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Fifth Quarterly Progress Report

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

For

NASA Electronics Research Center
Cambridge, Mass.

Contract: NAS 12-659

68-4176 (5)

October 14, 1969



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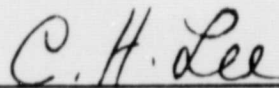
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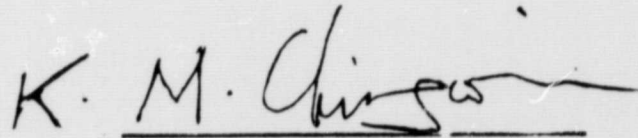
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October 14, 1969

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INTRODUCTION AND SUMMARY

This is the fifth quarterly progress report (the fourth quarterly progress report being the interim technical 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 14 May 1968 and will last to 14 July 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:

- Simplicity--A simpler system will be more reliable and more economical
- Automation--Additional automation will facilitate system manageability and increase aircraft safety
- 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.
- Protection--Better system protection will increase system safety
- Information Display--Better information display will also increase system safety
- Fault prediction, detection, and isolation--These will reduce maintenance cost and increase reliability
- Performance--Improved performance will result in higher efficiency and increased system capability
- 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 needs at that time with relatively small aircraft. 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 is therefore 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 in the sense of the objectives of this program.
- (6) Review and analyze the preferable power system heat transfer technique.
- (7) Specify the techniques and displays required such as failure prediction, detection and compensation, efficient energy management, and data monitoring for the acquisition and characterization of the electric power system.
- (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 in the sense of 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 classification of the electrical loads, and 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 three groups: (a) components in existing aircraft, (b) current technology components to be applied to aircraft, and (c) 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 effect 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.--During this quarter, trips were made to visit the General Electric Company in Waynesboro, Virginia, and the Westinghouse Electric Corporation in Lima, Ohio, to obtain their viewpoints, as the aircraft electrical hardware suppliers, on the aircraft electric power system. The results of these visits are described in this report.

Aircraft electrical equipment is classified into five groups according to the load function to be performed: i.e. heating, lighting, motor, control, and electronics. In discussing the optimum methods of supplying electric power to the loads, motor loads are treated first because they usually consume the largest amount of electric power. A graphical method of optimizing the electric drives for axial flow fans and centrifugal compressors is presented. With the aid of curves, the optimum speed and power required to drive any specific fan load for a given rate of volume and differential pressure can be determined. Investigations of optimum methods for: transferring fluids, heating, cooling, and control, as well as supplying power for electronic loads

are incomplete and are therefore not included in this report.

The possibility of applying new materials for aircraft electrical power components were investigated. Five types of materials are discussed here: (1) soft magnetic materials, (2) permanent magnet materials, (3) insulation materials, (4) conductor materials, and (5) structure materials. The weight savings of induction motors using hiperco 50 and transformers using supermendur are analyzed. Weight and efficiency data are presented on the brushless dc motor using samarium-cobalt material. The feasibility of using aluminum foil for transformer winding and sodium conductor for power transmission is evaluated. Also, the recent development in graphite composites that show high weight saving potentials in aircraft parts is briefly discussed.

Tradeoffs between component reliability and weight are discussed, and the mathematical relationship between design margin of safety and reliability is derived. Finally, specific examples of weight penalties resulting from improved reliability are given for some aircraft electrical power components.

Work Plan For The Next Reporting Period

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

- (1) Continue the study of optimum methods to supply electric power to individual loads.
- (2) Investigate component maintainability and its tradeoff against component weight and cost.
- (3) Survey and determine static and dynamic power requirements for present hydraulic and pneumatic powered loads, and establish the tradeoff criteria in the selection and application of electric or combined electric-hydraulic and electric-pneumatic power sub-systems for that purpose.
- (4) Specify techniques and displays required such as failure prediction, detection and compensation, efficient energy management, and data monitoring for the acquisition and characterization of the electric power system.
- (5) Survey and compare electric power system characteristic requirements for various types of aircraft such as supersonic, large subsonic, V/STOL, helicopter, small twin jet, executive jet, etc.
- (6) Determine the relative weight of factors that determine the "effectiveness" of the electric power system in the sense of program objectives.

INDUSTRY SURVEY

N70-25427

During the first year of this program, several visits were made to airframe manufacturers, government agencies, and aircraft users to obtain desired information for the study. Information sources missing from the complete industry survey in this field were generating system suppliers such as General Electric and Westinghouse.

August 6, 1969: GENERAL ELECTRIC
Specialty Control Department
Waynesboro, Virginia

The discussion at G.E. dealt with the subject VSCF cycloconverter, its history of development and the status of technology. G.E. stressed the need to look from an overall standpoint when evaluating various contemporary and new candidate electrical systems. Some of the advantages which would accrue with a VSCF system were pointed out as follows:

- (1) Single machine mounting on the engine accessory gearbox results in minimum nacelle space being occupied and reduced overhung moment. Engine interface could be optimized.
- (2) Pad speeds are not confined as with conventional systems, optimization yields weight and volume reductions.
- (3) Higher VSCF system efficiency will result in weight reductions because of lower fuel consumption and reduced cooling requirements.
- (4) At present it is felt that the G.E. system will have superior maintainability and higher reliability than the conventional system. The Navy has accumulated 1000 system hours for two 30-kVA systems. Only two failures were recorded: a failed diode in an undervoltage protection circuit and a ground fault in the stator winding of the generator (thermocouple wire for temperature recording failed).

Also, 800 system hours (270 airplane hours per system) were recorded on a Boeing owned 707-320 airplane with no failures. (3 x 40 kVA VSCF systems operated in parallel). Better maintainability will be achieved because of standardization, and 80 to 95 percent of all circuits will be common to all ratings. Modular construction for SCR's and heat sinks will allow selection of system ratings from 40 to 120 kVA. Possible combinations are:

Two 3-phase inverters in parallel for 40 kVA
Three 3-phase inverters in parallel for 60 kVA
One 9-phase inverter for 90 kVA
One 12-phase inverter for 120 kVA.

25427

Presently, G.E. is using a basic six-phase cycloconverter design for ratings from 30 to 75 KVA. In the range from 75 KVA to 100 KVA, a 9-phase design is used. For ratings above 100 KVA, 12 phases are being utilized.

- (5) Due to the better quality power which can be obtained from the VSCF system, some weight savings for portions of the loads may be realized. (Transformer design point is 400 Hz instead of 380 Hz as allowed for in MIL-STD-704). Also, less filtering will be required.

One of the disadvantages of the VSCF system is heavy weight. For example, the weight of a 60/75 KVA VSCF system for the Navy's S3A airplane being built by Lockheed was quoted at 126 lb. This includes the generator with 77 lb and the converter with control, protection and CT's with 49 lb. (A Sundstrand IDG drive of equivalent rating weighs only 103 lb).

G.E., however, claims that their 60/75 KVA system for the Navy S3A aircraft will still be lighter than a CSD system by 30-130 pounds, when considered on a total aircraft basis, by virtue of the higher efficiency obtainable from the VSCF and a 50 percent smaller generator oil cooler.

Another drawback for the VSCF is that it is a newcomer in the field. Lack of familiarity with this system will play a significant role in the eventual success of the application.

The following weight and efficiency figures were given for the various ratings and pad speeds (speeds are without step-up gear and generators are oil splash cooled containing PMG and oil pump).

<u>Rating, kVA</u>	<u>Generator Speed Range, RPM</u>	<u>Efficiency, %</u>	<u>Weight, lb</u>
40	10,000 to 20,000	83	95
60/75	9,400 to 20,000	84.2	126
90	9,400 to 18,800	84.5	170
90/110	12,000 to 20,000	84	131
120	9,400 to 18,800	85	250

There are possible future weight reductions by faster generator speeds and LSI going from discrete components to microminiature and hybrid circuits in the late 1970's.

General notes:

- (1) Generator weight is a function of oil temperature, the present 60/75 kVA generator (77 lb) requires 4 gal/min oil at a temperature of 120°C. (Conventional air cooled generator needs 7 lb/min air at 55°C inlet.)

Although generator design is a function of oil temperature, perhaps the most significant single factor which determines generator weight is the minimum generator speed at which full load must be delivered. For instance, in the above tabulation for the two 90 kVA systems, the weight reduction is resulted from the increase in minimum speed from 9400 to 12,000 rpm.

- (2) Converters utilizing 12-phase input require less filtering; reliability is down, however, because 36 more SCR's are utilized than for the 6-phase inverter.
- (3) Originally two differential protection zones were applied; one for the generator and high frequency feeders, the other for the converter and low frequency feeders. A new approach of detecting internal generator faults by sensing voltages at various points on the high frequency side eliminated the need for two separate DP zones.
- (4) A unique feature offered by the VSCF system is the ability to operate two or more systems electrically isolated but with their frequencies synchronized and in phase during all steady state and transient load conditions. With present paralleled systems it is in some cases very difficult to detect and isolate a faulted channel. Also the occurrence of beat frequencies is undesirable. This isolated-synchronized operation is the type of operation being designed by G.E. for the boeing SST.
- (5) The wide range of steady state frequency and voltage variations allowed for in MIL-STD-704 demand complicated regulated power supplies for many avionics systems. In addition, frequency and voltage transients on the power lines impose reliability reducing stresses on all the avionics loads. VSCF either eliminates completely or significantly reduces these long time problem areas. G.E. VSCF has the following output power quality:

Voltage Variation

Steady state	± 1 v
Transient	Smaller and shorter than that allowed for in MIL-STD-704A

Frequency Variation

Steady state	± 0.004 Hz, or ± 0.04 Hz, or ± 1 Hz
Transient	None
Drift	Same as steady state

Wave Form

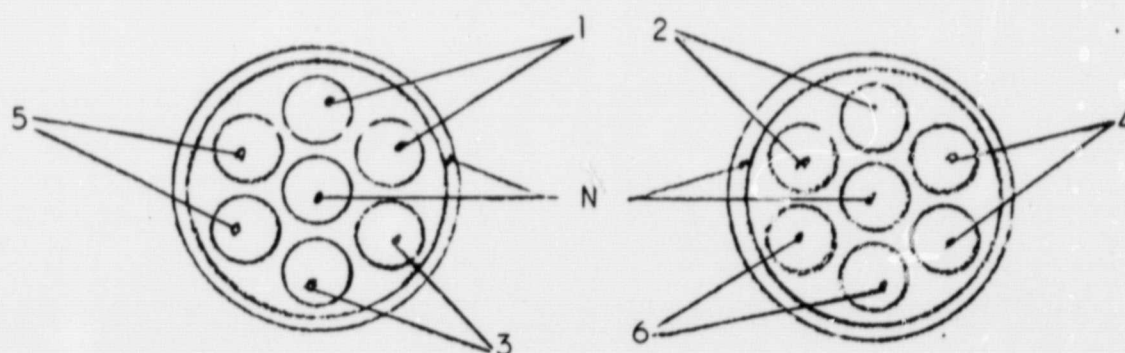
Single harmonic	3 percent
Total	4 percent

The acquisition cost of the VSCF system is approximately 10 to 15 percent higher than that for the conventional system. The operating cost quoted to the airlines, however, is lower than that of the IDG drive. A total of 8800 hours MTRF for the complete system was given.

Typical losses for a 60-kVA system are:

- (1) Converter, nearly constant 2.6 kW (two different types of filters)
- (2) Generator, 9.5-kW worst case efficiency at low speeds

High frequency feeders.--Feeders are shielded cables with a central neutral return. They are approximately 15 percent heavier than conventional feeders. A configuration for a 6-phase generator output is shown below.



Optimum Feeder Configuration for 6-Phase Inverter

G.E. concluded the discussion by summarizing the features of the VSCF and projecting potential improvements for this type of system within the next decade.

- (1) VSCF will eventually be lower in weight than IDG because it has more degree of freedom for variations.
- (2) It has better quality power.
- (3) It lends itself ideally for no-break power systems.
- (4) In the higher ratings (250 kVA) it could be adapted for engine starting
- (5) It may be utilized for emergency power by windmilling engines; VSCF can be programmed to supply several kW dc limited only by the low PMG output for the low speed.

During the course of the discussion, it was pointed out that for a high voltage system, significant transformer weight could be saved (as is the case with the Boeing 2707) when stepping down the high frequency energy at the end of the generator feeders.

August 7, 1969: WESTINGHOUSE
Aerospace Electrical Division
Lima, Ohio

Westinghouse is actively engaged in the aircraft electrical power field, both with conventional systems (latest concept of IDG) and VSCF systems. They have three different versions of VSCF in evaluation.

- (1) The natural commutated cycloconverter system (NCC)
- (2) The forced commutated cycloconverter system (FCC)
- (3) The dc link system

So far no preference of any of the VSCF schemes has been established but the NCC system is considered to be the most advanced.

For comparison the following figures for a 60 kVA system (projected flight hardware by 1972) were provided. Speed range approximately 10,000 to 20,000 rpm, control and protection circuits are included but not CT's.

	<u>IDG</u>	<u>NCC</u>	<u>FCC</u>	<u>DC-LINK</u>
Steady state full load efficiency, %	78	80	79	76
Generator weight, lb	43	80	62	62
CSD weight, lb	60	-	-	-
Converter and filter weight, lb	-	50	53	78
TOTAL WEIGHT, lb	103	130	115	140

Achievement of the FCC and dc-link weights are based upon development of adequate power switching devices.

The converter for the FCC system is heavier than that for the NCC system. This is because of the need for an input filter on the FCC, whereas the NCC appears able to operate satisfactorily without an input filter. The output filter on the FCC is smaller than that on the NCC. The increase in additional filter weight for the FCC system, however, is more than compensated for by the lighter generator design because of higher power factor. As a general guideline, factors were quoted for increased generator sizing over the conventional generator because of the displacement power factor of the inverter or rectifier load.

- (1) With the NCC system, the generator size increases by a factor of 1.65
- (2) With the FCC system, the generator size increases by a factor of 1.19
- (3) With the dc-link system, the generator size increases by a factor of 1.17

Further weight reduction was predicted for the dc-link inverter in the near future. Westinghouse feels that the dc-link approach has certain advantages over the cycloconverter because of more flexibility.

Westinghouse is working on a gate turn-off switch for their FCC system. This semiconductor switch is in development and will come in ratings to handle a 30- to 40-kVA system (III-A nominal). Switches of sufficient rating for systems rated as high as 120 kVA will be available within the next five years. In this connection, it was mentioned that when the present overload requirement could be relaxed, a much lighter weight system would result.

Reliability for converters at present is approximately 10,000 hours MTBF. An additional 10,000 hours may be obtained by specifically selecting and screening components.

During the discussion on power utilization the following weights of transformer-rectifier units were noted:

- (1) 100 A unit, unregulated fan cooled, 9-1/2 lb.
- (2) 100 A unit, regulated, forced air cooled, 22-1/2 lb.

Other Data

At the writing of this report it was learned that the Avco Corporation in Everett, Massachusetts is engaged in a research and development program for supercooled generators. Actual hardware models have been built and are presently being tested. According to verbal information, specific weights of 1/3 lb per kVA generator output for machines rated 300 kVA and higher can be achieved. The temperature of the dc exciter winding is kept down to 5°K.

For the next report it is anticipated that more data will be obtained from Avco on this type machine and its possible future use in aircraft.

N70-25428

OPTIMUM SUPPLY TO AIRCRAFT ELECTRICALLY OPERATED EQUIPMENT

Introduction

This section represents part of the material on optimum supply to aircraft electrically operated equipment. The remainder of the material will be presented in the next quarterly progress report.

Basically there are five different load functions to be performed in aircraft:

- (1) Heating and cooling
- (2) Lighting
- (3) Mechanical motion (Actuators, pumps, fans, etc.)
- (4) Controls and instrumentation
- (5) Electronics

While it is possible to power the first three load functions by means other than electrical energy, functions four and five require an electrical source with the possible exception of some fluidic or pneumatic control. However, one would have to discard all means of obtaining lighting loads from sources other than electrical as being entirely impractical and absurd. This reduces the loads that could be driven from other energy sources to two groups, mechanical loads and heaters. Mechanical loads are pumps, fans and blowers and a wide variety of actuators (both linear and rotary). These actuators range from miniature sizes producing a few inch-pounds to contrivances exerting forces of several tens of tons. All these mechanical load functions may be either electrically, mechanically, hydraulically, or pneumatically powered.

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

It is not intended in this section (nor is it possible within the allocated time frame) to analyze accurately the entire system of load mechanisms in order to determine whether a load should be electrically driven or not. Since this is a tradeoff study, which largely depends on specifics like aircraft size, mission, and flight objective, it is felt that this section should concern itself with the more generalized problem; i.e., if a load must be electrically powered, what are the optimum electrical parameters to satisfy the power demand. To do this, it is first necessary to examine the load characteristic itself.

Fans and Blowers

This subsection covers the optimum speed, weight, efficiency predictions for fans, compressors and electric blower motors. It reflects the current state of the art in these equipment types in graphical and chart form.

Axial flow fans.--The axial flow fan was selected because it is by far the most common type of fan used in aircraft. This is primarily due to its lower weight in comparison to other fan types. Appendix A outlines the graphical method for obtaining the size of axial flow fans for conservatively rated designs. From the flow and pressure rise requirements, the blade tip diameter of the fan is determined. Figure 1 shows curves for the lightest fans possible without motors versus fan blade tip diameter. This is empirical data, as it is not possible to produce a generalized theory for calculating the weight of a fan. Small fans are disproportionately heavy because connectors, wall thicknesses, ball bearings, etc. cannot be scaled down. Compare the curve for the weight of a cast aluminum fan with the curve $W \propto D^3$. The latter is set up to intersect the former at $D = 18$ in. If the 18-in. diameter fan was exactly scaled down to, say, 8-in. diameter, its weight would be 2.2 lb, whereas an actual fan would weigh at least 5.4 lb.

It should be noted that most designs will weigh more than the curves show as the curves represent the lightest designs. The addition of terminal boxes, heavy blade containment rings, heavy or complicated mounting brackets, inlet screens, thermal protectors, etc., will result in a heavier fan.

Centrifugal compressors.--The discussion of centrifugal compressors here is limited to low pressure type (less than 100 in. of water), using vaneless diffusers and rotor blades swept back 45 degrees at the tip. Appendix A gives the graphical method for sizing this type of centrifugal compressor. Figure 2 shows a curve for the lightest aluminum alloy construction centrifugal compressors. Again, this curve was obtained from empirical data, and the same comments (with regard to increased weight due to appendages) in the last paragraph to axial flow fans apply here. The compressor weight follows very closely the curve proportional to the cube of the diameter, set up to pass through 12 lb and 5.5-in. diameter. This is simply because the size range considered is very small, i.e., from 2- to 5.5-in. diameter.

Drive optimization for the axial flow fan and low pressure compressor.--

In an effort to reduce power consumption, noise level, and often system weight, an attempt is made to optimize aerodynamic efficiency. With a given rotational speed, the fan can be designed to provide almost any airflow rate at a desired pressure rise. In this case where the speed is fixed or the speed range is confined to the 400-Hz power supply, the system will not always yield optimum weight and efficiency for the specific work to be done. Fig. 3 shows the input power requirement in watts for common fan loads when driven from a conventional 3-phase, 400-Hz supply. For best results, however, there is a unique rotational speed that will produce an optimum aerodynamic

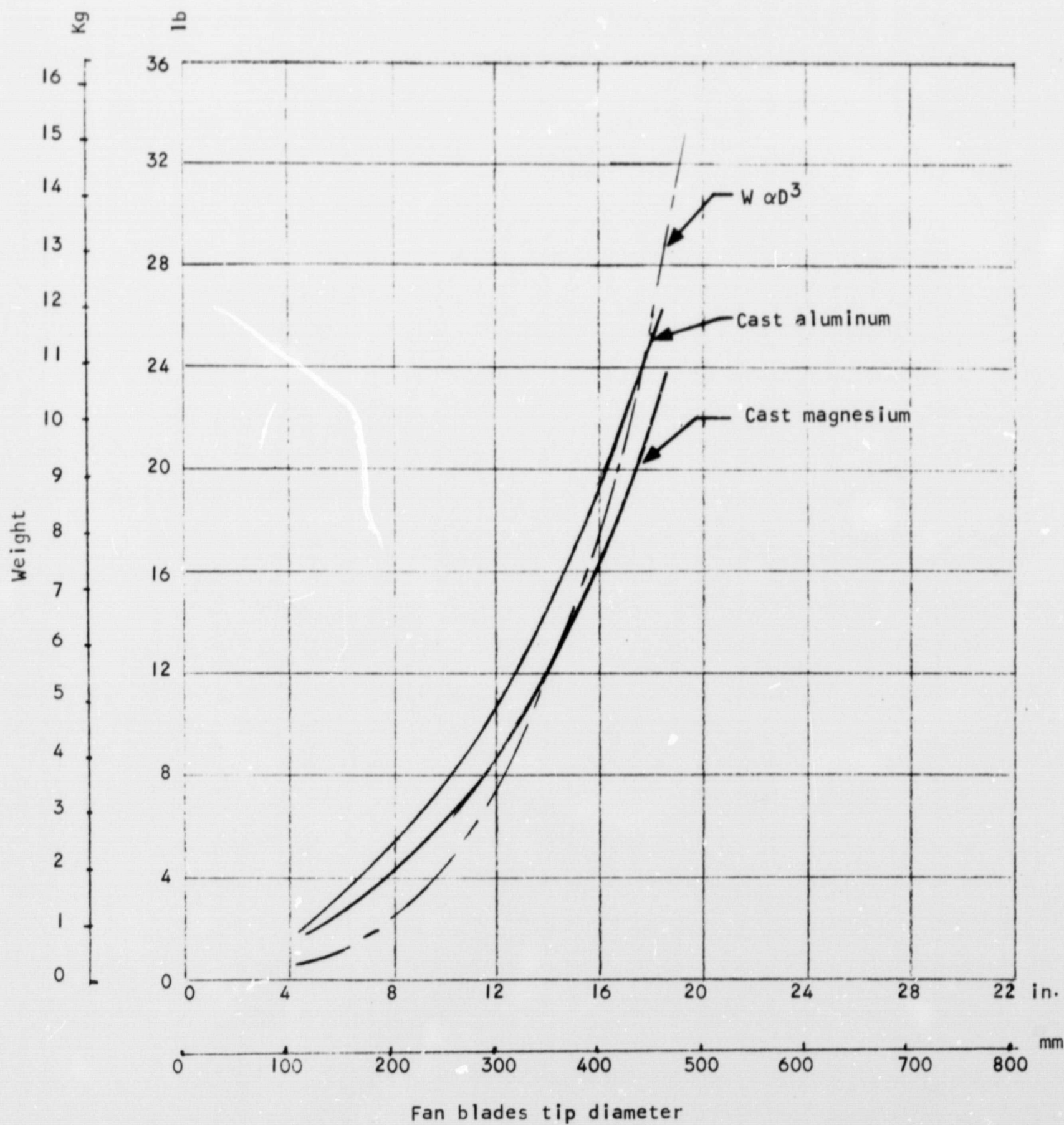


Figure 1. Weight of Lightest Flow Motor Driven Fans
Excluding Motor Weight

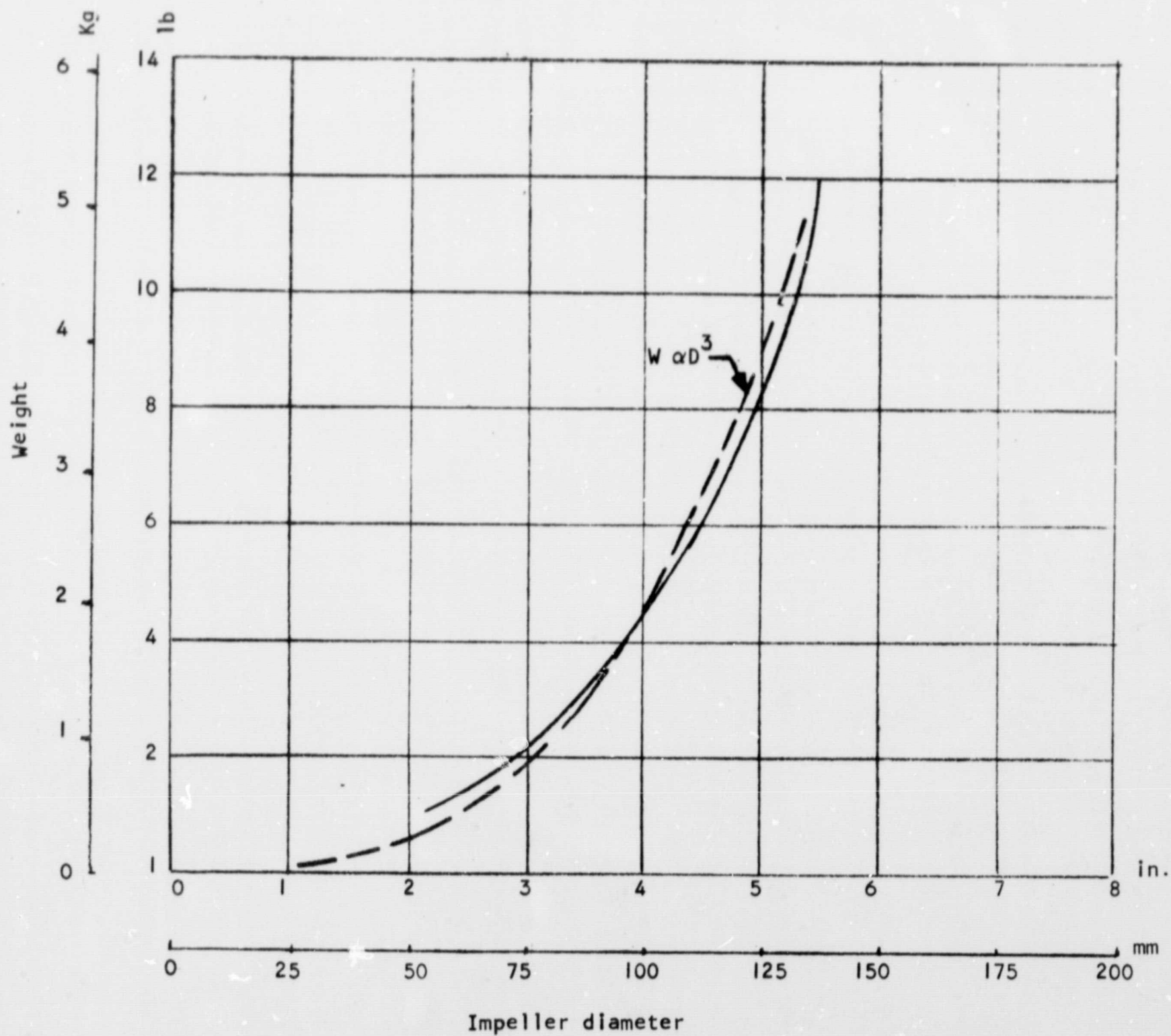


Figure 2. Weight of Lightest Driven Centrifugal Compressors Excluding Motor Weight

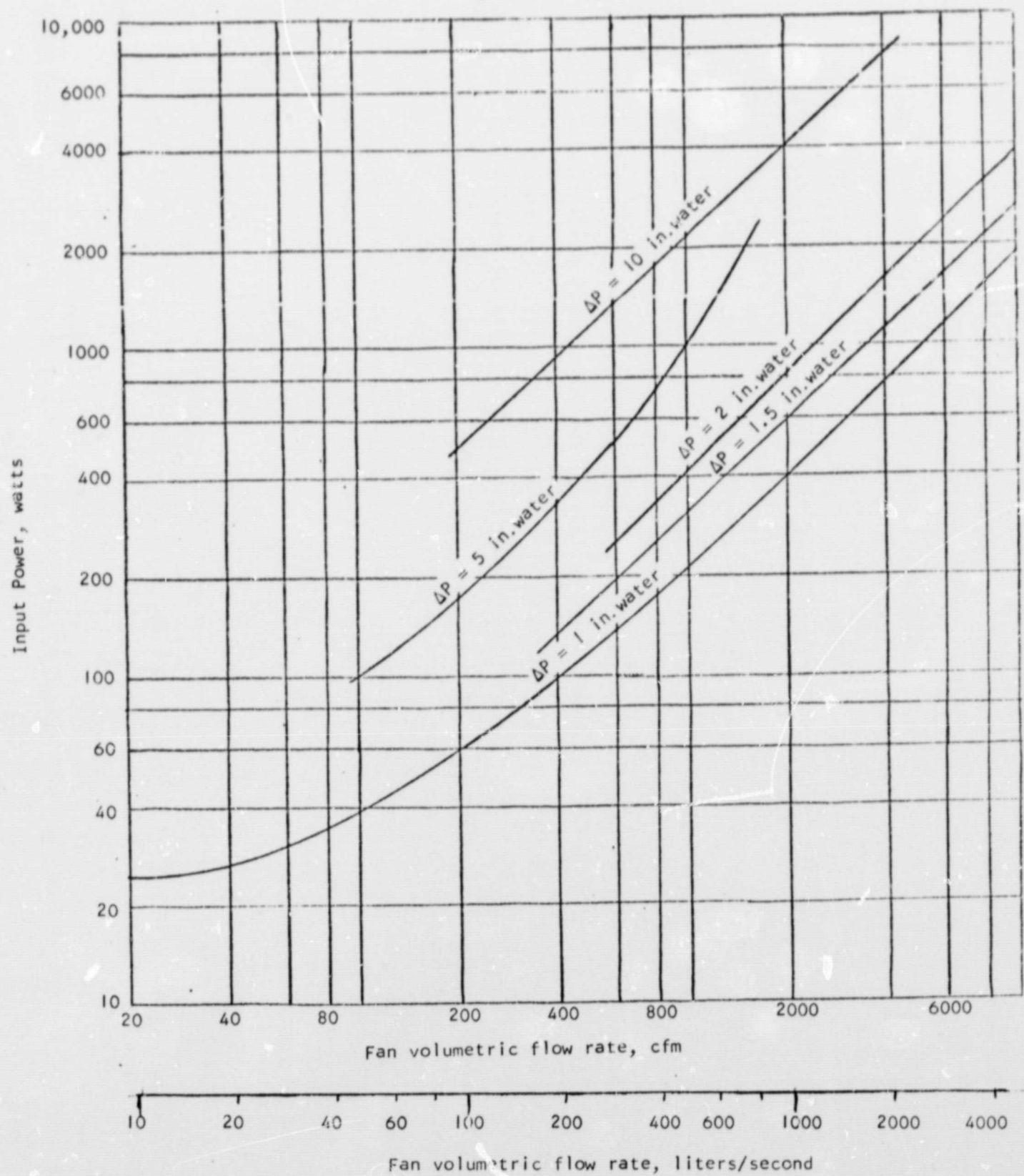


Figure 3. Trend of Power, 3-Phase, 400-Hz, Motor Driven Single-Stage Axial Flow Fans

efficiency in a machine of a given type. For axial flow fans and low pressure compressors, this occurs at a specific speed (N_s) of approximately 100,000 where:

$$N_s = \frac{\text{RPM (CFM)}^{1/2}}{[\Delta P(\text{in. H}_2\text{O})]^{3/4}}$$

Fig. 4 shows the relation between volume flow rate, pressure, and optimal fan speed. An indication for best impeller tip diameters for ideal rotational speeds is shown in fig. 5. Notice that these curves present only the optimum conditions for the single-stage axial fan and are of practical value only if the particular motor sizes and speeds, bearing lives, mechanical configurations, etc., are available. The curves may be best used in comparing the effects of varying flow or pressure rise parameters on fan or compressor size (and, thus, aerodynamic component weight). They are intended to give additional meaning to the "ideal" rotational speed trend curves. Both curves indicate the trend of data only and should not be used for design reference. They are most useful in showing the ways tip diameter and speed would vary as functions of flow and pressure rise for optimum efficiency fans.

It might be argued that it is often possible to produce a fan or compressor having an impeller tip diameter smaller than indicated on the graphs for maximum efficiency. Since the weight of the aerodynamic fan components vary in the range of the second to third power of diameter, a less efficient fan of small impeller tip diameter would probably be more desirable than a more efficient but larger diameter machine. When the increased weight of the drive motor, larger power cables, larger and heavier contactors, larger EMI filters (if required) and possible motor cooling problems are considered, the total system is usually heavier for a faster, low efficiency fan. This is particularly true as the fan or compressor size increases.

Electric blower motors.--Motors have either totally enclosed or open ventilated construction. Most dc motors are totally enclosed because of the increased demand for motors capable of operating in explosive environments that pass the oil splash test, and because of their use of commutators and brushes. Dc motors, ac single-phase and 3-phase induction machines are used for fans and blowers. Open ventilated ac induction motors can often pass the required environmental tests and, thus, are used in the larger motors for continuous duty because of substantial weight savings.

The fan load reflects a characteristic to a driving source having a torque requirement that decreases as the square of the reduction in speed. For the dc motor, the variable torque characteristic will require a constant speed machine such as the compound or the shunt type motor. In an effort to arrive at optimum configuration and motor data, it is impractical to establish a parametric relationship on a purely analytical basis.

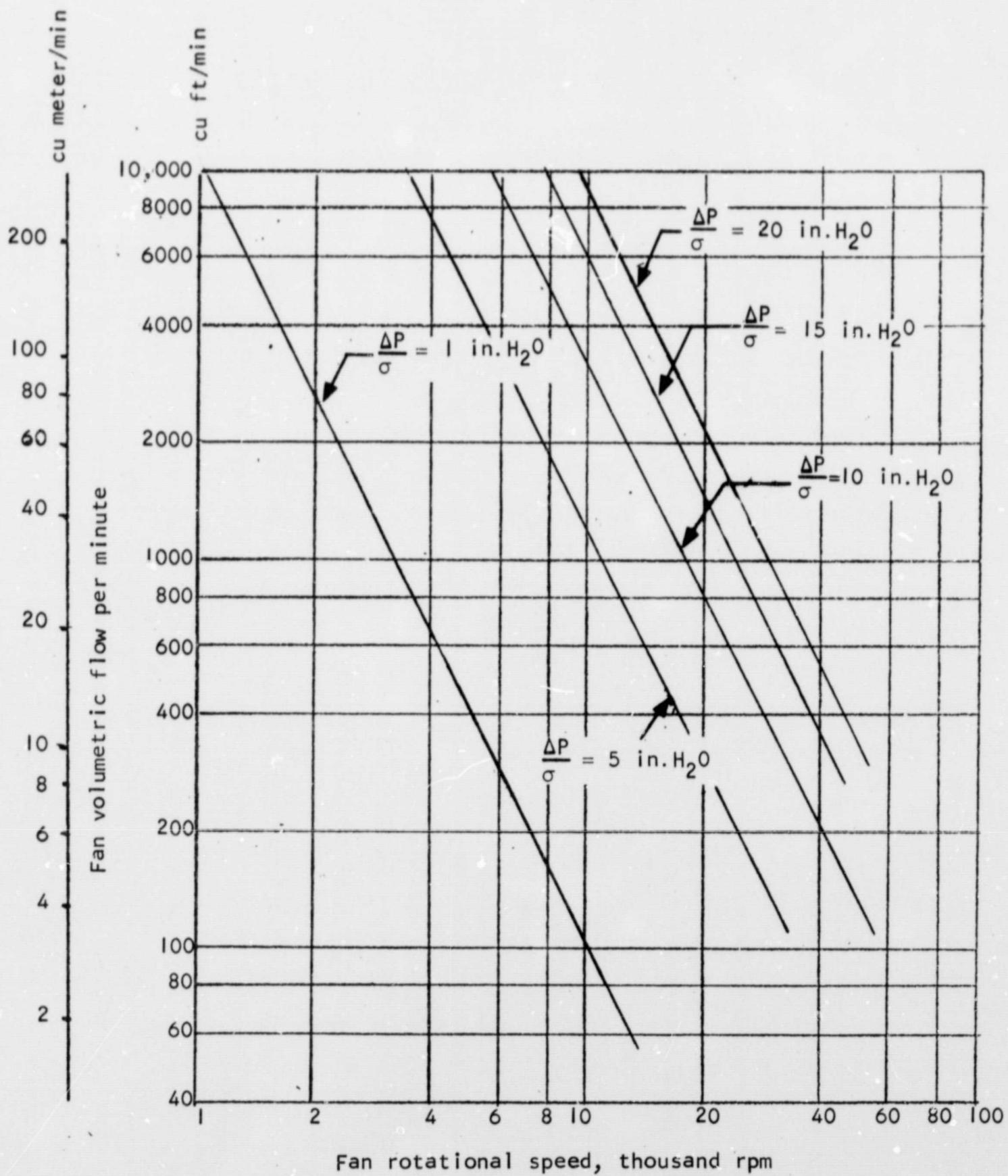


Figure 4. Fan Speed for Maximum Aerodynamic Efficiency of Single Stage Axial Flow Fans and Low Pressure Compressors

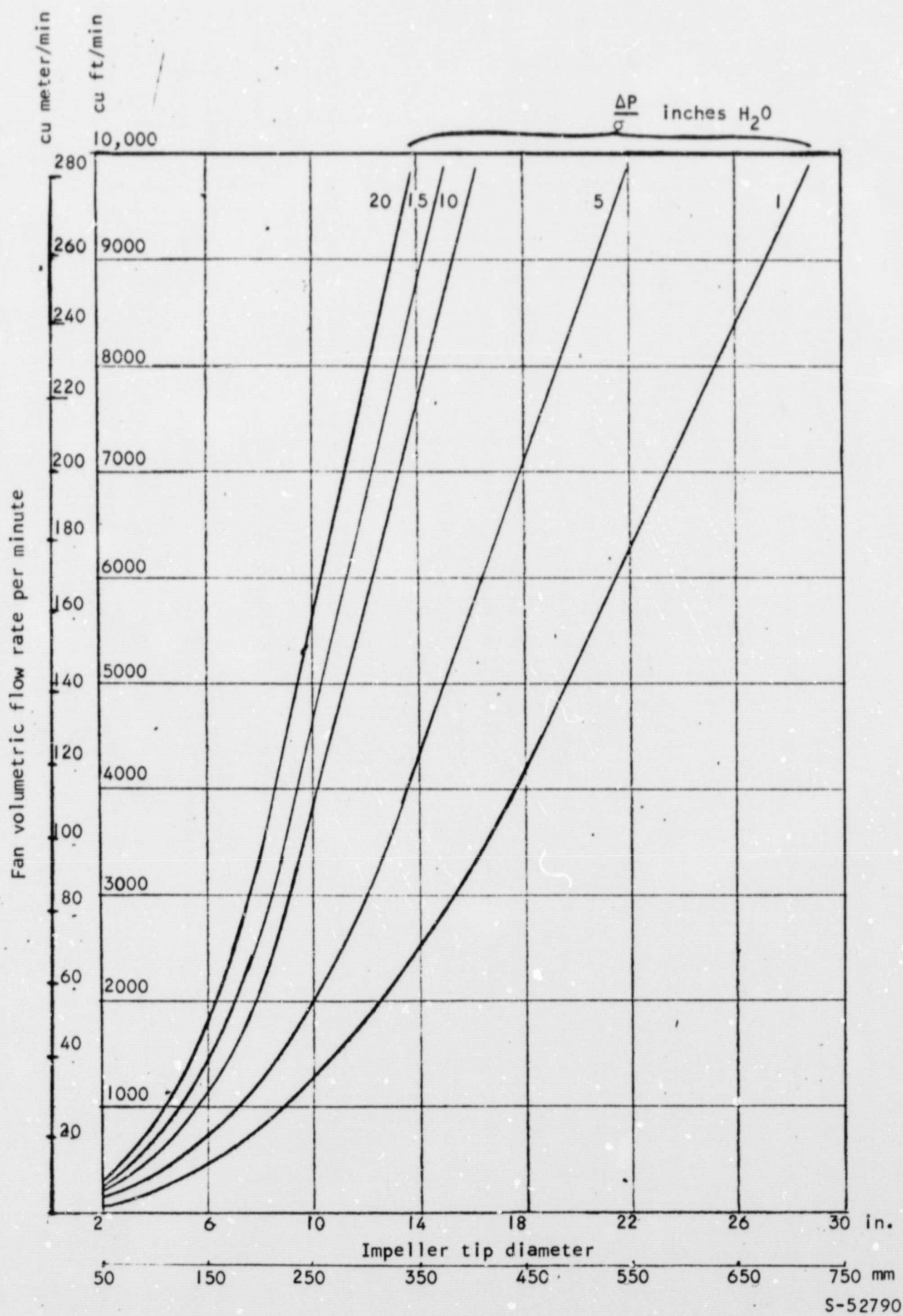


Figure 5. Impeller Tip Diameter vs Volumetric Flow Rate for Ideal Rotational Speeds

The analysis of many specific designs yields data that can be organized and extrapolated on the basis of physical reasoning--an approach used in preparing the data presented here. When this approach is used it is important that the inherent limitations be noted. Each single design characteristic is dependent on many independent parameters. In analyzing, organizing, and presenting data regarding such characteristics, it is necessary to neglect all but the most important. The result is an oversimplification of a complex problem. Such simplification can be both valid and useful, but it must be applied with care. Therefore, it is suggested that these data be used only in the preliminary design of motors.

Dc motors.--The motor size and speed vs weight trend is given in fig. 6. AiResearch design figures were used and a search was made for other sources for comparison and verification. The curves represent machines of 4- or 6-pole construction that are forced cooled with air at approximately 40°C. The volume of the machine in cubic inches can be approximated by multiplying the weight in pounds by a factor of 8.

Ac motors.--The data for motor size and speed vs weight plotted in fig. 7 was averaged from data on AiResearch and other major suppliers of fan motors. AiResearch weights were approximated, while data on other motor suppliers were taken as published. The trends for efficiency and power factors in fig. 8 were scaled and approximated from AiResearch design data.

A summary for fan motor sizing is given in table I.

TABLE I
SUMMARY OF CURVES FOR FAN MOTOR SIZING

Type of motor	Weight curve figure	Weight correction	Volume, cu in.	Approximate outside diameter of frame	Approximate motor ℓ
3 phase	14	None	7.5 to 9 x wt in lb	$\frac{\ell}{D} = 1 \text{ to } 3.5$	$\ell = \frac{4}{\pi} \frac{\text{volume}}{D^2}$
1 phase	14	1.1 to 1.43 x curve weight	7.5 to 9 x wt in lb	$\frac{\ell}{D} = 1 \text{ to } 3.5$	$\ell = \frac{4}{\pi} \frac{\text{volume}}{D^2}$
Dc	13	None	7.5 to 11 x wt in lb	6 to 11 in	$\ell = \frac{4}{\pi} \frac{\text{volume}}{D^2}$

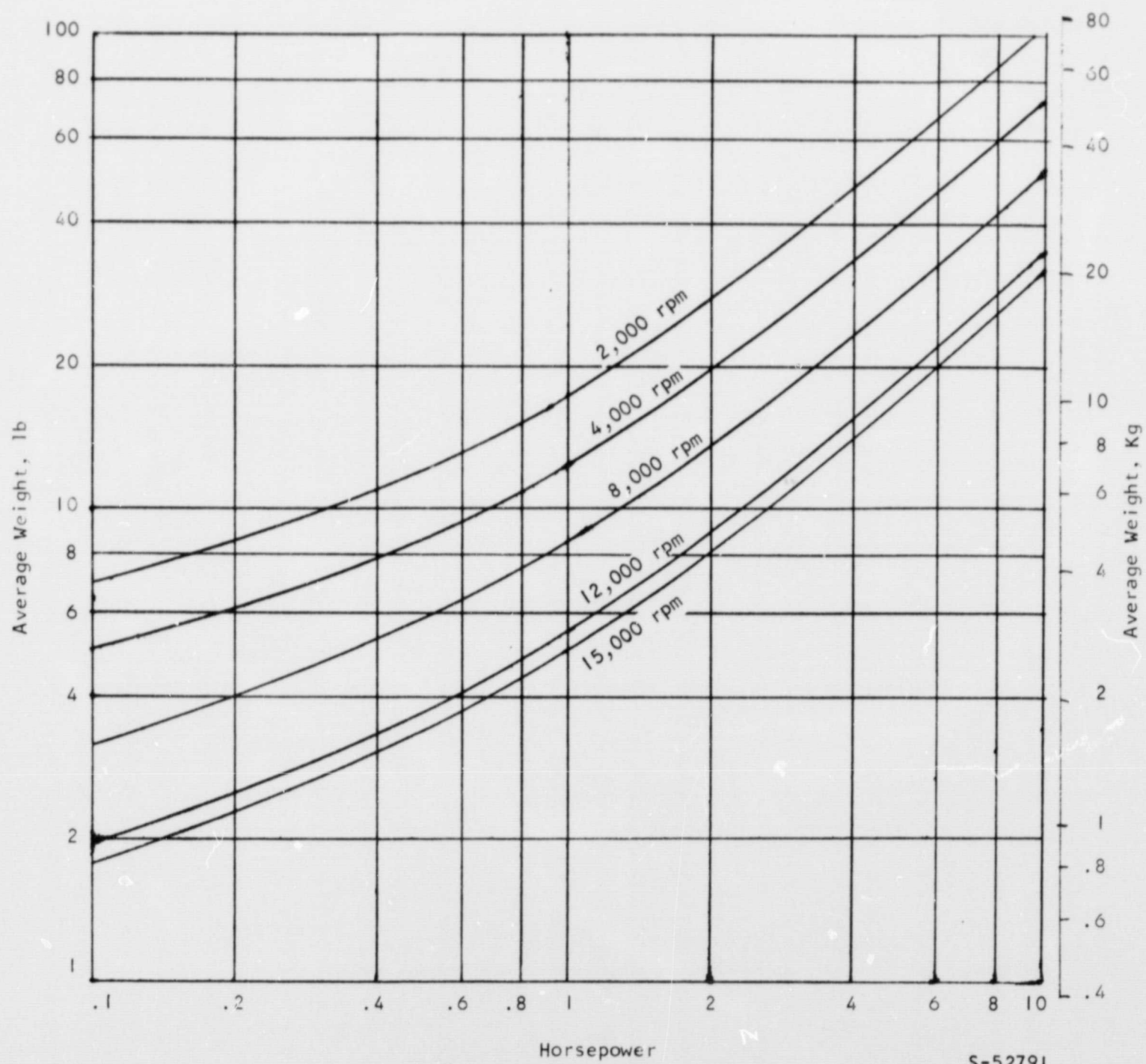


Figure 6. Average Weight of 28 vdc Aircraft Motor (Conventional Materials)

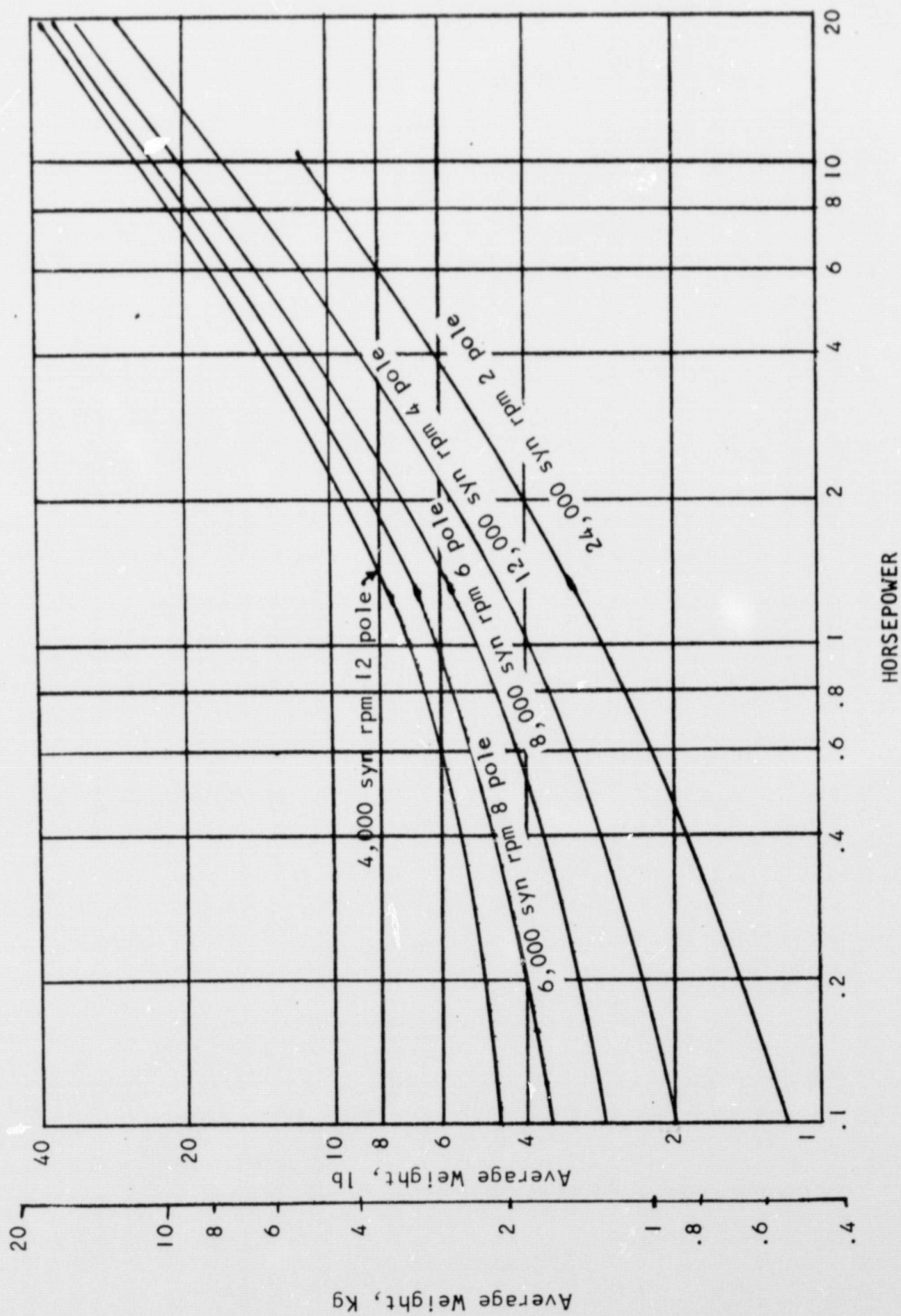


Figure 7. Average Weight vs Horsepower for 3 ph, 400 Hz, 115/200 V. Aircraft Induction Motor (Conventional Materials)

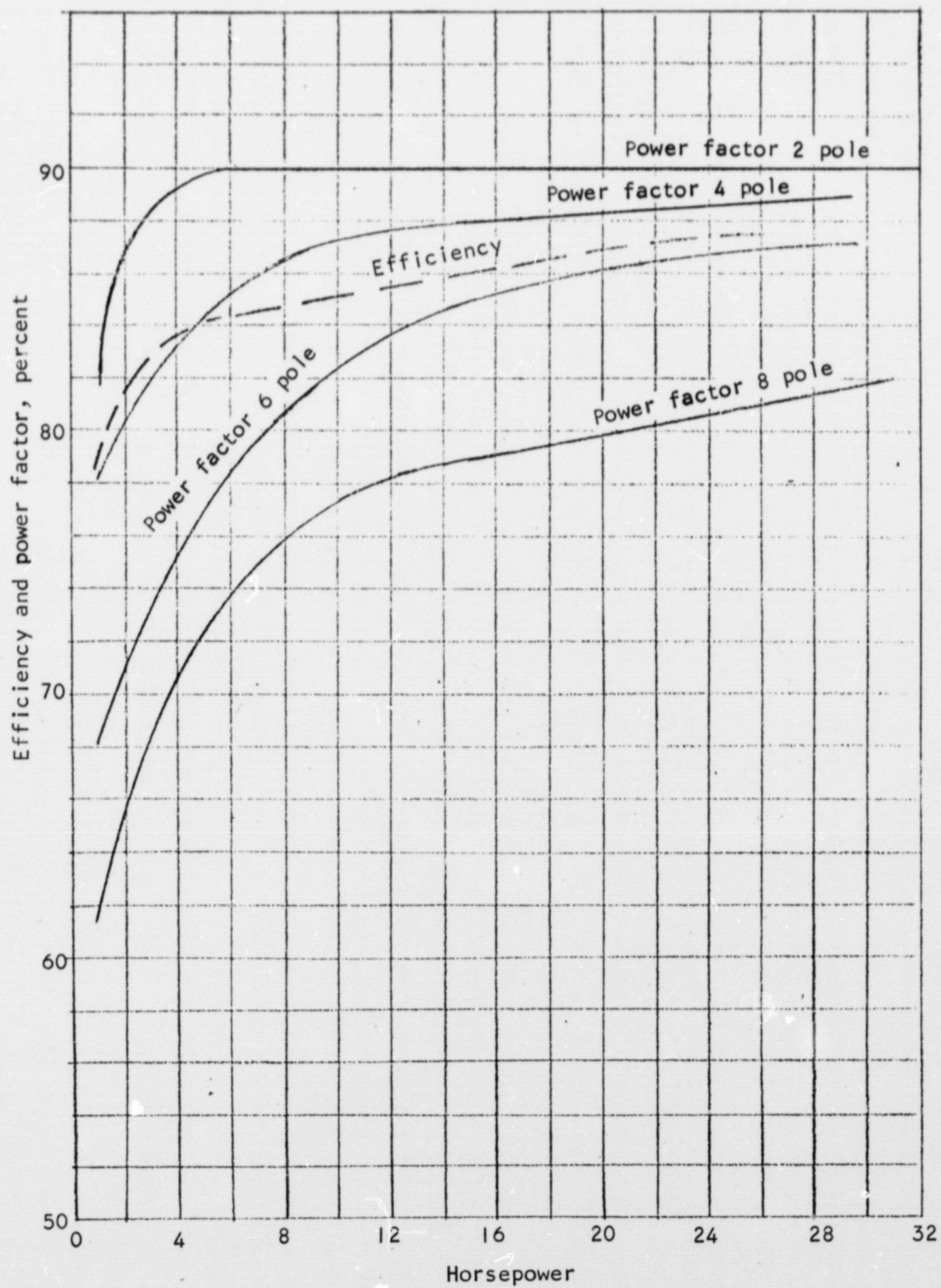


Figure 8. Horsepower vs. Efficiency and Power Factor
400 Hz Aircraft Induction Motors (Conventional Design)

An example will explain how to use the information given by figs. 6, 7, and 8. Assume a 15-hp, 7800-rpm motor (3-phase, 400-Hz) is required.

Ascertain the number of poles required for 7800 rpm (synchronous speed, 8000 rpm) from fig. 7. This being 6 poles, select the weight, power factor, and efficiency from figs. 7 and 8.

Weight = 24 lb

Power factor = 85 percent

Efficiency = 86 percent

The volume varies from 7.5 to 9 cu in./lb. Using 7.5, the volume of the motor will be 180 cu in.

Assume a 6-in. outside diameter on the motor.

Therefore, $\frac{\pi d^2 \cdot l}{4} = 180$, where l = length of motor
and d = outside diameter of motor

Solving for l , $l = 6.37$ in.

$$\text{Amperes/phase} = \frac{(\text{hp}) (746)}{(\text{pf}) (\text{efficiency}) (3) (\text{volts})} = \frac{15 \times 746}{85 \times 86 \times 3 \times 115}$$

≈ 45 A

APPLICATION OF NEW MATERIALS

N70-25429

Introduction

Trends in future development of electrical system components favor compact, lightweight design, higher operating voltage and temperature, and more stringent safety and reliability requirements. Improved design techniques and configurations will partially satisfy these requirements. Major advances, however, depend largely on improved properties of various materials. For electrical system components, these materials include:

- Soft magnetic materials
- Permanent magnet materials
- Insulation materials
- Conductor materials
- Structural materials

Soft Magnetic Materials

In an aircraft electrical power system, a great variety of electrical and electronic devices employ soft magnetic materials. These include: generators, motors, transformers, reactors, magnetic amplifiers, transducers, and solenoids. All these devices use soft magnetic materials to carry flux in the magnetic circuit. Therefore, the general requirement for magnetic materials is high-saturation induction, which must be achievable with low exciting fields and low coercive force. To be suitable for high temperature operation, the magnetic materials used in rotating parts must have high-strength capabilities, especially in resisting creep. Good magnetic properties are desirable but are secondary in this application. The magnetic amplifier requires a material that has a square hysteresis loop. Since the magnetic amplifier is a static device and is not subject to mechanical stress, the mechanical capabilities are less important. Some devices, such as the solenoid, have only dc flux in the magnetic circuit. Magnetic losses of the material, therefore, are not important.

There are four major groups of soft magnetic materials:

- Silicon-iron alloys
- Nickel-iron alloys
- Cobalt-iron alloys
- Soft ferrites and other materials

The silicon-iron alloys are the most widely used magnetic materials for power applications. These alloys, which contain about 0.5 to 4.5 percent of silicon, are commonly termed electrical steel or silicon steel. By cold rolling and annealing, preferred orientations in silicon steels can be obtained. During the last few years, silicon steel with a "cube-on-face" orientation has been developed. Its magnetic properties closely approximate those of a single crystal. Therefore, grain-oriented silicon steel has almost reached the limit of possible development.

New nickel-iron alloys usually have low core losses within the range of flux density at which they are used. Due to their relatively low saturation flux densities, nickel-iron alloys are not used for power frequency applications, they are used principally for electronics and communications transformers. The important nickel-iron alloys include various types of Permalloy, Hipernik, Nicalloy, and Supermalloy.

Electric motors must sometimes operate at temperatures of 300 to 600°C. In such applications, silicon and nickel alloys cannot be used because their Curie temperatures are low and the magnetic properties of these alloys deteriorate rapidly at elevated temperature. Cobalt-iron alloys have very high Curie temperatures and therefore, are the only magnetic materials suitable for high-temperature service. New cobalt-iron alloys include Hiperco 27, Hiperco 35, 2V permendur, and supermendur. With the exception of supermendur, these alloys have relatively low permeability and high hysteresis loss. However, their saturation induction is very high (about 24 kG), which is a preferred property for miniaturization.

The new materials have not been widely used due to their relatively high cost and unfamiliarity to the designers. Several new materials are briefly discussed herein.

Cubex steel.--Cubex is a new magnetic material that is available from Westinghouse Electric Corporation. This material, which offers weight reduction potential in aircraft generators at nominal cost increase, is a doubly grain-oriented, high quality, 3.25 percent silicon steel. The so-called "cube-on-face" orientation of the material offers almost equally high permeability and low loss in both the rolling and transverse directions. The material responds to annealing in a magnetic field, which imparts further improved magnetic properties to the alloy. The stress-relief-annealed condition is usually used in rotating machinery, while the field-annealed condition is reserved for high-performance transformers and magnetic amplifiers. By comparing the properties of Cubex with those of conventional silicon steel, it is found that for a given magnetizing field, the flux density of Cubex is approximately 10 percent higher. This means that by using Cubex, less material is required to carry a certain amount of flux in the magnetic circuit of the device, resulting in reduced volume and weight. It should be noted that the weight reduction is not limited to electromagnetic weight. Due to the reduction in volume, additional weight savings in the frame, shaft, and housing can be realized.

Since the magnetic properties of Cubex are approaching those of a single crystal, it is believed that the oriented silicon steel has almost reached the limit of possible development. The in-plant processing required for Cubex is similar to that required for conventional silicon steel. The properties of Cubex are shown in table 2.

Hiperco 27 alloy.--Hiperco 27 alloy, which contains 27 percent cobalt, is a high saturation, cobalt-iron alloy developed by Westinghouse Electric Corporation. Although Westinghouse has been manufacturing this material for almost 20 years, it was not until about 1960 that the problems in rolling the material into thin sheets were solved. When Hiperco 27 was initially applied, the brittle laminations introduced many manufacturing difficulties. Now, after several years of production experience, no manufacturing problems are encountered with this alloy.

Hiperco 27, because of high saturation induction and high Curie temperature, is suitable for use in aircraft generators and motors, where reduced size and weight are relatively important. Using Hiperco 27 instead of silicon steel in a machine can reduce electromagnetic weight up to 15 percent. In turn, reduced machine size makes possible a corresponding decrease in frame and shaft weights.

Being a single-phase material, Hiperco 27 follows the patterns expected at high temperatures. As temperature increases, the magnetization curve rises more rapidly at lower fields and then flattens out and saturates at lower inductions. The residual induction, coercive force, and core loss decrease as temperature increases. Hiperco 27 has good stability at elevated temperature. The 1000-hr stability test at 1000°F revealed that dc and ac magnetic properties after the stability test showed no significant change from those measured before testing. The tensile strength of Hiperco 27 follows the general pattern for solid solution alloys. At elevated temperature, there is a considerable change in slope, and the decrease in strength with increasing temperature becomes more rapid.

During manufacturing, Hiperco 27 alloy requires special handling in all stages. Additional annealing and melting are sometimes required to develop the required magnetic and mechanical properties. The normal heat treatment for material used in electric generators involves heating at 1472° to 1552°F in pure dry hydrogen, followed by rapid cooling in the same atmosphere. The complicated processing, together with the high cost of cobalt, makes the cost of Hiperco 27 relatively high. This has been a major drawback to the extensive application of this material. Properties of Hiperco 27 are shown in table 2.

Hiperco 50 alloy.--Hiperco 50 is a Westinghouse trade name for a high-saturation, cobalt-iron alloy similar to Hiperco 27. The composition of Hiperco 50 is: 2-percent vanadium, 49-percent iron, and 49-percent cobalt. The vanadium is added to improve the mechanical properties.

The magnetic and mechanical properties of Hiperco 50 vary according to the annealing process; the primary annealing parameter that affects the properties of Hiperco 50 is temperature. At present, two different annealing processes

are used for different requirements: No. 1 for laminations with optimum magnetic properties, No. 2 for high mechanical capabilities.

The No. 1 annealing process produces material suitable for stators and rotors that are not highly stressed. For rotors operating at higher speed, process No. 2 should be used, although a little sacrifice in magnetic properties is unavoidable.

The saturation induction of Hiperco 50 alloy is higher than that of Hiperco 27. Therefore, more weight savings can be expected with Hiperco 50. Replacing conventional silicon steel in a machine with Hiperco 50 can reduce electromagnetic weight up to 24 percent. In addition, the frame and shaft weight can be reduced because of the smaller size. Table 2 summarizes the properties of Hiperco 50 alloy.

Supermendur.--Supermendur is a highly purified vanadium-iron-cobalt alloy originally developed by Bell Telephone Research Laboratories. This alloy, consisting of 2-percent vanadium, 49-percent iron, and 49-percent cobalt, has exceptional physical and magnetic properties, which are achieved by close control and extreme care in the melting, rolling, and annealing processes. The alloy is compounded by melting the three elements in a controlled atmosphere furnace, using dry and wet hydrogen. Raw materials must be carefully selected and the melting process precisely controlled to minimize the concentration of impurities in the alloy. Unlike other soft magnetic materials, supermendur cannot be purified by heat treatment at high temperatures after all processing is completed. This limitation is due to a phase change in the alloy system that limits the temperature of the heat treatment to a relatively low level. Purification, therefore, must be completed during the melting procedure.

The ingot from casting is usually hot rolled to approximately 0.09-in. strip, then quenched in ice water from 910°C to obtain the required malleability for cold rolling to the desired thickness. Without intermediate anneals, the 0.09-in. strip can be cold rolled to 0.0003-in. sheet that has good ductility.

The temperature, time duration, and cooling rate of the heat treatment are not critical if they are fairly closely controlled. The heat treating temperature should be below the alpha-gamma transformation temperature (approximately 850°C); otherwise the magnetic properties are degraded by the phase change. The time duration at temperature should be sufficient--a cooling rate of 1°C per minute is suitable. Very fast or very slow cooling produces a material with inferior magnetic properties. To obtain superior magnetic properties and rectangularity of the hysteresis loop, the final heat treatment should be performed in a magnetic field of 1 oersted or greater.

Supermendur marked by its rectangular hysteresis loop, high saturation induction, low coercive force, and core loss, is suitable for use in transformers, inductors, magnetic amplifiers, and saturable reactors. When supermendur is used to replace the silicon steel, for the same size core, approximately 30 percent more power output can be realized in transformers. For magnetic amplifiers a size reduction of approximately 20 percent can be expected for the same output. The characteristics of the hysteresis loop of supermendur

indicate that the gain of the magamp can be increased 80 percent by changing from grain-oriented silicon steel to supermendur. In some cases, this increase in gain may even reduce the number of stages from two to one.

Recently, supermendur has been successfully fabricated into cut "C" core that are easily used in transformer and inductor manufacture. Properties of supermendur are listed in table 2.

Weight reduction in induction motors.--To evaluate a new material for rotating machinery application, it is desirable to determine the weight reduction afforded by replacing the conventional material with the new material. However, the weight of the machine depends on many design parameters and requirements. The design goal may be maximum efficiency, minimum weight, or satisfaction of a given performance requirement. To accomplish a certain design goal, tradeoffs are employed. For example, the weight of the machine can be traded for efficiency--or the cost can be traded for weight--and vice versa. Also, the machine design includes many nonlinear processes because many parameters are related to the geometry of the machine, and thermal and magnetic problems are inherently nonlinear. It is therefore almost impossible to determine the weight of the machine without detailed analysis and design work based on a specific machine. The objective here, however, is to estimate the weight reduction for typical machines by using simplified relations. Since Hiperco 50 is known as the best magnetic material for rotating machinery application, the evaluation of weight reduction by change from silicon steel to Hiperco 50 in a cage-rotor induction motor is performed. When motor speed is relatively high, depending on the rotor diameter, Hiperco 50 may not be applicable for rotor material because of limited strength. In such a situation (Example 1), only the stator material can be replaced. When motor speed is low and mechanical strength is not a problem (Example 2), both rotor and stator cores are replaced by Hiperco 50 to achieve maximum weight reduction. Fig. 9 illustrates the motor dimensions. The derivation and results of weight reductions for both situations are as follows:

Example 1.--The following assumptions prevail:

- (1) The comparison is made with cage-rotor induction motors using silicon steel in the stator and operating at 400 Hz.
- (2) The rotor requires high strength material; therefore, Hiperco 50 can only be used to replace the stator core material.
- (3) Flux density of the Hiperco 50 unit is 1.4 times that of the silicon steel unit.
- (4) The difference in total loss between the two units is relatively small and can be ignored.
- (5) Stacking factors and fill factors for the two units are the same.
- (6) The rotor configuration remains unchanged.

TABLE 2

PROPERTIES OF SOFT MAGNETIC MATERIALS

Physical properties	Silicon steel (M-15)	Cubex	Hiperco 27	Hiperco 50		Supermendur
				Optimum magnetic properties	High mechanical strength	
Curie temperature ($^{\circ}\text{F}$)	1400	1400	1697	1724	1724	1724
Solidus temperature ($^{\circ}\text{F}$)	--	2672	2732	2700	2700	2700
Specific heat (Btu/lb $^{\circ}\text{F}$)	--	0.109	0.102	0.098	0.099	0.098
Density (lb/cu in.)	0.276	0.276	0.287	0.295	0.295	0.295
Thermal conductivity (W/in. $^{\circ}\text{C}$)	0.4	0.75	1.39	0.75	0.75	0.75
Coefficient of thermal expansion $\times 10^{-5}$ (in./in.- $^{\circ}\text{F}$)	6.5	7.07	5.61	5.28	5.28	5.28
Commonly used thickness (mil)	14	12	10	10	10	4
Saturation induction (kG)	19.7	20	23.5	23.5	24.1	24.1
Core loss for above thickness at 400 Hz, 15 kG (W/lb)	18	15	36	19	110	5.5
Electrical resistivity $\times 10^{-6}$ (ohm-cm)	53	45	19	35	35	46
Ultimate tensile strength (psi)	74,000	40,000	75,000	80,000	200,000	--
Yield strength (psi)	59,000	34,000	40,000	48,000	150,000	--
Elongation (percent)	13	14	12	4	10	--
Modulus of elasticity $\times 10^6$ (psi)	27.7	22.0	31.4	28.9	28.9	34.7
Rockwell hardness	80B	--	85B	97B	--	--
Relative material cost (1966 est.)	1.0	3.5	20.0	35.0	35.0	--

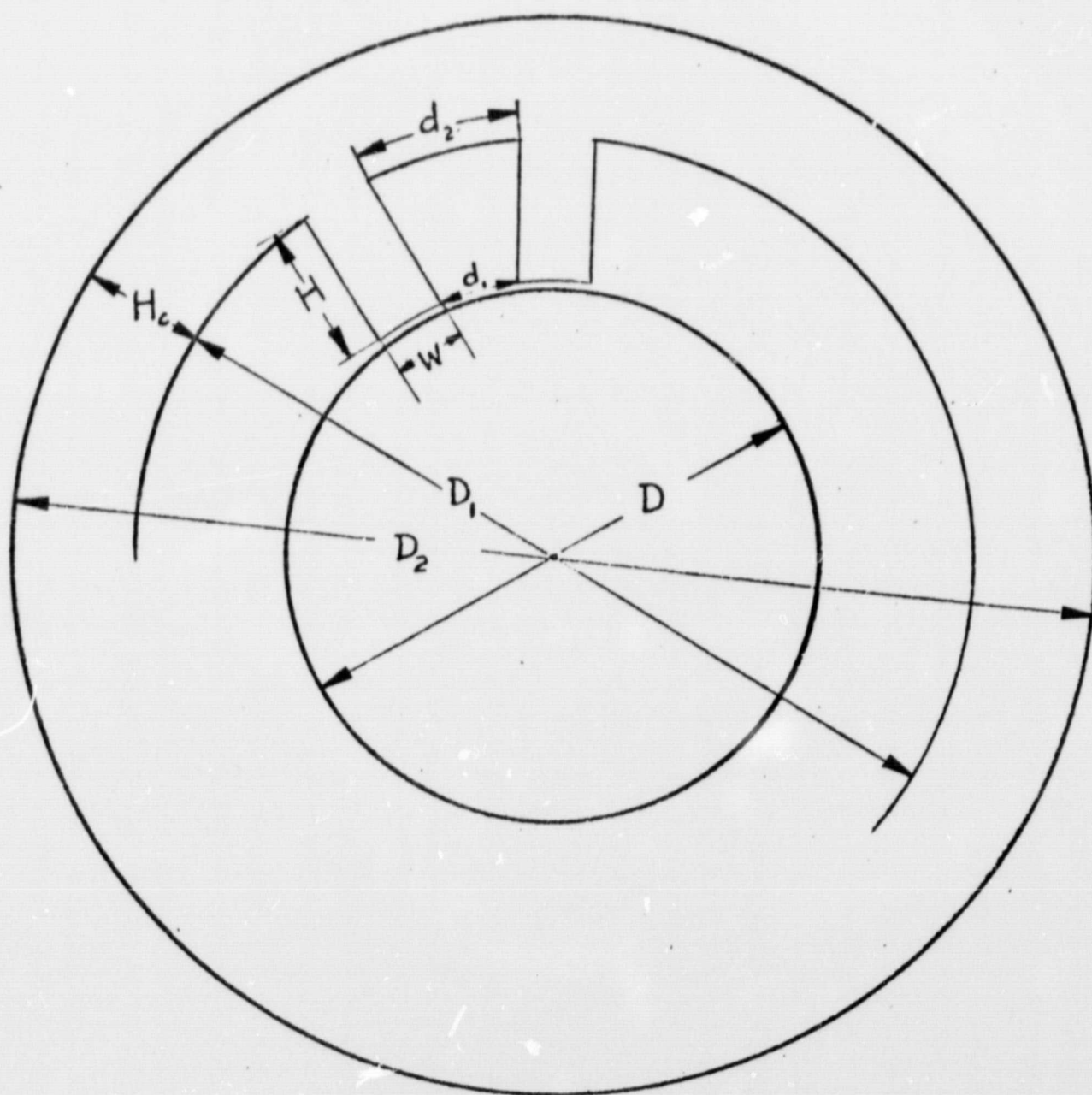


Figure 9. Illustration of Motor Dimensions

Since the stack length cannot be shortened, the width of the tooth and the yoke must be reduced while the slot area remains unchanged. Therefore we have (see fig. 9)

$$\frac{1}{2} (d_1 + d_2) H = \frac{1}{2} (d_1' + d_2') H' \quad (1)$$

The primed variables refer to the Hiperco 50 unit.

$$\begin{aligned} d_2 &= d_1 + \frac{2\pi H}{S} \\ d_2' &= d_1' + \frac{2\pi H'}{S} \end{aligned} \quad (2)$$

where S is the number of stator slots.

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

$$H' = \frac{-d_1' + \sqrt{d_1'^2 + 4 \frac{\pi}{S} H \left(d_1 + \frac{\pi H}{S} \right)}}{2 \frac{\pi}{S}} \quad (3)$$

In a typical design the tooth width is approximately 45 percent of the slot pitch, or

$$W = 0.82 d_1 \quad (4)$$

Since $d_1 + W = \frac{\pi D}{S}$, eliminating W ,

$$d_1 = 1.73 \frac{D}{S} \quad (5)$$

The rotor diameter remains the same, therefore

$$W + d_1 = W' + d_1' \quad (6)$$

Since the stack length is unchanged, the tooth width is inversely proportional to the flux density

$$W' = \frac{W}{1.4} \quad (7)$$

Substituting eqs. (7), (4), and (5) into eq. (6) yields

$$d_1' = 2.14 \frac{D}{S} \quad (8)$$

The yoke width H_c can be expressed as

$$H_c = \frac{B_g D}{B_c P S_f}$$

where B_g = air gap flux density

B_c = flux density in yoke

P = number of poles

S_f = stacking factor

For a typical design

$B_g = 40$ kilolines/sq in.

$B_c = 100$ kilolines/sq in.

$S_f = 0.93$

then

$$H_c = 0.43 \frac{D}{P} \quad (9)$$

Design experience indicates that the ratio (R) of stator outside diameter to rotor diameter is approximately a function of the quantity of poles. Values for different quantities of poles are as follows:

Pole	2	4	6	8
$R \left(= \frac{D_2}{D} \right)$	2	1.7	1.5	1.33

From this relation it is seen that for a certain number of poles, the tooth length H can be expressed as a function of D , hence

$$H = K D \quad (10)$$

where $K = \frac{R-1}{2} - \frac{0.43}{P}$

Substituting eqs. (5), (8), and (10) into eq. (3) yields

$$H' = \frac{-2.14 + \sqrt{4.57 + 4\pi (1.73 K + \pi K^2)}}{2\pi} D \quad (11)$$

$$= K' D$$

$$H'_c = \frac{H_c}{1.4} \quad (12)$$

The rotor weight

$$W_R = \frac{\pi D^2}{4} \alpha S_R \rho_R D$$

where $\alpha = L/D$

L = stack length

S_R = stacking factor of rotor lamination

ρ_R = density of rotor material

The core weight

$$W_c = \frac{\pi D^2}{4} \alpha \left[0.9 (f_1 - 1) + f_2^2 - f_1^2 \right] S_c \rho_c D$$

$$f_1 = D_1/D$$

$$f_2 = D_2/D$$

S_c and ρ_c are the stacking factor and the density of the stator laminations, respectively.

The copper weight

$$W_{cu} = \frac{\pi D^2}{4} \left(f_1^2 - 0.9 f_1 - 0.1 \right) S_{cu} \rho_{cu} \left[B (1 + K) + \alpha \right] D$$

S_{cu} and ρ_{cu} are the fill factor and the density of copper, respectively, and B is a function of the quantity of poles. Typical values are as follows:

Pole	2	4	6	8
B	1.31	0.736	0.598	0.57

Similarly, rotor, core, and copper weight for the Hiperco 50 unit can be obtained

$$W'_R = \frac{\pi D^2}{4} \alpha S_R \rho_R D$$

$$W'_c = \frac{\pi D^2}{4} \alpha \left[0.644 (f'_1 - 1) + f_2'^2 - f_1'^2 \right] S_c \rho'_c D$$

$$W'_{cu} = \frac{\pi D^2}{4} \left(f_1'^2 - 0.644 f'_1 - 0.356 \right) S_{cu} \rho_{cu} \left[B (1 + K') + \alpha \right] D$$

where ρ'_c = the density of Hiperco 50

and $f'_1 = D'_1 / D = D + 2H'$

$$f'_2 = D'_2 / D = D + 2(H' + H'_c)$$

The weight ratio of the silicon steel unit to the Hiperco 50 unit is therefore

$$\frac{W'}{W} = \frac{W'_R + W'_c + W'_{cu}}{W_R + W_c + W_{cu}}$$

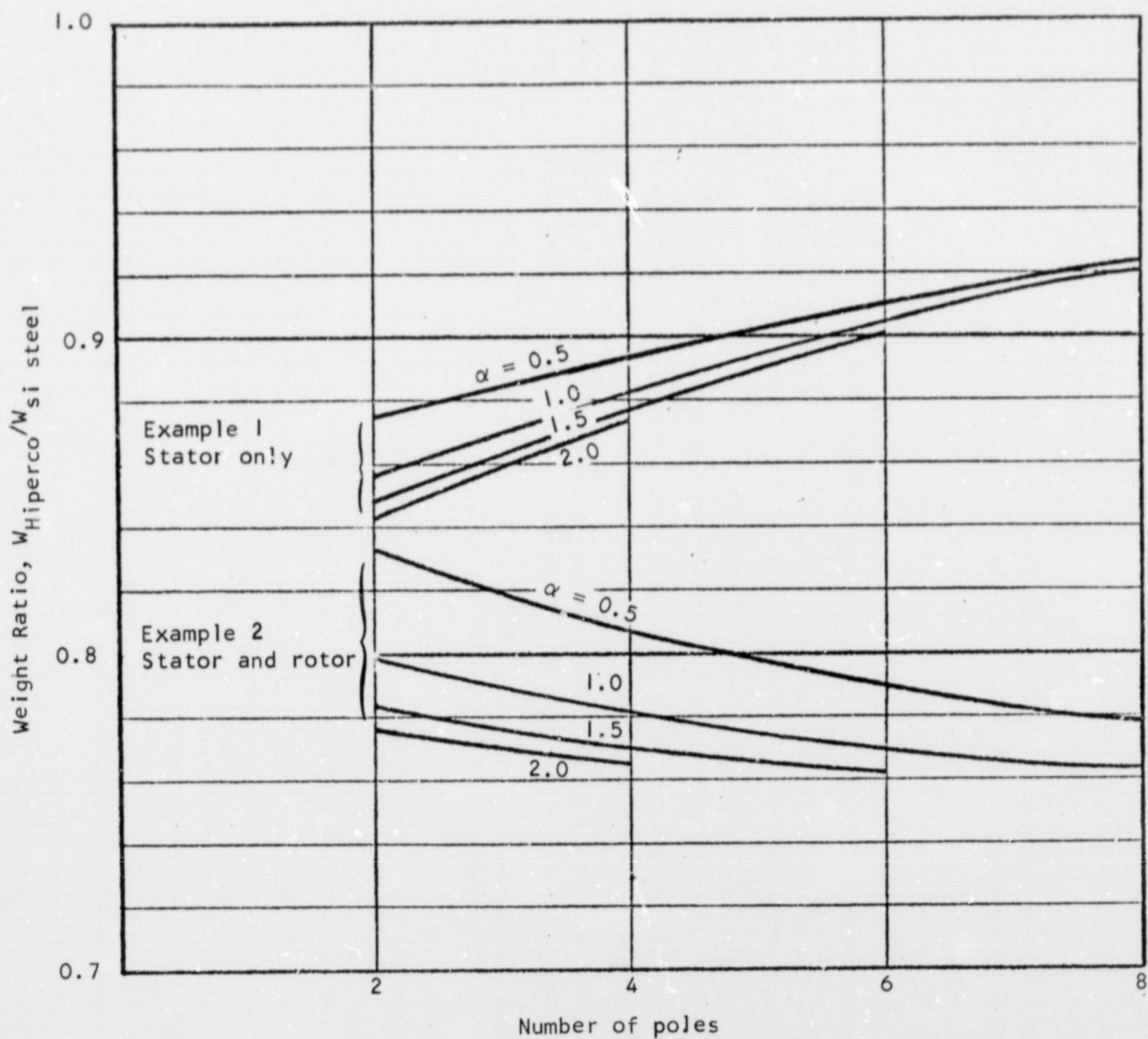
By using proper stacking factors and densities, curves relating the weight ratio and the number of poles are plotted in fig. 10 for several α values.

Example 2.--The following assumptions prevail:

- (1) The comparison is made with cage-rotor induction motors using silicon steel in the stator and rotor, and operating at 400 Hz.
- (2) The rotor is not subject to high mechanical stress and therefore both stator and rotor core materials can be replaced by Hiperco 50 alloy.
- (3) Flux density of the Hiperco 50 unit is 1.4 times that of the silicon steel unit.
- (4) The difference in total loss between the two units is relatively small and can be ignored.
- (5) Stacking factors and fill factors for the two units are the same.
- (6) Rotor and stator diameters remain unchanged; only the stack length is varied.

From these assumptions, it is obvious that the rotor, stator core, and copper weights of the silicon steel unit can be expressed as follows:

$$W_R = \frac{\pi D^2}{4} \alpha S_R \rho_R D$$



Example 1 = only stator core is replaced by Hiperco 50

Example 2 = both stator and rotor cores are replaced by Hiperco 50

α = stack length/gap diameter

Figure 20. Estimated Weight Reduction in Induction Motor when Magnetic Material is Changed from Silicon Steel to Hiperco 50

$$W_c = \frac{\pi D^2}{4} \alpha \left[0.9 (f_1 - 1) + f_2^2 - f_1^2 \right] S_c \rho_c D$$

$$W_{cu} = \frac{\pi D^2}{4} \left(f_1^2 - 0.9 f_1 - 0.1 \right) S_{cu} \rho_{cu} \left[B (1 + K) + \alpha \right] D$$

Since only the stack length is shortened by the factor of 1.4 (flux density ratio), the parameters in the Hiperco 50 unit that differ from those of the silicon steel unit are the density and the ratio of stack length to rotor diameter.

$$L' = \frac{L}{1.4} = \frac{\alpha D}{1.4} = \alpha' D$$

where $\alpha' = \frac{\alpha}{1.4}$

By substituting α' for α and using a different density value in the weight equations, the rotor, stator core, and copper weights of the Hiperco 50 unit can be obtained.

Curves relating the weight ratio and the quantity of poles for this case are plotted in fig. 20 for several α values.

Weight reduction in transformers.--Another major component of the aircraft electrical power system is the transformer, for which oriented silicon steels have been used as core material.

The invention of supermendur permits considerable weight savings to be realized by changing the silicon steel to supermendur, which has superior magnetic properties and is known as the best material for this application. As with rotating machinery design, transformer design depends on many parameters and requirements. Unless extensive design work is performed for a specific design, no accurate values of weight reduction can be obtained. However, by using simplified relations based on reasonable assumptions, approximated results of weight savings can be derived. The following assumptions prevail:

- (1) The comparison is made with a transformer using oriented silicon steel and operating at 400 Hz.
- (2) The silicon steel operates at 110 kilolines/sq in.
- (3) The supermendur operates at 140 kilolines/sq in.
- (4) Total losses of the two units are the same.
- (5) Stacking factors and fill factors for the two units are the same.

- (6) The geometric proportionality is retained and the linear dimensions of the two units differ by a factor of x .

For a given voltage and frequency, the rating of the transformer is proportional to the current density, the copper area, the flux density, and the cross-sectional area of the core. Hence

$$P_o \propto J_{cu} A_{cu} B_m A_{fe}$$

If flux density is increased by a factor of 1.272 (the ratio of 140 to 110) and the linear dimension is changed by a factor of x , the factors for the various parameters are

$$A_{cu} = x^2$$

$$A_{fe} = x^2$$

$$B_m = 1.272$$

To retain the same rating, the current density J_{cu} must be changed by a factor of $\frac{1}{1.272 x^4}$.

The copper loss and the core loss are

$$W_{cu} = J_{cu}^2 \rho_{cu} V_{cu}$$

$$W_{Fe} = W V_{Fe} \times d$$

where ρ_{cu} = resistivity of copper

V_{cu} = total volume of copper

W = core loss in watts/lb

V_{Fe} = total volume of core

d = density of core material

Therefore the factors for W_{cu} and W_{Fe} are

$$W_{cu} = \left(\frac{1}{1.272 x^4} \right)^2 \cdot x^3 = 0.617 x^{-5}$$

$$W_{Fe} = \frac{12}{12.2} x^3 \cdot \frac{8.15}{7.65} = 1.05 x^3$$

Assuming the ratio of copper loss to core loss for the silicon steel unit is β , in order to keep the total losses of the two units the same, the following expression must be satisfied:

$$1.05 x^3 + 0.617 \beta x^{-5} = 1 + \beta$$

or
$$1.05 x^8 - (1 + \beta) x^5 + 0.617 \beta = 0$$

For a fixed β , the value of x can be solved from the equation. The weight ratio of the supermendur unit to the silicon steel unit is, therefore

$$\frac{W'}{W} = \frac{8.15}{7.65} x^3 = 1.065 x^3$$

Fig. 11 shows the weight ratio as a function of β .

Permanent Magnet Materials

Permanent magnet materials are ferromagnetic materials that retain an appreciable amount of residual magnetism after a sufficiently high magnetic field was applied and then removed. In a present day aircraft, hundreds of permanent magnets are used, either with air gaps or with magnetic poles alone. The devices include small motors and generators, microwave tubes, relays, telephone receivers, and loudspeakers.

The mechanism of permanent magnetism has four classifications, as follows:

- (1) Anisotropy due to strain
- (2) Anisotropy due to directional order
- (3) Magnetocrystalline anisotropy
- (4) Shape anisotropy

In the first category, only Vicalloy (an iron-cobalt-vanadium alloy) is in substantial production. Its magnetic properties are improved by cold rolling.

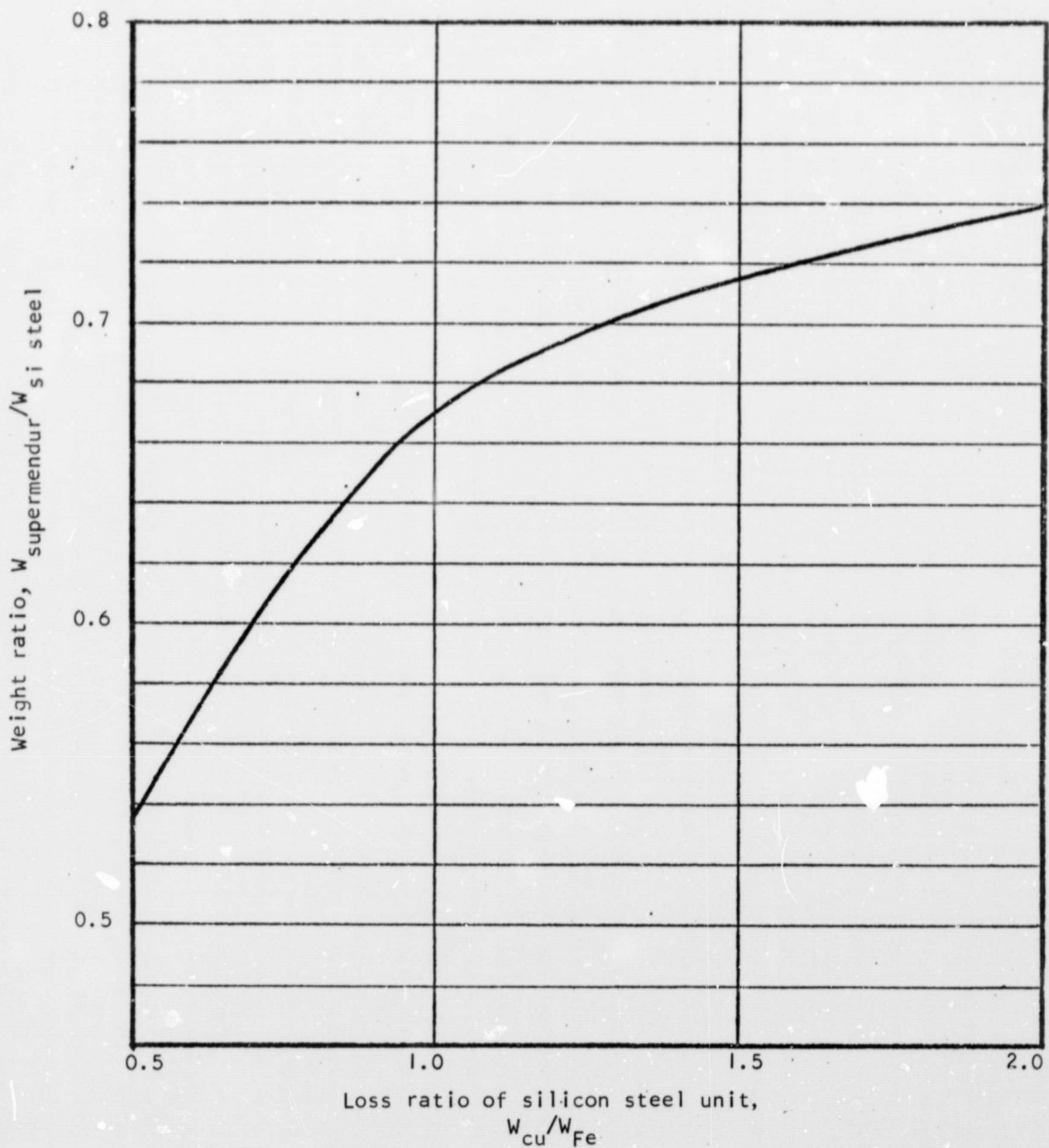


Figure 11. Weight Reduction in Transformer by Changing the Core Material from Oriented Silicon Steel to Supermendur

The second category, anisotropy due to directional order, is caused by the arrangement of different kinds of atoms in the lattice. No commercial material of this type, however, is produced in quantity.

In the third category, barium and strontium ferrites are the most useful materials in general application. Recent theory indicates that PtCo alloy also belongs in this category because its magnetic properties are due to the cubic crystal anisotropy. Intermetallic compounds with uniaxial anisotropy include materials such as MnBi, MnAlGe, and MnAl. Recently, a new material in this category has been developed: SmCo_5 . This rare earth-metallic compound is known as the strongest permanent magnetic material ever manufactured.

The last category includes the whole family of cobalt-nickel-aluminum-iron alloys, known as alnico, and the new elongated single-domain particle (ESD) magnets. Improved alnico permanent magnet materials have increased the coercive force to over 2000 oersteds for alnico 8C, and the maximum energy product to approximately 10 MG-Oe for columax 9. These values indicate that the progress with alnico alloys is approaching the limit of possible development, unless a technological breakthrough can be accomplished.

Samarium cobalt.--Platinum cobalt magnetic material, an alloy of approximately 77 percent platinum and 23 percent cobalt, has been acknowledged as the strongest permanent magnetic material in commercial production. It has a coercive force of 5000 oersteds and a maximum energy product of 9.5 MG-Oe. PtCo has been used in brushless dc motors, microwave tubes, and other devices where (1) extreme resistance to demagnetizing fields, (2) small volume, or (3) exceptionally good corrosion resistance is an important consideration. However, because of the high cost of platinum cobalt magnets, scientists have been seeking a substitute for many years. In early 1969, Raytheon Company announced the development of a new permanent magnet material: samarium cobalt.

This new material, made from cobalt and the rare earth element samarium, has a coercive force of 9000 oersteds and a maximum energy product as high as 20 MG-Oe. Samples manufactured by Raytheon test between 16 and 20 MG-Oe. This shows that the new material is four times as strong as most alnicos, and twice as strong as platinum cobalt.

Samarium is not a rare and precious element. Its present cost is about \$160 per pound; this will drop substantially when large amounts of the material are used. Therefore, samarium cobalt material is cheaper than platinum cobalt by a factor of 20 per unit weight. In addition, since the density of the new material is almost one-half that of platinum cobalt, in a microwave tube samarium cobalt can substitute for four times its weight in platinum cobalt. This means that if samarium cobalt is used to replace platinum cobalt in a microwave tube, a magnet cost reduction factor of 80 can be realized.

The new material also shows good high temperature stability, with a Curie temperature of 850°C, which exceeds that of platinum cobalt. Experiments indicate that SmCo magnets perform well in microwave tubes at 265°C; at this temperature, PtCo degrades 50 percent.

According to Raytheon, the processing involved for SmCo magnets is generally similar to that used in preparing ferrite ceramic magnets. Several steps are unique and proprietary. The new material will be commercially available in the near future. It will not only lead to cheaper, smaller, and lighter microwave tubes operating at higher power and frequency, but is also expected to be used in gyros, motors, generators, and other devices. The permanent-magnet, brushless dc motors have been using platinum cobalt magnets. When this material is replaced by samarium cobalt, considerable reduction in volume and weight will result. Table 3 compares the properties of platinum cobalt with samarium cobalt. Fig. 12 shows the demagnetization characteristics of several important permanent magnet materials.

TABLE 3
PROPERTIES OF SAMARIUM COBALT
AND PLATINUM COBALT

Properties	Platinum cobalt	Samarium cobalt
Specific gravity, gm/cc	15.5	8
Electrical resistivity, ohm-cm	28×10^{-6}	5×10^{-4}
Coercive force, Oe	4300	9000
Intrinsic coercive force, Oe	5300	25,000
Residual induction, G	6450	9000
Energy product (maximum), MG-Oe	9.5	20
Curie temperature, °C	480-500	850
Tensile strength, psi	~100,000	8000
Compressive strength, psi	--	>>10,000
Flexural strength, psi	--	12,000

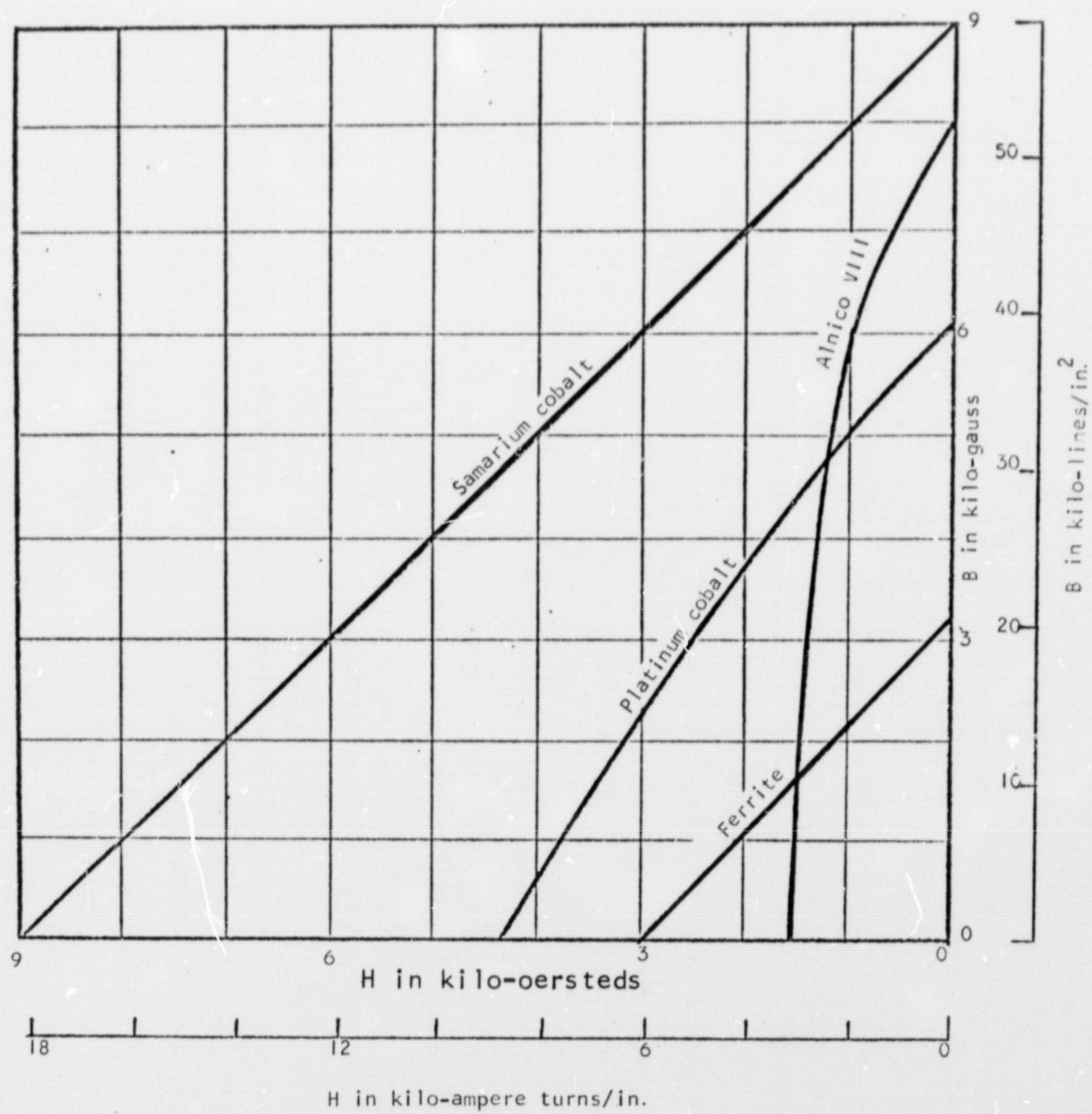


Figure 12. Demagnetization Characteristics of Magnet Materials

Brushless dc motors.--The brushless dc motor is more reliable and requires less maintenance than the conventional dc machine. In addition, the former can operate in special environments where the load characteristics dictate the brushless dc motor over the ac motor. Furthermore, a brushless dc motor can be designed to run at very high speed, while the ac motor is limited by the system frequency. In view of these advantages, it is evident that the brushless dc motor will play an important role in future advanced aircraft, especially when the primary electrical system is a high voltage dc system.

The discovery of samarium cobalt will not only lead to smaller, lighter, and cheaper motors, but also will raise the capacity of permanent magnet machines to higher levels, for which the use of platinum cobalt seemed unrealistic. The following is a design study using samarium cobalt for permanent-magnet, brushless dc machines.

Because of the lack of tensile strength in samarium cobalt, it is necessary to support the rotor magnets. AiResearch analysis of support of permanent magnets in radial-gap rotor assemblies indicates that a high-strength steel sleeve shrunk over the fabricated rotor is the best means of support. The study was therefore based on the use of the nonmagnetic Inconel 718 sleeve, which must occupy some of the allowable airgap region. It was determined by brief iteration that a rotor support using 30 percent of the gap would approximate an optimum condition.

From this configuration, various relations were established. By using a suitable sizing process based on a certain design, machine performance as a function of output power and speed was determined. The following are the basic assumptions for the analysis:

- (1) All motors are designed as four-pole machines, representing a practical compromise between fabrication and electromagnetic considerations.
- (2) The maximum allowable tip speed of the rotor is 640 fps. This is determined from the loading of the support ring based on a 20 percent overspeed requirement and an Inconel 718 yield strength of 150,000 psi.
- (3) When the size of the machine is varied, a certain geometric proportionality is maintained.
- (4) The magnet material, samarium cobalt, has twice the magnetic energy product of platinum cobalt.
- (5) The cooling capability is 20 W/cu in. If this limit is exceeded, the capacity of the machine is derated while maintaining the same weight.

The electromagnetic weight of the machine is contributed by the rotor, stator iron ring, copper winding, potting, and winding support. From the analysis, expressions for the volume of each component were assigned and multiplied by the densities of the respective materials. The final equation for the electromagnetic weight in terms of the rotor diameter, D , and the stack length, L , reduced to the following:

$$W_{em} = 0.372 D^2 L + 0.064 D^3$$

Use of an existing design and a proper scaling relation enable the weight to be expressed in terms of the machine capacity and speed, from which electromagnetic weight curves (for $L/D \approx 1$) for the permanent magnet machine are plotted in fig. 13. The curves in fig. 13 have a slope of unity. This is a characteristic of the permanent magnet machine. Similar weight versus horsepower curves for electromagnetic machines would have a slope of $3/4$.

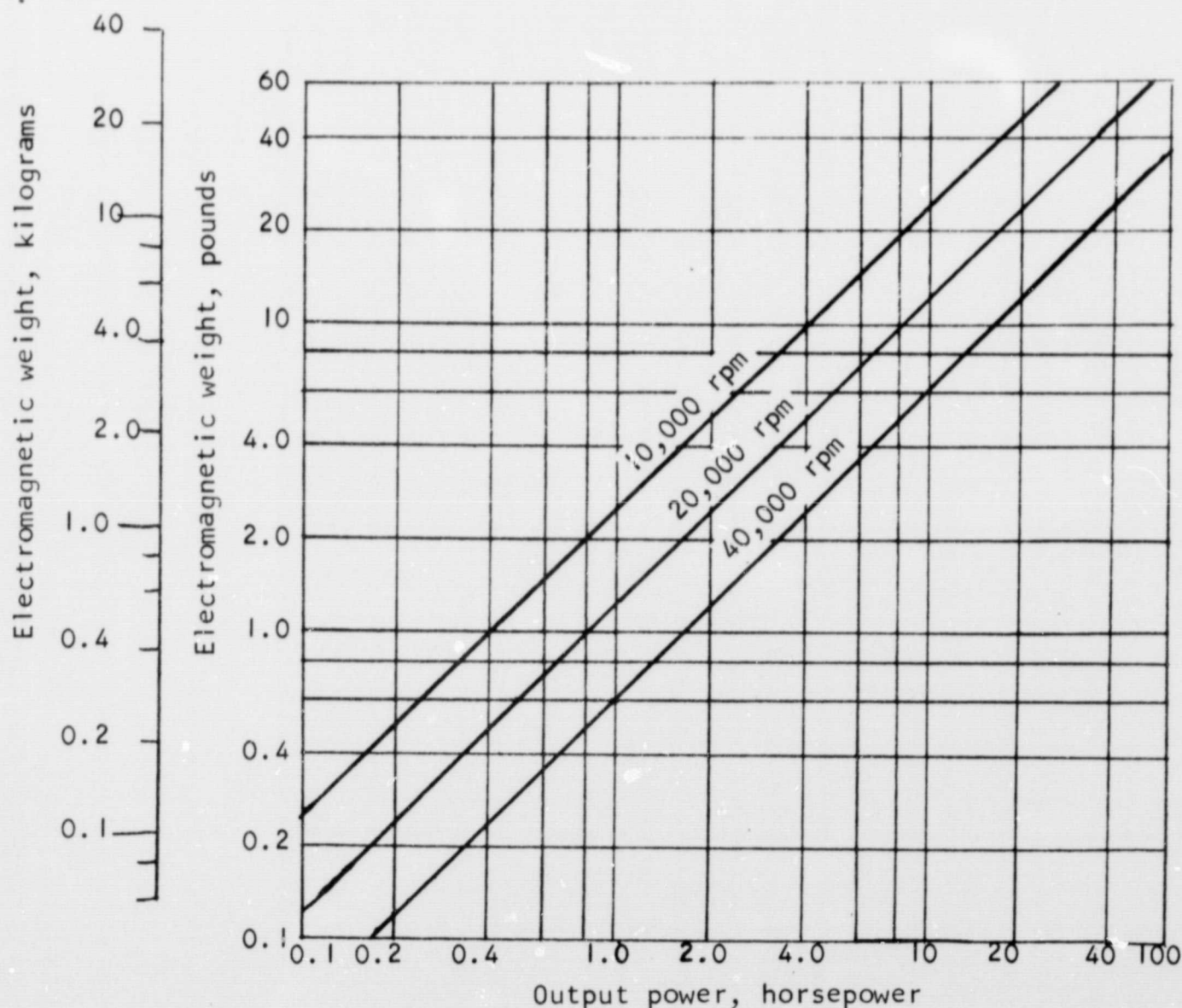


Figure 13. Estimated Electromagnetic Weight of Brushless dc Motor (PM Type) Using SaCo Magnet (Electronics Not Included)

The estimated motor weights (electromagnetic weight plus the structure weight) of brushless dc motors (electronics not included) using samarium cobalt and the conventional alnico 9 permanent magnets is shown in fig. 14. Use of SmCo in brushless dc motor results in a weight saving of about 1/3. If the mechanical strength of SmCo can be improved in the future such that Inconel sleeve in the rotor is not required, further motor weight saving can be achieved.

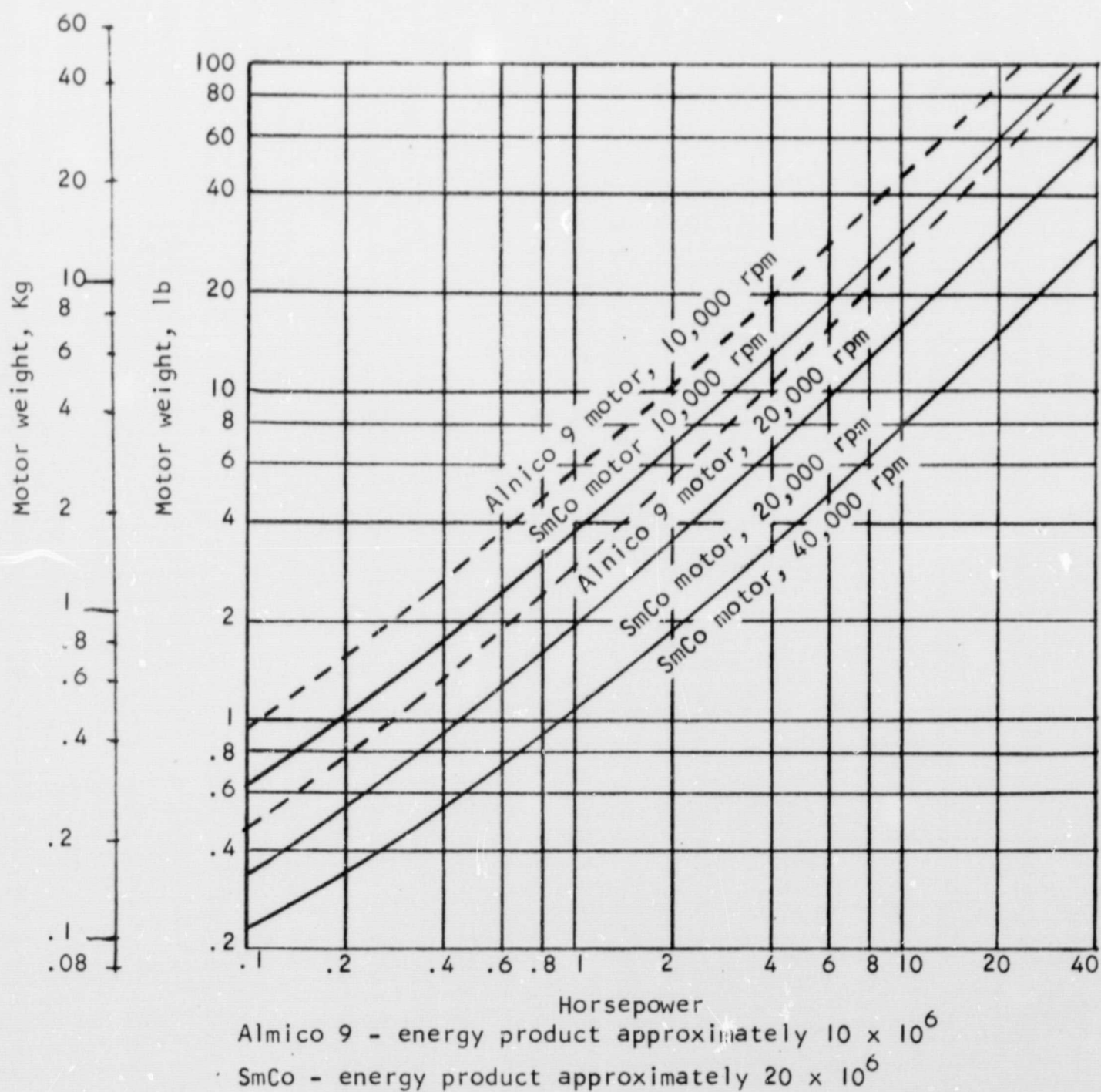


Figure 14. Estimated weight of brushless dc motor using SmCo and alnico 9 permanent magnets (electronics not included)

In the above motor weight estimate, a cooling requirement of 20 w/cu in. is used as a guide. When this thermal limit is exceeded, the machine is derated to satisfy the thermal requirement. The method of determining the loss values is explained below.

The efficiency expression was based solely on electromagnetic losses, viz., copper loss, eddy losses in the copper conductors, and iron loss in a laminated flux containment ring. The copper loss is dependent on the number of conductors in series per phase, the cross-sectional area of those conductors, and the current per phase. With the established geometric and magnetic relationships and an arbitrary voltage level, the necessary parameters were determined. The eddy loss in the copper conductors varies (1) with the second power of frequency, flux density, and wire diameter, and (2) inversely with wire resistivity. All these parameters are known except wire diameter. To compensate for the higher eddy losses at high speeds, a table was set up to progressively reduce wire strand size as design speed increased. The iron loss was dependent on the determination of a flux density.

The flux will have fringed somewhat before reaching the iron ring; thus the ring thickness was set to operate at a density of 55.8 kilolines/sq in. Tran-cor-T 4-mil lamination material was used in the calculations. The iron loss was calculated to vary with the 1.6 power of speed. The total losses used in calculating efficiency are thus defined.

$$\text{Watts loss} = \frac{1.065 \times 10^{10} P^2 (2L + 3.78D)}{D^4 N^2 L^2} + 16.9 \times 10^{-6} N^2 d^2 LD^2 \\ + 8.05 \times 10^{-8} D^2 LN^{1.6}$$

where P = motor rating in horsepower

L = stack length in inches

D = rotor diameter in inches

N = speed in rpm

d = wire diameter in inches

Fig. 15 shows the average efficiency as a function of output power for a rotor diameter to length ratio of unity ($L/D = 1$). As explained above, this efficiency is for motor only, losses in electronic circuit is not included.

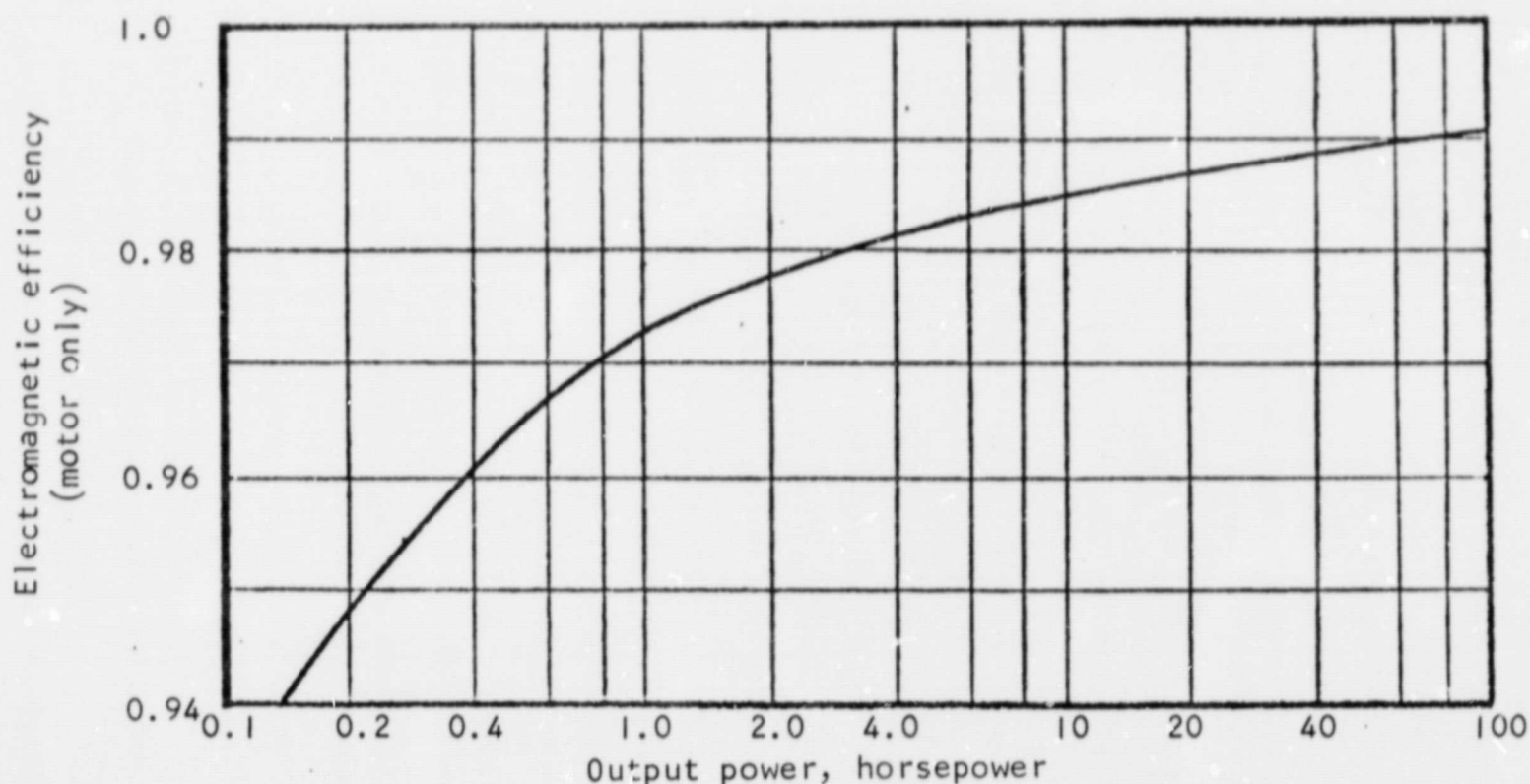


Figure 15. Estimated Electromagnetic Efficiency of Brushless dc Motor Using SaCo Magnet (Electronics not included)

Insulation Materials

As previously pointed out, trends in electrical and electronic equipment applications emphasize reduced equipment envelope, increased operating temperatures and voltages, tighter reliability and safety requirements, and more severe operating environments. These demands, plus unrelenting pressure for weight and cost reduction, are compelling motivators in the vigorous search for new insulation materials with improved electrical and thermal properties. New types of such materials glut the market. Even a cursory description of all available products is not feasible in this report; however, some of the more promising materials are discussed herein.

Kapton wire and cable insulation.--Several years ago, two types of Kapton polyimide films were developed by the DuPont Company and are now in commercial production. One, called Kapton polyimide film type H, is a condensation product of pyromellitic dianhydride and an aromatic diamine. The other, known as type HF, is an infusible product, a heat-sealable modification with one or both sides coated with Teflon FEP-fluorocarbon film. With superior electrical, mechanical, and thermal properties, these insulation materials offer distinct advantages in wire and cable applications.

Strong and tough, these Kapton films are capable of retaining good electrical properties at very high temperatures. The heat-sealable type HF film has increased resistance to water vapor permeation and chemical attack.

Table 4 compares typical properties of Kapton films, Mylar polyester film, and Teflon FEP-fluorocarbon film.

The Kapton films are available as tapes in width of 3/16 in. and up in 1/16 in. increments. These tapes are normally applied as a spiral wrapping with a 50 percent overlap. Depending on the requirement, single or multi-ply tapes can be used; either unidirectional or cross-lapped constructions are possible. After proper processing, the following properties of the wrapped wire are noted:

- (1) Weight and Space Comparison. Table 5 shows the weight and space comparison of 600-volt aerospace wires using different insulations. Obviously, substantial savings in weight and space are afforded by using wires insulated with Kapton polyimide film.
- (2) Dielectric Strength. The Kapton polyimide films have very high dielectric strength. At 25°C the dielectric strengths of Type HF and Type H films are approximately 4.5 and 7 kV/mil, respectively.
- (3) Temperature Capabilities. Wires insulated with Kapton films can sustain temperatures as high as 200°C and as low as 4°K without serious degradation in dielectric strength and flexibility.
- (4) Toughness. Wires insulated with Kapton films have superior cut-through resistance.
- (5) Radiation Resistance. Wires insulated with Kapton Type HF film exhibit good dielectric strength and flexibility after exposure to radiation.
- (6) Nonflammability. Wires insulated with Kapton films will burn if exposed to sufficiently high temperature flames. However, Kapton is self-extinguishing upon removal of the heat source.

Wires insulated with Kapton polyimide films have been used in many aerospace programs, including Titan III, Lunar Excursion Module, and SPRINT antimissile-missile. These wires offer many advantages over previously available materials; their continued wide and rapid acceptance for aerospace applications is considered ineluctable.

High-temperature wire enamels.--For operating temperatures around 400°F, organic enamels are usually used. There are several organic enamels with good thermal stability; each has its advantages and disadvantages. Polyimide wire enamels offer all the heat resistance required in magnet wire insulation for copper conductors. They exhibit good properties up to 400°F. However, polyimide enamels are expensive and the application process is rather difficult. Therefore, low-cost, easily applied enamels are eagerly sought, even if it is necessary to sacrifice some of their high-temperature advantages. Polyamide-imide enamels have excellent mechanical, chemical, and electrical properties, and show satisfactory stabilities up to 430°F. Their abrasion resistance is superior to the polyimide enamels. However, they are relatively expensive

TABLE 4
PROPERTIES OF KAPTON, MYLAR, TEFLON

Property \ Material	Kapton Type HF	Kapton Type H	Mylar	Teflon
Thickness, mils	1.5	1	1	1
Tensile strength, psi 25°C	16,000	25,000	23,000	3,000
Tensile strength, psi 200°C	10,000	17,000	7000	200
Elongation, percent 25°C	75	70	100	300
Elongation, percent 200°C	75	90	High	175
Tear propagating, gm/mil (Elmendorf)	20	8	15	125
Tear initial, gm/mil (Graves)	800	500	900	270
Water vapor permeability, gm/100 sq in. (24 hr)	0.8	5.4	1.8	0.4
Specific gravity	- -	1.42	1.39	2.15
Melt point (°C)	- -	none	250 - 265	260 - 280
Zero strength temp. (°C)	- -	815	248	255
Cut-through temp. (°C)	- -	435	190	- -
Flammability	- -	self- extinguishing	slow to self- extinguishing	self- extinguishing
Dielectric strength, kV/mil 25°C	4.5	7	7	5
Dielectric strength, kV/mil 200°C	4	6	5	- -
Dissipation factor, 1 Hz 25°C	0.0035	0.003	0.0047	0.0002
Dissipation factor, 1 Hz 200°C	- -	0.002	0.01	0.0002
Dielectric constant, 1 Hz 25°C	3.0	3.5	3.1	2.0
Dielectric constant, 1 Hz 200°C	- -	3.0	- -	1.95

TABLE 5

SPACE AND WEIGHT COMPARISON OF 600-VOLT AEROSPACE WIRES

Insulation	AWG 22		Weight Savings Percent	Space Savings Percent	TPSJ AWG 22		Weight Savings Percent	Space Savings Percent
	Weight (Nom.)	OD (Nom.)			Weight (Nom.)	OD (Max.)		
Kapton Type HF (6 mil)	2.76	0.042	22.3	35.3	12.83	0.112	26.6	49.8
Teflon Type E (11 mil)	3.55	0.052	0	0	17.48	0.158	0	0
Teflon - M.L (7 mil)	2.99	0.044	15.8	28.7	15.42	0.133	11.8	29.1
IMP Type R (10 mil)	1.94	0.050	17.2	8.1	16.23	0.158	7.7	0

and require special coating techniques. Polyester-imide enamels that are compatible with existing enameling equipment are less expensive than polyimide and polyamide-imide enamels. Polyester-imide enamels have good heat resistance and outstanding windability. However, their operating temperature is relatively low (360°F). Further, because of their ester linkage content, these enamels can cause problems in sealed applications where moisture cannot escape.

Solventless varnish trickling.--The use of solventless varnishes for impregnating random-wound stator and rotor coils has become popular for rotating machinery encapsulation. The major advantage of the varnish is increased reliability due to the elimination of voids. Therefore, mechanical and thermal properties are enhanced.

In the new trickling process, a stream of low-viscosity resin is poured onto the slowly rotating winding. The varnish penetrates into the winding uniformly and then sets up, encapsulating the winding. Compared with dip-dry processes, the trickling process is faster and can result in better uniformity and reduced masking. However, cure time of the resin, temperature of the winding, and rotation speed must be properly governed.

Continued improvement of the trickling process for applying solventless varnishes will result in their wider use in smaller machines. This technique enables the manufacture of better encapsulated windings at relatively low cost.

Conductor Materials

Conductor materials to carry electric current include busbars, cable conductors, and wires used in rotating machines, transformers, and other devices. For conductors that require relatively high mechanical strength, such as small-gage aircraft cables, alloys with balanced electrical and mechanical properties are desirable. For applications where mechanical strength is not a problem, desired improvements are concentrated on weight and cost reductions. In this section, a few special topics regarding conductor materials are discussed.

Aluminum foil conductors.--Recent developments indicate that the use of aluminum foil for transformers in both commercial and aerospace applications has the following advantages over that of conventional copper wires.

- (1) The resistivity of aluminum is higher than that of copper; however, because of its lighter weight, a better conductivity-to-weight ratio is observed.
- (2) An aluminum strip conductor is easier to wind than copper wire, thus reducing manufacturing costs.
- (3) With proper insulation, better space factors can be realized, creating a tightly wound unit.

- (4) Strip wound coils permit greater overloads because of better cooling capabilities; hot spots usually experienced in copper wire coils can be eliminated.
- (5) The turn-to-turn voltage stress is relatively lower.

Aluminum foil has two major disadvantages: lower volume conductivity in comparison to copper, and lead connection problems. It is determined that the aluminum-strip winding is about 50 percent the weight of an equivalent copper winding. (The resistivity-density product of aluminum is half that of copper.) The volume of the unit, however, is larger. Lead connections can be made properly but the connection cost is higher. In addition, multiple connections are frequently required.

The most difficult problem in aerospace application is turn-to-turn insulation where the foil thickness is small. Mylar has been used for turn-to-turn insulation but the temperature capability is limited to 150°C. The anodic coating, although satisfactory in regard to operating temperature and insulation thickness, is an expensive process for coating thin gages and often results in crazing of the coating, burred foil edges due to poor flexibility. Coating ML enamel on one side of anodized aluminum is another approach being used. The performance is satisfactory but the cost is relatively high.

Recent developments of polyimide and polyamide insulating materials have brought new hope to the turn-to-turn insulation problems. Kapton and Nomex (both of which have superior electrical, mechanical, and thermal properties) are available in thicknesses of 0.0005 and 0.002 in., respectively. Since Kapton and Nomex are high temperature materials, it is expected that by using them for interleaving insulation for the aluminum foil construction, good high temperature, lighter weight, and lower cost transformers can be realized for aerospace applications.

Feasibility of sodium conductors.--The use of sodium as an electric conductor for power transmission might result in significant weight savings in the aircraft electrical power system. To evaluate the feasibility of this unconventional conductor, the following analysis comparing sodium with aluminum was performed.

In order that the sodium conductor and the aluminum conductor have the same performance, (i.e., same total resistance) for a given transmission distance, the ratio of the cross-sectional areas must be equal to the ratio of their resistivities. Thus

$$\frac{A_{Na}}{A_{Al}} = \frac{\rho_{Na}}{\rho_{Al}} = \frac{V_{Na}}{V_{Al}}$$

where A = cross-sectional area of the conductor

ρ = resistivity of conductor

V = total volume of the conductor

the subscripts Na and Al refer to sodium and aluminum respectively. The ratio of the total weight is, therefore

$$\frac{W_{Na}}{W_{Al}} = \frac{V_{Na} d_{Na}}{V_{Al} d_{Al}} = \frac{\rho_{Na} d_{Na}}{\rho_{Al} d_{Al}}$$

where d is the density of the conductor.

Based on an operating temperature of 55°C it is found that

$$\frac{W_{Na}}{W_{Al}} = \frac{2.125 \times 0.971}{1.263 \times 2.7} = 0.605$$

A weight reduction on the order of 39.5 percent can therefore be realized. It should be noted, however, that the sodium is an extremely active metal. It has a low melting point of 97.5°C and can cause fire hazard when in contact with moisture. Some means of containment therefore, must be utilized.

The diameter of the No. 00 aluminum wire is 0.365 in. while the equivalent sodium conductor has diameter of 0.473 in. Assuming a stainless steel tube of 6-mil thickness is required for the sodium conductor, then the weight of the tube per unit length is

$$\pi \times 0.473 \times 0.006 d_{st} \text{ lb/in.}$$

The weight of the sodium conductor per unit length is

$$\frac{\pi \times 0.473^2}{4} \times d_{Na}$$

therefore

$$\frac{W_{tube}}{W_{Na}} = \frac{0.024}{0.473} \times \frac{7.7}{0.971} = 0.402$$

The weight ratio of the sodium conductor (with the stainless steel tube) to the aluminum conductor is

$$(1 + 0.402) \times 0.605 = 0.848$$

Therefore, the weight savings has been reduced from 39.5 percent to 15 percent.

Practically, the stainless steel tube of 6-mil thickness is probably too thin to satisfy the mechanical strength requirements. However, a 10-mil tube will increase the weight ratio to 1.01 and hence, the sodium conductor (include the stainless steel tube) is slightly heavier than the aluminum conductor.

Other materials, such as fluoroelastomers (Viton) and polytetrafluoroethylene (PTFE), might be suitable for confining the sodium conductor. These materials have much lower densities (about 2.0 g/cc) compared to stainless steel. They can also serve as part of the insulation material and offer flexibility. However, since the change of state of the sodium conductor (solid state to liquid state, or vice versa) must be considered, relatively high mechanical strength might be required. This must be accomplished by ensuring adequate reinforcement in the tubing. A practical construction of the cable using sodium as a conductor cannot be established without detailed analytical research and experimentation. Therefore, the weight savings, if any, cannot be determined.

The sodium conductor has many disadvantages:

- (1) Because a tube is necessary to confine the sodium conductor, the conductor has poor flexibility (or none).
- (2) The relatively large volume adds insulation weight to the wire.
- (3) The high corrosivity can cause a fire hazard.
- (4) Because of the nature of the conductor, special techniques are required in termination and installation.
- (5) The change of state of the sodium conductor from solid to liquid, or vice versa, may result in discontinuity or degraded performance in current conduction.

It was found that the use of sodium as an electric conductor creates many new problems and may not offer substantial weight savings. It is not likely that the weight savings will justify the sacrifices in other areas.

Structural Materials

Graphite and boron composites.--Structural materials comprise a large percentage of the total weight of various electrical components in the aircraft electrical power system. Structural materials are used in the shaft of the rotating machinery, the frame, case, chassis, and other supporting structures. Except for the shaft, relatively low mechanical strength is usually sufficient. Light weight, therefore, becomes the major interest. Research and development in lightweight structural materials has been conducted for years. Recently, Northrop Corporation announced development of a graphite composite that can effect great weight savings in the aircraft industry.

Graphite filaments are created by burning rayon fibers. The fibers break down into graphite under intense heat and the filaments are then bonded with industrial glues or resins into yarn with an 8-mil diameter. The yarn is formed into a sheet with several layers glued together. By applying pressure to the sheets in a heated environment, the final material is produced. According to Northrop Corporation, the new material is 40 percent lighter than aluminum, and reputedly can withstand a temperature of 500°F. It is expected that the graphite composite will find ready acceptance in aircraft parts such as engine cases, fan blades, flaps, stabilizers, speed brakes, and other components.

This graphite material presently costs about \$350 per pound, which is extremely high compared with \$1 to \$2 for aluminum. Northrop predicts, however, that the price per pound can be reduced to \$20 to \$30 in the next few years, as a result of increased production.

In addition to the graphite composite, a boron composite is also under development. The boron composite is produced by depositing boron gas on tungsten fibers that are bound together.

COMPONENT RELIABILITY AND WEIGHT TRADEOFF

Introduction

N70-25430

The reliability of the aircraft electrical power system depends upon the reliabilities of its components. Aircraft electrical components are usually designed for light weight and small size so as to maximize the payload of the vehicle. However, high reliability components are usually accompanied by heavy weight and high cost. Reliability as a function of weight, size, or cost is a tradeoff that often arises, particularly in airborne applications.

The life of an electrical component depends on many factors, typically operating voltage, current, power dissipation, stress, shock, vibration, temperature, cooling, humidity, altitude, corrosion, and radiation. It is not the intent of this study to perform a complete analysis of the reliability and weight tradeoffs of the above factors; only a general method of approach with a few specific examples will be given. Reliability improvements by redundancy and by better system protection are not included in this discussion. The tradeoff between reliability and weight, however, is investigated. In most cases, the component size and cost vary in the same sense as the component weight.

Designing for Reliability

Generally, the life of electrical components is closely related to their physical size, which varies with the designed mechanical strength, electric current and magnetic flux densities, amount of insulation used, operating temperature, etc. Obviously, one way to improve the component reliability is to design the component with more margin of safety. The relationship between the margin of safety and reliability can be derived as follows with the relationship between weight penalty and margin of safety being determined individually for each component and for each factor under consideration.

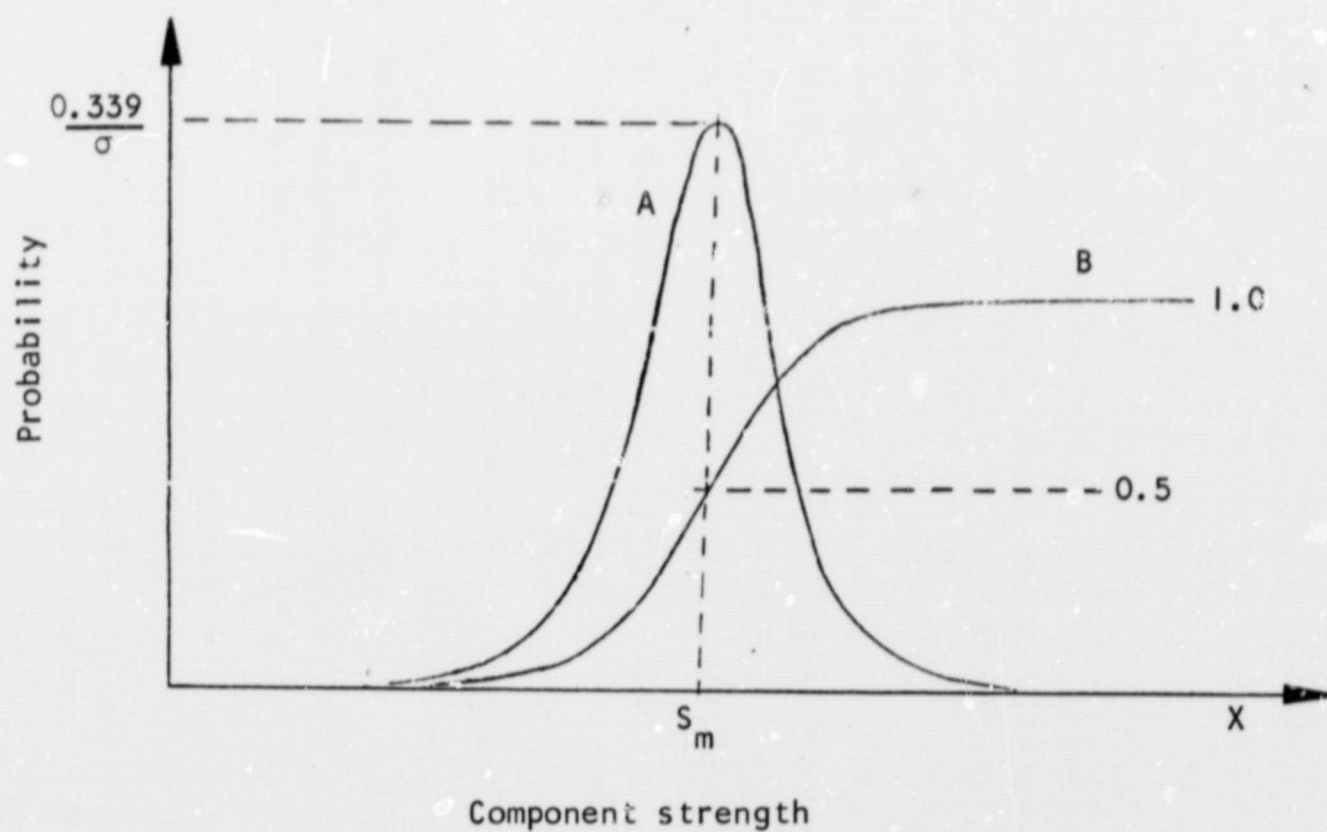
The actual strengths (mechanical, electrical, chemical, or thermal) of supposedly identical components vary according to the normal or Gaussian distribution. The probability of a component having a strength X is given by

$$\text{Probability} = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(X-S_m)^2}{2\sigma^2}} \quad (13)$$

where S_m = mean strength

σ = standard deviation of strength distribution

This probability curve is shown as Curve A in fig. 16. If this curve is integrated, the resulting Curve B (fig. 16) will show the probability that the component strength is less than X .



Curve A = strength distribution

Curve B = probability that strength is less than X

Figure 16. Probability Distribution of Component Strength

p_x = probability that strength is less than X

$$= \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{(x-s_m)^2}{2\sigma^2}} dx \quad (14)$$

Letting

$y = \frac{1}{\sigma} (X - S_m)$, eq. (14) is transformed into

$$p_x = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{X-S_m}{\sigma}} e^{-\frac{1}{2} y^2} dy$$

$$= \frac{1}{2} - \frac{1}{\sqrt{2\pi}} \int_{\frac{S_m-X}{\sigma}}^{\frac{S_m-X}{\sigma}} e^{-\frac{1}{2} y^2} dy \quad \text{if } X \leq S_m \quad (a)$$

$$= \frac{1}{2} + \frac{1}{\sqrt{2\pi}} \int_{\frac{X-S_m}{\sigma}}^{\frac{X-S_m}{\sigma}} e^{-\frac{1}{2} y^2} dy \quad \text{if } X > S_m \quad (b)$$

$$\left. \begin{array}{l} (a) \\ (b) \end{array} \right\} (15)$$

According to J. D. Williams (annual of mathematical statistics, vol.17, pp. 363-365):

$$\frac{1}{\sqrt{2\pi}} \int_{-X}^X e^{-\frac{1}{2} t^2} dt \cong \sqrt{1 - e^{-\frac{2X^2}{\pi}}} \quad (16)$$

and the error in above approximation is less than 0.75 percent for any value of X . Substituting eq. (16) into eq. (15):

$$p_x = \frac{1}{2} \mp \sqrt{1 - e^{-\frac{2}{\pi} \left(\frac{X-S_m}{\sigma}\right)^2}} \quad (17)$$

$$\left(\begin{array}{l} - \text{ if } X \leq S_m \\ + \text{ if } X > S_m \end{array} \right)$$

The applied load (stress) to the component is also distributed. The probability that the load is equal to X is given by

$$L_x = \frac{1}{\sigma_l \sqrt{2\pi}} e^{-\frac{(X-L_m)^2}{2\sigma_l^2}} \quad (18)$$

where L_m = mean value of maximum applied load

σ_l = standard deviation for load distribution

When the applied load is X , all the components with strength less than X will fail. Therefore, the integration of the product $p_x L_x$ indicates the probability of failure.

F = probability of failure

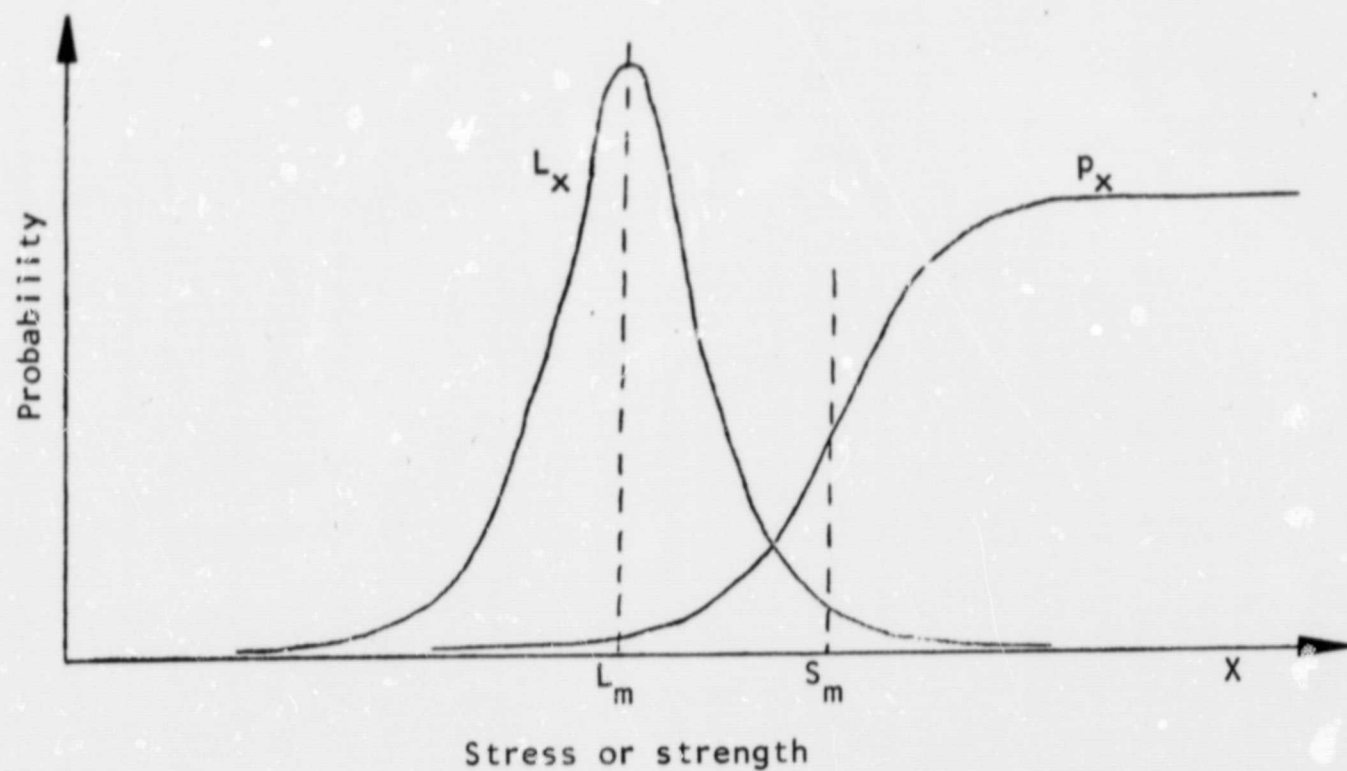
$$\begin{aligned} &= \int_{-\infty}^{\infty} p_x L_x dx \\ &= \frac{1}{\sigma_l \sqrt{2\pi}} \int_{-\infty}^{S_m} e^{-\frac{(X-L_m)^2}{2\sigma_l^2}} \left[\frac{1}{2} - \sqrt{1 - e^{-\frac{2}{\pi} \left(\frac{X-S_m}{\sigma} \right)^2}} \right] dx \\ &\quad + \frac{1}{\sigma_l \sqrt{2\pi}} \int_{S_m}^{\infty} e^{-\frac{(X-L_m)^2}{2\sigma_l^2}} \left[\frac{1}{2} + \sqrt{1 - e^{-\frac{2}{\pi} \left(\frac{X-S_m}{\sigma} \right)^2}} \right] dx \end{aligned} \quad (19)$$

Fig. 17 shows the p_x and L_x curves, and fig. 18 shows the product of these two curves.

The integration of eq. (19) can be performed by expanding the quantity of the square root into an infinite series. The result is:

$$F = \sum_{k=1}^{\infty} f(k) e^{-\frac{2k}{\pi} \left(\frac{S_m - L_m}{\sigma_l} \right)^2} + \sum_{k=1}^{\infty} f(k) \frac{e^{-\frac{C_1 k}{\sqrt{\frac{1}{\sigma_l^2} + \frac{2k}{\pi \sigma^2}}}}}{\sqrt{\frac{1}{\sigma_l^2} + \frac{2k}{\pi \sigma^2}}} \sqrt{1 - e^{-\frac{2}{\pi} C_{2k}^2}} \quad (20)$$

$$\text{where } f(k) = \frac{\frac{1}{2} \left(\frac{1}{2} - 1 \right) \cdots \left(\frac{1}{2} - k + 1 \right)}{2k!} \quad (21)$$



Curve L_x = load stress distribution

Curve p_x = probability that component strength is less than x

Figure 17. Stress and Strength Distributions

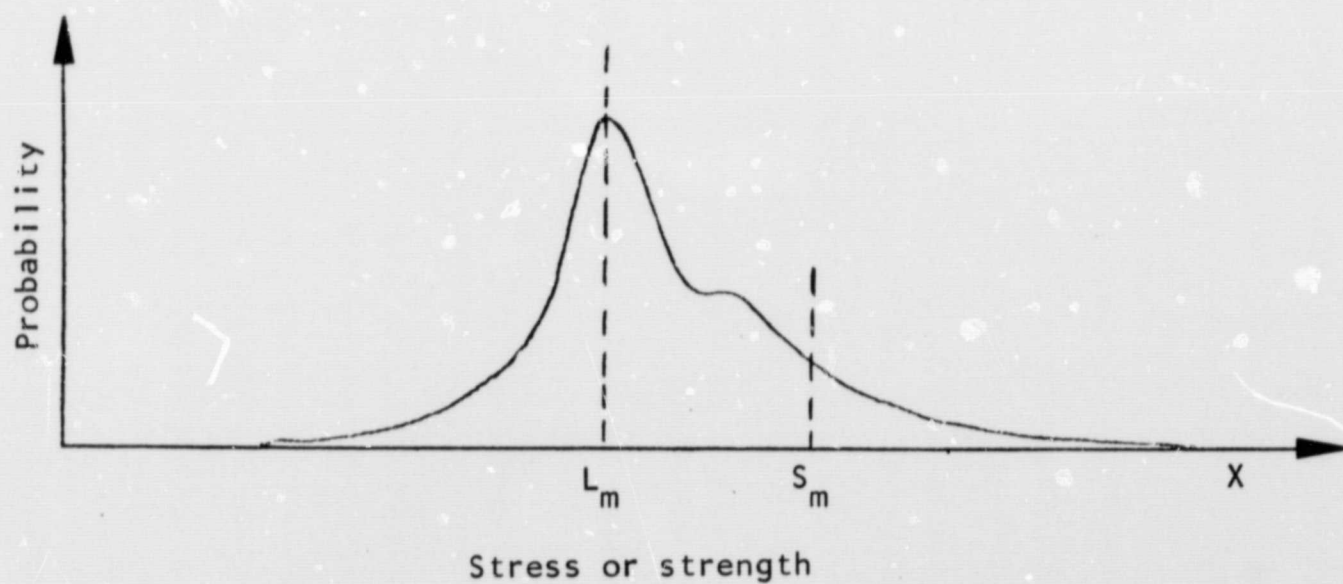


Figure 18. Product of L_x and p_x

$$C_{1k} = \frac{L_m^2}{2\sigma_l^2} + \frac{KS_m^2}{\pi\sigma^2} - \frac{\left(\frac{L_m^2}{2\sigma_l^2} + \frac{2KS_m^2}{\pi\sigma^2}\right)^2}{2\left(\frac{1}{\sigma_l^2} + \frac{2K}{\pi\sigma^2}\right)} \quad (22)$$

$$C_{2k} = \frac{S_m - \frac{\frac{1}{\sigma_l^2} + \frac{4kS_m}{\pi\sigma^2}}{\frac{1}{\sigma_l^2} + \frac{4k}{\pi\sigma^2}}}{\sqrt{\frac{1}{\sigma_l^2} + \frac{4k}{\pi\sigma^2}}} \quad (23)$$

For a particular case of $\sigma = \sigma_l = 0.05$, and $L_m = 1.0$, the variation of probability of failure F vs designed strength S_m is given in fig. 19. Another example of F vs S_m for $\sigma = \sigma_l = 0.1$ and $L_m = 1.0$ is shown in fig. 20.

The ratio:

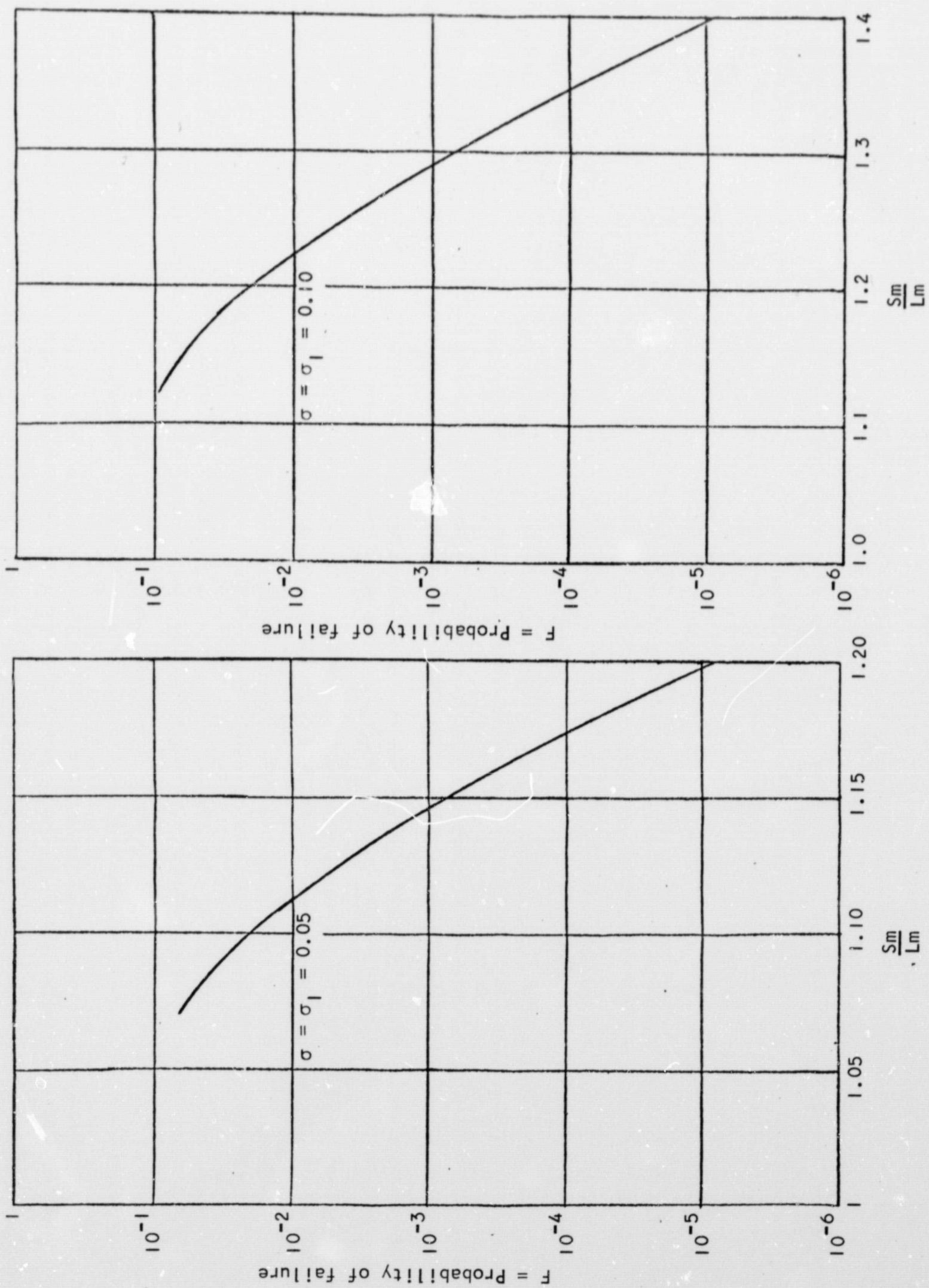
$$\frac{S_m}{L_m} = \frac{\text{design strength}}{\text{maximum possible load}}$$

is called the safety factor. (Some authors define the safety factor as the ratio of the designed strength to the nominal load. Under that definition, the safety factor is much greater than one.) The quantity $\frac{S_m}{L_m} - 1$

is the margin of safety. According to figs. 19 and 20, when the margin of safety is greater than 4σ of the stress distribution, the component is reasonably reliable (i.e., the probability of failure is less than 0.00093 percent).

Component Reliability and Weight Tradeoffs

Electric motors.--Aircraft electric motors are required to be reliable, light weight, small size, and able to withstand extreme environment. Reliability of aircraft ac motors is imparted by various design considerations, materials, and manufacturing practices. Some of these are discussed below.

Figure 19. F versus S_m/L_m , $\sigma = \sigma_I = 0.05$ Figure 20. F versus S_m/L_m , $\sigma = \sigma_I = 0.1$

Many aircraft ac motor windings are wound with a continuous wire instead of inserting separate coil groups for each pole. For example, in a 3-phase, 4-pole, (12 coils) conventional motor, there will be 24 internal electrical connections. If this motor is wound with the single-wire method, the number of internal electrical connections is only 4. Fig. 21 illustrates this difference. When the number of electrical connections is reduced, the reliability of the motor is increased. This increase in reliability does not increase the weight, but does increase the cost of the motor.

Another feature which will improve the reliability of 3-phase ac motor is to design the machine such that when one line opens or one phase is out, the motor will continue to operate and perform the load function. Two cases should be considered. For 3-phase 4-wire (grounded neutral) motors, 2-phase operation results when one line is open or one phase is out. For 3-wire motors, such a fault will result in single-phase operation. When a 3-phase motor is reduced to 2-phase or single-phase operation, motor torque capability will be reduced, and motor losses will be increased. Fig. 22 illustrates the relative torque at different modes of operation.

Since the single-phase motor has no starting torque, a 3-wire motor will not start if one line is open or one phase is out. However, the motor may continue to run if one line or one phase is out after the motor is started. If an aircraft 3-phase induction motor is required to operate with one line or one phase out, it must be designed with higher torque and thermal capacities so that under 2-phase or single-phase operation the motor will still be capable to deliver sufficient torque without becoming overheated. A motor which is designed with consideration for 2-phase operation will have about 25-percent weight penalty; and one which is designed with consideration for single-phase operation will have a weight penalty of about 50 percent. (In a delta connected motor, the case of one line open is not as bad as one phase out.)

Shrink-fitting the ac motor stator to the frame makes a stronger assembly and facilitates heat transfer from the stator to the frame.

The slot linear insulation for some ac and dc aircraft motors is formed by melting epoxy resin powder in the preheated stack. This slot liner improves the heat transfer and reduces space requirement.

Bearing is one of the weak links in the electric motor. Since aluminum frames are used for aircraft motors, stainless steel bearing inserts are used to prevent seizing of the bearing outer race or balls at low temperatures. (Aluminum has a larger temperature coefficient of thermal expansion.) Sometimes the outer race of one of the motor bearings is locked against the axial movement to enable the motor to withstand severe shock and vibration. The bearings are preloaded to prevent ball skidding and axial shaft movement, thus increasing bearing life and quietness in operation. Bearing clearances should be optimized for long operating life.

A proper lubricant for the bearings should be used to suit the motor speed and environmental conditions. Seals and shields are used for aircraft motor bearings to retain lubricant and keep dirt out. Submerged fuel transfer pump

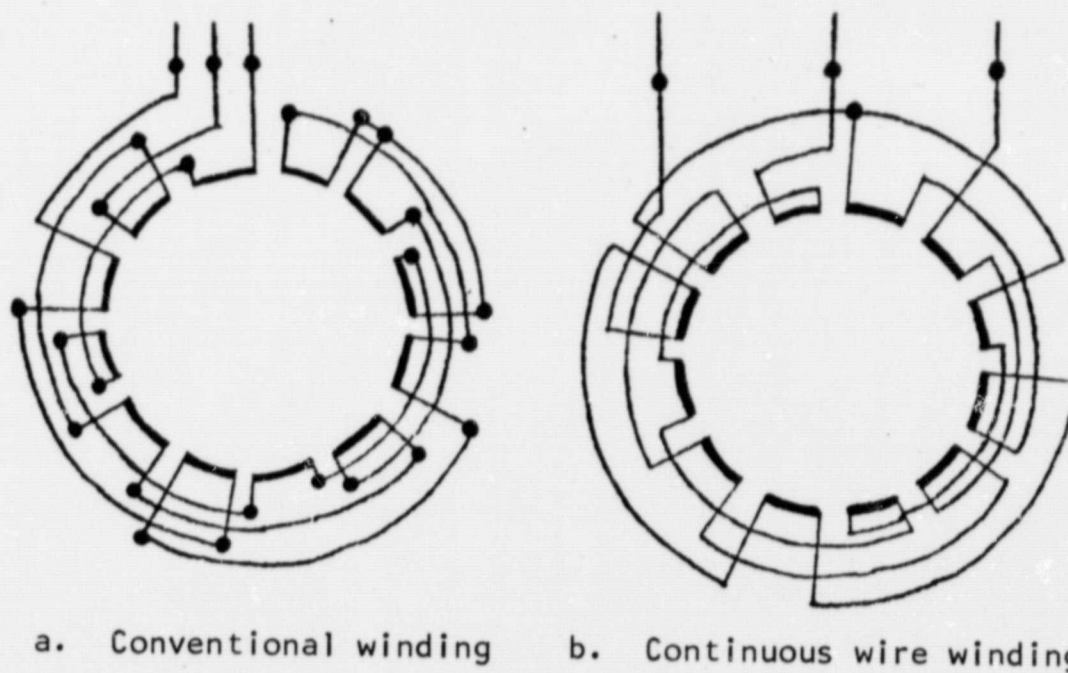


Figure 21. Wiring Diagram, 3-Phase, 4-Pole Motor

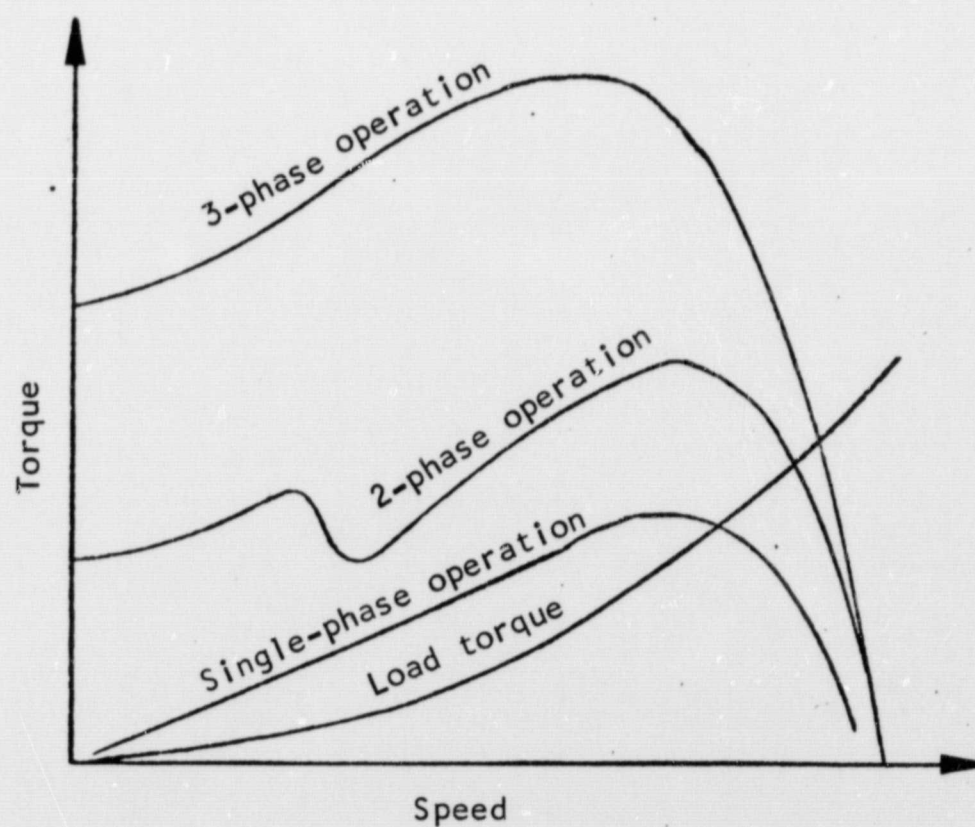


Figure 22. Torque Speed Curves, 3-Phase, 4-Wire Motor at 1-, 2- and 3-Phase Operations

motors and submerged cryogenic pump motors are usually lubricated by the fluids they pump.

The electrical failure rate of aircraft motors can be expressed in the equation

$$\lambda_e = \lambda_b \pi_g \pi_t \quad (24)$$

where λ_b = basic electrical mode failure rate dependent on hot spot temperature and class of insulation

π_g = adjustment factor for environmental service and MIL-T-27A construction grade

π_t = adjustment factor for type of motor

The representative values of λ_b are shown in fig. 23 as a function of hot spot temperature for various classes of insulation. This figure is taken from the RADC Reliability Notebook, vol. II.

An example will illustrate how to use the data in fig. 23 for the trade-off of reliability and motor weight. Consider a class H ac induction motor running at 180°C hot spot temperature. The basic failure rate shown in fig. 23 is about 0.001 percent per 1000 hr. To increase the motor life (considering electrical failure only) by 50 percent, or to reduce the failure rate to 0.00067 percent per 1000 hr, fig. 23 shows that the hot spot temperature should be reduced to 140°C. If the ambient temperature is 50°C, the hot spot temperature rise should be decreased from 130° to 90°C. This means approximately that the stator copper losses, hence the stator resistance, should be reduced to (90/130) or 70 percent. Lower operating temperature accounts for about 10 percent lower resistance. To obtain a 70-percent stator resistance, the area of the winding conductor must be increased by about 28 percent ($1 \times 0.9/1.28 = 0.7$). Therefore, to increase the motor life by 50 percent, the new motor must have about 28 percent more copper with slightly more iron. If the copper weight is about 1/3 of the motor weight, the new motor will be approximately 10- to 12-percent heavier.

The representative values of mechanical mode failure rate λ_m for aircraft electric motors are shown in fig. 24 (RADC Reliability Notebook, vol. II). If it is desired to improve the motor reliability by choosing a motor of lower operating speed, the tradeoff between reliability and weight can be obtained by using fig. 24 and the motor weight vs speed curves presented in the second quarterly progress report of this study program.

Transformers.--Like other electromagnetic components, the life of a transformer depends on the presence of moisture, vibration, corona, heat, etc. Heat is a stress of major importance in the steady state, as well as in temperature cycling and thermal shock. In ordinary reliability analysis, the failure rate of a transformer is expressed as

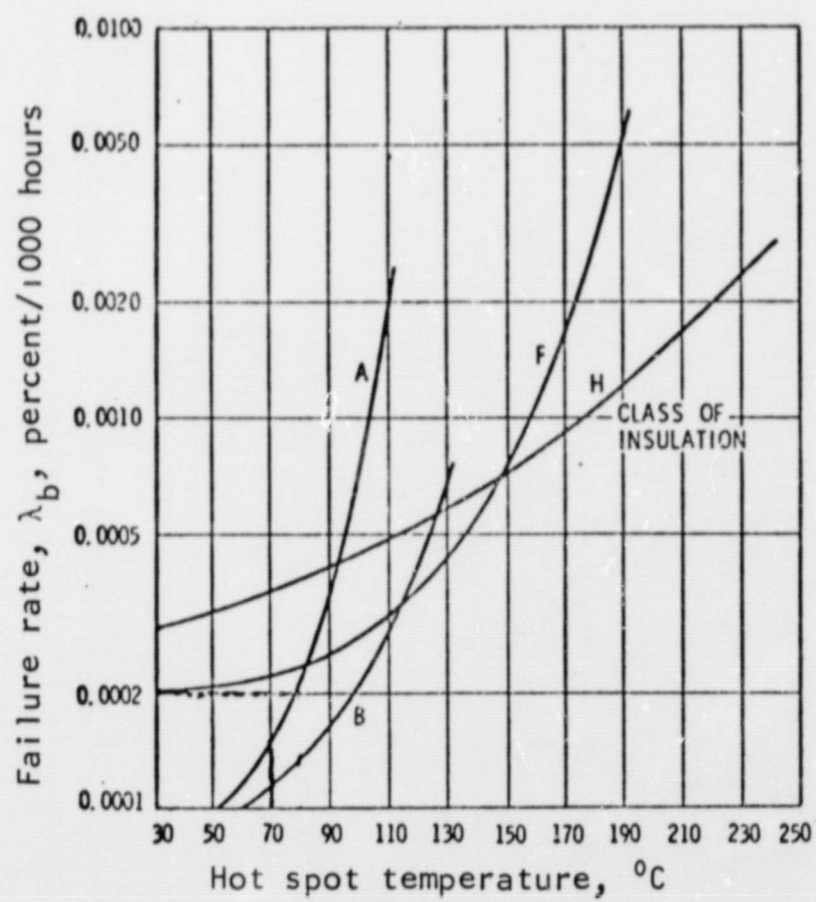


Figure 23. Basic Failure Rate, Rotating Devices
(from RADC Reliability Notebook)

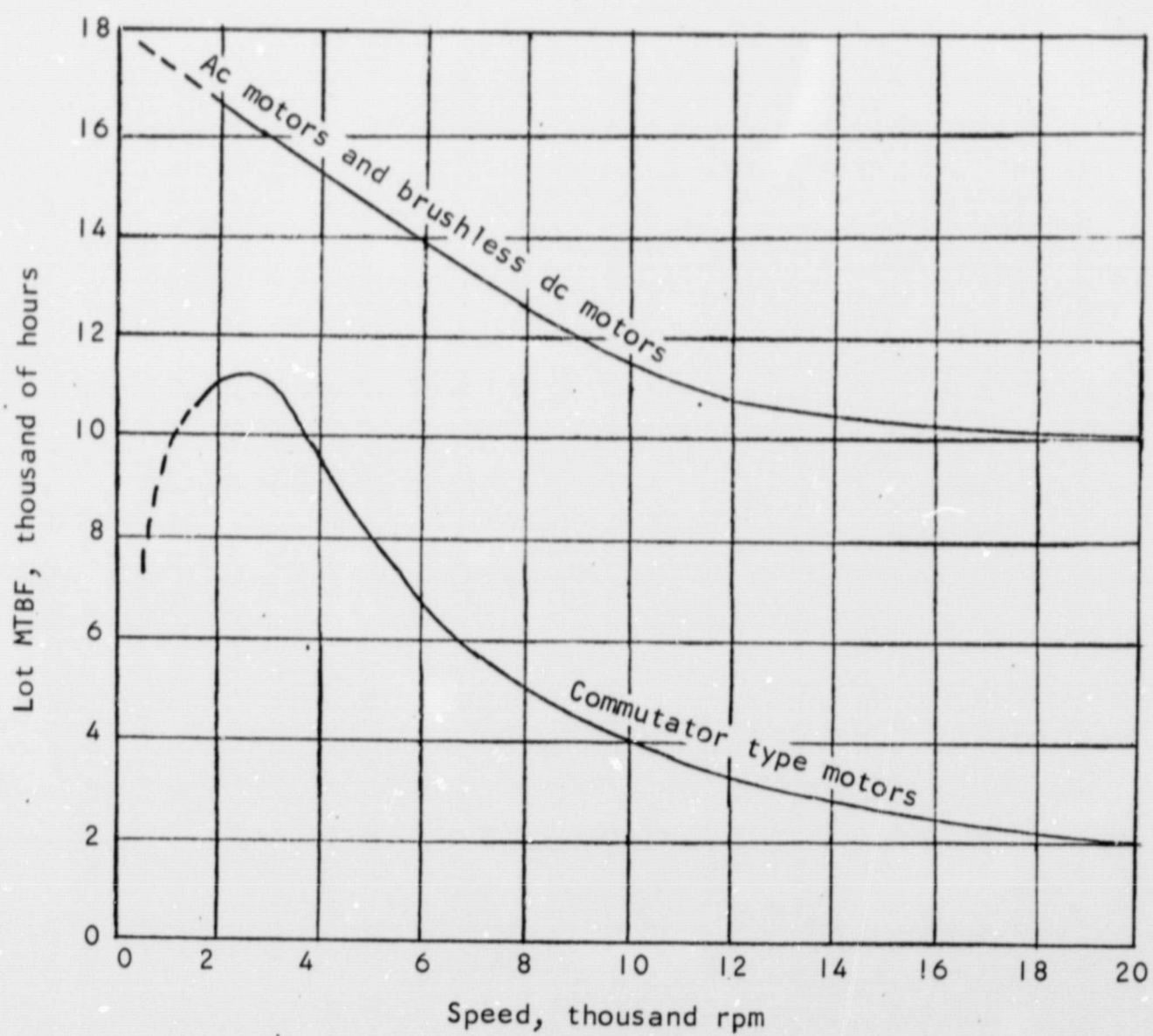


Figure 24. MTBF of Rotating Devices Mechanical Failure Only
(Conventional Design)

$$\lambda = \lambda_b \pi_g \pi_n \pi_f \quad (25)$$

where λ_b = basic failure rate based on hot spot temperature and insulation class

λ_g = modifier based on conditions of environmental service and MIL specification grade

π_n = modifier based on the number of terminals

π_f = modifier based on the relationship between transformer type and effect on failure rate

The reliability and weight tradeoff for aircraft transformers can be obtained from the curves in figs. 25, 26, and 27 which are taken from the RADC Reliability Handbook, vol. II. Fig. 25 is the basic failure rate with respect to hot spot temperature and class of insulation. Fig. 26 shows the relationship of average temperature rise and power loss for a transformer with various case symbol (MIL-T-27). Figure 27 shows the average temperature rise vs transformer weight with various power losses.

An example will explain how to use these curves for a reliability and weight tradeoff study. Given a 2-kVA transformer, class B insulation, 35 w total loss, 10 lb weight, case symbol GA, ambient temperature 30°C. Determine the weight penalty if it is desired to double the life of the transformer.

From either fig. 26 or 27, the average temperature rise of the transformer winding is 30°C. The hot spot temperature is therefore about 130°C (ambient + temperature rise + hot spot allowance). According to fig. 25, the basic failure rate for this class B transformer at 130°C hot spot temperature is 0.0007. To double the life, the failure rate should be reduced to 0.00035. This puts the permissible hot spot temperature to 115°C or the average temperature rise to about 65°C. Going back to fig. 26, assume that there is no change in the case. (This is a trial and error process. After determining the final weight of the transformer, if this assumption is off, a new case should then be used and the process will be repeated.) With case GA and 65°C temperature rise, the power loss is found to be about 29 W. Go to fig. 27, with 29 W loss and 65°C rise, the new weight of the transformer is found to be about 11 lb. (Since the weight increase is only 10 percent, the assumption of some outside case is about right.) The weight penalty is therefore only about 10 percent.

For a 3-phase transformer, $\Delta \Delta$ connection has some advantage from the reliability point of view. This is because when one phase is out in a $\Delta \Delta$ connection the transformer can still operate in open delta and continue to supply 3-phase power. However, there are many other considerations in selecting transformer connections. This is only one of the factors to be included in the selections.

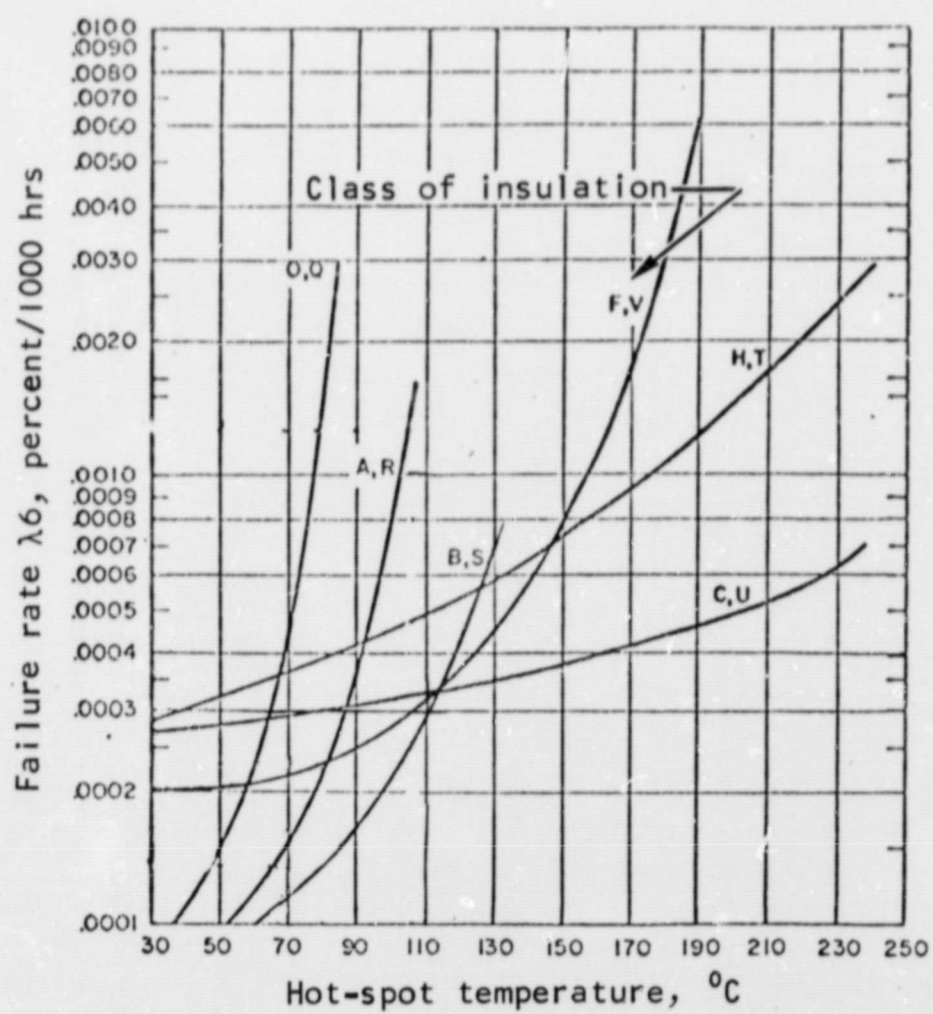


Figure 25. Basic Failure Rate of Transformers
(from RADC Reliability Notebook)

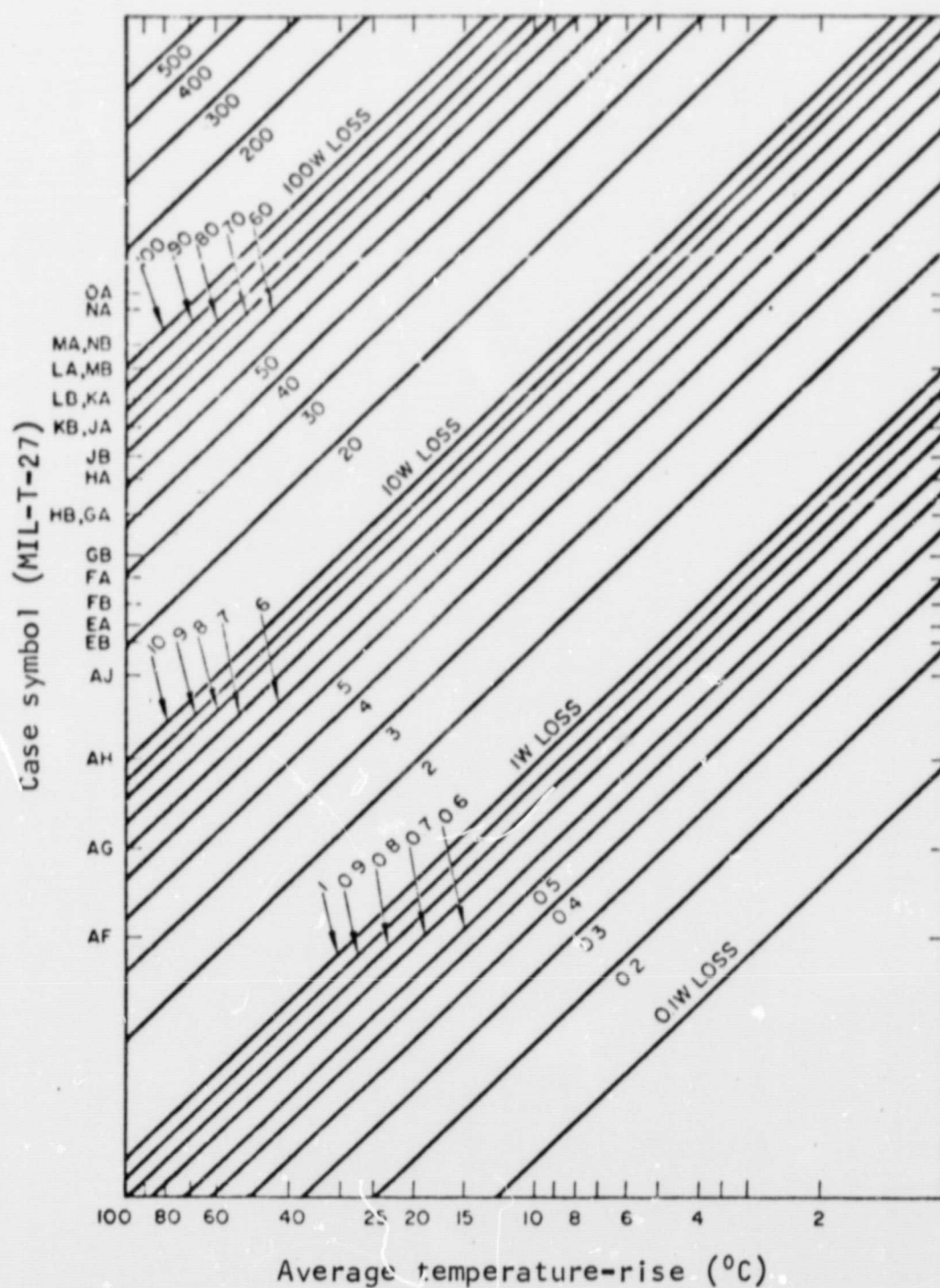


Figure 26. Transformer Case Symbol Versus Average Temperature Rise with Power Loss as Parameter (from RADC Reliability Notebook) (Conventional Materials)

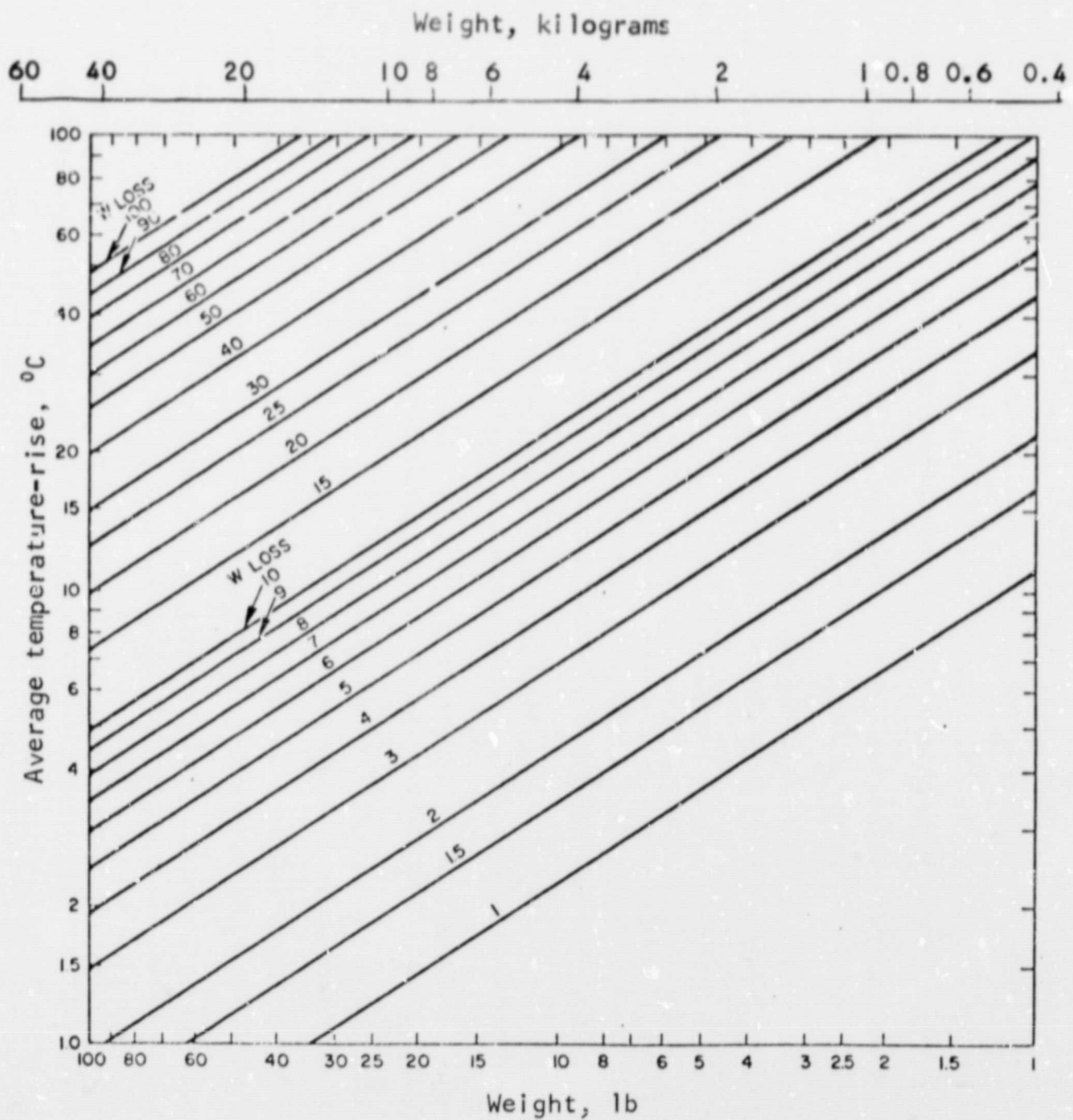


Figure 27. Average Temperature Rise Versus Transformer Weight with Power Loss as Parameter (from RADC Reliability Notebook) (Conventional Materials)

Synchros and resolvers.--Synchros and resolvers are low-speed, low-load rotating devices which are basically rotating transformers. They have the same electrical failure modes of transformers plus the additional problems of reliable connection and physical support for the rotating windings. Since they are low speed and low load, mechanical wear out problems are not serious; the electrical and thermal failure modes predominate. For synchros and resolvers which use three or four brushes, the failure rate can be a function of the number of brushes and the rotor activity in a given application. Where differential temperature coefficients are involved, such as between extended motor casings and cast caps, temperature cycling and temperature extremes may result in a cumulative "cocking" of the rotor and the eventual rubbing between the rotor and stator. Since these devices are built with small air gaps, this differential thermal expansion should be carefully considered in the design. The reliability data of synchros and resolvers can also be applied to other similar devices such as selsyns, servo motors, elapsed time indicators, etc.

The failure rate of synchros and resolvers can be expressed by the following equation:

$$\lambda = \lambda_b \pi_s \pi_n \pi_e \quad (26)$$

where λ_b = basic failure rate depending on the frame temperature

π_s = multiplier based on the type and size of the device

π_n = multiplier based on the number of brushes in the device

π_e = multiplier based on the environmental service

The representative values of basic failure rate as a function of the frame temperature is shown in fig. 28. The frame temperature rise is proportional to the total power loss in the device divided by the total frame surface.

In estimating the tradeoff between reliability and weight, the frame temperature rise of the device can be assumed to be inversely proportional to the weight of the device. This can be explained as follows:

Assume that a synchro or resolver is increased proportionally in all three dimensions by a ratio of X . The iron core area is increased by X^2 . The working magnetic flux density will decrease by a ratio of $1/X^2$. The iron loss per unit volume can be assumed to decrease by $1/X^4$ approximately. However, since the volume of the iron core is increased by X^3 , the total iron losses are decreased by a ratio of $\frac{1}{X}$.

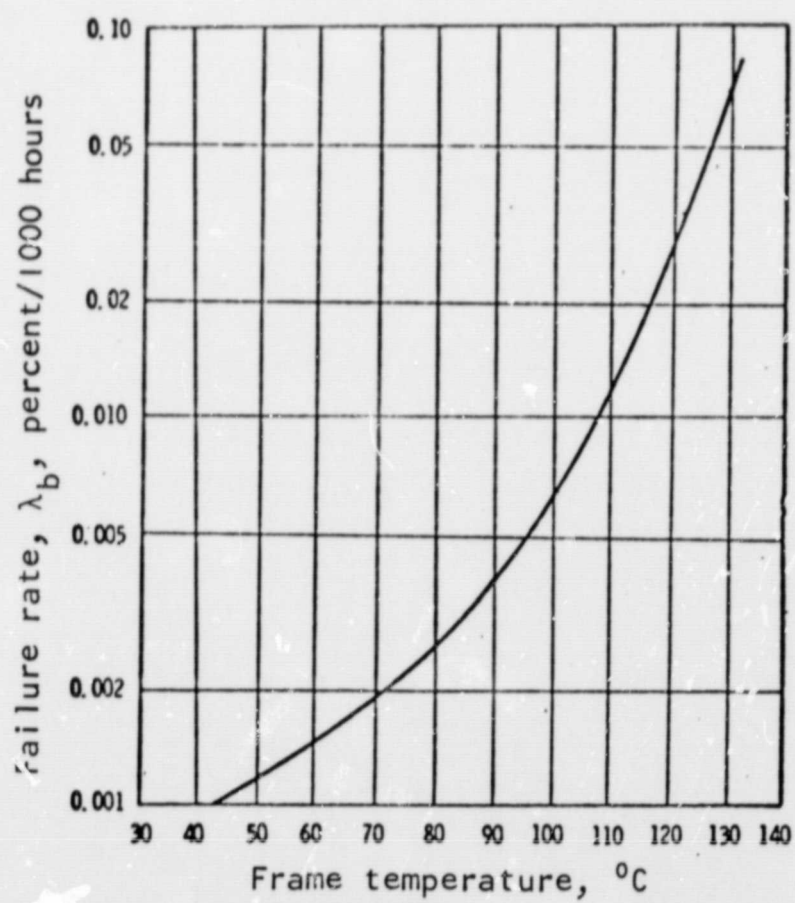


Figure 28. Basic Failure Rate for Synchros and Resolvers (from RADC Reliability Notebook)

The copper conductor area is increased by X^2 , but the length of mean turn is increased by X . Thus, the winding resistance will be reduced by a factor of $1/X$. With the same armature current, the copper losses are reduced by a ratio of $1/X$, the same as for the iron losses.

Since the frame surface is increased by X^2 , the temperature rise of the frame is proportional to $1/X^3$. The weight of the device is proportional to X^3 . Therefore,

$$\text{Frame temperature rise} \propto \frac{1}{\text{weight}} \text{ approximately}$$

Consider a synchro with a frame temperature of 100°C at 30°C ambient. The basic failure rate according to fig. 28 is 0.007. To double the life of the synchro, the failure rate should be 0.0035. Again from fig. 28, the frame temperature for $\lambda_b = 0.0035$ is 87° or 57°C rise. The weight of the new synchro then will be approximately:

$$\frac{70}{57} = 1.23$$

or a weight penalty of approximately 23 percent.

Connectors.--The rate of failure of connectors depends on many factors, including mechanical, electrical, thermal, chemical, and cycling effects. One of the major causes of failure is induced by the growth of films at points of contact. These films can cause either increased contact resistance or an open circuit.

Generally the failure rate of connectors is expressed by the equation:

$$\lambda = \lambda_b \pi_e \pi_p + N \Sigma_{\text{cyc}} \quad (27)$$

where λ_b = basic failure rate depending on the operating temperature of the contact insert and the insert material

π_e = factor based on the condition of environmental service

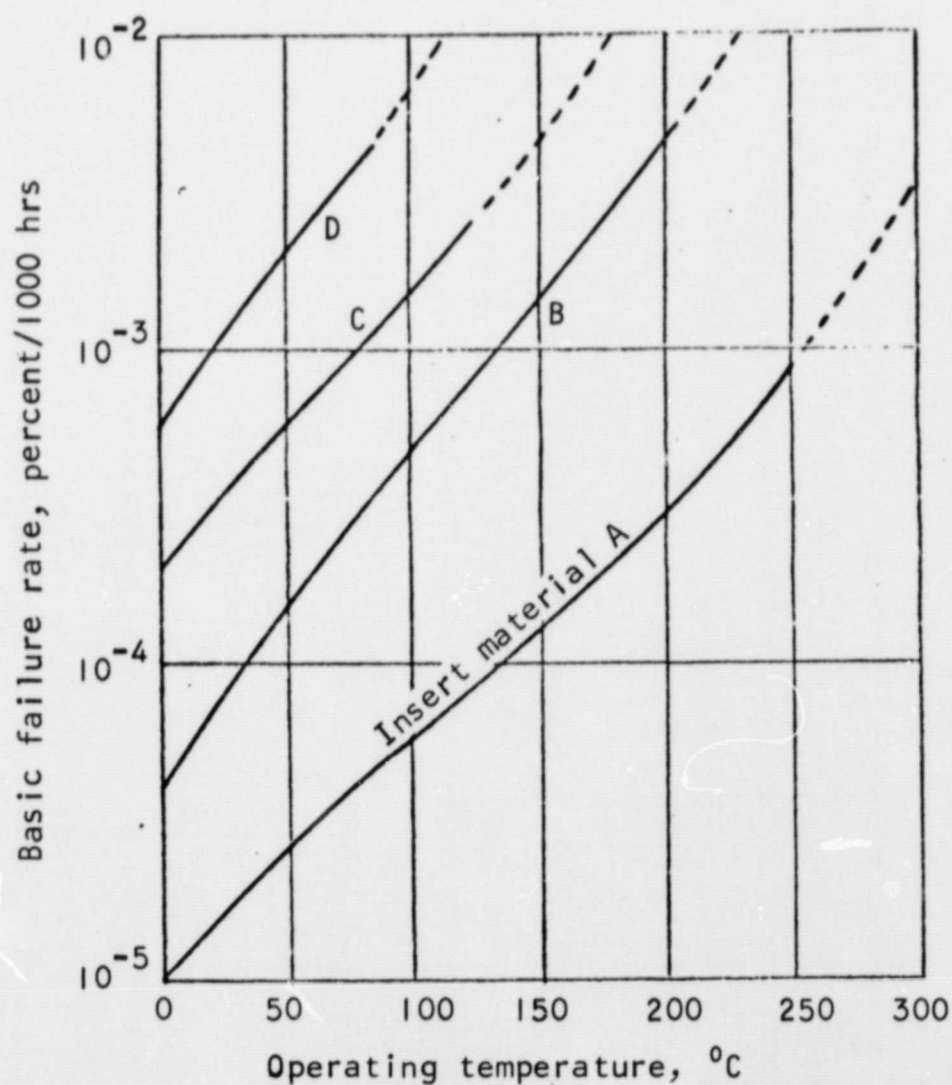
π_p = factor based on the number of active pins

N = number of active pins

Σ_{cyc} = factor based on reconnect cycling in cycles per 1000 hr

Representative values of the basic failure rate for connectors are given in fig. 29. The operating temperature is equal to the sum of the ambient temperature and the contact insert temperature rise.

The insert temperature rise is a function of the contact current density. This relationship is shown in fig. 30.



Insert material code	Common material	Temperature range, °C
A	Diallyl Phthalate, glass, ceramic	-40 to +250
B	Melmine, Neoprene, Si Rubber	-40 to +200
C	Teflon, Kel-F	-55 to +125
D	Nylon, Polychloroprene	-20 to +100

Figure 29. Basic Failure Rate of Connectors
(from RADC Reliability Notebook)

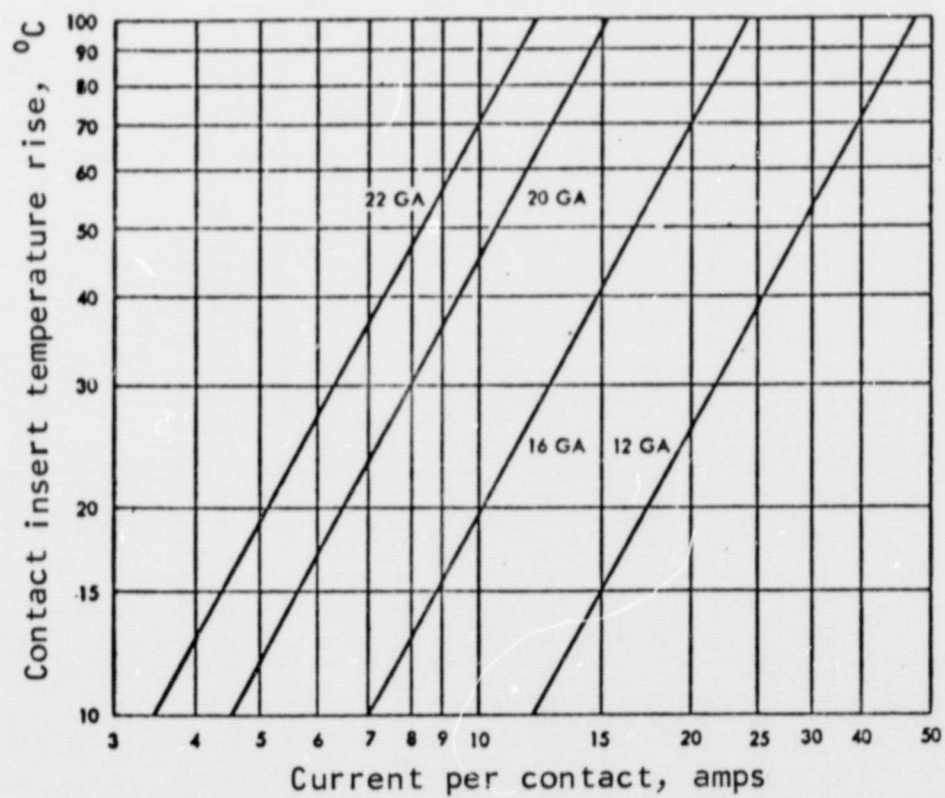


Figure 30. Contact Insert Temperature Rise Versus Contact Current and Contact Size (from RADC Reliability Notebook)

By using figs. 29, 30, and the manufacturer's data on connector's weight vs contact sizes, the tradeoff between reliability and weight for connectors can be determined.

Wires and cables.--The most common failure mode for connecting wires is conductor breakage at the termination, in chassis work as well as with inter-connecting harness. Where small conductors are used, conductor breakage has been a major source of trouble. In aircraft, copper conductors are limited to size 22 and larger. For special copper alloy conductors, sizes as small as 26 have been used. To avoid the conductor breakage problem, it is advised that proper stress relief of all wires be provided at connectors and extra care be taken in assembly. In this sense, reliability is related to cost more than weight.

Multiconductor cable failures are related to the component wires. Although most failures occur at connectors, a properly designed and terminated cable will have excellent life expectancy. Balanced cable construction (no short wires) and proper stress relief at connectors are important failure preventives.

The only tradeoff between reliability and wire and cable weight would be the use of large size conductor to reduce the operating temperature. Fig. 31 shows the temperature rise of a single copper conductor insulated with 10-15 mils of TFE in still air at normal atmospheric pressure. Temperature rise data for other types and thicknesses of insulation are not available. The temperature rise of a group of conductors at a bundle can be assumed to be twice that of a single conductor. The representative values of life vs operating temperature for three types of insulation are shown in fig. 32.

Lamps and heaters.--For incandescent lamps and small heaters, long life can be obtained by operating these components at low voltage levels. The operating power of lights and heaters is given by

$$P = \frac{V^2}{R} = \frac{1}{\rho} \cdot \frac{V^2 a}{\ell} \quad (28)$$

where V = operating voltage

a = cross-sectional area of the lighting or heating element

ℓ = length of the lighting or heating element

A strong lighting or heating element should have large a and small ℓ , resulting in small operating voltage V . On the other hand, any voltage other than the standard distribution voltage will require voltage transformation equipment. Low operating voltage may also result in large and heavy wiring. A tradeoff between reliability and weight or cost is therefore involved.

Capacitors.--The life of capacitors depends on many factors such as operating voltage, current, frequency, temperature, pressure, humidity, shock, and vibration. There are many different types of capacitors. In aircraft, ceramic (high K) and tantalum (solid dielectric) capacitors are the most popular. The

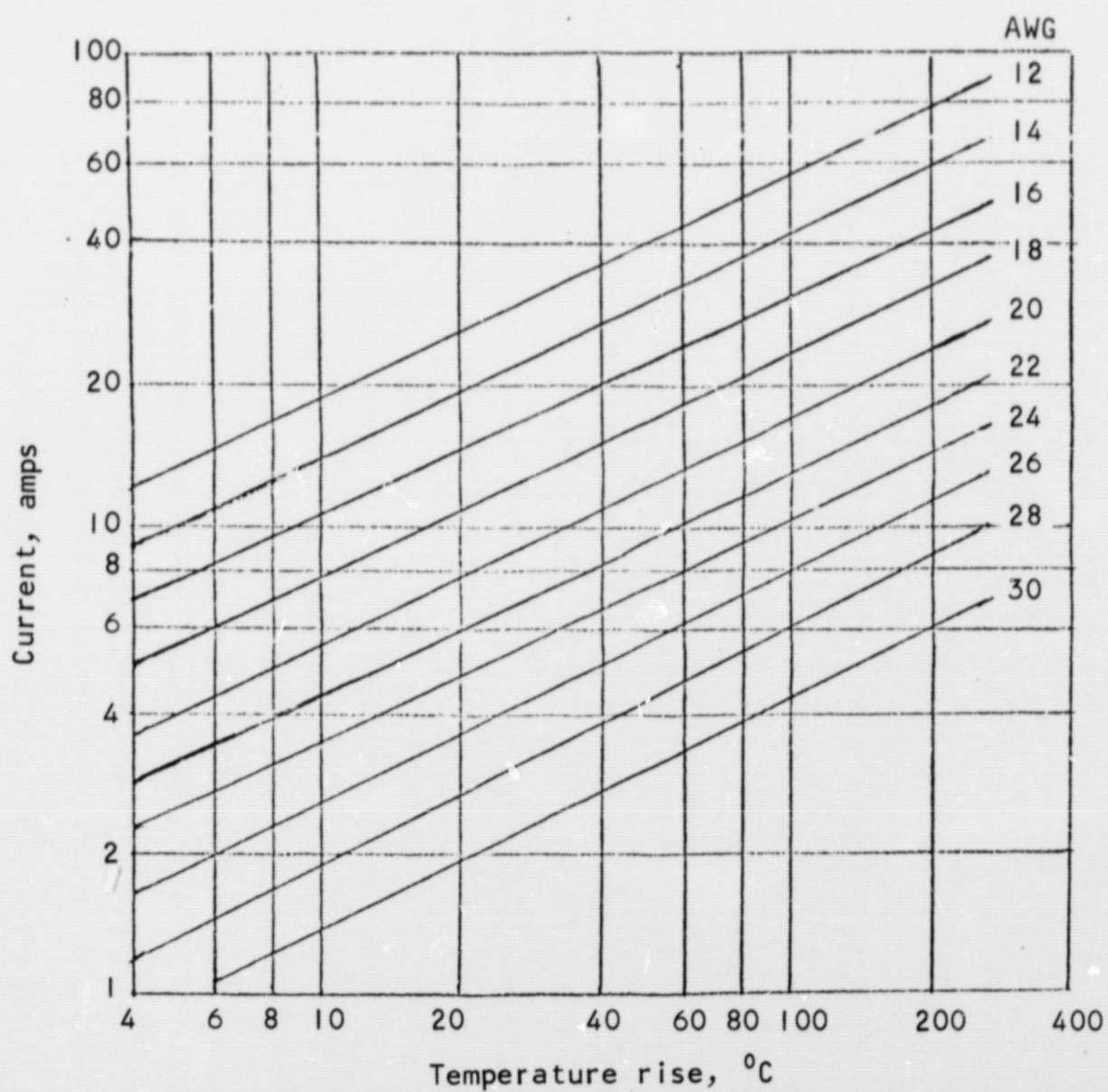


Figure 31. Temperature Rise of a Single Copper Conductor Insulated with 10-15 mils of TFE in Still Air and Normal Atmospheric Pressure (from MIL-HDBK-217A)

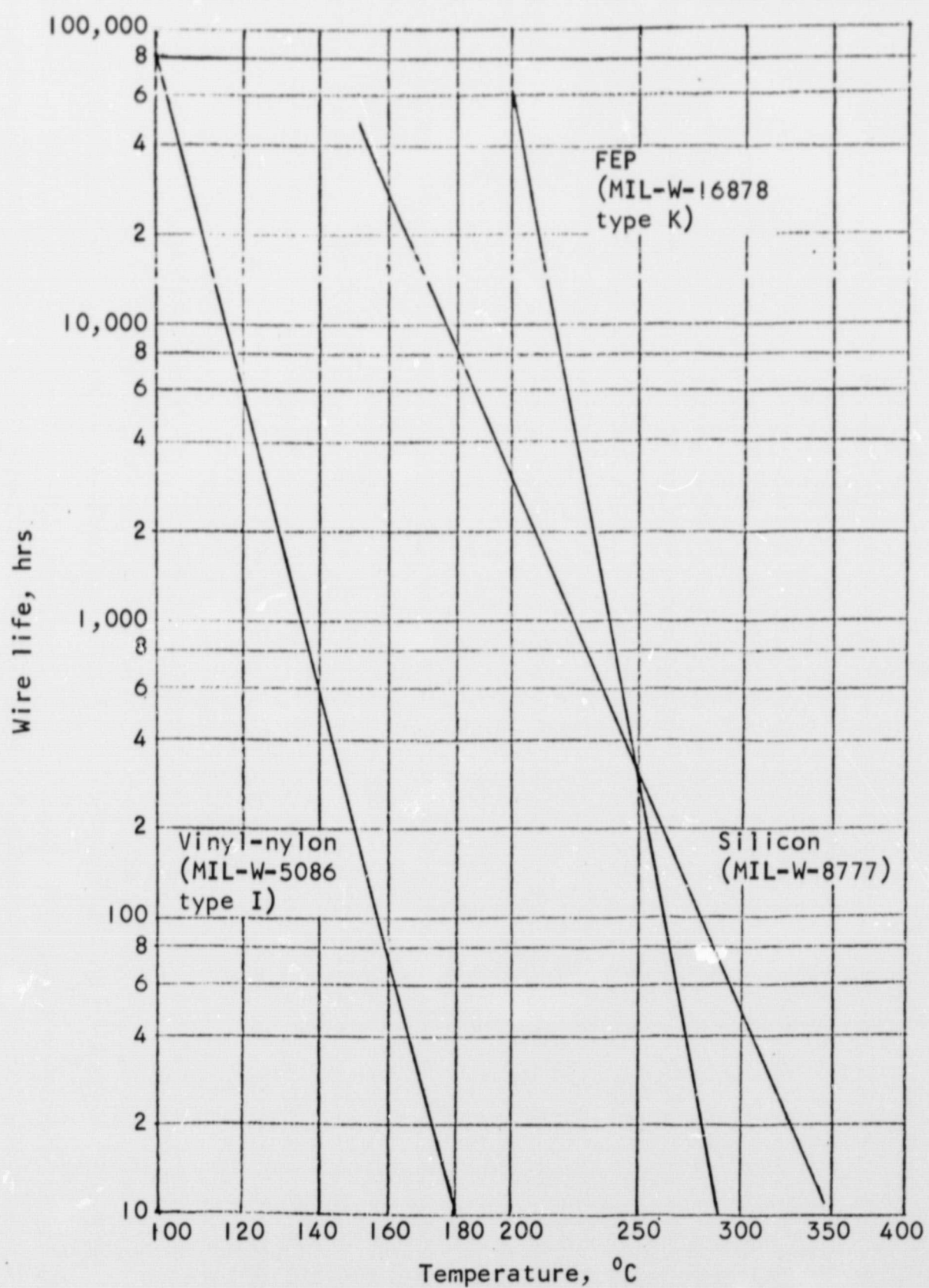


Figure 32. Effect of Operating Temperature on Wire Life (from MIL-HDBK-217A)

failure rate of these two types of capacitors is quite similar, and can be expressed as

$$\lambda = \lambda_b \pi_e + \Sigma_E \quad (29)$$

where λ_b = basic failure rate depending on temperature and stress ratio

π_e = multiplier based on the environmental service

Σ_E = environmental condition modifier

Typical values of basic failure rate for ceramic and tantalum capacitors are shown in figs. 33 and 34, respectively. The stress ratio is defined as

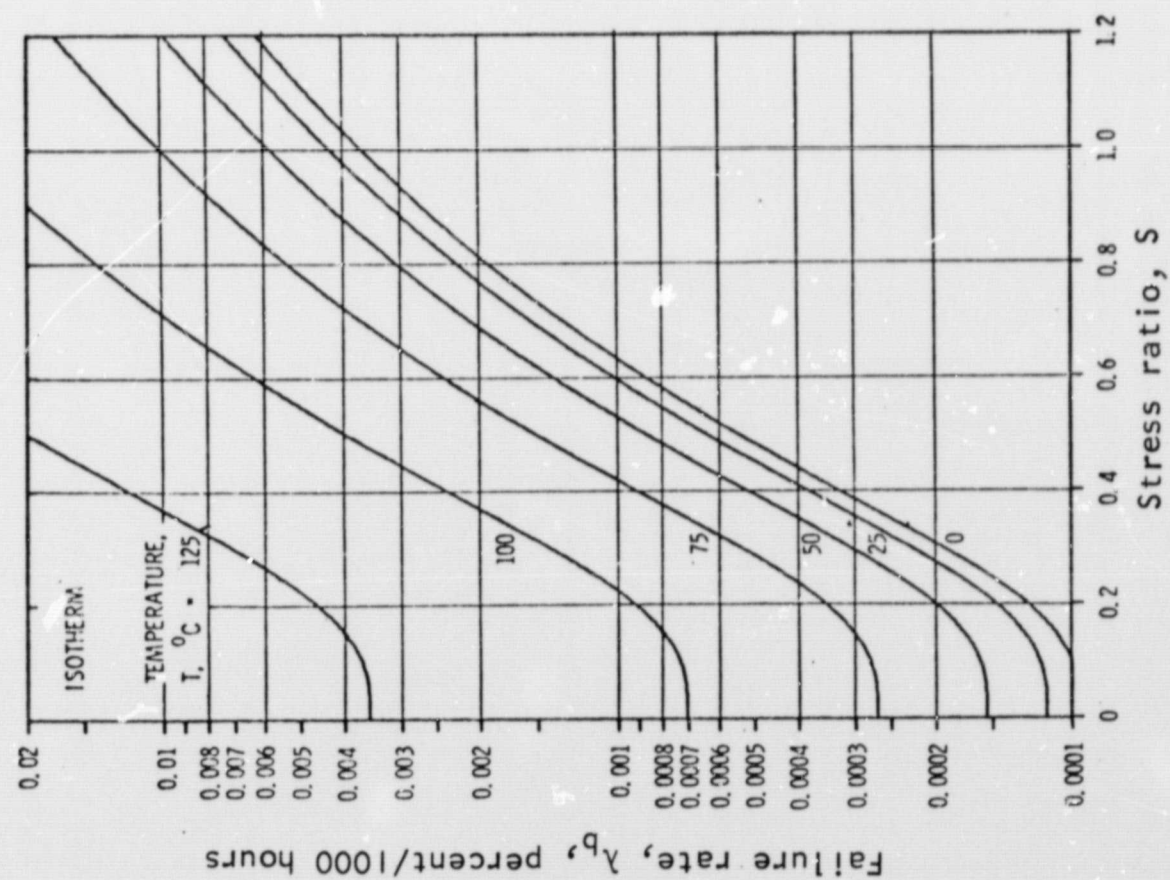
$$S = \frac{\text{operating voltage}}{\text{rated voltage}}$$

The environmental factors π_e and Σ_E for ceramic and tantalum capacitors are shown in table 6.

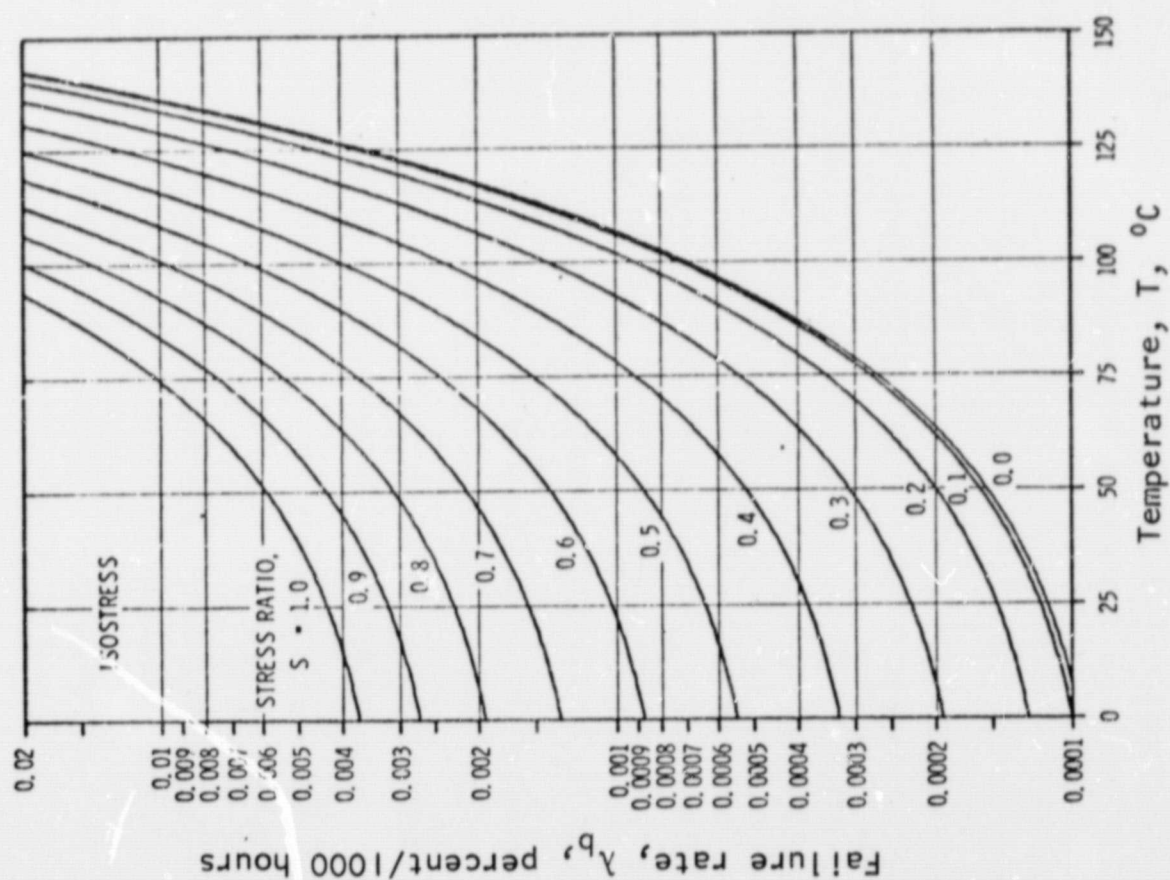
Data in this section plus the manufacturer's data on capacitor performance, weight, and cost will enable the designers to perform reliability, weight, and cost tradeoff studies.

TABLE 6
ENVIRONMENTAL FACTORS, π_e AND Σ_E

Capacitor type	Environment	π_e		Σ_E	
		Upper reliability grade	Lower reliability grade	Upper reliability grade	Lower reliability grade
Ceramic (high K)	Airborne inhabited area	4	40	0.0002	0.002
	Airborne uninhabited area	10	100	0.0006	0.005
Tantalum (solid dielectric)	Airborne inhabited area	4	40	0.0002	0.002
	Airborne uninhabited area	15	150	0.0008	0.008

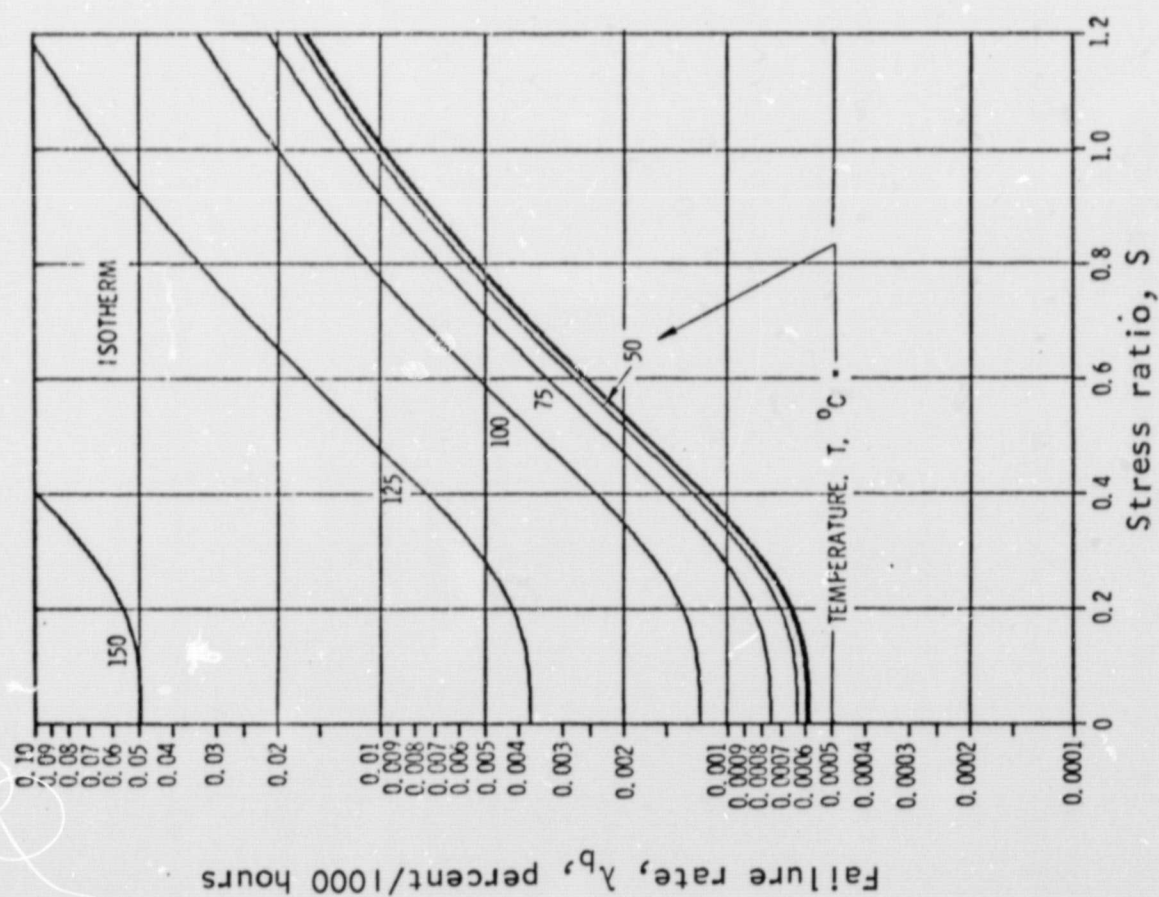


(a) Failure rate versus stress ratio

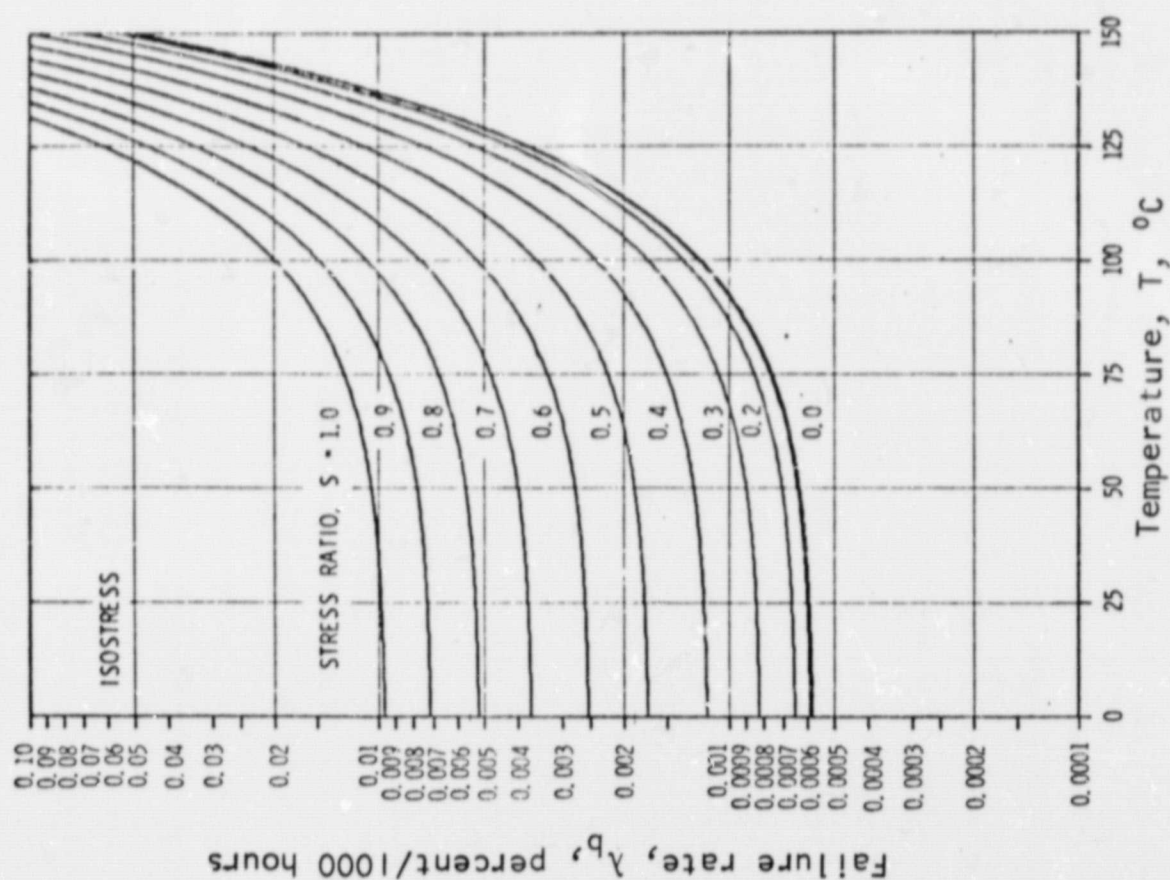


(b) Failure rate versus ambient temperature

Figure 33. Basic Failure Rate of Ceramic Capacitors
(from RADC Reliability Notebook)



(a) Failure rate versus stress ratio



(b) Failure rate versus ambient temperature

Figure 34. Basic Failure Rate of Tantalum Solid Dielectric Capacitor
(from RADCR Reliability Notebook)

Resistors.--The most popular kind of resistor used in aircraft is carbon composition type RC-22. In applications where precision values are needed, film resistors are used. The failure rate of resistors can be expressed as

$$\lambda = \lambda_b \pi_R \pi_e + \Sigma_E \quad (30)$$

where λ_b = basic failure rate

π_R = resistance factor

π_e = environmental multiplier

Σ_E = environmental condition modifier

The typical values of the basic failure rate for carbon composition resistors are shown in fig. 35. The stress ratio is the ratio of the operating power to the rated power. The values of π_R are shown in table 7, and the values of π_e and Σ_E are shown in table 8.

TABLE 7

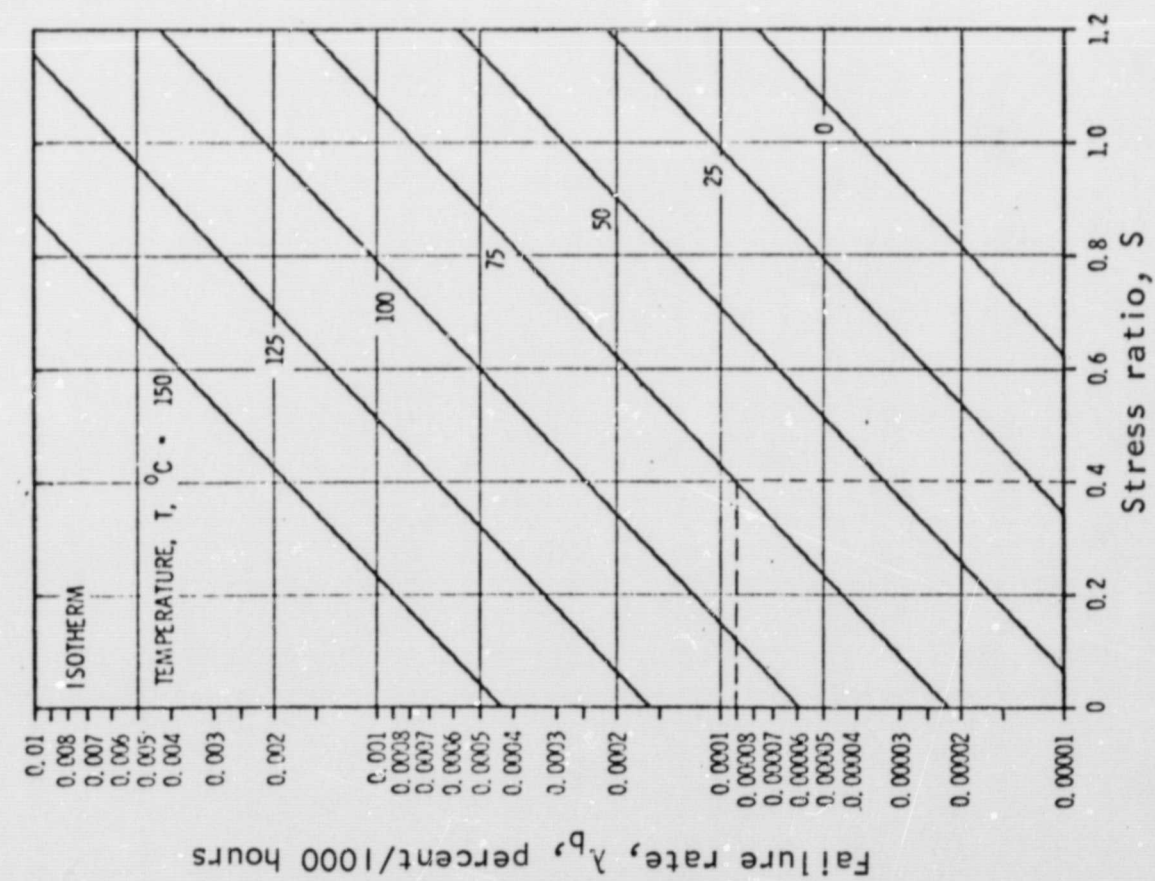
RESISTANCE FACTOR π_R , COMPOSITION RESISTOR

Resistance range (ohms)	π_R
< 100	1.1
100 to 100 K	1.0
> 0.1 meg to 1.0 meg	1.1
> 1.0 meg to 10 meg	1.6
> 10 meg	2.5

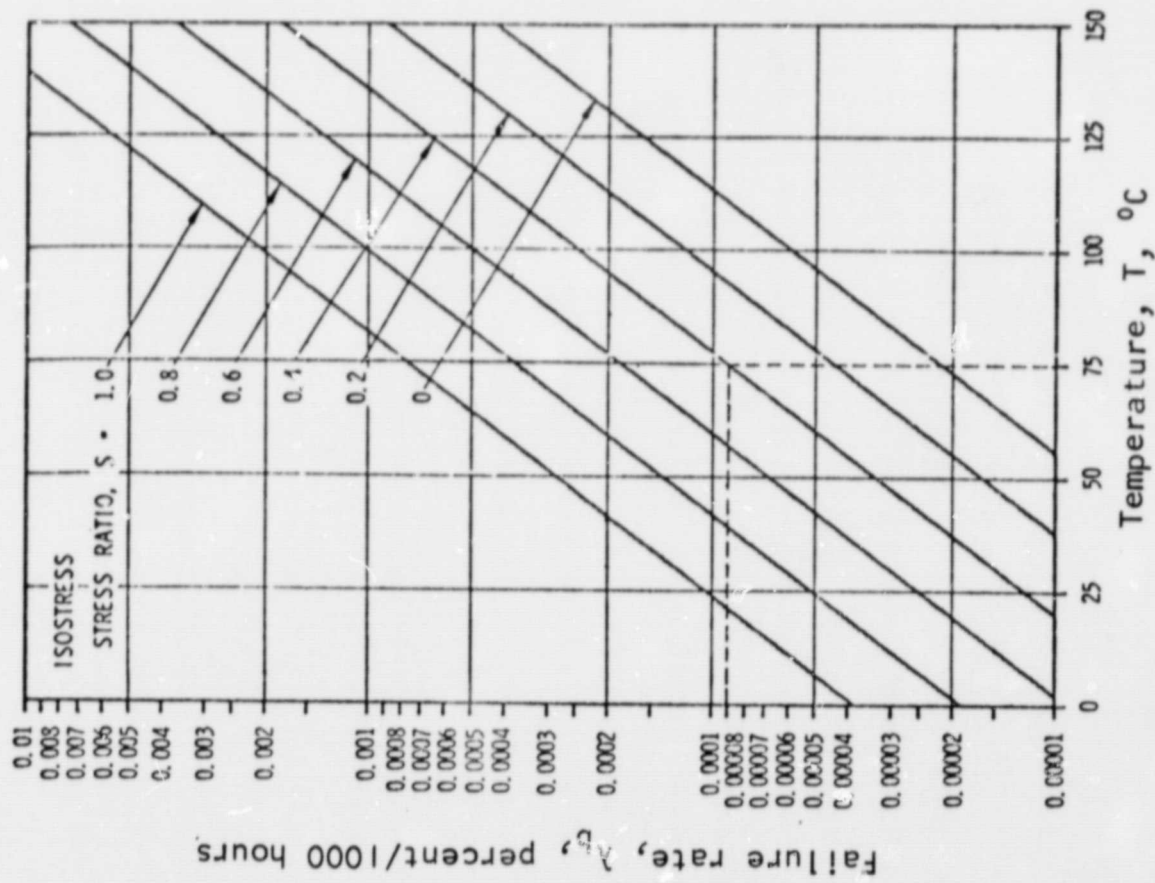
TABLE 8

ENVIRONMENTAL FACTORS, R-22 RESISTORS

Environment	Grade of reliability	π_e	Σ_E
Airborne inhabited	Upper	4	0.0006
	Lower	8	0.003
Airborne uninhabited	Upper	8	0.001
	Lower	20	0.005



(a) Failure rate versus stress ratio



(b) Failure rate versus ambient temperature

Figure 35. Basic Failure Rate of Carbon Composition Resistors, Style RC-22
(from RADC Reliability Notebook)

These reliability data and the manufacturer's information on weight, cost, etc. will enable the designers to perform reliability and weight, cost tradeoff studies.

Semiconductors.--The reliability data useful for the tradeoff studies between reliability, weight, and cost are given below.

Generally the failure rate is expressed as

$$\lambda = \lambda_b \pi_e \pi_a \pi_R + \Sigma_E \quad (31)$$

where λ_b = basic failure rate

π_e = multiplier based on environmental service

π_a = application factor

π_R = power rating factor for primary stress

Σ_E = environmental condition modifier

Silicon transistor (NPN).--The basic failure rate is given in fig. 36. The environmental factors, application factor, and power rating factor are given in tables 9, 10, and 11, respectively.

The stress ratio for transistors is defined as

$$S = \text{stress ratio} = \frac{P_{op}}{P_{max}}$$

where P_{op} = actual power dissipated

P_{max} = maximum rated power dissipation at 25°C for the type of application specified, i.e., in regard to ambient air or heat sink mounted

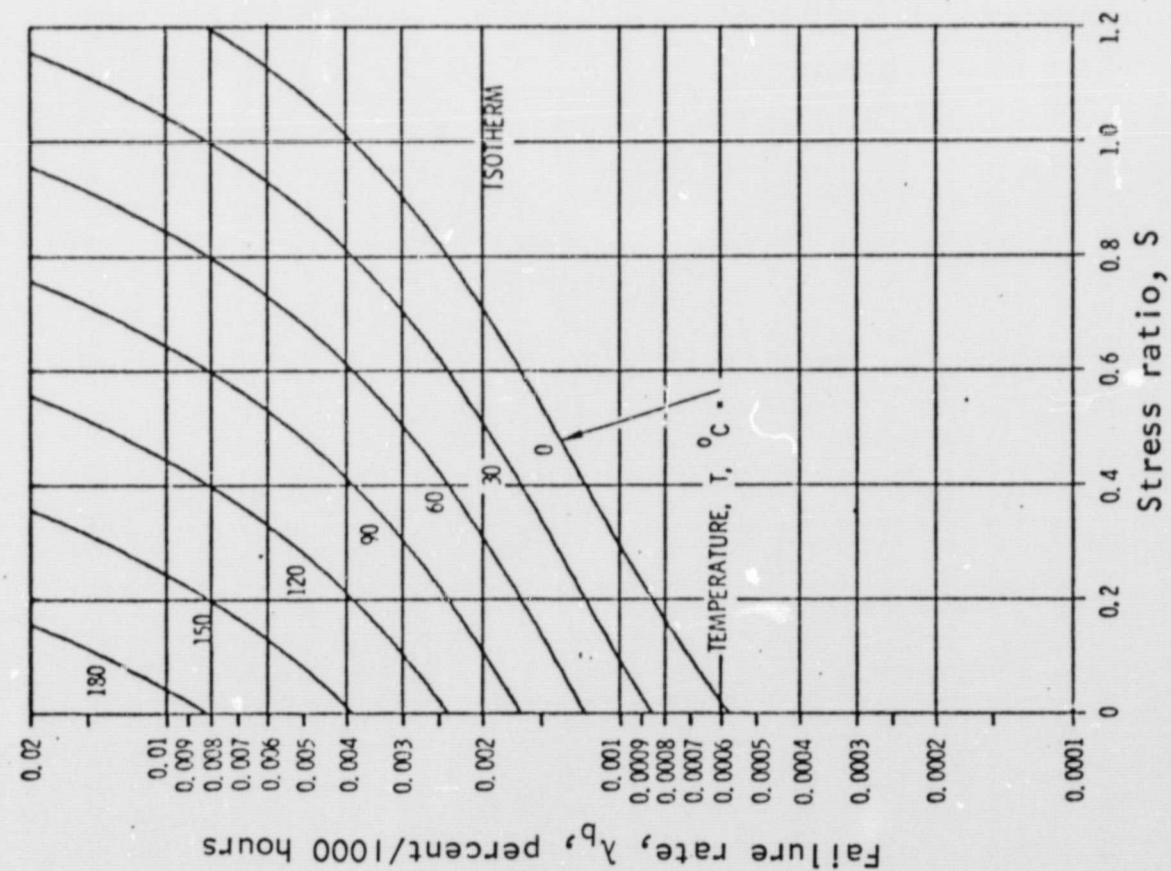
Silicon diodes and rectifiers.--The basic failure rate is shown in fig. 37. The environmental factors, application factor, and current rating factor are given in tables 9, 10, and 11, respectively.

The stress ratio for silicon diodes and rectifiers is defined as

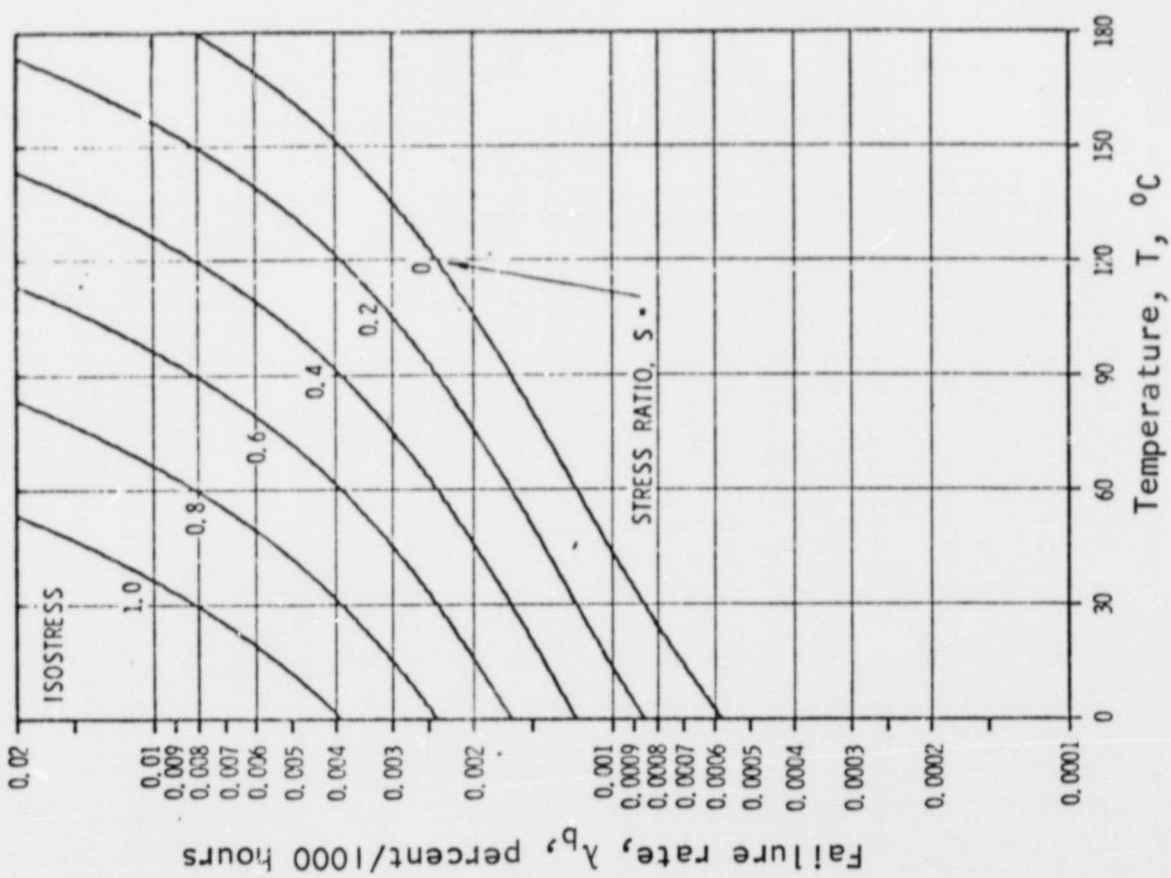
$$S = \text{stress ratio} = \frac{I_{op}}{I_{max}}$$

where I_{op} = operating voltage forward current

I_{max} = maximum rated average forward current at 25°C

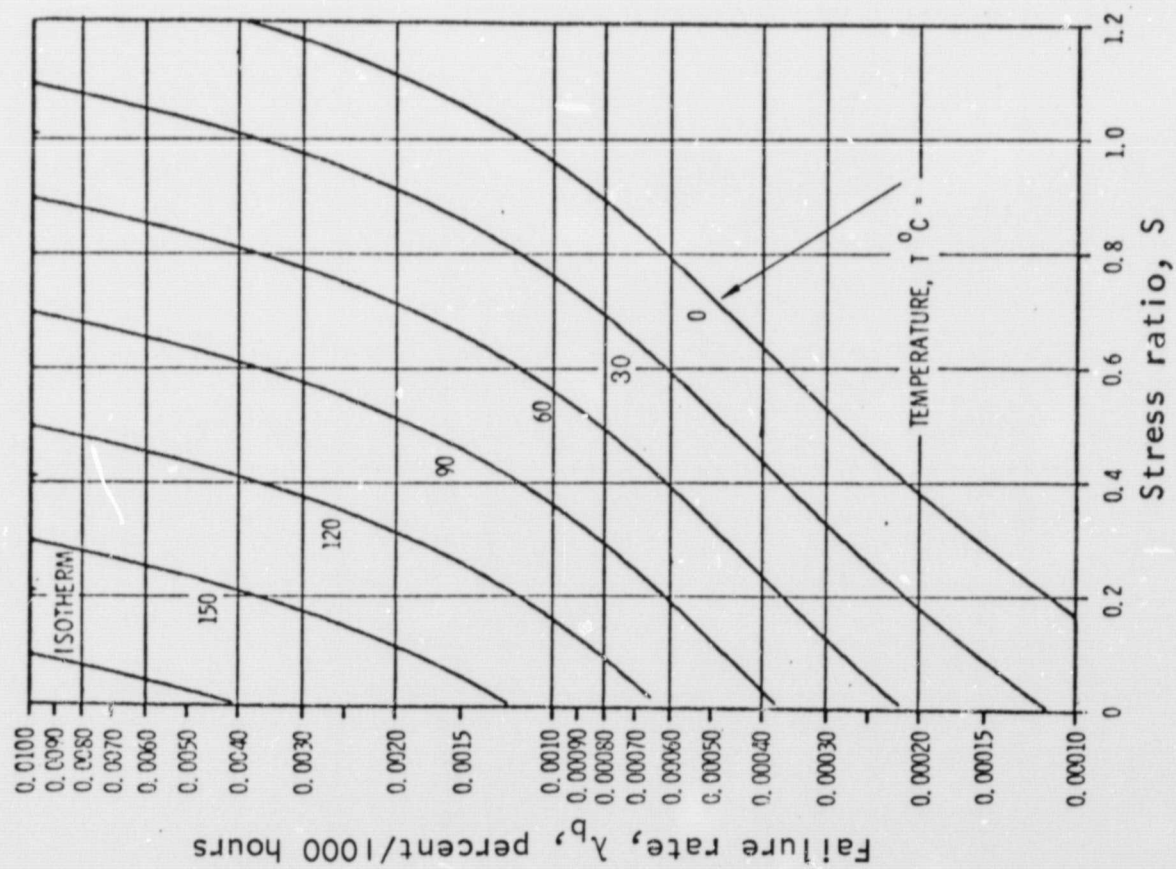


(a) Failure rate versus stress ratio

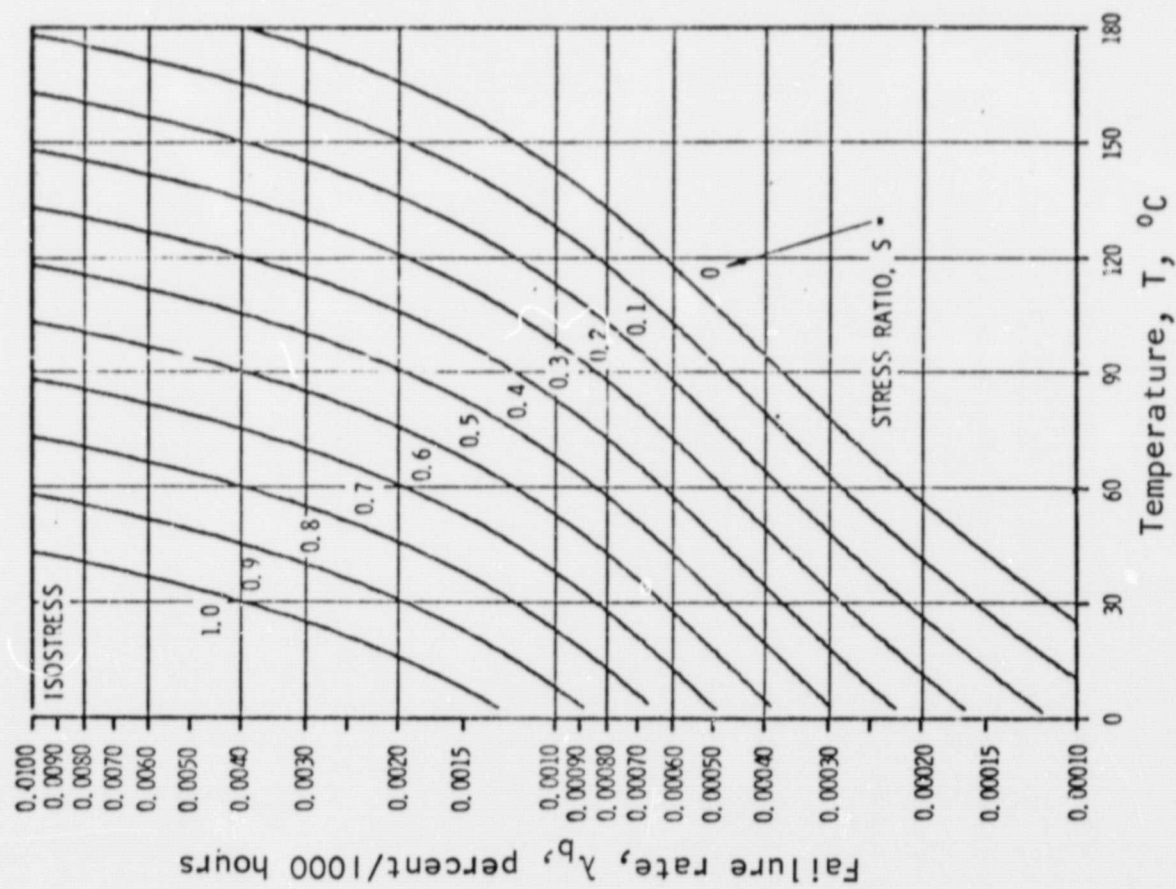


(b) Failure rate versus ambient temperature

Figure 36. Basic Failure Rate of NPN Silicon Transistors
(from RADC Reliability Notebook)



(a) Failure rate versus stress ratio



(b) Failure rate versus ambient temperature

Figure 37. Basic Failure Rate of Silicon Diodes and Rectifiers
(from RADC Reliability Notebook)

Silicon control rectifiers.--The basic failure rate is given in fig. 38. The environmental factors and rated average forward mode current factor are given in tables 9 and 11, respectively. For this case π_a is 1.0.

The stress ratio for silicon control rectifier is the same as that for silicon diodes given in the last paragraph.

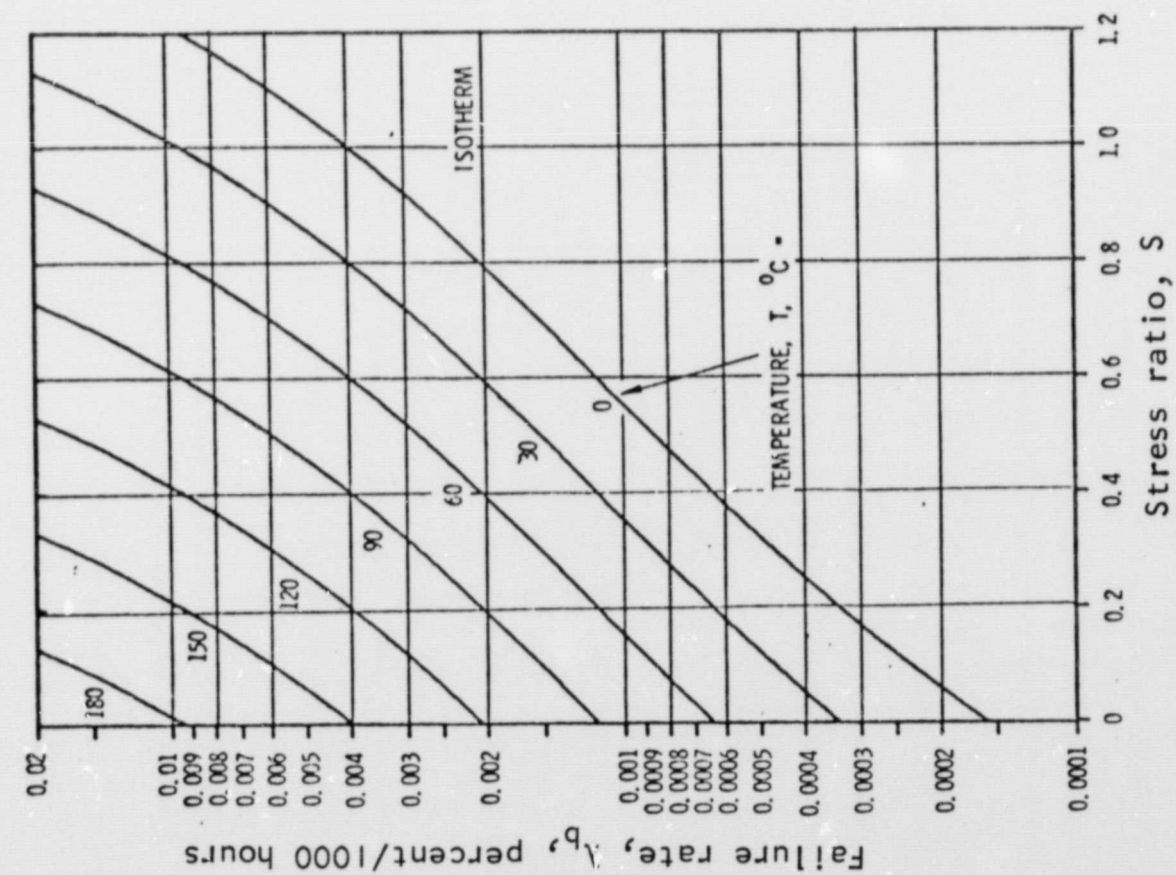
TABLE 9

ENVIRONMENTAL FACTORS VS SEMICONDUCTOR COMPONENTS

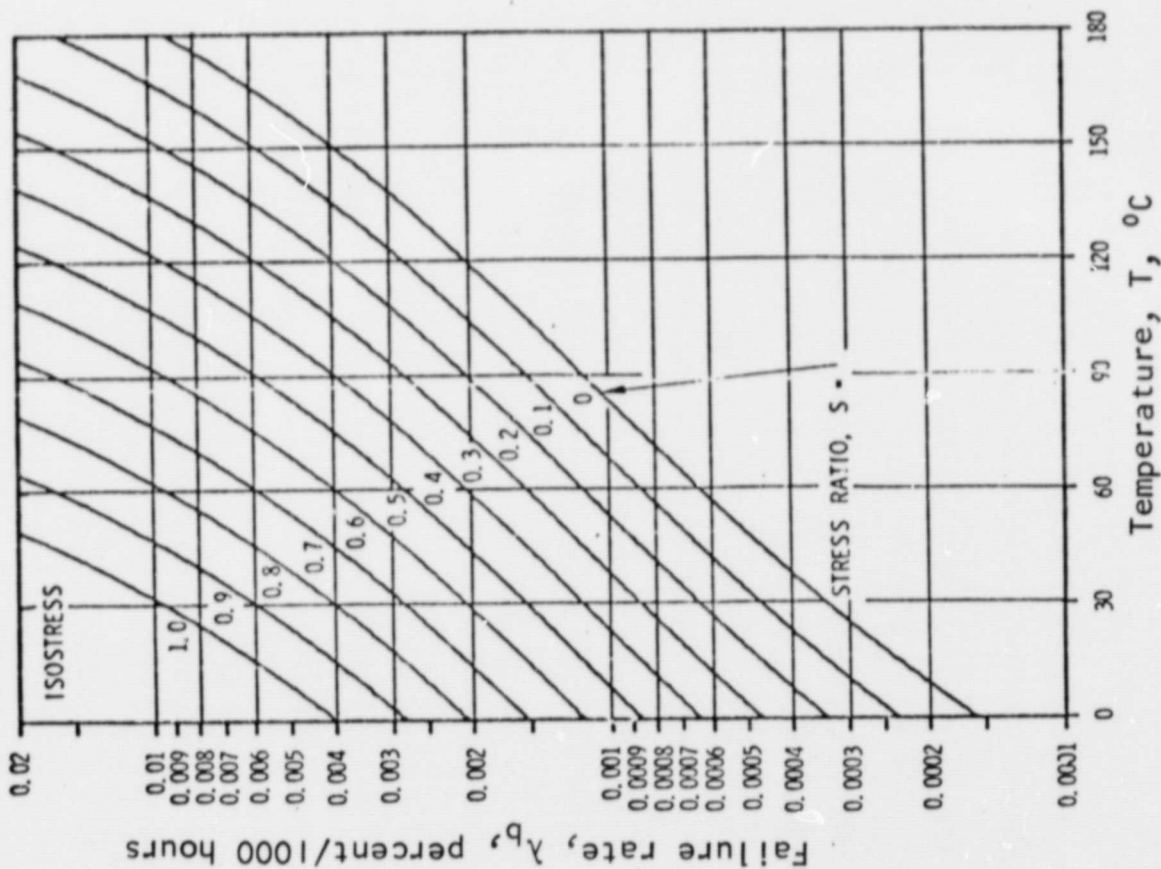
Environment	Silicon transistors (NPN)				Silicon diodes and rectifiers				SCR			
	π_e		Σ_E		π_e		Σ_E		π_e		Σ_E	
	UQG	LQG	UQG	LQG	UQG	LQG	UQG	LQG	UQG	LQG	UQG	LQG
Airborne inhabited	30	300	.004	.04	30	180	.002	.02	30	300	.005	.1
Airborne uninhabited	50	500	.005	.05	50	300	.006	.06	50	500	.005	.1

UQG = upper grade of reliability

LQG = lower grade of reliability



(a) Failure rate versus stress ratio



(b) Failure rate versus ambient temperature

Figure 38. Basic Failure Rate of Silicon Control Rectifiers
(from RADC Reliability Notebook)

TABLE 10

APPLICATION FACTOR OF SEMICONDUCTOR COMPONENTS

Silicon transistors (NPN)		Silicon diodes and rectifiers	
Application	π_a	Application	π_a
Linear (ac)	1.0	Signal (audio)	1.0
Linear (dc)	2.0	Signal (IF, RF)	1.5
Low noise (audio)	1.5	Logic switching	0.3
High frequency (RF)	3.0	Power rectifier	2.0
Low noise (RF)	4.0	Power rectifier $V_{max} > 600$	2.5/junction
Logic switching	0.5	Forward reference	0.3

TABLE 11

RATING FACTORS OF SEMICONDUCTOR COMPONENTS

Silicon transistors (NPN)		Silicon diodes and rectifiers	
Power rating (watt)	π_R	Current rating I_{max}	π_R
Up to 1	1.0	0 to 100 ma	1.2
> 1 to 5	1.5	> 100 to 500 ma	1.0
> 5 to 20	2.0	> 0.5 to 1 a	1.1
> 20	2.5	> 1 to 3 a	1.5
		> 3 to 10 a	2.0
		> 10 a	2.5

SCR	
Rated average forward anode current (amp)	π_R
0 to 0.5	1.2
> 0.5 to 1	1.0
> 1 to 10	1.5
> 10	2.0

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APPENDIX A

PRELIMINARY DESIGNS OF FANS AND COMPRESSORS

Axial Flow Fans

The graphical method for obtaining the size of axial flow fans has developed for conservatively rated designs. It was not intended to give an absolute and final answer on what size fan is needed to meet a given requirement, but rather to give a size that is most likely feasible. It is still necessary to do a detailed analysis of the air velocity vector triangles across the blade span to determine whether a design is really practical, particularly at low hub/tip ratios.

Assumptions.--An axial flow fan with the following parameters is assumed (see Nomenclature I p. A-11).

- (1) Aerodynamic efficiency, $\eta = 60$ percent
- (2) Pressure rise coefficient, $\psi = 65$ percent $= 2\Delta u/u$
- (3) Blade tip air inlet angle, $\alpha = 21.8^\circ$; i.e., $V_x/u_t = 0.4$
- (4) Axial stage inlet and outlet air velocities
- (5) Constant axial velocity
- (6) Free vortex design
- (7) No inlet guide vanes
- (8) One rotor and one stator stage
- (9) Five percent motor slip

Graphs.--Fig. A-1 shows airflow per unit area, Q/a , plotted against pressure rise, $\Delta P/\sigma$.

From fan laws

$$u_t \Delta u = \frac{2188}{\eta} \frac{\Delta P}{\sigma} = u_t^2 \frac{\Delta u}{u_t}$$

Substituting assumption (2) into the above equation:

$$u_t^2 \frac{\Delta u}{u_t} = u_t^2 \frac{\psi}{2}$$

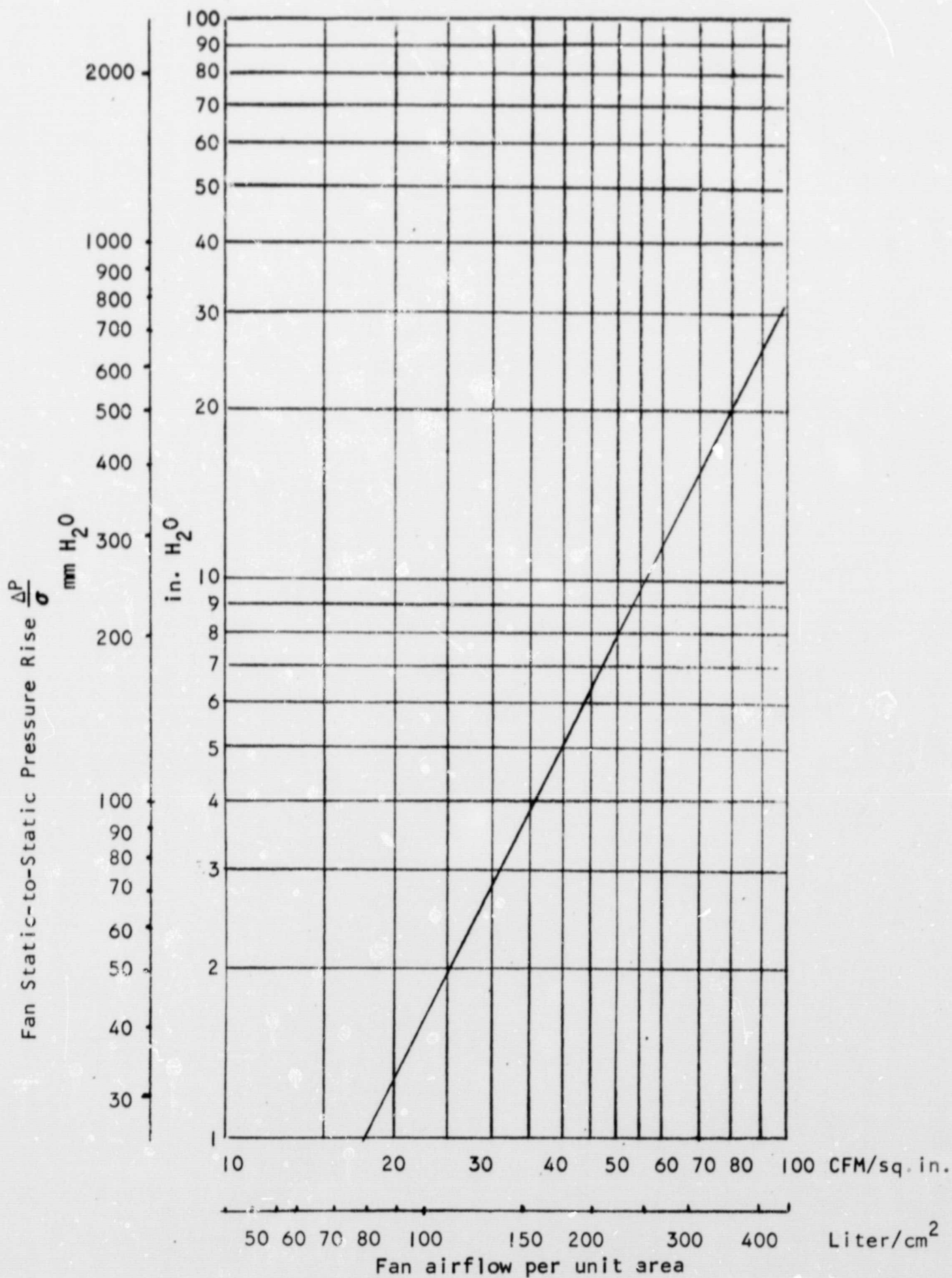


Figure A-1. Fan Airflow vs Pressure Rise

Therefore,

$$\psi = \frac{4376}{u_t^2 \eta} \frac{\Delta P}{\sigma}$$

Substituting assumptions (1) and (2) into the above equation:

$$\frac{\Delta P}{\sigma} = 8.92 \times 10^{-5} u_t^2 \quad (A-1)$$

Substituting assumption (3) into eq (A-1):

$$\frac{\Delta P}{\sigma} = 5.58 \times 10^{-4} V_x^2 \quad (A-2)$$

since $V_x = \frac{1440}{60a} = \frac{2.40}{a}$

therefore $\frac{\Delta P}{\sigma} = 3.22 \times 10^{-3} \left(\frac{Q}{a}\right)^2 \quad (A-3)$

Fig. A-1 is a plot of eq. (A-3). Fig. A-2 is a plot of eq. (A-1).

The fan tip speed is given by:

$$u_t = \frac{\pi DN}{720} \quad (A-4)$$

For ac electric motors, with slip (s) of 5 percent

$$N = \frac{120f(1-s)}{N_p} = \frac{114f}{N_p} \quad (A-5)$$

Fig. A-3 is a plot of eqs. (A-4) and (A-5).

The annulus flow area is given by

$$a = 0.785 (D^2 - d^2) = 0.785 D^2 (1 - h^2) \quad (A-6)$$

Fig. A-4 is a plot of eq. (A-6).

Figs. A-5 and A-6 represent

$$\text{Specific speed} = \frac{NQ^{0.5}}{\Delta P^{0.75}} \quad (A-7)$$

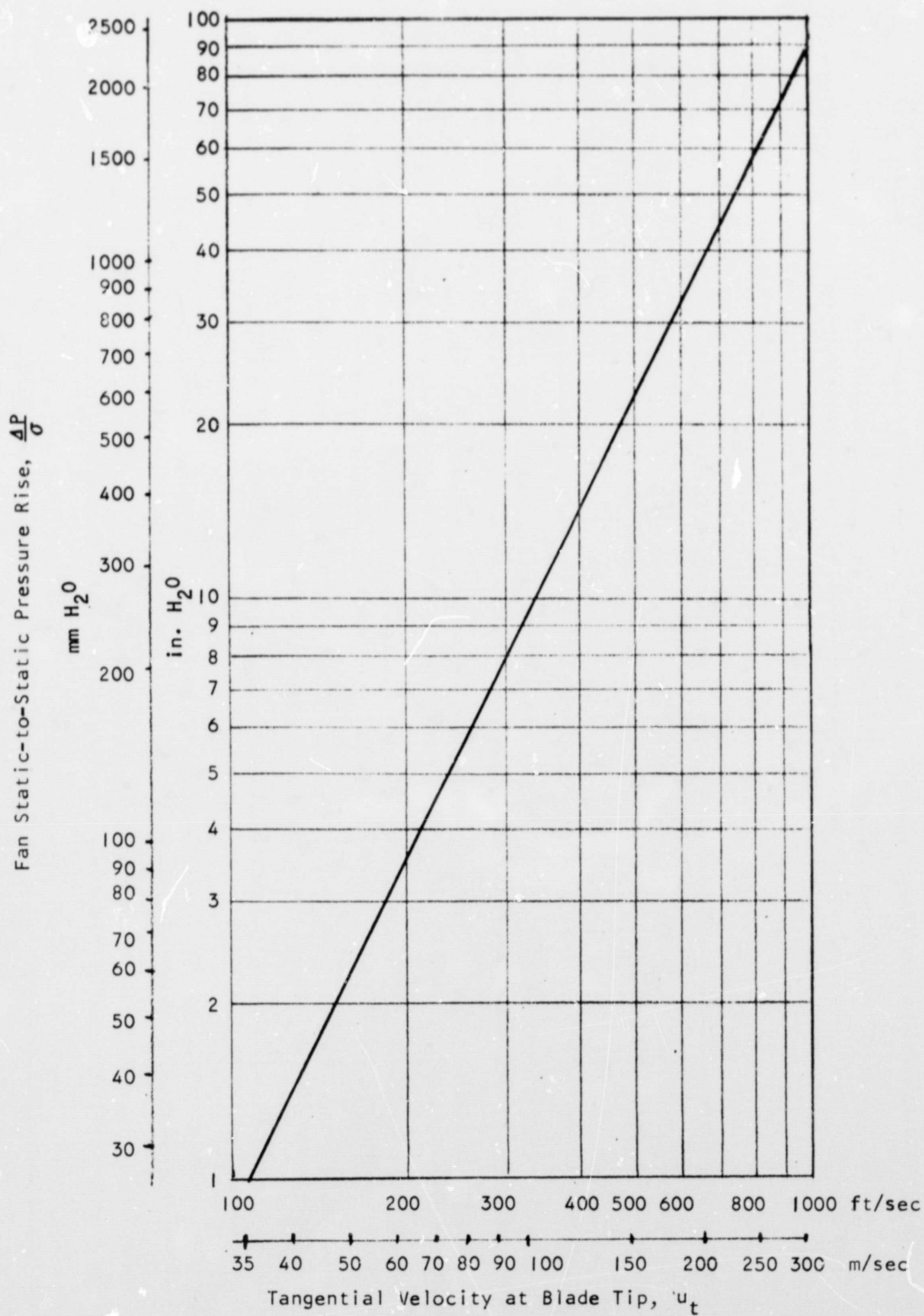


Figure A-2. Velocity vs Static Pressure Drive

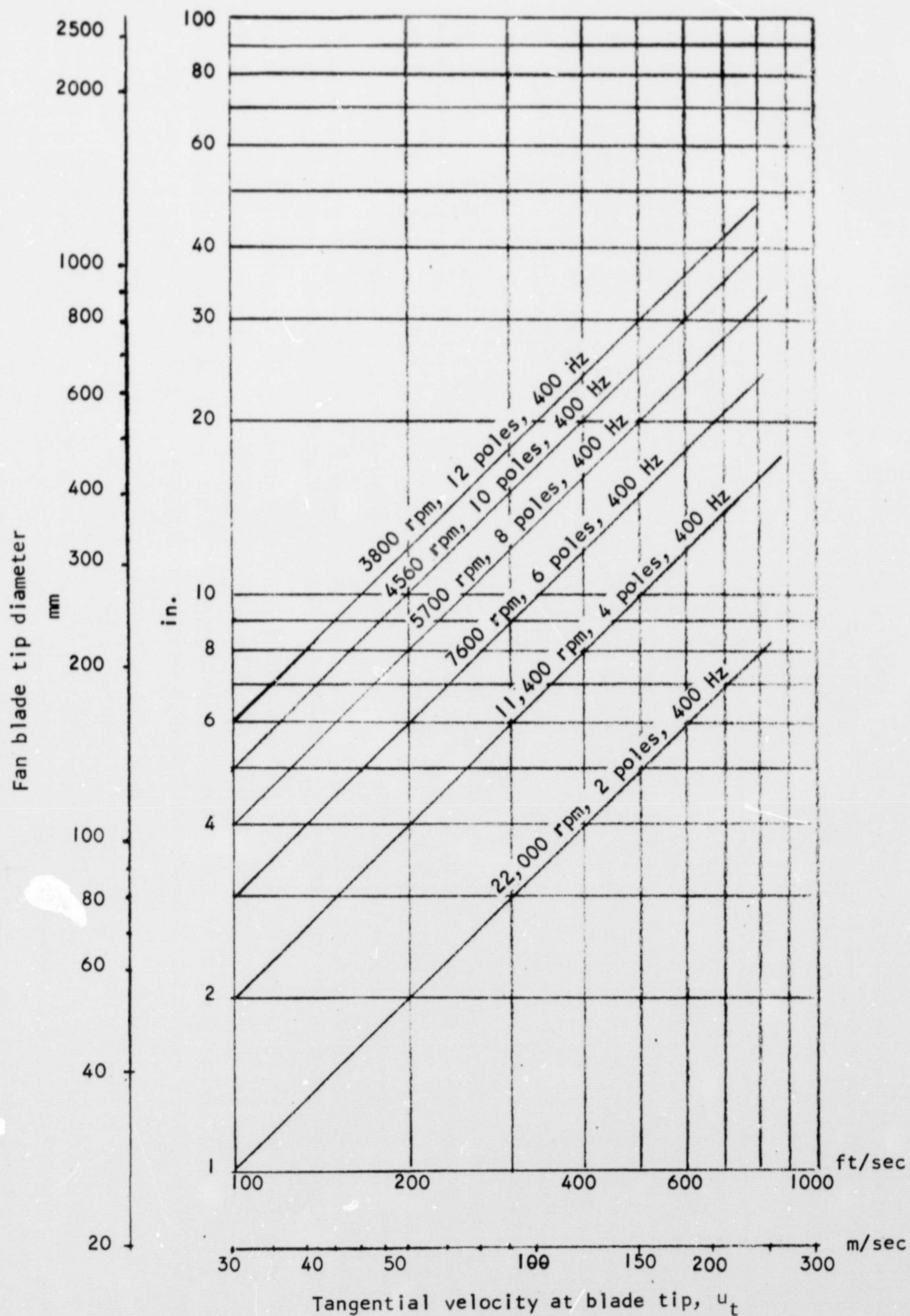


Figure A-3. Velocity vs Fan Variables

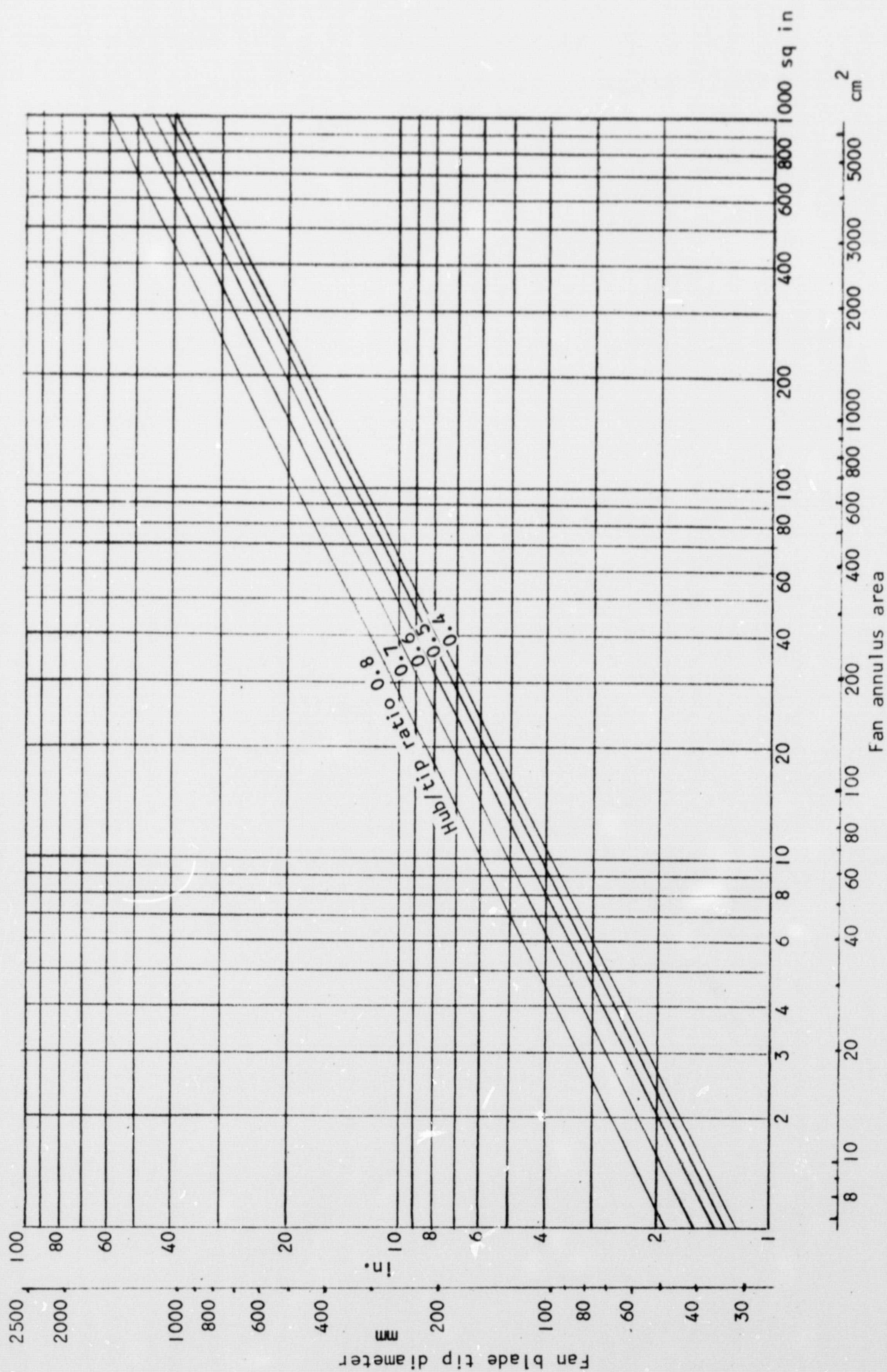
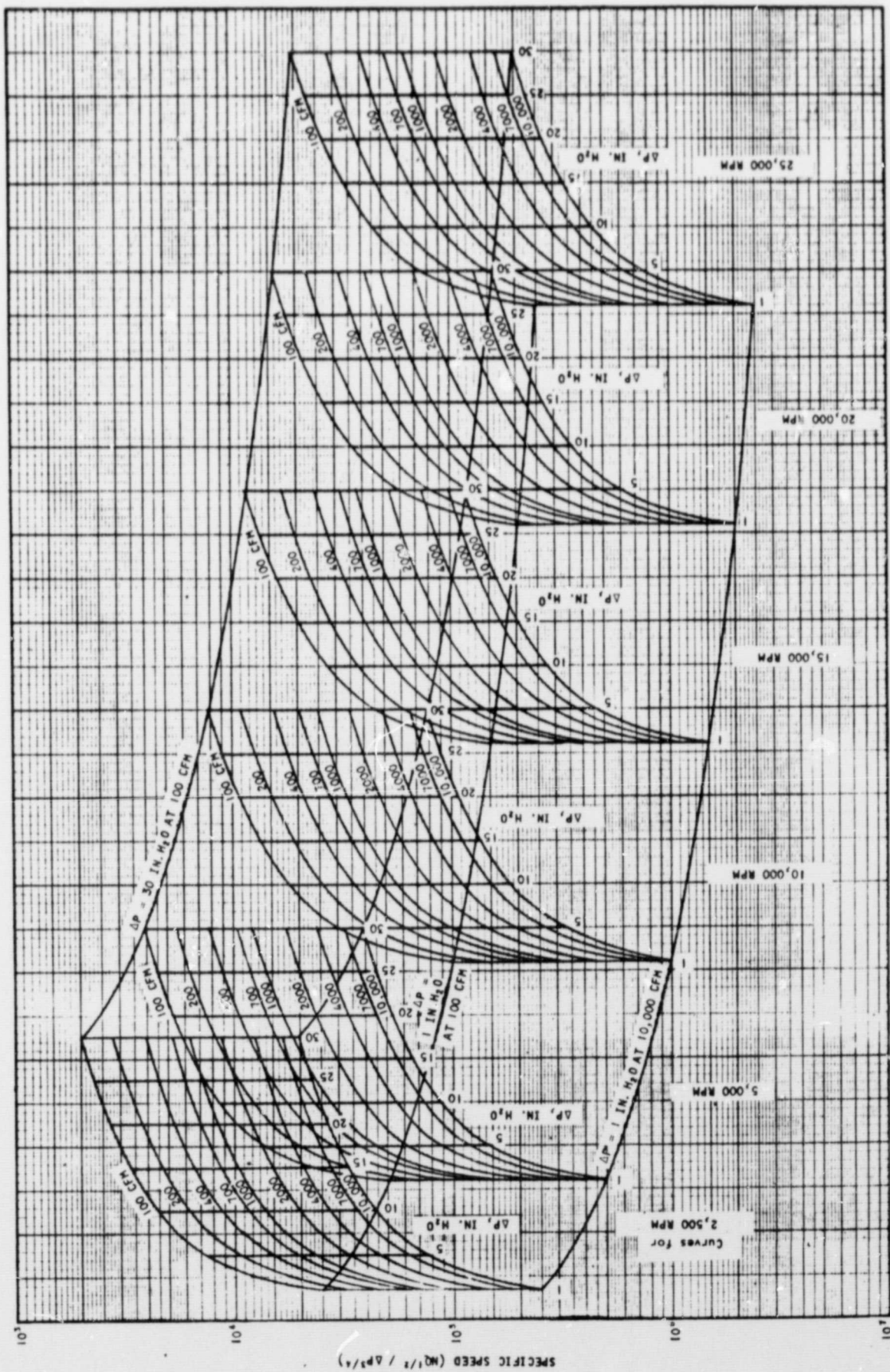
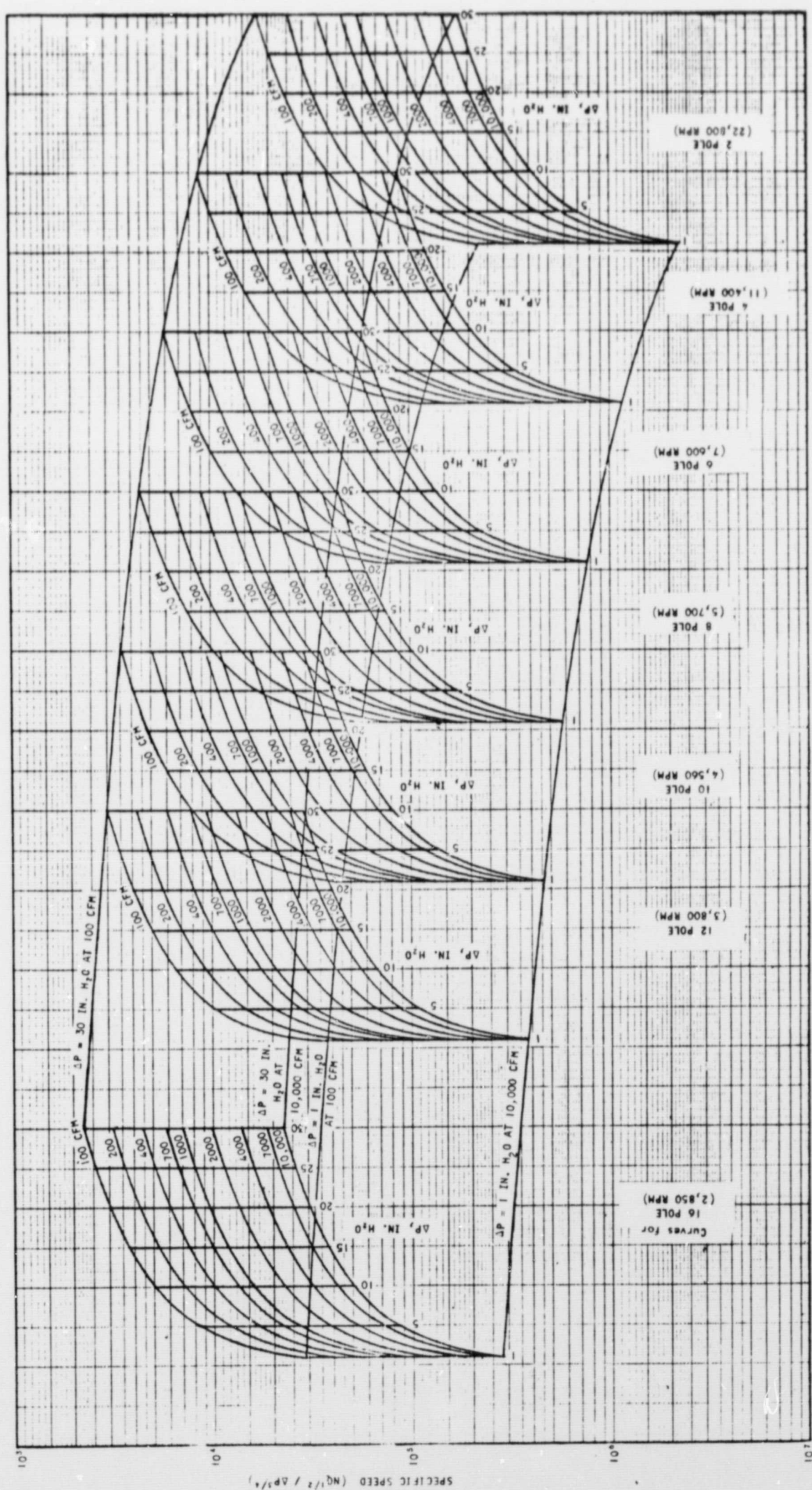


Figure A-4. Fan Annulus Area vs Fan Variables



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Figure A-5. Specific Speed Curves for Fans



Figs. A-5 and A-6 are carpet plots of pressure rise vs specific speed with flow as a parameter, with separate plots for various speeds. On Fig. A-5 these plots are spaced out proportionally to the speed, thereby permitting accurate interpolation for speeds not shown. However, as the majority of motor driven fans are driven by 400-Hz induction motors, fig. A-6 is plotted to show the most common speeds directly. In this case the plots are spaced proportionally to the number of poles.

Fig. A-7 is an empirical plot of aerodynamic efficiency vs specific speed.

Technique for using graphs to find size of axial flow fan.--The following technique should be followed to find the axial flow fan size:

- (1) From fig. A-1, pick off Q/a for the $\Delta P/\sigma$ as required.
- (2) From fig. A-2, pick off u_t for the $\Delta P/\sigma$ required.
- (3) From fig. A-3, with this value of u_t , choose a tip diameter D and speed compatible with the speed and size limitations of the installation.
- (4) From the value Q/a found in (1), and the required flow, Q , calculate a . With this value of a and D from (3) obtain h from fig. A-4. If the values of a and D do not correspond to a value of h given, i.e., from 0.4 to 0.8, then a new choice of D and N in (3) has to be made and repeated until a solution is reached.
- (5) Using the value obtained for N , determine the specific speed from figs. A-5 and A-6.

If the aerodynamic efficiency for the specific speed obtained in (5) is less than 60 percent, a new speed must be selected from fig. A-5. The problem must then be reworked from (3).

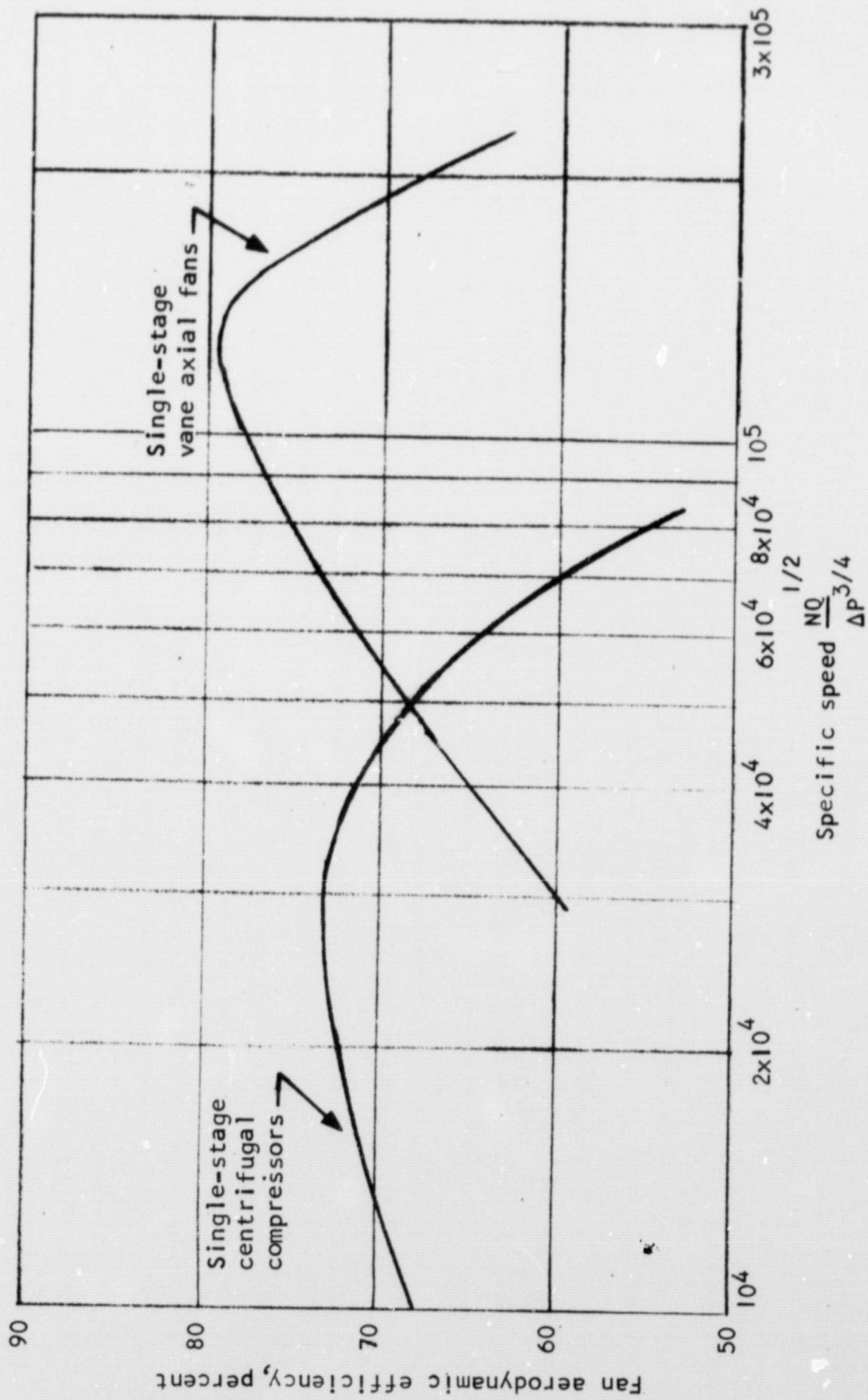


Figure A-7. Specific Speed vs Efficiency

Nomenclature I For Axial Flow Fans

a	Annulus through flow area, sq in.
d	Diameter of root of blades, in.
D	Diameter of tip of blades, in.
f	Electrical supply frequency, cps
h	Hub/tip ratio = d/D
N	RPM
N_p	Number of poles in motor stator
P_i	Inlet absolute pressure, in. Hg
ΔP	Static pressure rise across fan, in. H_2O
Q	Airflow rate, cfm
S	Motor slip factor
T_i	Inlet absolute temperature, $^{\circ}F$
u_t	Tangential velocity at blade tip, fps
Δu	Change in whirl velocity of air at blade tip, fps
V_x	Air axial velocity, fps
α	Air inlet angle from tangential, degrees
η	Aerodynamic efficiency, percent
σ	Air relative density
ψ	Pressure rise coefficient, percent

Centrifugal Compressors

The graphical method for sizing centrifugal compressors described here is limited to low pressure rise compressors (less than 100 in. of water), using vaneless diffusers and rotor blades swept back 45 degrees at the tip. Unlike the axial flow fan sizing graphs, these can be used for design purposes, because the centrifugal compressor is essentially a simple machine, and detailed flow analyses are not necessary for these low pressure rise compressors.

Assumptions.--A centrifugal compressor with the following parameters is assumed (see Nomenclature II, p. A-16).

(1) Overall aerodynamic efficiency, $\eta_o = \eta_i = 70$ percent

(2) Aerodynamic slip, $S = \frac{V_{u3}}{V_{ub}} = 0.71$

(3) $\beta_2 = 45^\circ$

(4) $V_x = V_r$

(5) $d_i = 0.45D_i$

(6) Zero prewhirl

(7) $\Delta P_i = 0.87 \Delta P_o$

(8) $\Delta P_d = 0.13 \Delta P_o$

(9) $V_{xi} = 50$ fps

Graphs.--Fig. A-8 shows the compressor volume flow vs the inlet duct diameter. This is merely a plot of the equation:

$$Q = \frac{60 V_{xi} a_i \text{ cfm}}{144}$$

where $a_i = \frac{\pi}{4} (D_i^2 - d_i^2)$

Substituting assumptions (5) and (9) into the above equation:

$$Q = 13.0 D_i^2 \text{ cfm}$$

Fig. A-9 gives the compressor total-to-total pressure rise vs impeller tip tangential velocity. From the fan laws:

$$u^2 \Delta u^2 = \frac{168 \left(\frac{\Delta P}{\sigma} \right) \rho}{\eta_{ip} 0.0765} = \frac{2188}{\eta_i} \frac{\Delta P_i}{\sigma} = u_2 V_{u3} = u_2 S V_{ub} \quad (\text{A-8})$$

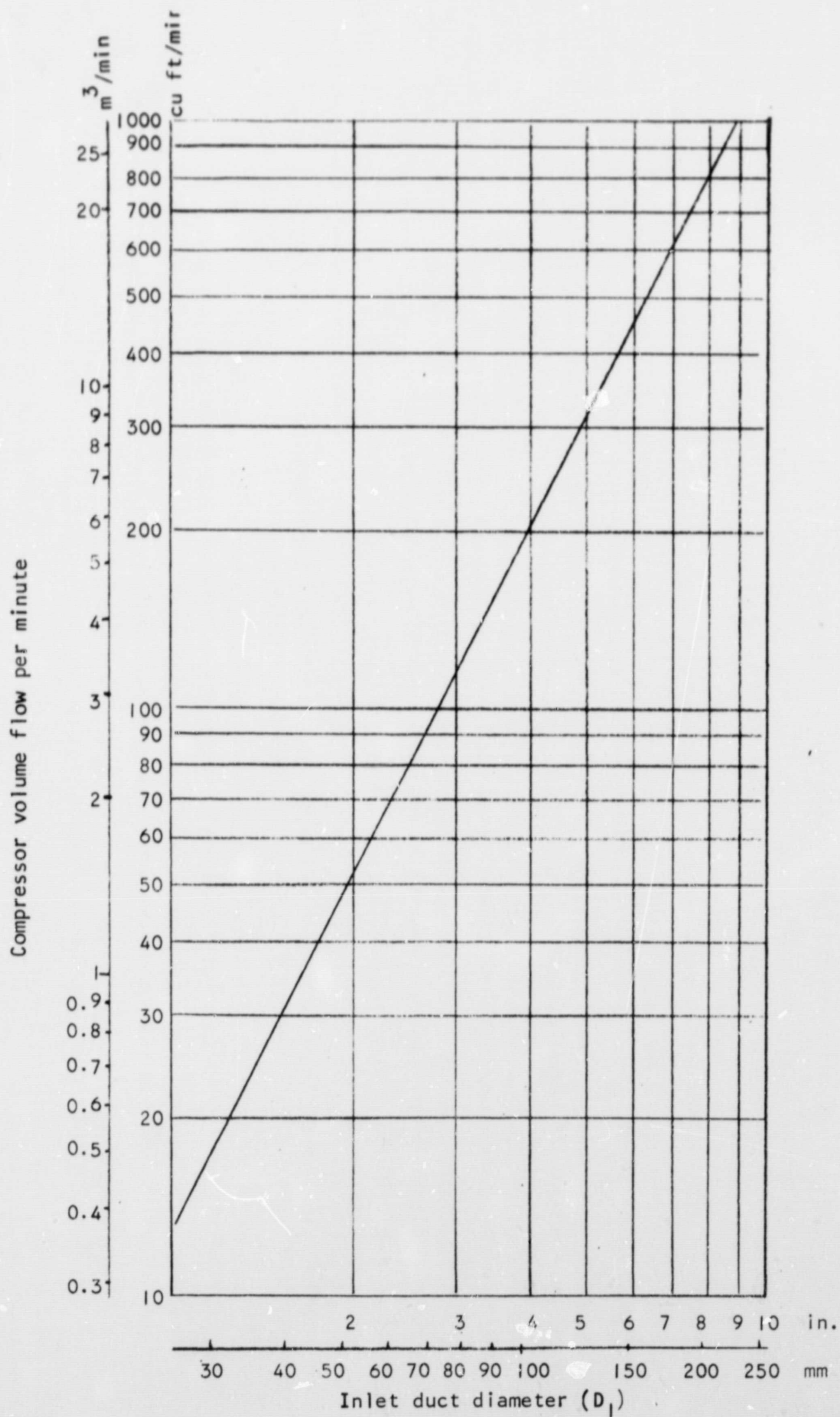


Figure A-8. Compressor Inlet Duct vs Volume Flow

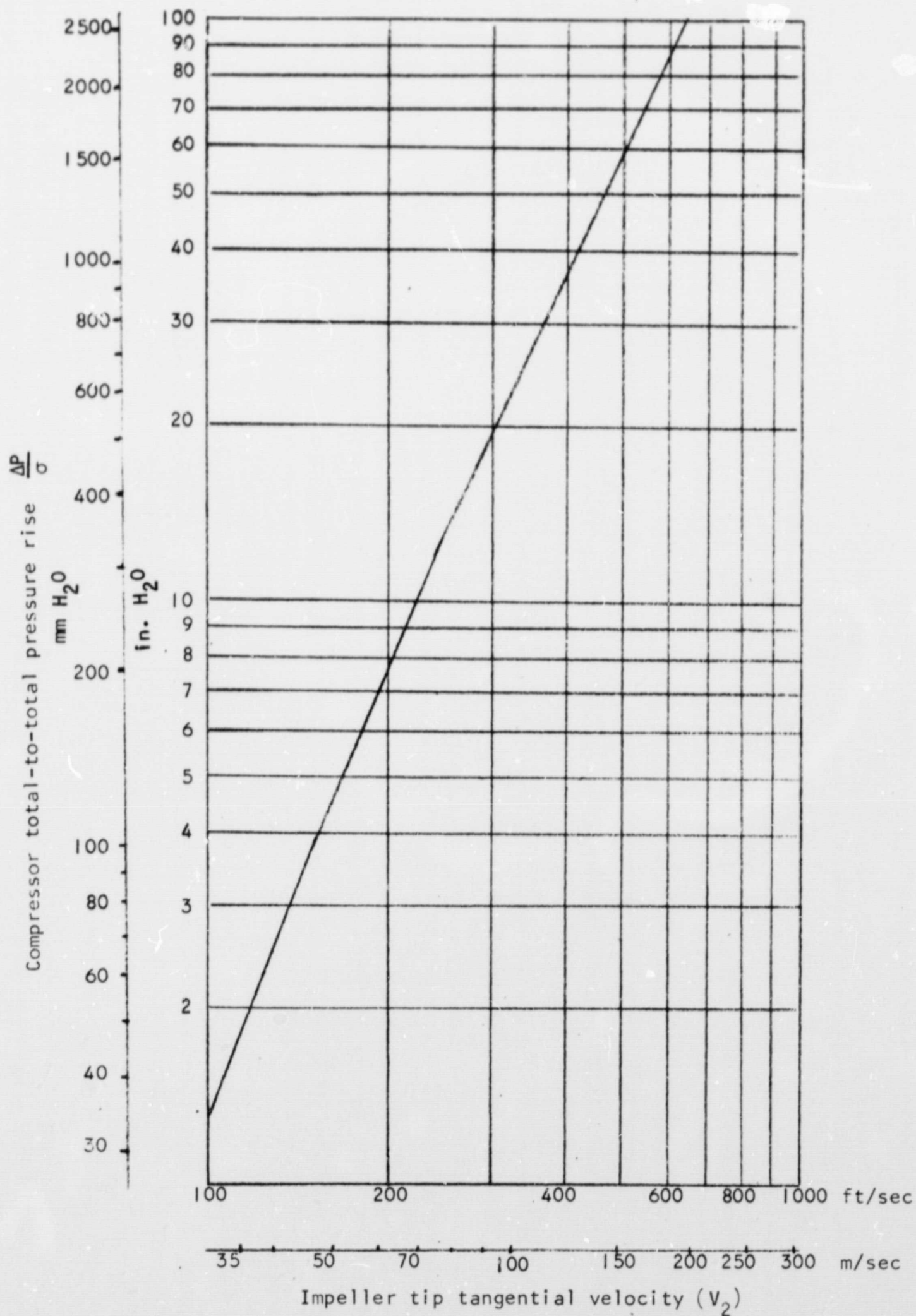


Figure A-9. Compressor Impeller Velocity vs Total-To-Total Pressure Rise

But, because $\beta_2 = 45^\circ$, $V_{ub} + V_r = u_2$

Therefore

$$u_2^2 \cdot \Delta u_2 = S (u_2^2 - V_r u_2) = S (u_2^2 - V_x u_2)$$

Substituting assumption (9) and eq. (A-8) into the above equation:

$$\frac{2188}{\eta_i} \frac{\Delta P_i}{\sigma} = S (u_2^2 - 50 u_2)$$

Substituting assumptions (1), (2), and (7) into the above equation:

$$\frac{\Delta P_o}{\sigma} = 2.62 \times 10^{-4} (u_2^2 - 50 u_2) \quad (A-9)$$

This equation is plotted on fig. A-9.

Technique of using graphs to find the size of a centrifugal compressor.--
Pick off the inlet diameter D , in., from fig. A-8 for the volume flow, Q , cfm, required.

Pick off the impeller tip tangential velocity from fig. A-9 for the pressure rise, $\Delta P/\sigma$, inches H_2O , as required.

Select impeller tip diameter D , in., from fig. A-3 compatible with the speed desired. Higher rpm results in smaller and lighter compressors at the expense of cost and life. Also, the tip diameter should be at least 1.5 times the inlet duct diameter.

With the chosen speed, N , rpm, determine the specific speed from figs. A-5 and A-6, and refer to fig. A-7. The specific speed should be within the range where the aerodynamic efficiency is at least 70 percent.

The overall diameter of the centrifugal housing will be about 1.7 times the impeller tip diameter for compressors with axial discharge. Those with radial discharge will have a volute casing superimposed on this diameter.

Nomenclature for compressors is given in Nomenclature II, p. A-16 and figure A-10.

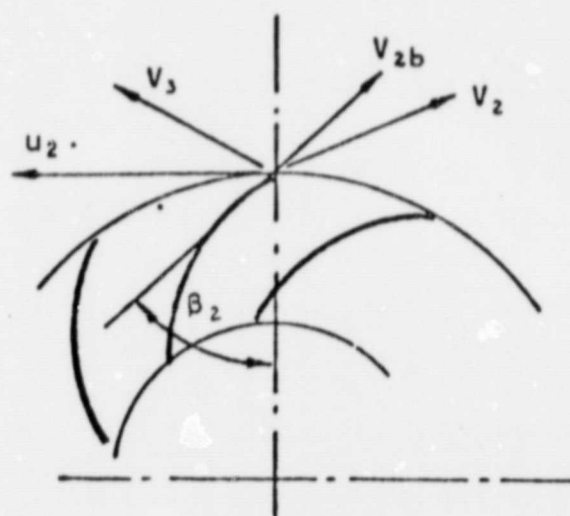
Nomenclature II
(Reference fig. A-10)
For Centrifugal Compressors

a_1	Impeller inlet annulus area, sq in.
d_1	Impeller inlet inner diameter, in.
D_1	Impeller inlet outer diameter, in.
D_2	Impeller outlet tip diameter, in.
ΔP	Pressure rise, in. H_2O
Q	Volume flow rate, cfm
S	Slip = Vu_3/Vub
u	Tangential velocity
Δu	Change in tangential velocity, fps
V	Gas velocity, fps
Vu	Tangential component of gas velocity, fps
α	Air angle, deg
β	Blade angle, deg
η	Efficiency
ρ	Density of gas, pcf
σ	Relative density of gas

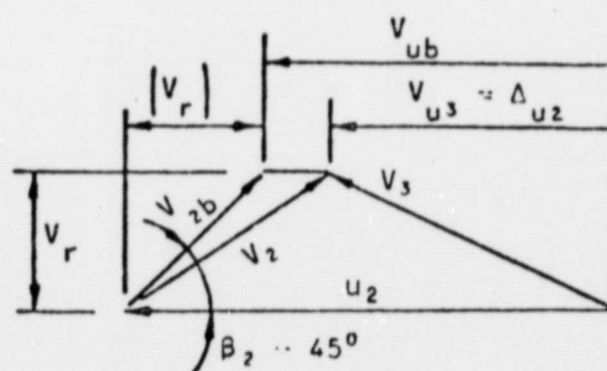
Subscripts

b	Blade	r	Radial
d	Diffuser	x	Axial
i	Impeller	1	Inlet, relative to impeller
o	Overall	2	Outlet, relative to impeller
		3	Outlet, absolute

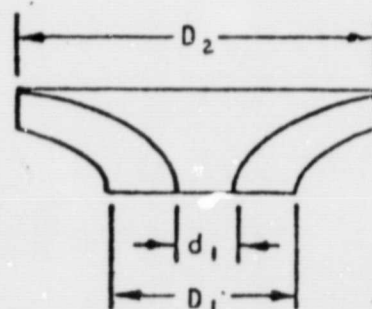
View in blade-to-blade plane



Outlet velocity triangle



View in meridional plane



Inlet velocity triangles and view of blade inlet

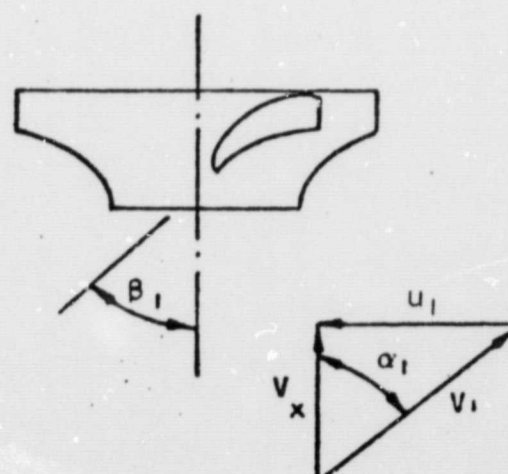


Figure A-10. Nomenclature for Centrifugal Compressors