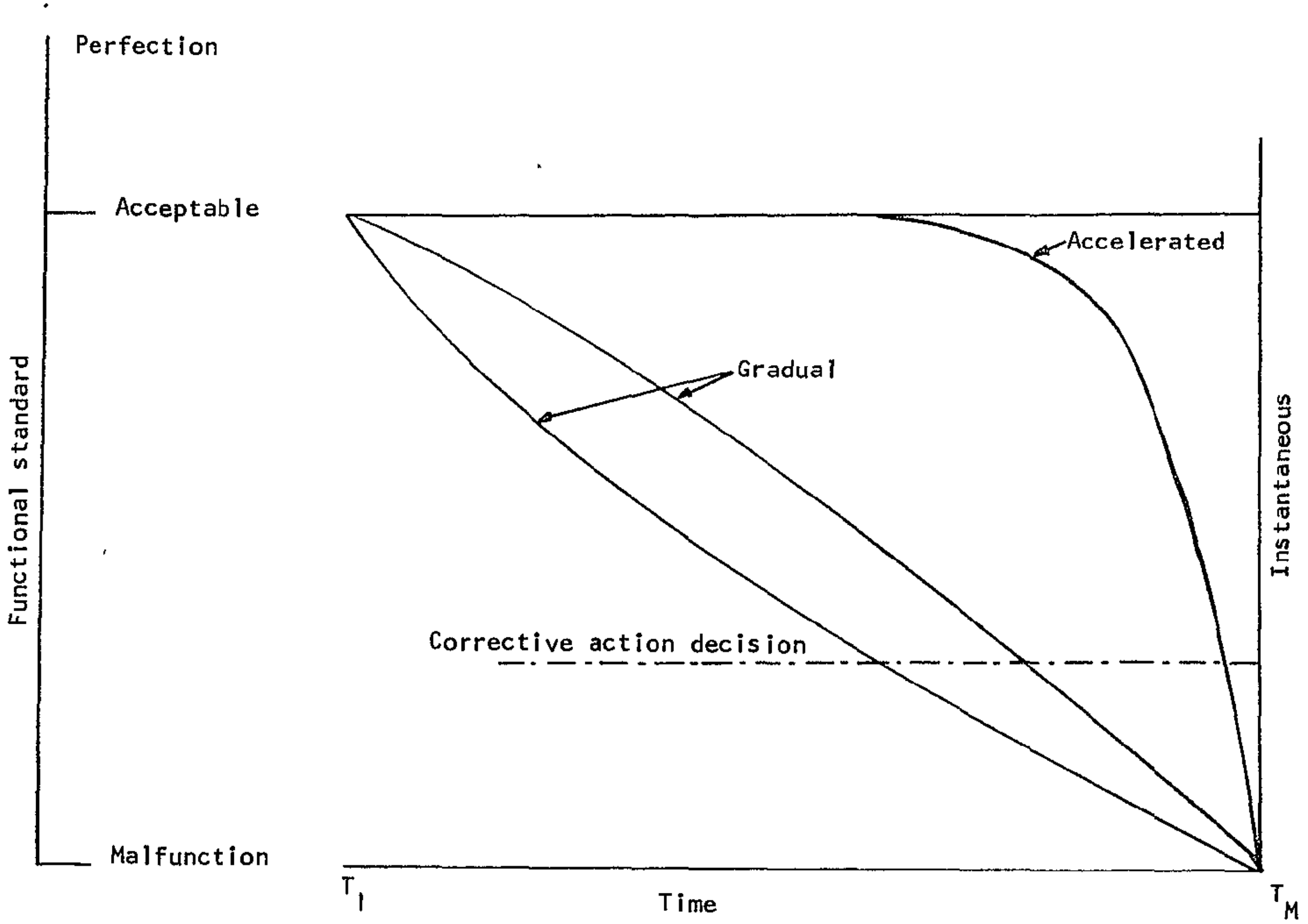


Figure 7-1. Deterioration Modes

Although criteria can be developed to test the effectiveness of one group, they cannot be compared on an absolute basis. Thus, some ingredient of expertise will remain in the initial selection of parameter subsets for evaluation (i.e., in the selection of ways of detecting various line replaceable unit (LRU) failure modes). These matters result from the AIDS group experience and understanding of new applications as well as their receptiveness to new developments. With sufficient experience, innate considerations are actually made without any formal rules. This greatly simplifies, but does not completely satisfy, the parameter selection process. These general considerations are discussed in succeeding paragraphs.

Subsystems analysis techniques.--In cause and effect analysis, the various modes in which failures are most likely to occur in each system are tabulated. Each failure is then individually analyzed as to what its effect might be, both primary and secondary and for the parameters which might reflect this effect. This assists both in selecting those parameters which include the majority of anticipated failures and in diagnosing the original fault by logical checking of a progressive signal sequence.

Failure data analysis: In this technique, historical failure data on the aircraft subsystem or on the component of interest (or on similar subsystems) are analyzed with regard to such factors as failure frequency, hazard rating, cost rating (including maintenance labor and logistics support), and correlation of failures to cumulative time (time since overhaul or stress life). The combined figure of merit, which can be derived from the analysis, provides a useful ranking for parameter selection.

Mathematical modeling: The function of most complex aircraft subsystems can be described by an appropriate mathematical model. By measuring the properly selected system parameters, it is possible to determine the deviations in system performance due to certain component deterioration.

As a practical consideration, the mathematical model for many subsystems, although theoretically feasible, may not produce sufficient unique data output to be cost effective for inclusion in AIDS programming. The technique is extremely useful in particular cases, however, where a comprehensive performance analysis is required.

General engineering analysis: Under the category of general engineering analysis is a group of extremely critical evaluations in which system interface relationships are evaluated. These are listed below:

(1) A detailed study of aircraft subsystem configuration, including wiring, electrical junction points, signal levels, LRU details, transducer used for non-AIDS instrumentation, etc., to arrive at an AIDS design which is functionally adequate but has a minimum of aircraft modification requirements.

(2) A review of current non-AIDS maintenance procedures, with emphasis on subsystems and LRU's that are high-maintenance-man-hour items or that offer special troubleshooting difficulty to the normally available maintenance crew.

(3) A review of logistic costs of providing sufficient spares at each terminal, both on a non-AIDS and AIDS basis, with emphasis on AIDS assistance for monitoring high-cost LRU's.

Cost-effectiveness tradeoff studies: Although cost effectivity is the overall goal of the AIDS systems analysis and is therefore implicit in all of the other analyses, specific studies related to parameter selection are useful. In previous studies, for example, AiResearch has utilized four basic parameter selection criteria as inherent measures of cost effectivity. These are:

(1) Sensitivity--the relationship of the magnitude of changes in individual parameters to changes in evaluation functions derived from these parameters; low sensitivity implies additional cost necessary to make acceptable use of the data.

(2) Feasibility--the determination as to whether a particular measurement approaches the state of the art. Again, measurement cost increases with such close approach.

(3) Balance--the relative weighting of the cost of obtaining a particular data item against the utility derived from the information.

(4) Adequacy--the measure of data necessity as weighed against alternate non-AIDS procedures.

Technical feasibility.--The technical feasibility of monitoring a given parameter is a function of the original signal form and the complexity of the sensing, transduction, and conditioning equipment required to transform the signal into a form compatible with AIDS input requirements.

In general, signals that are already electrical in nature offer maximum AIDS capability since usually only isolation and scaling circuitry are required on an individual channel basis, while conditioning and/or conversion can be furnished on a time-shared basis within the AIDS hardware. In this category are dc or low-frequency ac voltages and currents, synchro signals, pulses at low repetition rates, variable resistances, etc.

Exceptions to this are signals containing very high frequencies, special waveshapes, or transient components. Monitoring the RF output of a transmitter or pulses in a radar or doppler set is technically feasible but expensive since special purpose signal conditioners are required for each such channel and would not usually be capable of time-shared use.

Nonelectrical parameters, such as pressures, temperatures, displacement, and acceleration, may necessitate additional transducers for interfacing with AIDS. This is true if the interface characteristics of the transducer inhibit paralleling AIDS across the transducer outputs.

From a technical feasibility viewpoint, therefore, the likely priority for AIDS monitoring is (1) parameters with electrical signals available in AIDS-compatible form, (2) parameters with electrical signals available, but not in AIDS-compatible form, (3) parameters with no available electrical signals, but for which standard transducers are available, and (4) parameters requiring non-standard transduction and/or signal conditioning.

Adequacy.--The measure of data necessity to the user is dependent on the priority assigned to AIDS objectives. For the dual objectives of improving dispatch reliability and reducing aircraft turnaround time, for example, the emphasis is placed upon (1) those subsystems necessary for takeoff and (2) the particular LRU's which could impose the greatest delay in ability to turn the aircraft around quickly for another flight. For the objective of reduced maintenance costs, however, emphasis is upon monitoring high-maintenance-man-hour items and high-cost LRU's. These may in some cases correspond and in other cases conflict with the parameters selected for the first two objectives.

Where parameters are defined by users, they will be adhered to in ranking parameters for adequacy. In other cases, AiResearch will utilize its previous AIDS experience to recommend an adequacy ranking.

Sensitivity.--To some extent, the sensitivity extension overlaps technical and economic feasibility factors, since, for example, a low-sensitivity parameter can have its sensitivity increased through the addition of electrical or mechanical amplification at some point. If, however, even with reasonable amplification to deviations in a parameter, values are insufficient to permit accurate fault detection and isolation, the parameter will not be recommended for monitoring by AIDS.

Failure Modes of Components and Subsystems

The aircraft electrical power system includes three major subsystems: power generation, power distribution, and power utilization. In each subsystem, numerous devices of various types are used. Without an extensive evaluation of the failure modes of the components and subsystems and the associated characteristics, it is extremely difficult to determine which components should be monitored and which parameters should be measured. From a preliminary investigation, however, some techniques and approaches are found to be feasible. In the following sections, the failure modes and the possible means of detecting and predicting failures for the above mentioned subsystems are discussed.

Power generation.--In a modern commercial aircraft, the electrical power generation system usually consists of a primary ac system and a dc system. The primary ac system is a 400-Hz, 115/208-V, 3-phase system with one generator per engine. It is a critical system of the aircraft and is required for the proper functioning of all control and conditioning systems. Electrical power is supplied by the engine-driven synchronous generators while in flight and by the APU generator (if so equipped) on the ground. The constant speed drive (CSD) and generator package constitute the primary source of maintenance and fault problems in the primary ac system. These should be of principal concern for AIDS.

Also, certain generator parameters (e.g., voltage and current) will indicate the condition of the remainder of the primary ac system with few exceptions. A long history of operating performance on aircraft CSD-generator packages gives clear indication of the major causes for failure or the need for maintenance in this package. Based on experience and technical documents, the generator elements most likely to fail are considered, in order of importance, to be (1) bearings, (2) spline or coupling, (3) electrical windings, (4) voltage regulator, and (5) rectifiers.

The first two items are the most significant and have resulted in the routine maintenance schedules. A typical schedule might be (1) the removal of the complete generator package after a certain number of service hours, (2) the replacing of all bearings and couplings, (3) the checking of insulation resistance and rotor balancing, and (5) cleaning or painting for reuse. In-service inspection of these components generally has been found unfeasible. Failure modes are of both the gradual and instantaneous mechanical type resulting principally from shock, vibration, excessive temperature, etc.

Bearing failure is normally preceeded by a period of erratic breakdown and reconstitution of oil film between the journal and the bearing or between the balls or rollers and the bearing races. Impending bearing failure can be predicted by measuring the electrical insulation (due to oil film) between the journal and the bearing or between the bearing races. When the electrical insulation begins to show erratic short circuit, the bearing is about to fail.

Voltage surges caused by sudden load changes and shorted or open circuits also may result in deterioration or breakdown of electrical insulation in any part of the system. However, there is no reliable relationship between voltage spikes or surges in an electrical power system and the voltage gradient across a given insulating medium in a certain section of that system. Hence, voltage abnormalities that can be measured with relatively simple instrumentation would be of little value in predicting generator insulation failures. Excessive temperatures also degrade electrical insulation. Possible methods of relating insulation life to temperature will be discussed later. The temperature rise in a generator winding can serve as a valuable indicator of some abnormality, such as the shorting of several coils in the stator winding, abnormal load, or open circuit in the primary ac system. Another possible means of predicting insulation failures is by monitoring the insulation resistance. The relatively few failures that might be predictable in this manner, however, might not justify the high cost and complexity of such measurements.

The silicon rectifier assembly generally used on the brushless machines is extremely reliable and maintenance free. Although voltage spikes will destroy a silicon rectifier, all silicon rectifiers used in this application are usually operated at low voltages (1/3 or less of rated values) and are protected by semiconductor surge suppressors. The failure of the silicon rectifier is of the instantaneous type, and there is no known method for predicting the failure.

The voltage regulator, although packaged separately from the generator, can be considered as part of the primary ac system since it controls voltage levels. The regulator contains no moving parts and operates at low insulation stress levels. It is therefore not subject to any gradual deterioration and should never require maintenance. Failure of this component can probably result only from excessive temperature and extreme voltage surges. Temperature might be the only parameter that can be monitored for predicting regulator failures.

To summarize, the following parameters should be monitored for the generator and voltage regulator.

(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).

The hydraulic constant speed drive requires frequent maintenance and therefore is worth consideration for failure prediction and detection. Impending failure of the CSD is indicated by hydraulic unit wear. Hydraulic unit wear is best shown by measurement of volumetric efficiency or case drain leakage. Measurement of variable displacement unit cam plate angle appears to be a good method of measuring volumetric efficiency. An investigation revealed that this method is not practical due to excessive accuracy requirements imposed on engine speed and cam plate position measurements. Direct measurement of case drain flow from each hydraulic unit is believed to be the best method, based on direct measurement with a rotor-type flow measuring device (±10 percent accuracy is satisfactory).

CSD oil temperature rise is a measure of CSD efficiency, but establishment of operating limits is a function of engine speed and generator load, which would slow transient behavior following changes in load or flight condition. Comparison of the several drives on the aircraft will give a better indication of trouble in one unit. This same philosophy could be applied as easily to simply measuring temperature level (not temperature rise), assuming that all oil coolers were identical and had identical cooling air flows.

Measurement of trim head current will indicate drift of the CSD speed control nominal speed setting during parallel operation.

For CSD, the following parameters should therefore be measured and recorded.

(1) Hydraulic unit case drain flow

(2) Output speed

(3) Oil temperature

(4) Trim head current

The emergency APU generator can be treated the same as the main generator. The storage battery is considered as a reliable item. Cell temperature sensing, terminal voltage, and periodic ground check give sufficient indication of the working condition of the batteries.

Power distribution system.--The power distribution system includes such components as cables, busbars, switchgears, transformer-rectifier units, and connectors.

There are large numbers of cables, switchgears, and connectors on the aircraft. It is rather impractical to provide sensors in each component and to bring the large amount of signals to a central processing computer for failure prediction. The added sensors and signal wiring may reduce the system reliability to the extent that improvement in maintainability is meaningless. Presently, circuit breakers and fuses are used to protect cables and busbars, which is still the most sensible approach.

Since failure of rectifier units is of the instantaneous type, failure prediction for the rectifier is not practical. To aid in the fault analysis and general system performance analysis, however, the direct current outputs of the transformer-rectifier units should be measured and recorded. These output current values will indicate the condition of the TRU's and the variations in dc loading.

Fuses with blown indicators facilitate location and replacement by maintenance personnel and are therefore desirable.

Power utilization system.--Since there are large numbers of utilization devices in the aircraft, failure prediction schemes for only a few of the essential larger components that require extensive maintenance services are justified.

The load devices for mechanical motion basically consist of the various types of motors and actuators. The failure modes of these components are very similar to those of the generator. They include (1) bearing, (2) coupling, (3) brush-commutator assembly (for dc motors), (4) electrical insulation, and (5) electronic commutator (for brushless dc motors). For the bearing, temperature and oil film are good parameters to monitor for failure prediction. For the coupling, measuring the vibration is a possible approach. There is almost no economical means of monitoring brush wear or predicting brush failure in the brush-type machine. Brush lifetime can be predicted quite well from past experience, and barring failure from excessive voltage spikes, this is the only useful indicator of required maintenance. For electrical insulation, possible techniques include measuring the insulation temperature and/or insulation resistance. Since semiconductors fail instantaneously, there is no means of predicting the electronic commutator failure. The incandescent light filament and the coil of the heating devices fail instantaneously. Although the change of resistance in some cases indicate the aging phenomena, no reliable relationship between the change of resistance and the deterioration of the element has been established. Predictive types of monitoring for these components are therefore impractical.

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, 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:

$$\ln t = \frac{b}{T} - a \qquad (7\text{-}1)$$

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

$$\ln R = b \left[\frac{1}{T_o} - \frac{1}{T}\right] \tag{7-2}$$

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. 7-2 to eq. 7-1, it can be derived that the relative aging is

$$R = \frac{t_o}{t} \tag{7-3}$$

where t_o and t are the insulation lives at temperatures T_o and T, respectively. Fig. 7-2 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.

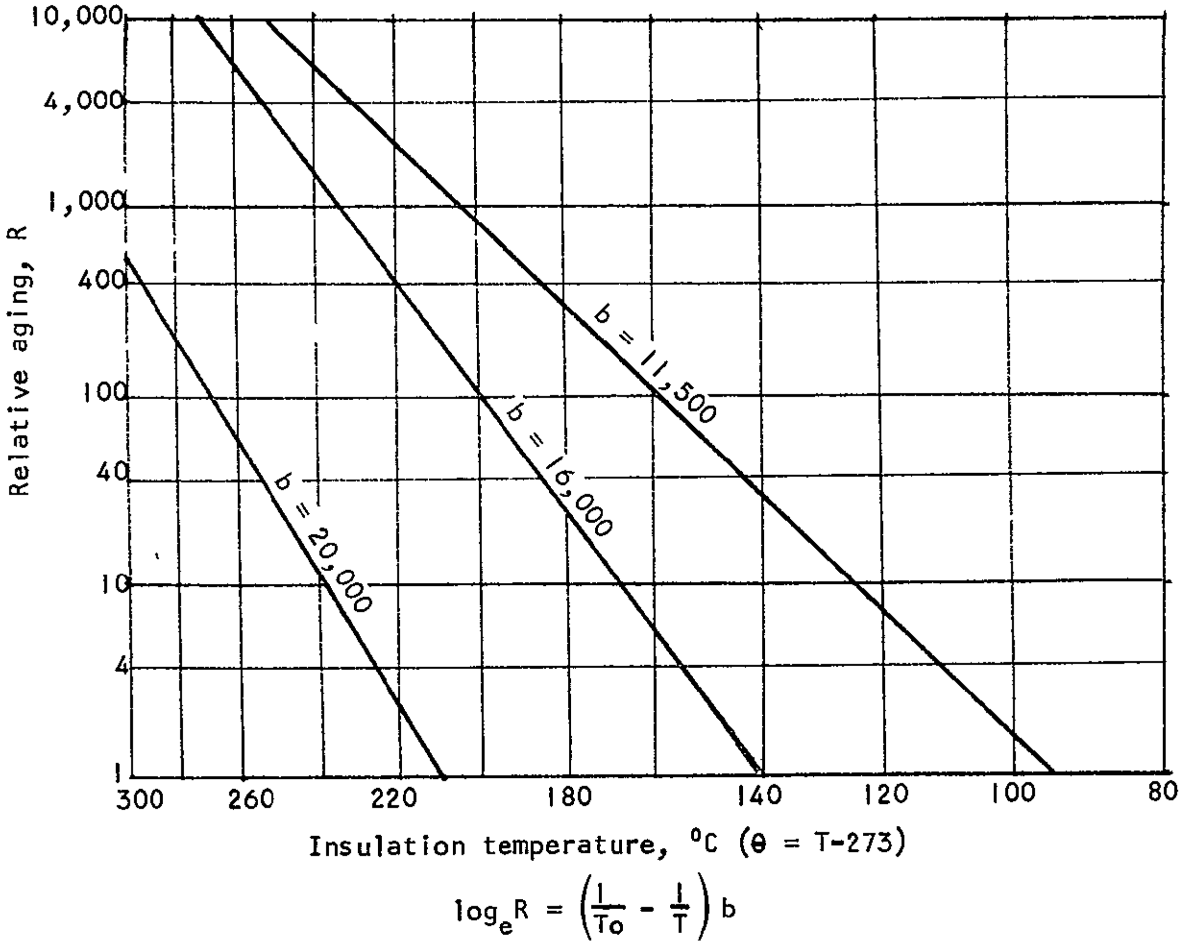


Figure 7-2. Examples of Relative Aging Curves with Representative Reference Temperatures and Various Aging Rates (Values of b) (Ref.11)

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.

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. 7-3 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.

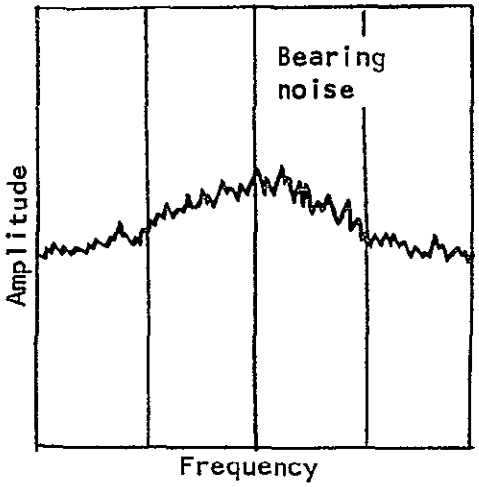


Figure 7-3. A Malfunctioning Bearing Noise

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.

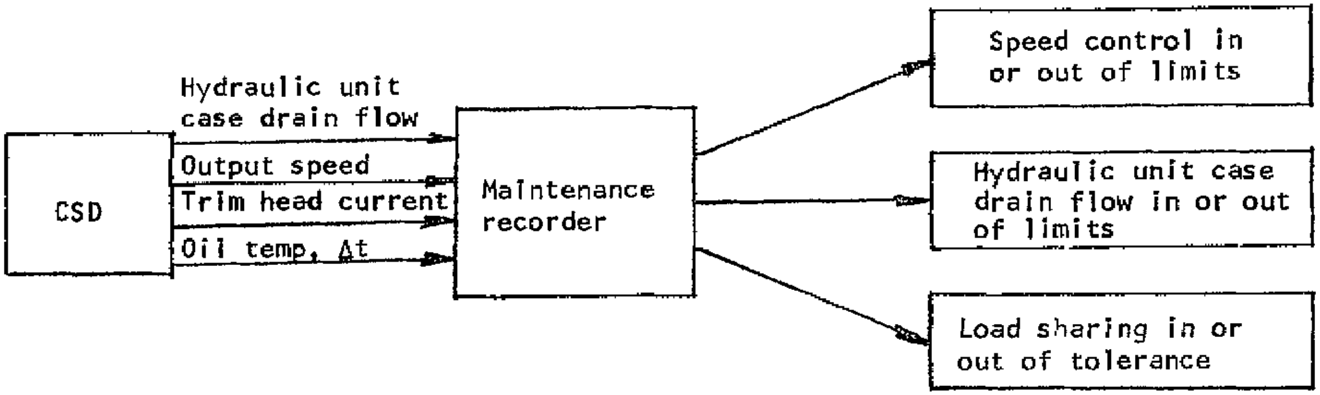
CSD parameters.--CSD hydraulic unit wear is best measured by the case drain flow. The case drain flow information is fed into a computer to compare with a preset limit that is a function of generator load. Limits will be programmed for cruise and for idle engine input speeds to accommodate inflight and 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. 7-4.

The unscheduled maintenance actions for the CSD with the above measurement scheme are shown in table 7-1.

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 7-4. CSD Failure Prediction, Maintenance Scheme

TABLE 7-1

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

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. 7-5, 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.

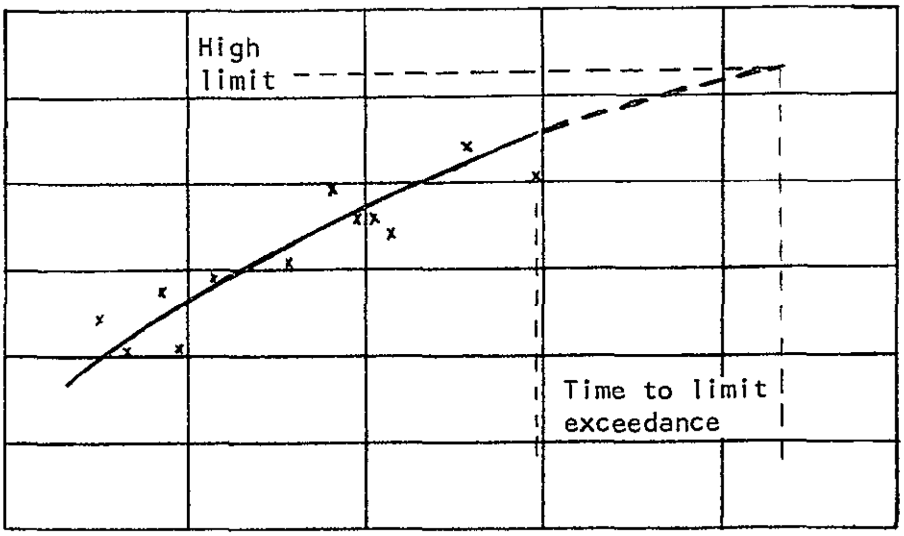


Figure 7-5. Least Squares Curve Fitting

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,

$$\bar{X}_t = \bar{X}_{t-1} + \alpha \left[X_t - \bar{X}_{t-1} \right] \qquad (7\text{-}4)$$

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

$$\bar{X}_t = \alpha \sum_{i=0}^{t-1} (1-\alpha)^i X_{t-i} + \alpha (1-\alpha)^t X_o \qquad (7\text{-}5)$$

which shows why the process is called exponential smoothing.

Exponential smoothing may be represented by an operator as follows:

$$S_t (X) \equiv \bar{X}_t = \alpha X_t + (1-\alpha) S_{t-1} (X) \qquad (7\text{-}6)$$

For higher degrees of smoothing, the nth order operator is defined

$$S_t^n (X) = S \left[S_t^{n-1} (X) \right] = \alpha S_t^{n-1} (X) + (1-\alpha) S_{t-1}^n (X) \qquad (7\text{-}7)$$

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.

$$\bar{X}_{t+\tau} = a_t + b_t \tau \qquad (7\text{-}8)$$

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

$$a_t = S_t \ (X) = \bar{X}_t \approx \alpha \ X_t + (1-\alpha) \ S_{t-1} \ (X) \tag{7-9}$$

$$b_t = S_t \ (\Delta X) = \bar{\dot{X}}_t = \beta \ (\bar{X}_t - \bar{X}_{t-1}) + (1-\beta) \ S_{t-1} \ (\Delta X) \tag{7-10}$$

since $\bar{X}_t - \bar{X}_{t-1} = \alpha \ (X_t - \bar{X}_{t-1})$

$$b_t = \bar{\dot{X}}_t = \beta \ \alpha \ (X_t - \bar{X}_{t-1}) + (1-\beta) \ \bar{\dot{X}}_{t-1} \tag{7-11}$$

where $\bar{\dot{X}}_t$ 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 $X_{t+\tau}$ in eq. (7-8) by the limit of parameter L and solve for τ; therefore

$$\tau_L = \frac{L - a_t}{b_t} \tag{7-12}$$

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. 7-6 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.

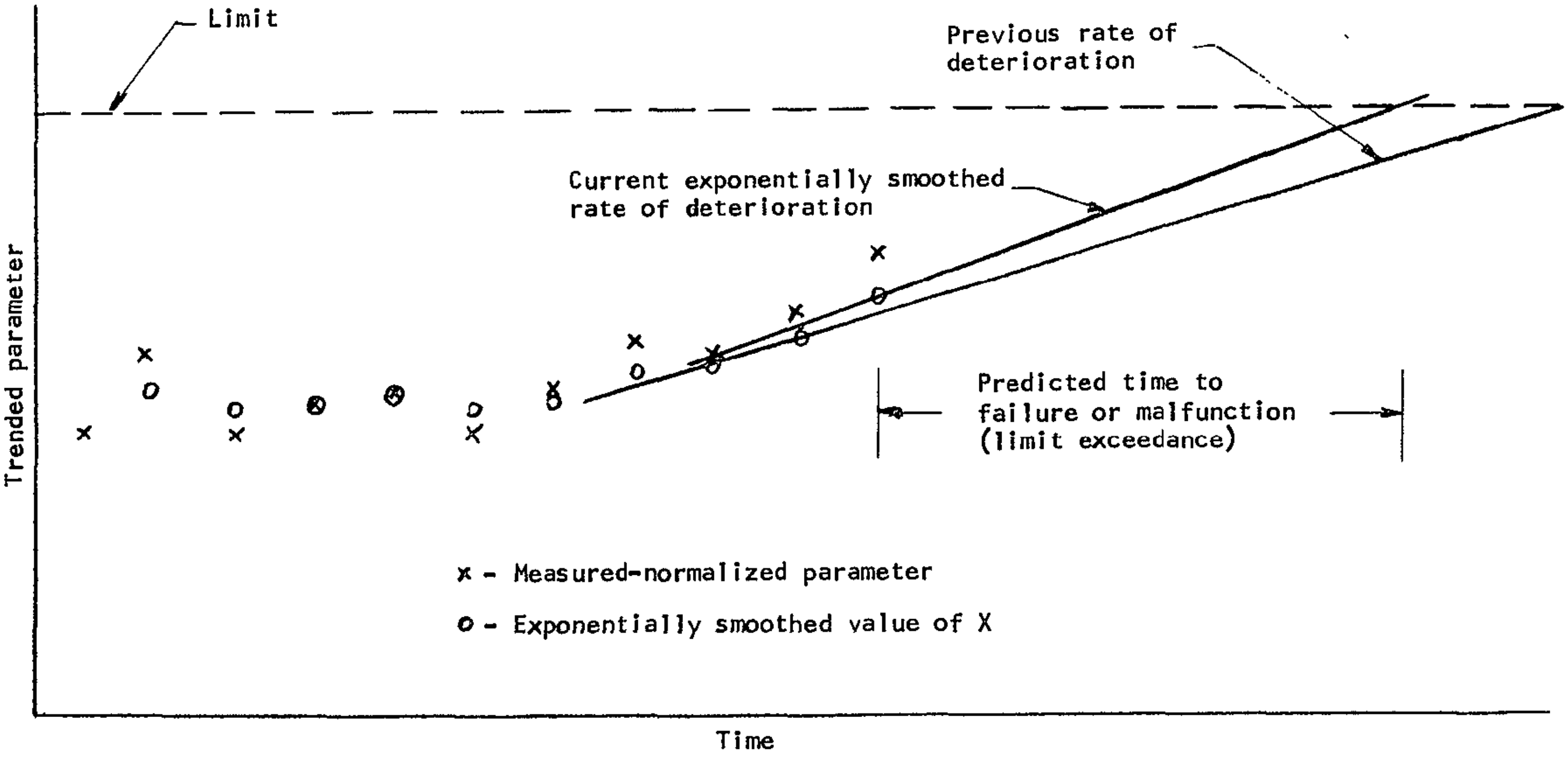


Figure 7-6. Exponential Smoothing Technique for Trend Analysis

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.

Information Display

Information displays of AIDS provide the flight crew with conditions of the monitored parameters (or components and subsystems). Since most of the tests are of the out-of-tolerance type, test indication will be bilevel, i.e., go or no go. This type of information can be easily displayed by appropriate lights or flags. Fig. 7-7 shows the failure annunciation panel of the L-1011 generator system manufactured by Lockheed. The indication lights are arranged in a matrix form wherein each row refers to a specific generation channel and each column represents the same type of components in various channels. When the condition of numerous components are to be displayed, appreciable panel space is required. A newly developed approach incorporates the use of a cathode-ray tube (CRT) display in which the condition of any component shows up as a color flag. As shown in fig. 7-8, a matrix of 8 by 12 corresponding to 96 components appears in real time or a color cathode-ray tube. Different colors of squares can be used to represent various conditions, such as white for normal, red for limit exceedances, and green for low values. In addition, a camera positioned to take color photographs of the target screen would provide a self-programming system.

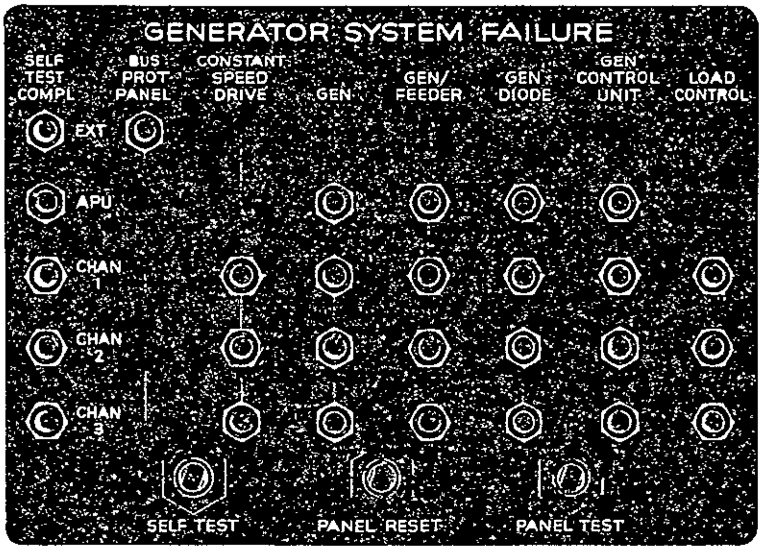


Figure 7-7. Failure Annunciation Panel, Lockheed L-1011 Aircraft (ref. 5)

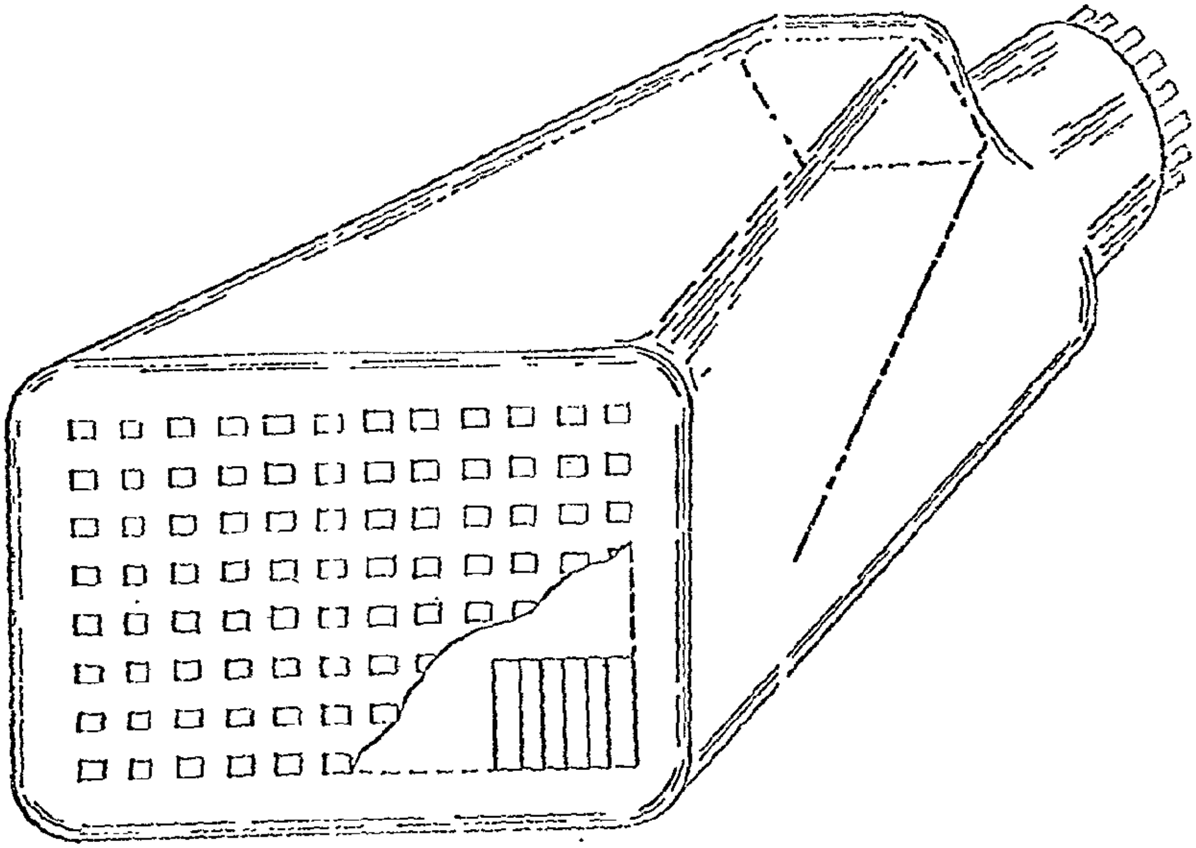


Figure 7-8. Cathode-Ray Tube Information Display

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.

SECTION 8

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