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***Report on***  
**AIRCRAFT ELECTRIC SYSTEM GUIDE**

***Prepared by***  
***Subcommittee on Aircraft Systems of the***  
***AIEE Committee on Air Transportation***



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## FOREWORD

This draft of the Report on Aircraft Systems Guide indicates the degree of progress which has been made in the compilation of this extensive informative report. The present material is in tentative form and suggestions for improvement are welcomed.

One very important part of the work of the committee concerns the establishment of appropriate procedures for evaluating the electrical behavior of composite systems (computing voltage drop; defining available short-circuit current magnitudes, etc.). While this material is nearing completion, it is not in shape to be included in this printing.

This report was prepared by the Subcommittee on Aircraft Systems of the AIEE Committee on Air Transportation. The personnel of this subcommittee was as follows:

R. H. Kaufman, *Chairman*

J. W. Allen

J. C. Cunningham

H. J. Finison

R. J. Lusk

J. R. North

W. A. Petrasek

K. R. Smythe

A. J. Snyder

A. F. Trumbull

# Report on AIRCRAFT ELECTRIC SYSTEM GUIDE

## 000. INTRODUCTION

### General

Preparation of material incorporated in this report has been undertaken by the AIEE in the belief that it will materially aid in the realization of a better aircraft electric system. This conviction is confirmed by opinions expressed in joint meetings, including representation from SAE, NASC, NEMA, Army Air Forces, and the Bureau of Aeronautics.

### Quality Attainment

Superior quality of performance in an aircraft electric system can be obtained as a result of:

- (1) Improved device performance.
- (2) Better application technique.

Improved device performance is the result of more effective utilization of material or the incorporation of ingenious design features in a particular device while better application technique is concerned with selecting the most appropriate combination of devices and coordinating them in the most effective manner so as to realize the best overall results in a composite functional equipment.

### Scope of This Report

Material comprising this report is directed expressly at the attainment of improved application technique—the attainment of the highest possible quality of performance from a combination of particular devices to perform a given function. The performance qualities exhibited by a composite system composed of numerous devices will be influenced by the character of devices which are selected to work together and the manner in which they are interconnected or correlated. The extent to which such composite systems may be benefited by proper application technique is much greater than would be expected or imagined.

Realization of the stated objectives involves comprehensive treatment of the following character expressed quantitatively in simple compact form.

1. An explanation of the fundamental electrical problems involved.
2. Typical characteristic performance data of the various elements and devices of which the system is composed which shall define inherent limitations as well as meritorious qualities.
3. Methods of analysis or test by which the

qualities and limitations of a particular composite-device system may be evaluated.

4. Formulation of particular application practices which may be accepted with the assurance that good performance quality will be realized.

5. Formulation of a general analysis procedure (preferable in chronological order) which will outline the various factors which must be examined or checked.

While it will be the purpose of this report to refrain from defining or dictating specific characteristics of particular devices, it is quite possible that desirable features brought out by application considerations may be of considerable assistance to other groups in creating new devices or improving existing ones.

Electrical applications in aircraft assume many peculiar aspects. Weight and space in aircraft are of great importance, and reductions in these quantities deserve infinitely greater consideration than in equipment for land service. Equipment must be capable of successful operation in the presence of wide variations in ambient temperature, humidity, and altitude. In general, equipment must be capable of withstanding severe vibration in the member which supports it. Apart from these considerations which are peculiar to aircraft service, all knowledge accumulated through years of industrial experience should be used to the fullest advantage in bettering the performance of aircraft electric systems.

The electrical divisions of present aircraft manufacturing organizations are, for the most part, relatively young and include personnel who have not had extensive experience in electrical application. The electric system incorporated in a typical aircraft has grown from simple non-essential character (resembling that incorporated in an automobile) to an extensive general-purpose system incorporating vital functions, all in the span of a few years. It is apparent that immense benefits can result from a readily available summary of good application principles which are founded on sound engineering fundamentals.

The unprecedented expansion of size and number of aircraft with ever-increasing electric systems which has occurred since the beginning of the war, principally for military service, has resulted in the accumulation of much knowledge and experience relative to good electrical application practice. It is important that this vast reservoir of knowledge be tapped, coordinated,

and compiled in the form of a permanent record.

In the final analysis, the resulting benefits will be measurable in terms of

1. Improved reliability; fewer outages; less maintenance.
2. Lighter weight.
3. Simplification of installation; operation; maintenance.
4. Greater safety to electric equipment; airplane; personnel.
5. Lower monetary cost of aircraft electrical service.

## 100. PURPOSE AND REQUIREMENTS OF THE ELECTRIC SYSTEM

110. The fundamental requirement of an aircraft electric system is its ability to properly operate all electrically-powered equipment under all load demands to be encountered. Safe operation of the aircraft shall be maintained in the presence of outages in individual components which reasonably occur in service.

111. The aircraft system voltage (and frequency if alternating current) shall be maintained within limits necessary to sustain operation of all components.

112. All components of the electric system shall be capable of operating under the most unfavorable conditions of loading, ventilation, and ambient temperature.

113. The reliability of individual functions which are electrically actuated shall be consistent with their effect on the safety of the flight. The basic generating and distribution system delivering power to the buses from which the utilization circuits are connected through individual circuit protectors must have the same reliability as associated with the main engines of the airplane. The design of the generating system shall be such that the electric system will continue to fulfill its requirement as stated above with a maximum number of main engines inoperative but yet consistent with maintaining the airplane in safe flight (in multi-engine aircraft this is currently interpreted to mean that sufficient generator capacity shall be distributed among all the engines to provide for 50 percent engine failure and the maintenance of 100 percent electric load requirements).

113.1 It is necessary to establish a definition of terms before embarking on a discussion of reliability of individual electrical functions. In

general, three degrees of reliability are sufficient for all practical purposes.

### Critical Equipment

Definition: Malfunctioning of which, under the most adverse flight condition which would normally be flown, will jeopardize the safety of the remainder of the flight.

Examples: Failure of all gyro flight instruments or radio communications occurring when flying on instruments would create a definitely unsafe condition.

### Essential Equipment

Definition: The malfunctioning of which in combination with one other unsafe circumstance occurring in the airplane will result in jeopardizing the safety of the remainder of the flight.

Example: Malfunctioning of flap operating mechanism and simultaneous loss of brakes.

### Non-Essential Equipment

Definition: The malfunctioning of which will in no way jeopardize the safety of the flight but which will detract from the operation (good will, efficiency, economy).

Example: Malfunctioning of buffet heating heating equipment or passenger cabin lighting.

### Evaluation of Reliability

In the evaluation of reliability one must consider the probability of malfunctioning as well as the ability to correct the difficulty in flight, assuming that the flight crew personnel are qualified and *have the time* to perform the necessary corrections.

## 120. Evaluation of Serviceability

The basis for all discussion of serviceability lies in the establishment of a service life characteristic for the equipment (reference, Figure 1). The preferred and by far the most useful source of data for compiling this characteristic is from actual service experience on the airplane in scheduled operation. It is possible to secure reasonably accurate service life characteristics for certain types of equipment by subjecting them to controlled laboratory tests. There are some factors, however, which do not appear in these ground tests such as mishandling and misuse due to lack of familiarity with the equipment. In the absence of actual operating experience it is important that the laboratory test conditions be selected which most closely represent the duty and environment under which the equipment will be expected to operate in service.

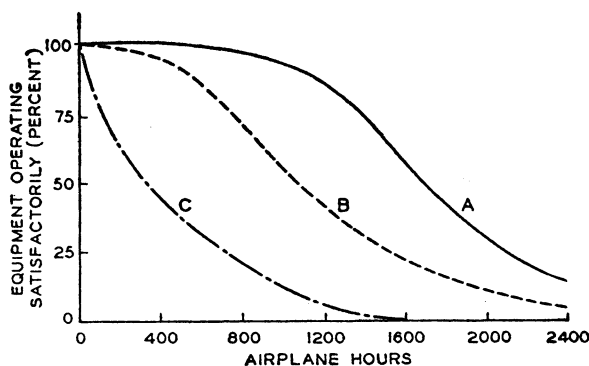


**Figure 1**  
**Service Life Characteristic**

The first use of this characteristic would be to establish a periodic change time which would be consistent with the degree of reliability that is desired. The comparison of curves A and B of Figure 1 demonstrates that serviceability and reliability are not synonymous. The same degree of reliability can be obtained from two types of equipment of widely different serviceability. Once having established the periodic change time, the maintenance cost of this equipment can be reasonably evaluated. The first determination is to check the conformance of the necessary change time with existing service procedures. If this time does not fall into the existing scheme of maintenance, then additional costs will be incurred. A second consideration in the evaluation of maintenance cost is to determine the cost of line maintenance. This cost will involve such factors as labor required for replacement in the field, the frequency of such replacement, inventory of spare parts required to meet these contingencies, and the cost of routing replacement parts throughout the system. The final direct maintenance cost is the cost of overhauling the equipment and consists of labor cost, cost of replacement parts, tools, and test equipment.

In addition to the above maintenance costs attending the serviceability of equipment, we have the cost of operations whenever malfunctioning of the equipment results in a delayed or interrupted flight. In the case of interrupted flights, one might establish as a minimum cost the loss of revenue flying time (currently about \$180 per hour). Moreover, it is not uncommon for such flight interruptions to result in missed connecting schedules which in turn result in cancelled fares and loss of good will. Even more costly is the coincidence of bad weather grounding the delayed aircraft for perhaps a day or more and resulting in the loss of several thousands of dollars of potential revenue earnings.

This wide variation in the consequences of delayed or interrupted flight, plus the intangible effect of good will, makes the evaluation of equipment serviceability extremely difficult.

The problem of forecasting the probable frequency of flight delays and interruptions is quite difficult. The only available source of information for such prognostications is the record of past experience. It has been found that the probability of equipment failure resulting in a delay will be largely decided by the nature of operation of the equipment and the importance of its function. For example, the landing light bulb has a high ratio of delays to failures. The reason is obvious when it is considered that a bulb nearing the end of its service life is operated just prior to departure time with the addition of vibration of recently started engines. Furthermore, the aircraft cannot be dispatched without both of its landing lights in operating condition.

#### Evaluation of Weight

It is possible to place a dollar value on the addition of a pound of weight to commercial aircraft. This evaluation is obtained by multiplying the number of dollars per pound mile for the year by the number of miles flown and by two additional factors. The first is called the weight load factor which is the ratio of the average weight of payload carried to the average available payload of the aircraft. This is, in a sense, a measure of the available business and is currently about 0.80. The second factor is called the weight restricted flight factor and represents the percentage of those flights where payload is left behind and diverted to other carriers because of aircraft gross weight limitation. This factor is approximately 0.60.

#### 130. Safety

Aside from consideration of reliability and effect of failure of equipment upon the safety of the flight, there are other considerations regarding safety which are worthy of separate attention.

131. There shall be no hazard presented to persons occupying the aircraft in the form of exposed wiring which under any conditions could result in electric shock.

132. The type of electric equipment, the installation and ventilation afforded this equipment shall be such that there will be no possibility of explosion or fire in the event of fuel or other explosive vapor accumulations in those areas of the airplane susceptible to such hazards.

133. The installation of an electric bus, wiring, and equipment in junction boxes and through-

out the airplane should be such as to minimize the possibility of electric system faults to ground caused by accidental loosening of connections, etc. There should be no normally exposed electric bus or terminals in areas where loose control cables, mechanics' tools, etc. may be present during ground servicing operations.

134. Suitable circuit protection shall be provided so as to minimize the possibility of fire resulting from faults to ground.

#### 150. Military

The purpose and requirements of the electric system of a military airplane differ from the purpose and requirements of electric systems for commercial aircraft primarily in the terms by which they are defined.

The usual military airplane in addition to the requirements of carrying a cargo must perform the additional function of fighting and/or dropping bombs or performing some other duty during the flight or mission. Engaging in combat also subjects the electric system to possibilities of battle damage in addition to the normal wear and tear experienced by commercial airlines. Thus the reliability of individual functions which are electrically actuated shall be consistent with their effect on the ability of the airplane to perform its assigned mission. In evaluating reliability, the probability of malfunctioning due to combat damage imposes an additional factor in the design of the electric system.

The evaluation of serviceability is much the same as for commercial operation, although different weighting may be assigned the pertinent factors due to short maintenance periods, less intensive periodic maintenance, and more dependence upon daily maintenance.

The evaluation of weight is somewhat nebulous, but the factor of improved flight reliability versus decreased cargo capacity and/or performance and crew morale must be considered.

## 200. GENERAL CONSIDERATIONS

### 210. Factors Affecting Choice of Operating Voltage

Electric power as measured in kilowatts or kva is composed of volts and amperes. The flow of current or amperes always involves losses due to conductor resistance and therefore also causes heating of the conductor paths through which it flows. For a given current, the size of conductor must be selected to keep the losses low and to provide sufficient surface area to dissipate the losses without encountering excessive conductor temperature. In order to minimize the size of the conductor paths it will usually be the

objective to keep the current for a given amount of power as low as possible by using the maximum permissible voltage. There are, however, definite limits on the maximum voltage which can be effectively utilized due principally to insulation, arc interruption and safety problems.

### 211. Weight Economy

A major factor in the selection of voltage is the influence of voltage and the current on the weight of system components:

#### 211.1 Generators

Voltage has relatively little effect on the weight of generators. The active material required for a given output at a given speed is not a function of voltage. There are, however, some secondary effects. For d-c apparatus particularly, current collecting parts will be a minimum for some intermediate voltage, the particular voltage increasing some with increased rating. Most a-c machinery does not require the use of current collecting devices so that it is less affected by voltage rating. The space which must be devoted to insulation increases as voltage increases above 30 volts. For d-c machines, commutator diameter, brush spacing, and creepage distances increase with voltage, and these considerations may require a decrease in the number of poles, with a resultant increase in weight.

#### 211.2 Distribution Circuits

The size of conductor is determined in three ways:

(1) Conductors carrying light currents are determined by mechanical requirements. These conductors are not affected by voltage and no weight may be saved by increasing voltage.

$$W_c = K$$

(2) Conductors carrying heavy currents for short spans are usually determined by thermal limits. For an increase in voltage, the conductor size and weight decreases somewhat faster than the voltage increases.

$$W_c = K/E \text{ (or less, depending on conductor size)}$$

(Double voltage usually permits a reduction of four AN gauge numbers).

(3) Conductors carrying heavy currents for long spans will generally be determined by voltage regulation. The size of conductor will vary inversely as the voltage squared for a given amount of kva to be transmitted.

$$W_c = K/E^2$$

With increasing voltage, class (3) conductors will become class (2) and then finally class (1) conductors.

With alternating current allowance must be made for reactance of the wiring in determining regulation. Also copper must be provided for carrying circulating reactive power.

The polyphase alternating-current system requires three conductors plus a metallic structural neutral. The d-c system requires only a single line if a grounded metallic structure is employed. This is a weight disadvantage for alternating current for class (1) conductors, but is not a weight disadvantage for class (2) and class (3) conductors. For the same kva transmitted, a 120 volt system will require 1/18th the copper that would be required at 28 volts for identical regulation direct current or unity power factor alternating current.

Fig. 2 shows the power that can be transmitted by a single AN-4 cable without exceeding either the thermal limit or 3 percent voltage drop (applicable to direct current or unity power factor alternating current). For example, on a 100 foot span curve B crosses the thermal limit (135 amperes) at about 115 volts. This indicates that up to 114 volts voltage drop is a limit and the thermal capacity of the conductor is not completely utilized. Above 114 volts the limit is the thermal capacity of the conductor. Note that for the 100 foot length, 114 volts is the voltage at which the conductor changes from class (2) to class (3). For conductor sizes smaller than AN-4, a still higher voltage is required to fully use thermal capacity.

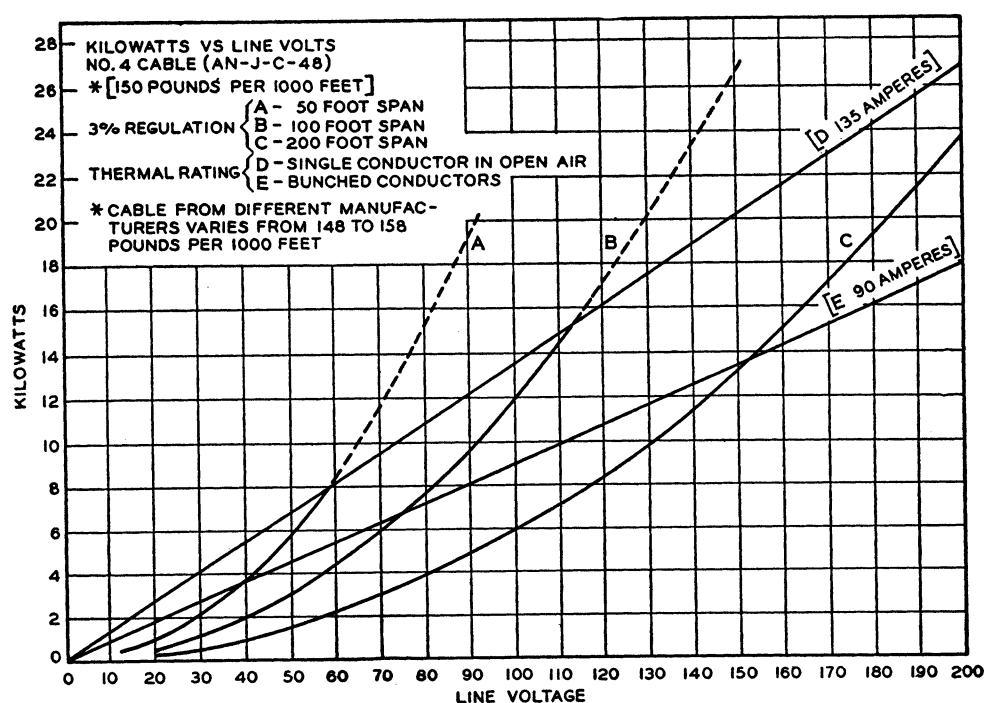


**Figure 2**  
**Kilowatts versus Line Volts**  
**No. 4 Cable (AN-J-C-48)**

Fig. 3 shows the effect of voltage as an influence in the required conductor weight to transmit five kilowatts of direct-current or unity power factor alternating-current lead.

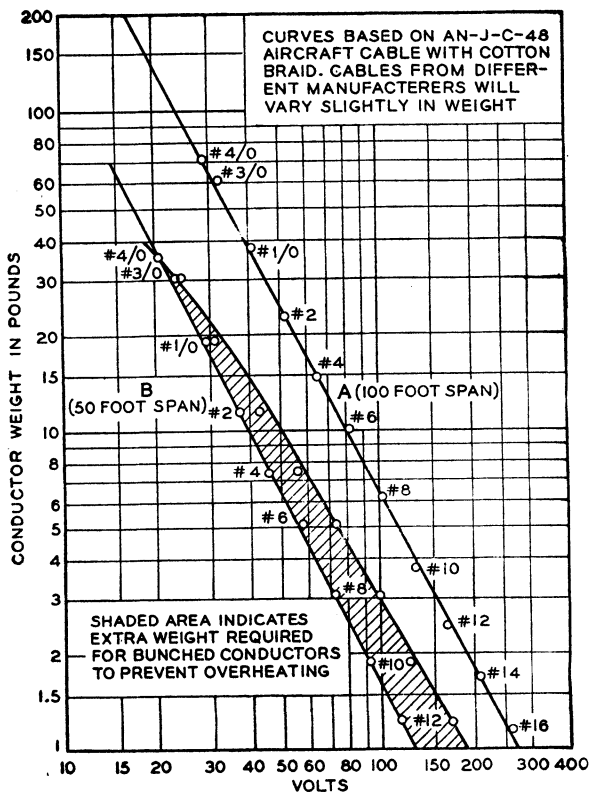


Figure 3  
Conductor Weight to Carry 5 Kilowatts  
with 3 Percent Voltage Regulation

### 211.3 Utilization Equipment Motors

Voltage has relatively little effect on the weight of motors. As is the case with generators, transformers, and in fact, practically all equipment except capacitors, the active material required for a given output at a given speed (or frequency) is substantially independent of voltage. The secondary effects of voltage changes may be greater than for generators because of the greater range in ratings encountered in motors. Small d-c motors may be heavier at high voltages because of the need for fine wires, extra insulation, extra commutator bars, wider brush spacings, and increased creepage distances. A-c motors may also be heavier at high voltages, especially in the smaller sizes which require extremely fine wires. Small wires have relatively poor space factor, both because of the percentage

of insulation and because of the difficulty in winding the turns in uniform layers.

### Lamps

Incandescent lamp characteristics are such that a low voltage for lighting is desirable. Low voltage lamps, up to 28 volts, are inherently stronger, more rugged and slightly more efficient than higher voltage lamps. Where the basic power system is alternating-current it will probably be an advantage to furnish low voltage, preferably 14 volts, for lighting by means of transformers located near the load center. For fluorescent lamps, most satisfactory performance with the size adapted to aircraft service will be obtained with voltages in the range of 120 volts.

### Control

Most control functions are independent of voltage. Some consideration must be given to the magnitude of current to be handled and the voltages to be interrupted (see below).

### Rectifier

Weight increases with voltage approximately at the same rate that rating increases; i.e., two discs carry the same current as one and handle twice the voltage.

### Electronic Control

Usually lighter with increasing voltage. Although 28 volt tubes are available they will handle relatively little power and d-c amplifiers of more than one stage are impractical.

### Power Factor Correction (For a-c systems only)

If static capacitors are used for this purpose, they will be relatively heavy at low voltages. There will be little advantage with increasing voltage after voltage is high enough to stress the dielectric to its safe potential.

### Small Coils for Relays, etc.

Wire size is frequently the limiting factor when voltage is increased on small relays, and may frequently necessitate larger and heavier relays. Creepage distance must be increased as voltage increases. Normally, this is not much of a problem, but it does cause trouble on multi-contact relays since the change on one circuit must be multiplied by the number of circuits.

### Radio

High-voltage systems will permit the operation of radio receivers and low-power transmitters without the use of dynamotors and will save some weight.

### Instruments

High voltages, either a-c or d-c, permit the use of electronic control devices without the added weight of inverters or dynamotors.

## 212. Safety to Operating Personnel

This is difficult to evaluate since the voltage which will cause dangerous or fatal shock varies from less than 100 volts to several thousand volts, according to the conditions of contact. The National Electrical Code for ground installations permit a maximum of 150 volts to ground for circuits where contact with inexperienced personnel is possible. Systems having a voltage of 120 volts to ground, which is the maximum being considered at the present time, are not considered dangerous.

## 213. Installation and Arc Interruption Problems

In general, insulation problems are not difficult at voltages up to 250 volts. For 30 volt equipment, a 500 volt ground test is adequate; for higher voltages, the standard ASA C50 test or double voltage plus 1000 volts is used.

The problems encountered in interruption of current flow are complex functions of both current and voltage. For a given size power system, the available fault current will be reduced as the system voltage is increased. Thus, problems associated with current flow such as the effects of magnetic forces or short-time thermal stresses are less severe for higher voltage systems. The ability of a particular interrupter to interrupt current flow will vary widely depending on construction but some types have the characteristic of being capable of interrupting substantially constant volt amperes over a wide range of voltage. That is, as voltage is increased the interrupting current ability of the device is decreased by the same ratio. However, for widely different voltage levels completely different forms of interrupters may be required. For example, the usual double gap interrupter is usually considered adequate for d-c voltages up to about 30 volts. At higher d-c voltages, other forms of interrupters, such as those which utilize an arc chute to divide the arc into a greater number of increments or the use of pressurized switches or insulating liquid switches, may be considered. Because the current in an a-c line periodically passes through zero, it is usually easier to interrupt alternating current than direct current.

## 214. Advantages of Single Voltage Main System

It is frequently the case that utilization voltages other than would be suitable for the major part of the system load or which cannot be satisfactorily generated and distributed will be required for specific load apparatus. Where there are a number of such loads that require these special voltages, there are possible two basic methods of distributing the special power to the points of utilization:

1. Common special voltage supply unit (forming a second distribution system).

2. Individual special voltage supply unit for each load.

In the first method, power from the main system is fed into a single conversion unit at one point from which it is distributed by a special current distribution system. By the latter method the special voltage is converted by individual units at or near each point of utilization.

Comparison of these two basic methods of supplying the special power on an airplane involves comparisons of weight economy, reliability and maintenance. In general, the advantage is usually in favor of the individual conversion unit for each load rather than the dual supply system.

The reasons are as follows:

1. Weight economy. The dual voltage system involves duplication of equipment for generation, conversion and new distribution. In order to provide reliability for both systems, it is usually necessary to carry reserve capacity on both systems. Duplication of equipment is also encountered in control and supervisory function.

For these reasons, weight economy is usually in favor of the individual supply for each utilization device in spite of the fact that the aggregate weight of the conversion units would exceed that of the units supplying a separate power system.

Further disadvantages of the dual voltage system result from increased complication.

## 220. Factors Affecting Choice of Direct Current or Alternating Current.

### 221. Factors Favorable to Alternating Current

1. Presence of loads requiring alternating current (eliminating the need of inverters)
2. Commutation and brush wear problems
3. Simplicity, and low maintenance of alternating-current motors
4. More favorable for high speed motors due to absence of commutators
5. Voltage flexibility by transformers which are lighter and simpler than direct-current voltage converters.

### 222. Factors Favorable to Direct Current

1. Generators can be driven directly from main engine take-off shafts without variable ratio constant speed transmissions.
2. Paralleling of d-c generators relatively easy.
3. D-c motors are capable of greater peak torques and starting torques than are a-c motors of the same weight.
4. Direct-current motors are more adaptable to speed control.

5. Single wire distribution with ground return and single pole switching possible with direct current on metal structure airplanes.

6. Wiring weight is less at the same voltage because it is not necessary to transmit the reactive kva associated with alternating current at power factors other than unity.

7. Energy storage by use of batteries is possible with direct current.

### 223. General Comparison of Alternating Current and Direct Current

It will be recognized from the above that the choice of alternating current or direct current for a particular airplane will depend upon many factors including weight economics, maintenance and availability of equipment. Of these only weight can usually be quantitatively evaluated although sufficient quantitative analysis can be made of the other factors to indicate trends. The availability of equipment while it may be a major obstacle for short range planning is not so significant for long term projects but there will always be the problem of anticipating sufficient use to justify development of special apparatus.

Probably the most important advantage of direct current over alternating current is the convenience of generating constant voltage with the variable speed generators. Where the main engine drive is used as the prime mover for the electric power, the convenience of a direct-current shunt generator possesses advantage. An alternating-current system from which motors are operated must keep voltage and frequency in direct proportion to each other. Since most other loads require constant voltage, motor loads dictate that frequency must also be constant. As a result either a complicated variable ratio drive or else a separate prime mover must be supplied whenever an alternating-current system is installed.

The outstanding advantage of the alternating-current system arises from its flexibility of voltage by use of the transformer. This factor is especially important where there are many loads which require operating voltages far different from the economical distribution voltage whether it be higher or lower. For example, radar and high-power radio loads require anode voltages far above the maximum permissible distribution voltage. With an alternating-current power supply, these voltages can readily be obtained by the transformer. With a direct-current power supply the higher voltages must be obtained either by rotating dynamotors or by first converting the direct-current power to alternating current and thereafter transforming it. Such arrangements are complex and heavy.

Additional factors which may be considered include the type of airplane and use for which it is to be designed.

(a) *Altitude*—The maximum altitude for which the airplane is designed affects the choice of power supply, particularly if the airplanes and the electric loads are such that voltages higher than 30 volts appear necessary or desirable. In general, the higher the altitude, the more the probability that alternating current will give better operation and lighter weight than direct current, as far as circuit interruption problems at voltages above 100 volts are concerned.

(b) *Loads*—Most loads are adaptable to either alternating-current or direct-current operation. Radar and high-power radio loads require alternating current. It is more efficient and requires less weight to generate alternating current than to convert any large amount of power from direct current to alternating current. Note that constant frequency is not necessary for these loads although constant voltage is. The amount of electric load may also be a factor, since the complication of alternating-current systems may be justified for large-capacity systems more easily than for small systems.

(c) *Size*—Extra large aircraft have long power transmission distances which will usually require a high voltage system. This favors alternating-current operation if other factors are comparable. See Section 213.

(d) *Desirability of parallel operation*—Parallel operation of several generator units is desirable on any airplane, but is much more important on some airplanes than on others. If parallel operation is essential, this will have considerable bearing on the choice. The means to be provided for driving the generators will also have considerable bearing. Direct-current generators may be paralleled easily with any means of drive. Alternators may be paralleled only if speeds are synchronized and provisions made to divide both real and reactive power. Variable-frequency systems cannot usually be operated in parallel.

(e) *Complications of distribution*—The fact that a polyphase alternating-current distribution system is considerably more complicated than a direct-current distribution system should be considered, as well as the fact that copper must be provided to carry reactive circulating current.

(f) *Brush problems*—Altitude brush problems are by no means a major factor in determining the system to use, but all use of brushes requires added maintenance and this is a powerful argument for the use of alternating-current motors. Alternators and exciters require brushes in any

case, but operating conditions are not as severe as they are for most direct-current motors.

(g) *Energy storage*—There is no equivalent to the direct-current battery for storing alternating-current power. Small engine-alternator sets may be provided in place of the battery, but these do not give the instant availability of power given by storage batteries, nor do they operate satisfactorily at altitude. However, batteries are of lesser importance to the direct-current power system than was formerly the case. They are, however, a valuable source of transient and steady-state capacity as well as supplying power of small amounts at times when the major power supply is not in operation.

(h) *Reliability*—Operating experience is not available to compare alternating-current and direct-current systems.

(i) *Maintenance*—Operating experience is not available to compare generator control equipments. Motors will require less maintenance when designed for alternating-current operation. Alternators will probably require slightly less maintenance than direct-current generators.

(j) *Control*—The designer choosing an alternating-current system must be prepared to use more complicated control than would be required for a direct-current system. Most control functions can be handled more simply if direct-current power is used. Evidence is given by the prevailing practice of using direct-current control circuits in power plant practice. Excitation necessarily requires direct-current power, and most magnetic devices operate better if designed for direct-current operation.

The following are to be considered in this connection:

(a) *Circuit breakers*—Direct-current control coils are contemplated even when arc systems are to be used. Arc interrupting is easier with alternating current than with direct current.

(b) *Speed control*—Required only for alternating-current systems operating at constant frequency.

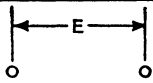
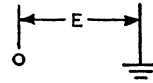
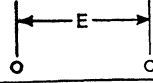
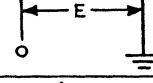
(c) *Electronic controls* — Alternating current makes it possible to get desired operating voltages.

(d) *Voltage regulators* — Alternating-current regulators require rectifiers, adding to complications. Wave form is a factor in the operation of the regulators. Equalizing circuits for alternating-current regulators are more complicated than for direct-current regulators.

(e) *Excitation*—Must always be direct current.

A comparison of alternating-current and direct-current systems useful in weight evaluations is shown in Fig. 4. Note that in this comparison alternating current differs mostly from direct current by the fact that alternating current requires transmission of reactive volt amperes. For the same power transmitted to the load a higher current is normally experienced for most loads with alternating current due to a power factor of less than unity. Note that single phase and 3 phase alternating-current systems are comparable providing the single phase supply voltage is compared to the phase-to-neutral voltage of the 3 phase system.

FIG. 4  
COMPARISON OF POWER SYSTEMS

| SYSTEM                  | CONFIGURATION                                                                       | NO. OF CABLES | POWER TRANSMITTED      | RELATIVE CONDUCTOR WEIGHT* |
|-------------------------|-------------------------------------------------------------------------------------|---------------|------------------------|----------------------------|
| DC—2 wire.....          |  | 2             | $EI$                   | $2/E$                      |
| DC—Grounded.....        |  | 1             | $EI$                   | $1/E$                      |
| AC—1 Phase, 2 wire..... |  | 2             | $EI \cdot PF$          | $\frac{2}{E \cdot PF}$     |
| AC—1 Phase, Grounded..  |  | 1             | $EI \cdot PF$          | $\frac{1}{E \cdot PF}$     |
| AC—3 Phase.....         |  | 3             | $\sqrt{3} EI \cdot PF$ | $\frac{1.73}{E \cdot PF}$  |

\*Varies somewhat due to conductor insulation and allowable current density.  $PF = \text{Power Factor} = \frac{KW}{KVA}$

#### 224. Factors Affecting Choice of Frequency

The selection of frequency depends to a large extent upon the type of utilization equipment used in the airplane. In general, selection should be made for minimum weight of the entire electric system which will provide satisfactory performance. It is desirable to operate motors at high speeds, up to the limits of good bearing performance, since this tends to minimize equipment weight even when reduction gears are required. The frequency should be high enough to permit motor speeds in the order of 8000 to 12,000 rpm and yet not so high as to require at such speeds too many motor poles for efficient motor design. Much of the direct-current motor driven apparatus used on present day aircraft is designed for motor speeds of 8000 rpm. This has been found satisfactory for continuous operation of grease packed ball bearings. For intermittent operation, grease packed ball bearings in small sizes operate satisfactorily up to 12,000 rpm. It is desirable to utilize these same speeds insofar as possible to avoid unnecessary redesign of gear reduction mechanisms and to make use of maximum speed permitted by practical bearing design. It is desirable, therefore, to select a frequency which will provide these speeds.

The frequency should be selected so that speeds up to 24,000 rpm are not ruled out since such speeds may be desired for lightweight turbo-alternators which hold promise for the future. Such machines would probably be designed with oil pressure lubrication on the bearings which is feasible. Again, certain gyroscopic instruments may require speeds of this order.

For motors which are not geared, the frequency should be such that at least the majority of these motors can be designed with a number of poles (preferably four, six or eight) which will result in the required speed with an efficient, lightweight design. The frequency should be high enough so that a sufficient number of speed steps are available in the desired motor speed range to permit flexibility in application, yet without requiring an excessive number of poles.

Iron core transformers become lighter with increasing frequency within practical limits so that this becomes a consideration in applications.

High frequency reduces the size of capacitors (in microfarads) necessary to accomplish power factor correction, but increases dielectric losses at the same time.

Filter components for radio are smaller at high frequencies although inductive pick-up effects may be increased.

Instruments such as synchroties and position

indicators are smaller and lighter at high frequencies.

Tuning fork control of frequency is more practical at 400 cycles and higher than at lower frequencies, and has been considered for some instrument requirements.

If too high a frequency is used, skin effect in conductors, eddy current and penetration effects in iron cores increases the weights of wiring and equipment. Except for frequencies well above 400 cycles, however, these effects are not significant for most wire sizes and equipment designed for use in aircraft. For example, for all wire sizes equal to or smaller than AN-8, the skin and proximity effects at 400 cycles increase weight and losses by less than 1 percent. This includes the majority of wires on the 208Y/120 volt system now contemplated. For larger wire sizes, skin and proximity effects increase considerably. Thus for AN-0 it is 11 percent and for AN-0000 it is 30 percent at 400 cycles. These figures are based on minimum practical spacings with insulated aircraft cables.

#### 230. Automatic Protection Principles

##### 231. General

231.1 To prevent dangerous or abusive service

231.11 Use of electric interlocks

231.111 To limit travel

231.112 To block operation if improper conditions exist

231.113 To secure a prearranged sequence of operation

231.114 To insert a definite time delay between successive operations

231.2 To prevent excessive temperature in machines or circuits

231.21 Current-time facsimile thermal units

231.22 Direct temperature responsive units

231.23 Combination direct-facsimile units

231.24 By manual supervision

231.25 Others

231.3 To protect against electrical faults which may result in: disruption of complete power system, damage to power switching equipment in service at the time, extensive burning and splattering of molten metal at the fault location, damage to nearby equipment (non-electric as well as electric), injury to personnel

231.31 Means of fault detection and degree of discrimination between healthy and faulty circuit operation

231.32 Means of securing rapid fault isolation so as to:

**231.321** Minimize the disturbance to the main system

**231.322** Insure that electric-system collapse is not induced

**231.323** Result in minimum burning and metal splash

**231.324** Promptly de-energize the faulty member to avoid recurrent fault-current flow due to vibration or movement of personnel

**231.4** Application of manual override

**231.41** To thermal protector operation

**231.411** Should be used with caution. Operator is a poor judge of degree of distress. To force the machine or circuit to failure is destructive and accomplishes no useful result

**231.412** Temperature limits are not critical boundaries but represent an economical balance between working stress and equipment life

**231.413** Some electrically operated functions are of the most vital character and may warrant manual bypassing of thermal protective function

**231.42** To fault protector operation

**231.421** Extensive damage may result from fault-current flow of one second duration

**231.422** Operator is incapable of responding in time intervals of such short duration

**231.423** Must be regarded as dangerous and to be avoided

**231.424** Manual reset of a tripfree circuit breaker does not override protection and can be permitted

**232. Generator Circuits Application**

**232.1** Cut-in—Cut-out switching

**232.11** Absolute voltage controlled cut-in

**232.12** Differential voltage controlled cut-in

**232.13** Factors influencing cut-out point

**232.2** Avoiding thermal distress

**232.21** Service variation in cooling air flow

**232.22** Manual supervision

**232.221** Individual ammeters

**232.222** Temperature indicators or thermal alarm

**232.24** How accomplished

**232.3** Fault protection

**232.31** Methods of detection

**232.32**

**232.33**

**233. Power Bus Application**

**233.1** Fault protection predominately

**233.2** Comparative merits of various protective methods

**234. Transmission Circuit Application**

**234.1** Thermal protection

**234.11** In a multiple channel mesh network automatic trip-out of one channel may initiate a chain of successive trip-outs which would be fatal

**234.2** Fault protection

**234.21** Comparative merits of various protective methods

**235. Unit Load Circuit Application**

**235.1** Thermal protection

**235.11** Representative characteristics

**235.12** Independent self-resetting thermal protector in load unit.

**235.13** Thermal relay in load machine operating on a remote power switching device

**235.14** Use of facsimile thermal relays

**235.15** Methods of indicating operation

**235.2** Fault protection

**236. Auxiliary-Circuit Application**

**236.1** Protection problems involved in control power circuits, instrument circuits, etc.

**240. Unit Load Application Objectives**

**241.** Adequately meet the requirements of the end service.

**242.** Be most economical of weight and space.

**243.** Incorporate simplicity—installation, operation, maintenance.

**244.** Make use of one common type and voltage of power supply, insofar as possible.

**250. Nature of Individual Load Electrical Behavior**

**251. Starting (or initial) Current-Voltage Relation**

**251.1** Loads which exhibit high in-rush demands

**251.11** Motors

**251.12** Incandescent lamps

**251.13** Others

**251.2** Means of artificial reduction

**251.3** Duration

**251.31** Normal

**251.32** Maximum

**252. Steady-State Running Current-Voltage Relation**

**252.1** Normal voltage operation

**252.11** Constant load

**252.12** Variable load

**252.2** Subnormal voltage operation

**252.22** Constant resistance character

**252.23** Constant current character

252.24 Constant power character

**253. Transient Running Current-Voltage Relation**

253.1 Behavior becomes rational when expressed as a *change* in current associated with a given change in voltage.

253.2 Typical classifications

253.21 Static constant impedance circuits

253.22 Static impedance circuits in which impedance is variable as a function of time or temperature

253.23 Rotating machines—series excitation  
Rotating machines—shunt excitation

**260. Electric Connections and Terminations**

261. Function is to allow separation of conductor at desired points, yet operate normally as a single continuous cable

**262. Individual Conductor Splices**

262.1 Soldered or welded

262.2 Pressure connectors

262.3 Separable connectors

**263. Banked Conductor Junctions**

263.1 Strip terminal blocks

263.2 AN connectors

264. Limitations as to current-carrying capacity.

265. Limitations as to low contact drop in circuits sensitive to voltage drop

266. Limitations relative to number and size of pins in AN connectors

267. Use of silver faced contact surfaces

268. Importance of pressure on contact surface

269. Effect of vibration and corrosion

**270. Cable Installation Practice**

271. Separate complimentary power channels

272. Take full advantage of protection afforded by structural members of airplane

273. Avoid large concentration of cables at any one spot

**274. Cable Grouping in Bundles**

274.1 Reasonable number of cables per bundle

274.2 Run interdependent cables in one bundle

274.3 Advantages of keeping main power cables separate

274.4 Use of quick-open supports.

274.5 Avoid awkward paths through structure latticework

274.6 Thermal effects of bundling loaded cables

**275. Use of Conduit**

275.1 To facilitate replacement

275.2 To protect against mechanical damage

275.3 To provide radio shielding

276. Use of metallic armor

**300. POWER EQUIPMENT CHARACTERISTICS**

**310. Aircraft Generators**

Aircraft generators resemble large industrial machines built in miniature and operated at extremely high overloads. Cost considerations are primarily based on weight; the economics of aircraft operation are such that almost any expense may be justified if it will reduce the weight, but performance and reliability are also important factors. Existing generators, however, attest to the fundamental reasonableness of conventional electrical construction. Freak ideas have no place in generator design; only old and well-tried principles, ingeniously applied, appear to accomplish much toward weight reduction.<sup>1,5,7</sup>

Fan-cooled machines are equipped with an internal fan, attached to and rotating with the rotor. Air flow is over the commutator or slip rings and axially through the machine. The use of main-engine-driven fan-cooled generators is limited to low altitudes and smaller machines, since the air available for cooling the generator is circulated through the generator from the already warm engine accessory compartment, so that the temperature of the available cooling air is usually too high for effective cooling. This condition grows progressively worse as the weight of air passing through the generator decreases with increased altitude.

Main-engine-driven blast-cooled generators are cooled by bringing blast air from the propeller and/or forward motion of the airplane through a tube to the commutator or slip ring end of the generator. The cooling air passes through the generator and is exhausted into the engine accessory compartment. Installations are being considered, however, wherein the air is taken from the generator through an exhaust tube to a low-pressure area to aid the air flow. In special cases of jet aircraft, the generator itself has been located in a high-pressure area, no blast tube has been used, and blast effect was obtained by exhausting air through the generator to a low-pressure section of the jet engine.

Auxiliary engine-driven generators are usually of the fan-cooled type or are designed for blast cooling and main-engine use adapted for use on auxiliary engines. If the blast-cooled type is used, cooling air is usually bled from the engine cooling system. Unless the engine is supercharged, fan cooling is sufficient since the resultant decrease in generator capacity at altitude is matched by a similar decrease in the rating of the engine.

### 311. Normal Rating

In aircraft generators as in other electric machinery, the limiting factor in rating of the machine is temperature. Because of the importance of weight, it would be expected that special high-temperature insulation would be required, but Class B insulation is generally used because of its better mechanical properties. For the relatively short design life for airborne equipment, Class B insulation may be operated at maximum continuous temperature of 150C to 160C. However, usual specifications prescribe no limit on operating temperature requiring only that the generator meet the specified requirements for operating life.

The normal continuous rating of an aircraft generator at sea level is that current or kva which will produce a temperature that will result in satisfactory life with satisfactory commutation for direct-current machines at a specified terminal voltage over a specified speed range under specified conditions of cooling. Temperatures of shunt and series windings and brushes are determined during test. Commutation is also observed as a load-limiting factor and should be such that satisfactory brush and commutator life will be obtained. Brush and commutator wear in properly designed direct-current and alternating-current machines is generally a function of both brush grade and load, and the selection of the proper brush grade depends largely on expected operation conditions (whether at low or high altitude). In high-temperature machines, commutator risers are usually brazed to armature conductors to avoid throwing solder at high loads.

The continuous rating of the same generator at altitude<sup>3,9</sup> is approached from the standpoint of determining the load required at various altitudes under specified conditions of cooling to give the same total temperature. This approach leads to the permissible output of the generator for constant insulation life at all altitudes.

For fan-cooled generators, the specified conditions of cooling are given by stating the ambient temperature and the density of the air in which the machine is operating. Ambient air temperature for main-engine-driven generators is more a function of nacelle design than outside air tem-

perature. Nacelle air temperatures are generally quite high (20C to 40C). As air density decreases with increasing altitude, the effective cooling decreases, and at approximately 20,000 feet altitude, most fan-cooled generators are rated at zero output, the cooling being only enough to dissipate the losses of the machine itself.

In the case of blast-cooled generators, ambient air temperature becomes unimportant, and blast air pressure and temperature determine the amount of cooling. Since these factors vary widely between different airplanes and flight conditions, a usable rating for such a machine is somewhat difficult to determine. Furthermore, the amount of blast air and the temperature of blast air available to the generator in a given airplane is not always known for the various flight conditions. However, when applying a generator to an airplane, the capacity of the generator at the cooling air conditions which will exist in the airplane at the various flight conditions should be determined.<sup>9</sup> Ambient air temperature and density at various altitudes are specified by AAF and NACA standards and methods. Methods giving approximate capacities of machines at various amounts and temperatures of blast air referenced to a known rating are used by most generator manufacturers, although actual tests are to be preferred for accurate results. Consideration should also be given to the temperature rise of the blast air from the outside air temperature due either to an adiabatic change or heating from sources external to the blast tube.

Internal fans alone, as already stated, do not provide enough ventilation to make generators satisfactory above 20,000 feet. However, the use of an internal fan in a blast-cooled generator will provide some ground power capacity, but this additional ground capacity may be gained by increasing the weight and overhung moment of the generator to include the fan.

### 312. Overload Capacity

Overload requirements cover short-time ratings which tend to increase machine temperature above safe limits, but because of the short time involved and the thermal inertia of the machine do not dangerously reduce machine life. The short time required may also permit poorer commutation in direct-current machines during overload.

#### 312.1 Typical Requirements

Typical overload requirements for alternating-current machines are 150 percent rated load for five minutes and 200 percent rated load for five seconds. For direct-current machines a typical overload rating is 150 percent for two minutes. Usually the generator must meet the above or

similar requirements over the specified speed range after having reached terminal temperature at full load if a variable-speed machine, but in some cases the overload requirement may be waived at low speeds. Since overload requirements sometimes govern size of machine and prime mover, care should be exercised in specifying such requirements.

### 312.2 Thermal Limits

The thermal ability of the generator to supply overload current varies widely with operating speed of a variable-speed machine and is also affected by initial winding temperatures. A constant-speed machine may be inherently self-protecting in that increased temperature of the machine will result in reduced excitation and ability of the machine to produce overload. This inherent self-protection feature may also be present at low speed in a variable-speed machine, but at higher speeds overloads of several hundred percent of full-load rating may be carried continuously and the reduction in excitation due to high temperature will reduce the overload only slightly. Under such conditions, dangerous temperatures may be encountered and the generator user must choose between no protection against this contingency and the inclusion of an overload protection element in the generator controls which may operate a warning device or automatically operate to reduce load on the generator.

### 312.3 Volt-Ampere Limit

The maximum power which a direct-current generator will supply is shown by the volt-ampere or external characteristic of the generator (Fig. 5). The volt-ampere characteristic varies with speed and the resistance in the shunt field circuit. The volt-ampere characteristic is frequently obtained largely from calculated data using measured no-load voltages and armature circuit resistances at some given machine temperature to obtain the points that require generator operation at dangerous temperatures or require power in excess of limits of test equipment. It should be noted that the power outputs defined by the volt-ampere characteristic at higher-than-minimum rated speed will result in overheating.

### 313. Operation under Subnormal Conditions

Some operating conditions of the airplane may require that the generator provide power at less than rated speed and/or less than rated ventilation. Such requirements are especially severe when imposed under emergency conditions; i.e., when part of the generating system is not in operation and the remaining unit or units must supply more than their normal share of load.

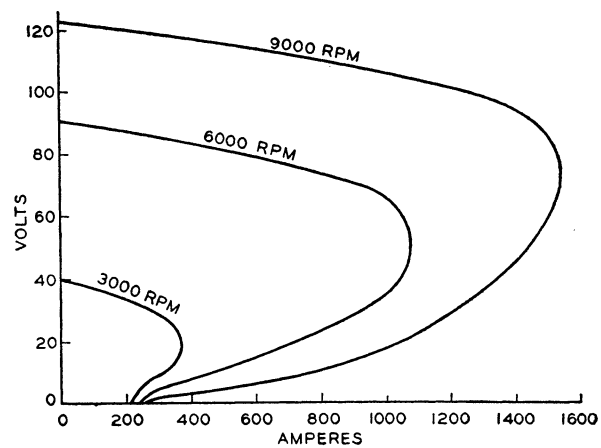


**Figure 5**  
**Volt-Ampere Characteristic**  
**300 Ampere 30 Volt Generator**  
 $\frac{3}{4} \Omega$  in Field Circuit

### 313.1 Subnormal Ventilation

A blast-cooled generator may be required to supply power at less than normal ventilation, particularly when the airplane is taxiing or when the engines are operating with the airplane stationary, in which case the blast air must come from propeller blast alone. The amount of blast air available in such cases is usually 10 to 25 percent of rated cooling air, and the continuous power available from the generator is approximately 50 to 80 percent of rated power at rated cooling air. More power may be available for a short time, but this must be considered an overload short-time condition. (See Figure 13 where rated cooling is at 6 inches of water total head.)

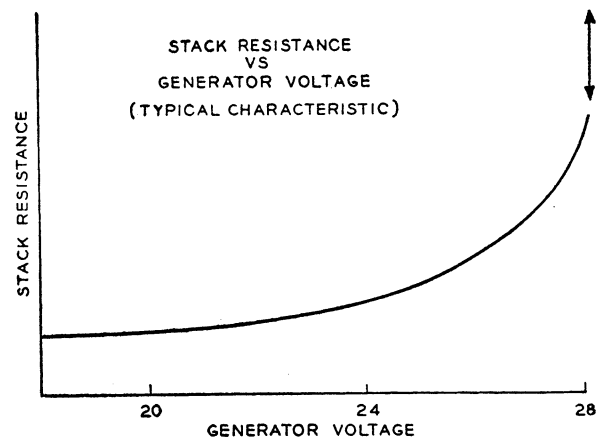


**Figure 6**  
**Newton Type Carbon-Pile Voltage Regulator**  
**28 Volt Rating**

### 313.2 Subnormal Speed

During ground operation, a direct-current generator may be required to supply power at less than rated speed. If the resistance in series with the shunt field is a fixed value, the current available at a given voltage will decrease linearly with speed. In most cases high performance generators are controlled by carbon-pile voltage regulators and the resistance inserted in the field circuit decreases as the terminal voltage drops below normal value, as shown in Figure 6. The result of this resistance variation and operation at speeds below rated speed is shown in Figure 7.

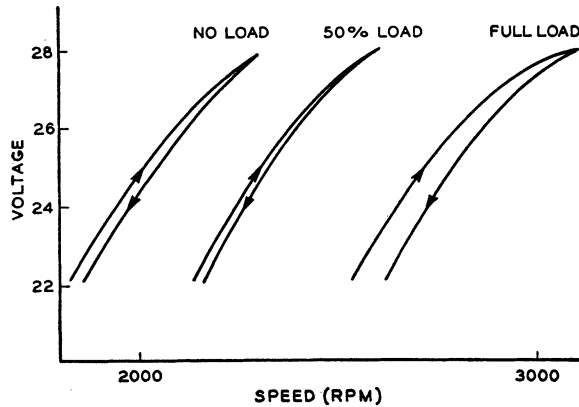


**Figure 7**  
Load versus Speed Curves  
30 Volt Aircraft Generator (3000-9000 RPM)  
with Carbon-Pile Regulator  
(Rated Cooling on Generator)

### 314. Load Pick-Up and Short-Circuit Currents

The imposition of a shock load on a direct-current generator results in an initial peak current followed by a steady-state value of current and voltage determined by the generator external or volt-ampere characteristic. Oscillograms at various generator speeds and at various values of load are shown in Figures 9 and 10. The initial peak

current and its associated terminal voltage may be determined for any load by the use of the generator "transient" volt-ampere characteristic. This "transient" characteristic may be derived from the curves of Figures 9 and 10 and can be simulated by assuming the presence of an internal resistance equal to  $\Delta E / \Delta I$  (Fig. 8) which is equal to armature circuit resistance plus a component which is a function of generator speed. Thus the transient resistance is a fictitious value of resistance considerably greater than real armature resistance and dependent on generator speed. This fictitious resistance may be used to calculate maximum system short-circuit currents for selecting interrupting devices. The initial peak current is reached approximately 0.01 second following imposition of the load, and the transition from the initial peak current value to the steady-state value has been observed to fall consistently in the region of 0.05 to 0.10 second. The steady-state value will be maintained for a period dependent on the thermal ability of the generator.

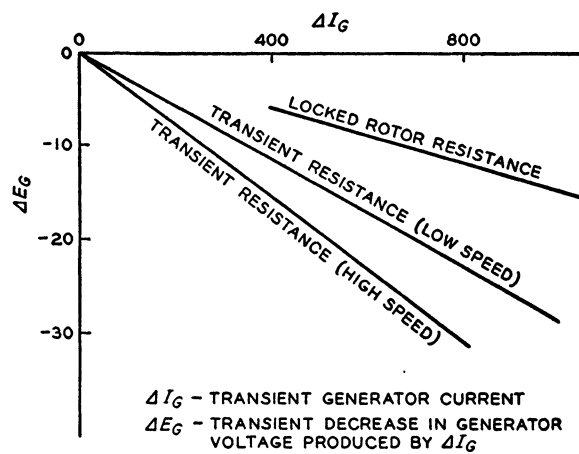


**Figure 8**  
Transient Volt-Ampere Characteristic  
Direct-Current Aircraft Generator