

Report on
**AIRCRAFT and MISSILES
ELECTRIC SYSTEMS GUIDE**

Sections 500 and 800

*One of several parts
(See Preface)*

(Published for trial use)



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PREFACE

Purpose

The purpose of this document is to provide in compact form recommendations and technical reasons for the selection, design, and application of aircraft electric systems and electrically-actuated load equipment, without going into specific detailed designs. It forms a fitting companion reference document to the "Design Manual on Aircraft Electrical Installations" put out by the Aircraft Industries Association, in that the latter stresses specific application and installation practices with a minimum of technical explanation.

Form

This pamphlet is one of a series comprising the Report on Aircraft and Missiles Electric Systems Guide, and has been so printed in order to allow for more convenient revision and addition of Sections as available without necessitating a reprint of the entire Guide.

As of the time of printing this pamphlet the available Sections are:

No. 750.1—Sections 000 — Introduction
100 — Criteria for the Electric System
200 — Principal Subdivisions of Electric System
300 — Selection of the System

No. 750.4—Section 400 — Installation Practices

No. 750.5—Sections 500 — Equipment Characteristics
800 — Electric System Design Procedures

No. 750.11—Appendices I — Characteristics of Alternating-Current Generators
Affecting Their Application
II — Distribution System Design
III — Symmetrical Components

Acknowledgment

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Aircraft and Missiles Electric Systems Guide

500-EQUIPMENT CHARACTERISTICS

510 FLIGHT VEHICLE GENERATORS

Flight vehicle generators are designed and built to obtain the greatest possible output for their weight. The economies of operation justify almost any expense to reduce weight. This minimum weight is obtained by careful design and development, to the end that the maximum capabilities of all parts, electric, magnetic, insulating and mechanical, are realized. Forced ventilation or other special cooling means permit compact designs. Required life is far less than in industrial equipment, one thousand hours being a common requirement. This allows operation of the generator insulation at a higher temperature level, giving high output with relatively small size and light weight, consistent with the reliability requirements of the installation.

Figure 510-1 shows presently-available sizes of constant-frequency three-phase aircraft generators.

Reliability is the vital requirement. The vehicle and the lives of the people it may carry depend to an increasing extent upon the electric system, as does the mission which the vehicle is required to complete. Electric power may be used to operate the control surfaces, so that an electrical failure might render the vehicle unflyable. Reliability comes from sound design, careful manufacture, thorough inspection, sound application, proper installation, and correct maintenance.

511 Mechanical Considerations

Mechanical and electrical considerations are intimately related in the design of generators. Certain aspects of mechanical design are especially significant in the application of the generators and warrant discussion here. The many and severe vibrations of large reciprocating engines results in a difficult design problem. The acoustic noise of jet engines causes severe vibration, extending to higher frequencies. Both high- and low-frequency vibrations are prevalent on turbo-prop installations. In all cases, acceleration loads resulting from maneuvering and aerodynamic flutter and turbulence must be considered. When generators are driven by hydraulic or pneumatic constant-speed drives, or by an auxiliary engine or gas turbine, special problems of torsional resonance near the natural frequency of the governor may be encountered.

511.1 Mounting

The mounting-flange dimensions have been standardized by military specifications. Design strength, however, will vary depending on the type of service expected of it. Thus aluminum might be used for the mounting flange on a turbine engine, while the same generator must be built with a steel flange for large reciprocating engines.

511.11 The accessory drives of some engines are so crowded that special provisions are necessary to make it possible to replace a generator without disassem-

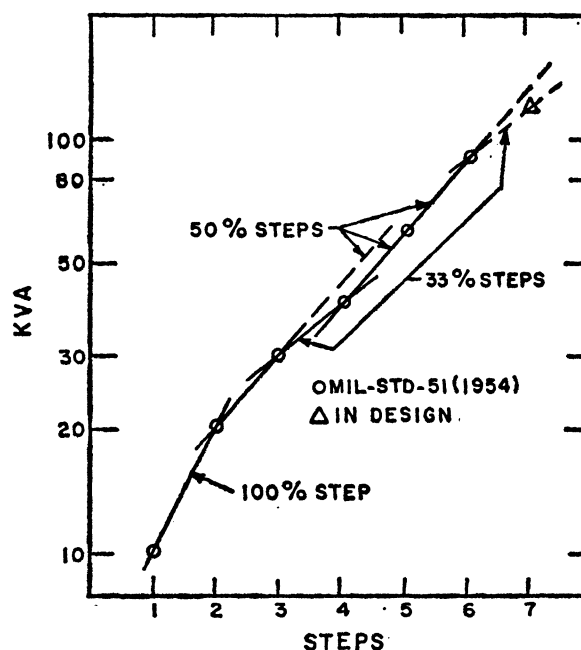


Figure 510-1 Standard Alternating-Current Generator Ratings.

bling much of the engine. This is especially true in some jet engines that pack two tiers of accessories in the nose cone. A simple design to ease the mounting problem is the "button-hole" which permits the generator to be removed by a slight rotation of the flange after the holding nuts are merely loosened. More elaborate quick-attach-detach (QAD) mounts are available that do not require accessibility to any of the mounting nuts, but only to one clamping ring nut which may be located in a position which is easy to reach.

511.2 Natural Frequency

The natural frequency of the entire generator should be well above the worst vibration frequencies of the engine or engine-propeller combination by which it is driven. When the generator is driven by an auxiliary engine or constant-speed drive, the generator torsional natural frequency should be well above the natural frequency of the speed governor. Pernicious cases of frequency and voltage modulation with such drives have been solved by raising the generator natural frequency to a value three or four times higher than the governor natural frequency.

511.3 Drive Shaft

Resilient couplings are generally incorporated in generators for use on reciprocating engines or auxiliary power units to absorb a large part of the torsional

vibration of the engine. This often takes the form of a long inner "quill" shaft which extends from the engine takeoff drive to the opposite end through the hollow outer shaft. The inner shaft is resilient, due to its long length, it is free to twist. This resiliency may introduce other vibration modes, especially in paralleled-generator systems.

In addition, some other means of coping with the torsional vibration of the engine may be necessary. This can take the form of a friction damper, consisting of some form of metal surfaces held together by spring force. One (or more) surface is fixed relative to the rotor of the generator and the other(s) to the input shaft, so that torsional oscillation in the resilient coupling results in rubbing of the surfaces, thereby absorbing energy and preventing build up to large amplitude.

The "clearance" drive has been very successful in some applications. It involves a rotational dead band that is relatively large compared to the amplitude of the torsional vibration experienced. Therefore the torsional impulses are not transmitted regularly and resonance does not occur.

Turbine-engine applications are not necessarily free of torsional vibration problems, as the vibration can be induced by the electric system, especially in systems involving paralleled generators. Transient loads can excite an unstable governor or initiate lightly damped shaft torsional oscillations, resulting in voltage and frequency modulation.

511.4 Bearings

Aircraft generators generally have grease-packed sealed-type ball bearings, with no provision for addition of lubricant. Bearing life is usually that specified for the generator, or at least for generator life-to-overhaul. Aircraft generator bearings should be handled with care. Bearings that have been pulled off a shaft by the outer race may have brinnelled races and should not be reused. For high-temperature applications, special bearings and greases may be required. For very high speeds, oil lubrication may be used.

The pressure differential across a bearing should be very low, otherwise grease will be forced out of the bearing. In some cases, the drive-end bearing must be protected by holes through the mounting flange to equalize pressure.

Considerable difficulty has been experienced in bearing application design because of difference in the expansion of the shaft and the end bell, resulting in pinching of the balls of the bearing. This is caused by two factors:

- a. Difference in the temperatures of the shaft and end bell; the shaft is heated by the rotor, with very little cooling surface on the shaft, while the portion of the end bell at the bearing is fairly remote from the heat sources and may be well cooled.
- b. Differences in expansion coefficients of the shaft and end bell. The shaft is generally steel, and the end bell may be made of magnesium or aluminum.

The former problem requires very careful consideration of bearing fits and clearances. The latter problem can generally be solved by using steel inserts in the bearing housing of the end bell which are sturdy enough to absorb the differential compressive loading due to temperature changes, or by use of tangential supports which rotate the bearing housing instead of compressing it.

512 Cooling Methods

Forced air cooling is used on aircraft generators to increase the watts that may be dissipated per pound of installed equipment, and thereby greatly reduce the weight of a generator of a given output rating. The balance between the machine rating and the pounds of cooling air per minute required is affected by:

- a. The temperature and density of the cooling air.
- b. The maximum safe temperatures in the machine.
- c. The heat transfer characteristics.
- d. The machine efficiency (since this controls the losses which must be dissipated for a given power output).
- e. Efficiency of air distribution within the machine.

A consideration of these factors has led to the establishment of the requirements of Figure 3 of MIL-G-6162 which is based on sea level conditions.

High altitudes and high speeds are becoming more and more of a problem in cooling of equipment:

- a. Higher speeds result in greater ram rise in temperature of the cooling air, so that the cooling is less effective.
- b. Lower densities make necessary very high volume of flow to get enough cooling air through the equipment.
- c. Heat transfer characteristics vary with the density and rate-of-flow of the air over the cooling surfaces.
- d. Higher air velocities through the machines may change the distribution of the airflow through the various air passages through the machine.

The type of cooling system acceptable to the particular vehicle and its mission will determine the method to be used in the generator. The generator must be designed to meet the needs of the vehicle.

512.1 Fan Cooling

Fan-cooled machines are equipped with an integral fan, this is usually attached to and rotates with the rotor. Air flow is directed over the commutator and slip rings and axially through the machine, discharge air should be baffled to prevent it from re-entering the air intake. Air in the compartment from which air is taken should be as cool as possible. The use of fan-cooled generators is limited to small machines and low altitudes, unless this cooling method is supplemented by use of ram air, or the loads are of extremely short duration.

512.2 Blast Cooling

This is the most common system at present. Genera-

tors are arranged so that a difference in pressure exists between the two ends of the machine. Usually air enters at the slip-ring or commutator end, passes over the brushes and the windings of the machine, and then exhausts at the drive end.

Ducting is generally required at one or both ends of the machine to establish this difference in pressure. Inlet ducting, connected to the generator through a "blast cap," may be run to a high-pressure area, such as a scoop to pick up ram-air pressure due to speed of the airplane. Bleed from the compressor of a turbojet engine offers another convenient source of high pressure. This compressor bleed air must, however, be cooled for use; this is generally done by using it to do work in an expansion turbine. Exhaust shrouds may be used around the drive end of the generator to gather the exhaust air into a duct leading to a low-pressure area. This might be on the surface of the wing, in the intake to a turbine engine, or elsewhere. The combination of high-pressure and low-pressure areas and ducting used will be determined by the airplane, the engine configuration, and the type of engine. Whatever the source of air, it must be of the proper temperature, pressure differential, and quantity. In cases where the generator has not been designed with inherent protection against moisture, it may be necessary to provide for removal of excess moisture from the air. Excess moisture has caused unstable commutation and exciter polarity reversal in some generators.

The quantity of cooling air passing through the generator will depend on the difference in pressure in the openings of the intake and exhaust ducts, the pressure-loss characteristics of the ducts, the density of the air, and the characteristics of the generator. The above factors are affected by the speed and altitude of flight, the temperature of the air, etc. The particular airplane configuration is very important. Some installations have encountered zero or reversed air flow under certain operational conditions.

Fans are sometimes built into blast-cooled generators to aid in cooling during operation on the ground. These must be used with great caution, as they tend to exhibit constant-volume characteristics, and are very apt to restrict the flow of air at altitude, where the volume for a given mass is very much increased.

The rotors exhibit some of the characteristics of a fan—sometimes in the wrong direction. The speed of rotation may increase or decrease the flow of air—or it may have little effect on the air flow—depending on the effective fan action of the rotor and/or the presence of a fan.

Usually the generator has been built to a detailed specification that specifies the duct configuration and pressure head to be used in the evaluation of the machine. In the actual installation, pressure differential as well as temperature and density may be considerably different, and the effect on generator output must be evaluated as discussed below under "Rating", Section 513.

At transonic and higher speeds, the ram-air pressure

available is so high that special measures may be necessary to prevent damage to the generator or faulty operation. Such effects may include expulsion of grease from bearings, disturbance or breakage of brushes, rain erosion, or other results. The generator manufacturer should be consulted on such applications.

512.3 Cooled Air

Air obtained from a turbine-engine compressor may be too hot for effective cooling. This same condition may arise in high-speed planes using ram-air inlets. As the pressure in these cases is also usually higher than required by the generator, an expansion turbine may be used to reduce the temperature by extracting energy from the air. Shaft work might be utilized to drive a blower on the exhaust side of the generator.

Air may be cooled by spraying water into it. This might especially serve for an airplane flying at low enough speeds for direct ram cooling most of the time, with water sprayed into the air during the short periods of high-speed flight.

High-speed planes may require refrigerated air for the pilot and for certain electronic equipment. After use for these purposes it may still be cool enough to be suitable for generator cooling, but allowances should be made for possible reduction of cooling effect caused by changes in the cooling circuit.

512.4 Expendable Coolant

The high heat of vaporization of some fluids, especially water, allows a large quantity of heat to be removed by the evaporation of a relatively small weight of fluid. This may be done by jacketing the generator, or by introducing the fluid to the heat generating parts of the machine. The vapor is allowed to escape. This is especially applicable to missiles and other short-time flights; on flights of long duration, expendable coolants may not offer any weight saving. This will depend on the relative cost in performance of obtaining ram air for cooling. As flight altitudes increase, the use of expendable coolants will become more attractive because the equipment can be made to be relatively independent of ambient air conditions.

512.5 Liquid Cooling

There are several sources of coolant liquids that might be used for generators. The airplane may have a recirculating refrigerant system for cooling the crew and electronic equipment. Some additional heat load from the generator might require relatively little additional weight. Or the generator might be provided with cool oil from the engine oil-cooling system.

Especially on turbine engines, the fuel may be a heat sink of large capacity. Under high-speed flight conditions, when ram cooling is least effective, the fuel flow is very high and would be able to absorb all generator losses. Use of a heat exchanger may be desirable instead of passing fuel through the generator.

513 Rating

The rating of a generator depends on many factors which must be appreciated and evaluated by the user. These are imposed by the wide range of operating conditions inherent in flight vehicle operation. There are limitations arising from the necessity of designing for minimum weight. There are considerations of desired life and of duty cycles. All this makes rating a subject worthy of thorough study by those concerned with flight-vehicle generators.

Because the engineer is faced with the problem of adapting standard machines to non-standard conditions, it is very important that the manufacturer be prepared to furnish him with sufficient performance data to enable him to analyze properly the provisions he must make to meet the peculiar problems of his application. The desired types of data are listed in Section 519.

513.1 Factors Limiting the Rating

In generators, as in other electric machinery, temperature limitations of the insulation limit the rating of the machine. Nevertheless, the relatively short design life permits higher temperatures. Furthermore, specifications call for performance rather than specifying operating temperatures. Solder used to make connections, or for balancing, may set a temperature limit. Because of this, silver solder or brazing is often used for connections where high temperatures will be encountered.

Commutation in direct-current machines is a load-limiting factor. Even though adequate cooling may be available to insure low temperatures, the output cannot exceed what may be commutated without producing sparking severe enough to cause progressive deterioration of the commutator surface or shifting of the commutator bars. Brush life also is affected by load current.

A generator cannot handle equally well a given load at all speeds. Operation at low speeds may be limited by flux and by field excitation or field heating. Operation at high speeds involves increased commutator losses in a direct-current generator, and in some blast-cooled machines there may be a reduction in air flow due to adverse fan effects. Therefore, wide-speed-range generators often are not capable of continuous operation at rated load over the speed range, but instead are rated for continuous operation at approximately average speed.

513.2 Altitude Rating

The continuous rating of a blast-cooled generator at altitude is approached from the standpoint of determining the loads at various mass flows of air through the generator and various air temperatures which will give the same total temperature in the generator as will normal rated load at sea level under rated cooling conditions at the same generator speed. The mass flow of air is a function of the air density (altitude), of the pressure differential, and of the air-flow resistance of the machine. It should be noted that this air-flow resistance varies with altitude and volume flow, especially in machines with internal fans. This approach leads to the permissible output

of the generator for constant insulation life at all altitudes. Data sheets showing these calculations as a family of curves applicable to a large number of generators are available. These have been substantiated by test and experience over a moderate range of altitude and pressure differential. Further study for very high differentials and for high temperatures is in progress. In rating generators, all applicable conditions must be considered. A generator can transfer heat to a cool engine pad, but may receive much heat from a hot pad, and thereby be capable of less output. High ambient temperature surrounding a generator may reduce the output of the generator, regardless of the method of cooling employed. Figure 512.2-3 shows the form of a typical altitude rating chart for blast-cooled generators. It has been taken directly from "Interim Method of Presenting Blast-Cooled Generator Rating Data" prepared by the Airborne Electric Apparatus Rating Subcommittee of the Air Transportation Committee in July, 1954. The complete "Interim Method of Presenting Blast-Cooled Generator Rating Data" is included in the "Standardization of Presentation of Aircraft Generator Characteristics" prepared by the AERM Subcommittee.

514 Overload Capacity

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

514.1 Overload Requirements

Overload requirements arise from several factors. The load analysis of a typical airplane system will show numerous short-time high load conditions in various portions of the flight plan. For instance, these may be caused by operation of the landing gear, wing flaps, water injection pumps, gun turrets, or other large intermittent loads. It is economical in weight to use the short-time thermal capacity of the generators to supply such loads. In a system of parallel-operated generators, it is a general requirement to design the system to supply all loads with at least one generator out of service. Under emergency conditions, when the number of working generators has been reduced to the design emergency number, some monitoring of non-essential loads is usually necessary. In this case it is important to allow time for the crew to meet the emergency and perform the necessary load monitoring before the damage point is reached on the remaining good generators. Air planes have been lost because of inadequate allowance for this factor.

Typical overload requirements for alternating-current machines are 150 percent rated load for two minutes and 200 percent rated load for five seconds. Direct-current overload requirements have not been standardized. Where given, they range from 150 to 200 percent for thirty seconds and 125 to 150 percent for two minutes. The two-minute overload ratings are intended to take care of the normal short-time loads and the emergency monitoring time. The five-second

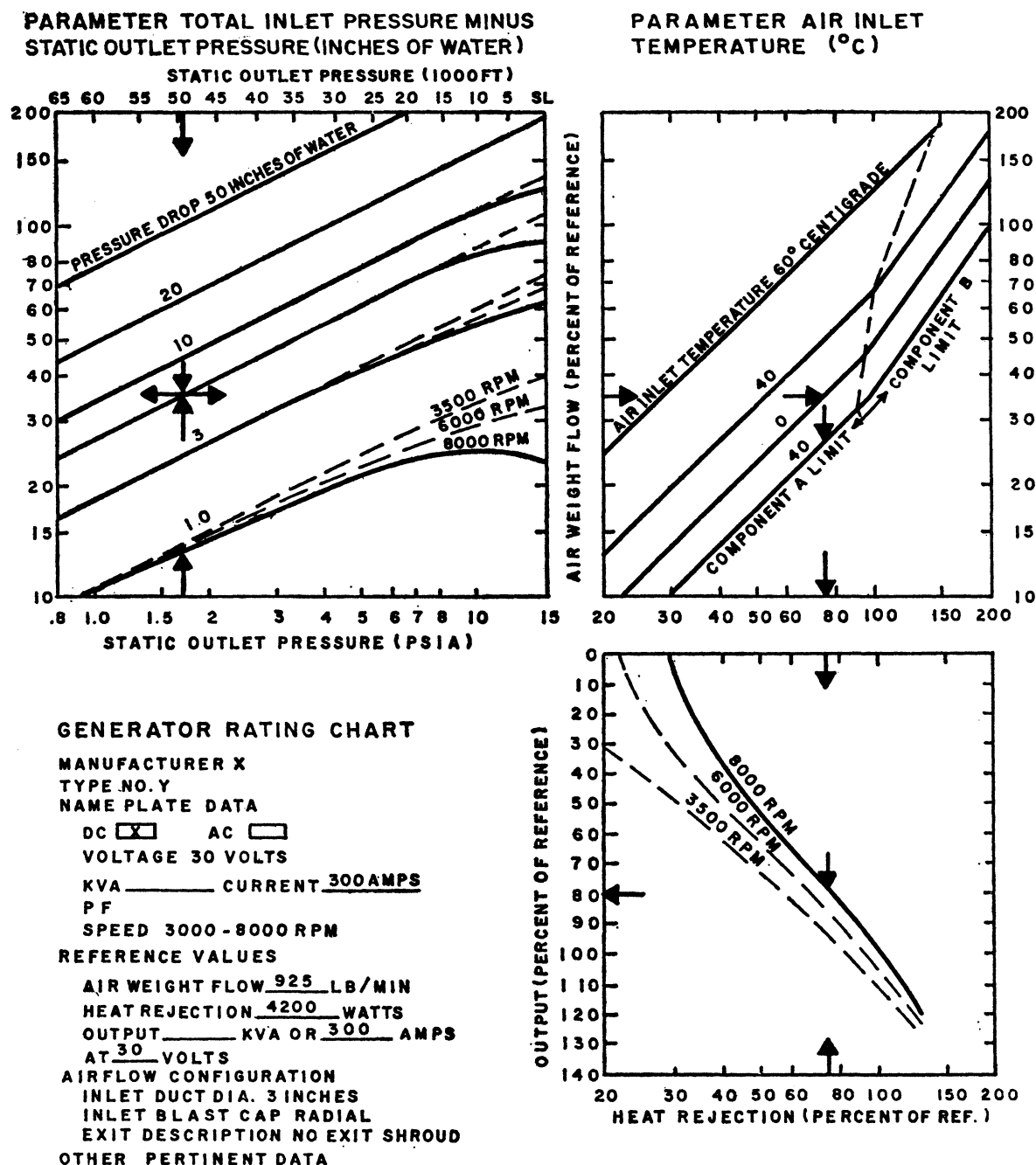


Figure 512.2-3 Generator Rating Curves.

overload rating for alternating-current generators provides capacity to handle large motor-starting in-rush currents and to clear faults on the longer low-current distribution circuits. The clearing capacity for heavy faults is discussed in Section 516.2.

Overload requirements usually apply after the generator has stabilized in temperature at full rated load. To avoid too great a penalty in weight, the requirements usually do not apply to base speed on variable-speed machines, but to a higher speed so that the flux-carrying ability of the generator is not determined by the overload requirement. Even when such a precaution is taken to avoid having the overload requirement dictate the size of the generator, it may

well determine the size of a prime mover such as an air turbine. Therefore, care should be exercised in specifying overload requirements.

514.2 Thermal Limits

A generator designed for minimum weight will operate at close to the maximum safe temperature of its insulation. Therefore, it inherently does not have much thermal overload capacity. This is especially true of direct-current generators, where much of the weight is in copper carrying load current (armature winding, commutator, compensating field, and commutation-pole winding). In a 120/208 volt alternating-current generator a smaller proportion of ma-

chine weight is in armature copper, so that it is relatively easy to provide sufficient copper to carry the overload required without exceeding safe temperatures. This is why direct-current requirements have not been specified to the extent that alternating-current requirements have.

In general, machines are not self-protecting in the matter of overloads. Except at minimum rated speed, they are usually capable of putting out load currents that will quickly cause destruction. Even at minimum speed the excitation circuit may be destroyed.

514.3 Volt-Ampere Limit

The maximum power which a generator will supply is shown by the external characteristic of the generator. A typical curve for a direct-current machine is shown in Figure 514.3-1. The volt-ampere characteristic varies with speed and with the resistance in the shunt-field circuit, in this case 0.75 ohm is in the field circuit external to the generator; this is a standard minimum value for carbon-pile regulators and their leads. These characteristics are used to determine system behavior under fault conditions, they may also be used to determine the required strength of the components of the generator drive. Curves for alternating-current generators are similar except that power factor is another parameter. Also, as alternating-current generators have exciters of some type, the curves usually do not fold under as do the direct-current curves taken on self-excited machines.

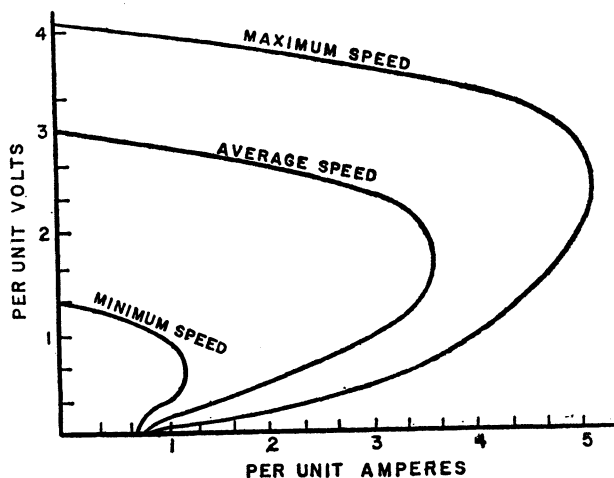


Figure 514.3-1 Direct-Current Generator Volt-Ampere Characteristic Curves.

515 Operation Under Subnormal Conditions

Some operating conditions may require that the generator provide power at less than rated speed and/or less than rated ventilation.

A blast-cooled generator may be required to supply power at less than normal ventilation, particularly when an airplane is taxiing or stationary. Then, the air must come from propeller blast or from idle-engine suction. The amount of blast air will usually be between 10 and 25 percent of the rated value. In some cases, the use of

separate blowers or an integral fan to supply adequate ventilation may be necessary during operation on the ground.

With some engine and nacelle configurations it may be found that negative differential air pressures will exist under certain taxi or low-speed flight conditions. This is detrimental to proper cooling and will require careful study. A possible solution is to provide an alternate duct inlet and/or outlet, with an automatic flapper valve operated by differential pressure to select the desired air path.

516 Transients and Fault Clearing

To permit calculation of system behavior under transient conditions, generator characteristics must be known. These will be considered for direct-current and alternating-current generators separately.

516.1 Direct-Current Generator Transient Performance

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. 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 and can be simulated by assuming the presence of an internal resistance equal to $\Delta E/\Delta I$ (Figure 516.1-1) 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 and commutating ability of the generator.

516.2 Alternating-Current Generator Transient Performance

Minimum steady-state short-circuit current is usually specified to insure proper operation of protective devices. Commonly specified is 300 percent rated current at average rated speed for narrow-speed range machines and 250 percent rated current at minimum rated speed for wide-speed-range generators.

Transient performance is calculated from the generator impedances involving the synchronous, transient, subtransient, negative-sequence and zero-sequence reactances. Unbalanced loading and single-phase operation can be analyzed, using these constants. Maximum transient recovery voltage should be considered.

517 Direct-Current Generators

Direct-current systems have predominated in the past and will continue to be important despite the increased use of

alternating current. The standard direct-current system voltage is 28, with 30 volts the generator rating. Smaller generators are available for the 12-volt systems. Some 120-volt generators have been used, although there has been only limited interest in direct-current systems over 30 volts because of commutation and switching problems. Thirty-volt generators are available in many ratings, typical being 100, 200, 300 and 400 amperes; and several speed ranges, such as 3000 to 8000 revolutions per minute, 4000 to 8000 revolutions per minute and 2500 to 4500 revolutions per minute. (But see Section 513.1)

517.1 Generator Field Design

Fields of 30-volt direct-current generators generally are designed to operate with a carbon-pile voltage regulator having the following characteristics:

Minimum resistance, including wiring.....	1.25 ohms
Maximum resistance	35 ohms
Maximum current, steady-state	8 amperes
Maximum power dissipation	90 watts

518 Alternating-Current Generators

In recent years, there has been a marked increase in the use of alternating-current generators on modern aircraft. Increased electric loads on military aircraft have required the use of higher-voltage systems. With many of the loads requiring alternating-current power, the use of alternating-current generators has been desirable.

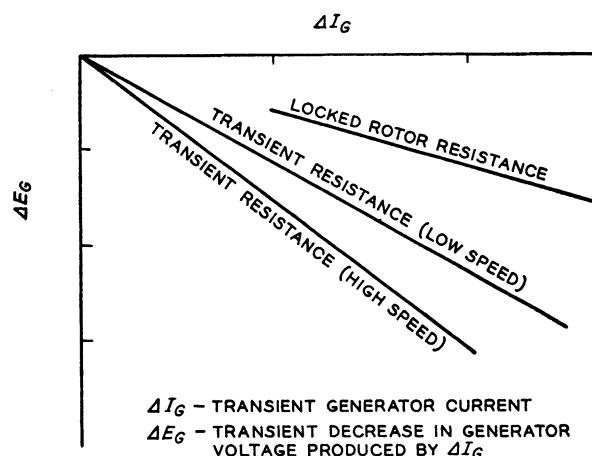


Figure 516.1-1 Transient Volt-Ampere Characteristic Direct-Current Aircraft Generator.

Consequently, for the sake of standardization, there has been considerable development on three styles of alternating-current generators: (1) 120/208-volt, 3 phase, 380-420 cycles per second, (2) 120/208-volt, 3 phase, 400-800 cycles per second, and (3) 120/208-volt, 3-phase, 320-480 cycles per second; (4) for missile work, 3200 cycles per second has been proposed, no voltage or phase standard has been adopted. Common machine ratings are: 9, 15, 20, 30, 40, 60, 90 and 120 kva. The lower-rating machines are in general use, while the higher-rating units are in development.

The more-widely-used machines have included integral exciters on a common shaft with the rotor of the alternating-current generator, or have been self-excited with a portion of the output of the generator being rectified to supply controlled field current. In addition to these types, several others have been investigated experimentally.

These include alternating-current generators having permanent-magnet field structures, induction generators using capacitor excitation, and self-excited cascade generators. These machines have not been used extensively, because of difficulty in regulating and controlling them.

518.1 Regulating Field Design

The regulating fields of integral exciters generally are designed to operate with carbon-pile, magnetic amplifier or transistor voltage regulators. Newer regulator designs are either magnetic amplifier or transistor amplifiers, with some instances of both being used in the same unit. So far, each regulator is designed to work with a given generator.

To keep the external field circuit minimum resistance to a value low enough to avoid objectionable limitation of generator overload capacity requires the use of relatively large wire. On a large airplane, this means a considerable weight increase above that which would be required solely for reasons of current-carrying capacity. Future consideration to the design of regulating fields and voltage regulators for a higher excitation voltage would allow a significant saving in wiring weight.

519 Performance Data

To evaluate a generator application, the user needs performance data covering important factors. The following lists are typical of the data desired. Obviously some factors apply only to particular types of machines. Many of the items have been discussed in the sections above.

519.1 Direct-Current Generators

The following information is generally desired:

- Brush life at various altitudes, speeds, and loads.
- Airflow versus head at various speeds (Figure 512.2-1).
- Regulation curves, field current versus load at various speeds.
- Unregulated volt-ampere characteristic (Figure 514.3-1).
- Efficiency at various loads and speeds.
- Underspeed performance.
- Altitude, temperature and air pressure rating data (Figure 512.2-3).
- Short-time overloads.
- Saturation curves, volts versus field current at no load and rated load.
- Resistances.

The following additional data may be useful in making more complete and accurate system studies:

- Short-circuit oscillograms.
- Radio interference and ripple voltage.
- Shunt field time constant.
- Maximum speed for regulation.

519.2 Alternating-Current Generators

The following information is generally desired:

- Brush life at various altitudes, speeds and loads.
- Airflow versus head at various speeds (Figure 512.2-1).
- Voltage regulation under various operating conditions.

Harmonic content (wave form).
 Voltage unbalance under unbalanced loading.
 Short-circuit oscillograms.
 Parallel operation.
 Efficiency at various loads and speeds (Figures 519.2-1 and 519.2-2).
 Underspeed performance.
 Steady-state short-circuit current (Figure 519.2-3).
 Synchronous reactance in direct and quadrature axes.
 Negative-sequence impedance.
 Zero-sequence impedance.

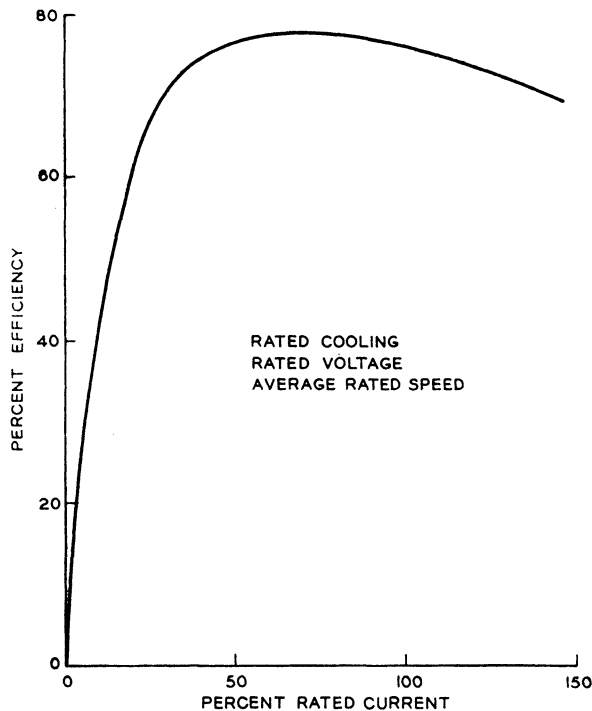


Figure 519.2-1 Direct-Current Generator.
 Efficiency versus Load.

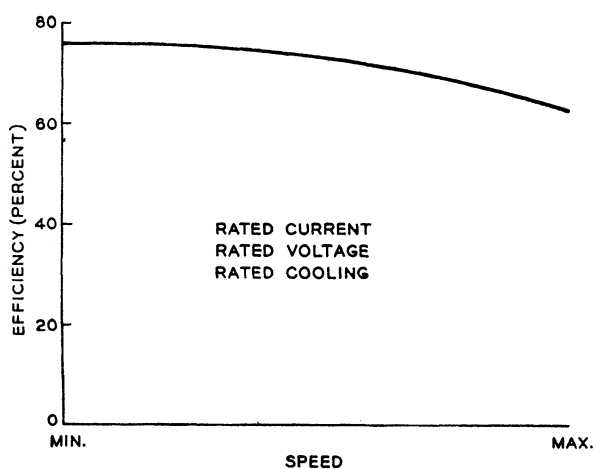


Figure 519.2-2 Direct-Current Generator.
 Efficiency versus Speed.

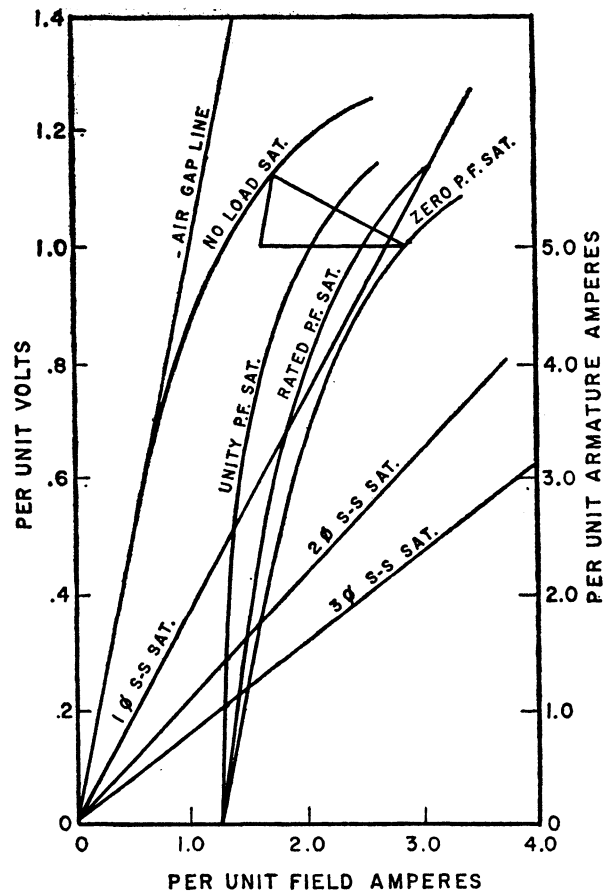


Figure 519.2-3 Alternating-Current Generator
 Saturation Curves.

Altitude, temperature and air pressure rating data (Figure 512.2-3).

Short-time overloads.

Saturation curves (Figure 519.2-3).

Unregulated volt-ampere characteristics.

Resistances, hot and cold.

The following additional data will be useful in making more complete and accurate system studies:

Transient and subtransient reactances in direct and quadrature axes.

Time constants.

Maximum speed for regulation.

Radio interference.

Amplitude modulation.

Frequency and voltage modulation.

Section 510 Bibliography

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- b. Rating Tests of a 40-kva Alternator, E. O. A. Naumann. Wright Air Development Center, Wright-Patterson AFB, Ohio, WADC Technical Memorandum Report WCLE 53-338, December 1953, 27 pages.

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520 PRIME MOVERS AND CONSTANT-SPEED DRIVES

521 Main Propulsion Engines

521.1 Reciprocating Engines

This type of engine is normally provided with one or more 5-inch diameter bolt-circle round mounting flanges, rotating clockwise, on which generators of up to approximately 65 pounds weight, 15 inches long, and 6.5 inches diameter can be mounted. These mounting pads are usually as described by Government Design Standard AND-20002. The axes of rotation of these mounting flanges are usually parallel to the axis of rotation of the engine; however, in some instances these axes are at other angles and most aircraft generators are capable of operating at any angle including the vertical. The gear ratio between the generator drive and the crankshaft on current reciprocating engines is usually about 3:1, which results in the following approximate operating speeds of generators:

Engine idling	1500-1800 rpm
Aircraft minimum cruise	3300-5300 rpm
Aircraft takeoff	8000-9000 rpm

Some applications involving sustained high-speed engine operation require a lower gear ratio to permit full-capacity output of the generator. Older large reciprocating engines and some current small engines are provided with a variety of drive means and ratios for generators, predominate among which are the 5-inch diameter bolt-circle drive with a 1.5:1 ratio to crankshaft speed and a four-stud square drive with the same ratio. The operating speeds of generators on these drives are one-half these indicated in the tabulation above.

521.2 Turbo-Jet Engines

This type of engine is normally provided with one or more 5-inch and/or 10-inch bolt-circle round mounting flanges for generators. The 5-inch flange has the same capabilities as for reciprocating engines, and the 10-inch flange, whose rotation is also clockwise, can mount generators of up to 225 pounds weight, 20 inches long, and 11-inch diameter. Some types of engines have a single 5-inch mounting flange on which must be mounted a combination starter-generator. These mounting pads are usually as described by Government Design Standards AND-20002, AND-20006 and AND-20007. The axes of rotation of the generator drives are usually parallel to the axis of rotation of the engine, and the drive is frequently located in the engine air inlet duct, thus complicating the cooling and inspection problem. The gear ratio between the generator drive and the engine rotor varies considerably due to the wide range of rotor maximum operation speeds which are primarily limited by turbine blade tip velocity; however, the generator drive speed is usually 6000-6400 revolutions per

minute at 75 percent nominal sea level static output of engine. The speed versus thrust characteristics of turbo-jet engines are such that the generator drive speeds are approximately as follows at SEA LEVEL STATIC CONDITIONS:

Idling	1700-2900 rpm (28-45%)
Minimum Cruise	3800-5000 (63-78%)
75 per Output	6000-6400* (100%)
Full Power	6200-7400 (103-115%)

As air speed and altitude are increased, the engine speed approaches the maximum for all operating conditions, including idling; hence, the generators may operate at a substantially constant speed under most aircraft flight conditions.

521.3 Turbo-Propeller Engines

This type of engine is normally provided with the same generator drive facilities as described for turbo-jet engines above; however, the drives are usually located on a gear box which also drives the propeller. This gear box is sometimes clutched to the engine after it has been started, accordingly electric power from engine-driven generators may not be available until the gear box is clutched into the engine. Some turbo-prop engines are substantially constant-speed with steady-state speed being maintained with an accuracy of the order of one percent under all normal flight conditions. During takeoff the speed may be as much as 10 percent above normal but this will not occur when maximum power is being delivered by the engine at appreciable flight speeds, as the speed is raised at the takeoff for the purpose of increasing propeller efficiency at zero and low flight speeds.

The so-called constant-speed alternating-current and direct-current aircraft generators can be driven directly from such turbo-propeller engines and attain nearly the same performance as when they are driven by a constant-speed drive or an auxiliary power plant. Nevertheless, it should be noted that alternating-current generators cannot be paralleled because it is considered to be impractical to control the engine speed and phase angle with accuracy sufficient for this purpose. Although essentially constant frequency may be obtained in this manner, the attainment of any *particular* frequency, such as 400 cycles per second, will require close coordination of engine governed speed and gear ratio. Further, not all turbo-propeller engines are constant speed, in particular, the twin-spool or free-turbine engines tend to be wide speed range.

522 Auxiliary Power Units

522.1 Reciprocating Power Plants

This type auxiliary power plant is often used to drive aircraft-type generators to supply power during ground operation of the aircraft and also to provide electric power at low altitudes, particularly as a standby for main-engine-driven generators during landing and takeoff operations. Operation at altitudes above a few thousand feet requires either supercharging or a reduction in output. In some applica-

*This is a tolerance in engine-to-generator-drive gear ratio rather than a speed variation.

tions of auxiliary power plants, only stowage is provided and the power plant is always removed to the ground prior to operation. The relatively high fuel consumption of reciprocating power plants (0.6 to 0.8 pound per horsepower hour), when compared to that of main propulsion reciprocating engines which is approximately 0.5 pound per horsepower hour, usually makes continuous in-flight operation of auxiliary power plants uneconomical from the weight standpoint. Where the capacity of the auxiliary drive engine is inadequate to drive the generator at overload conditions, control means must be provided to limit the generator output to the capacity of the drive engine. The main propulsion engine can usually provide this overload capacity when required without appreciably affecting its propulsion function. During main propulsion engine idle and let-down flight conditions, the main-engine-driven generator has little or no overload capacity available due to the low speed of operation. Typical reciprocating type auxiliary power plants are as follows:

<i>Continuous Rated Output*</i>	<i>Gen. Drive Speed</i>	<i>Wt. with Generator</i>
2 kw	3400 rpm	113 lbs
5	6500	122
10	4800	205
30	3600	525

522.2 Turbine Power Plants

522.21 The gas-turbine auxiliary power plant has the same applications as described for the reciprocating type above. However, this type has the advantage of lighter weight than the reciprocating engine; but the fuel consumption is higher (1.5 to 2.0 pounds per horsepower hour), the life expectancy is shorter, and operation at altitude is relatively more difficult than with the reciprocating engine. A typical gas-turbine power plant delivers 40 kilowatts continuously from a generator operated at 6000 revolutions per minute, and weighs 285 pounds.

522.22 Air-turbine motors may be used to drive generators when a source of compressed air can be made available, either by bleeding from the aircraft main-propulsion-engine compressor or from an auxiliary compressor. The compressed air is used at pressure ratios in the range of 6:1 to 8:1 and at a temperature of 250 to 350 F. Extraction of power from the main engine by airbleed is usually less efficient than by other generator drive means; however, in specific instances the airbleed system may be preferable for some of the following reasons:

- Propulsion engine has such a mismatch between compressor and turbine that it is necessary for some air to be bled, thus resulting in a power extraction at less penalty than from a more properly matched combination.
- Aircraft operating altitudes are below engine design altitude, which results in capability of airbleed without appreciable sacrifice in aircraft performance.

* Little or no overload capacity available.

- The ability to manifold air from several engines to fewer generators results in reduced electric system weight.
- The combination of the air-driven generator system with a starting system, and/or a system to provide power when main engines are not operating, results in a combined system saving.
- A short flight time requirement makes the light weight of the air-drive components, rather than their efficiency (fuel weight), the governing factor.

The air-turbine motor can be governed to nearly any reasonable steady-state accuracy; however, it is relatively "soft" drive due to the compressibility of air and the inertia of the air in the line from the air source. It does not have much overload capacity unless deliberately designed oversize. With a turbine designed to match the overload rating of the generator, during 100 percent load change the speed may change 3 percent and take one second to return to rated value. A typical air duct for a 70-horsepower air turbine is 5.0 inches inside diameter, 40 feet long, is thermally insulated and weighs 34 pounds. The 70-horsepower air turbine, complete with governor and 10-inch bolt circle drive, operating at 6000 revolutions per minute (turbine speed about 35,000 revolutions per minute), weighs 57 pounds and requires 105 pounds per minute of 217 F air at 78 inches of mercury absolute inlet pressure for full output at sea level.

522.23 Gas-turbine motors are practically identical to the air-turbine motor except that fuel is injected and burned, thus increasing the efficiency and output per unit size and increasing the weight considerably in the larger sizes. The same considerations are involved in the application of gas-turbine motors as for air-turbine motors. The use of gas-turbine motors may have greater advantage at higher horsepowers above, say, 50 horsepower. A typical gas-turbine motor of 125 horsepower output with a 10-inch bolt-circle drive, operating at 6000 revolutions per minute, weighs 85 pounds and requires 67.5 pounds per minute of 330 F air at 90.5 inches of mercury absolute inlet pressure and 1.1 pounds of fuel per minute for full output at sea level.

522.24 A gas-turbine compressor is a gas turbine with an oversized compressor from which air is bled to operate air or gas-turbine motors to drive generators. The combination of the compressor and the motor comprises an auxiliary power system which is independent of propulsion engine operation. The output air of the gas-turbine compressor may be used for propulsion-engine starting (with air-turbine starters) or for other auxiliary uses, such as air conditioning. A gas-turbine compressor capable of supplying sufficient air to operate a 25-horsepower air-turbine motor or a 75-horsepower gas-turbine motor at full load at sea level weighs 175 pounds and requires 1.61 pounds of fuel per minute to deliver 43 pounds of 337 F air at a pressure of 86 inches of mercury absolute at sea level.

523 Transmissions

The term "transmission" is applied to an assembly which forms a link between the main propulsion engine and the driven generator. It is variously known as a generator drive, a remote shaft, or a torque converter.

523.1 Constant-Speed Transmissions

This type of transmission has the characteristic of relatively constant-speed output over a range of input speeds. Its primary purpose is to achieve a so-called constant-frequency electric system, using the main propulsion engine as a prime mover over its operating speed range. The output speed is normally 6000 revolutions per minute due to the predominance of generators designed for operation at that speed, although 8000 revolutions per minute drives are in

existence, and 12000 revolutions per minute a possibility. The output speed can be held to any reasonable steady-state accuracy, and speed transients due to 100 percent load changes can presently be limited to less than 10 percent with a duration not to exceed one second. Present constant-speed transmissions are predominantly of the hydraulic or combination hydraulic-mechanical type, with development work being done on pure mechanical types. Hydraulic pressures of up to 5000 pounds per square inch are used in some hydraulic types. Non-flammable fluid is also used.

523.11 In unit-type constant-speed transmissions the primary functions are accomplished within one assembly. The unit may be a cartridge inserted into the engine, using engine services such as oil cooling; it may be mounted on the propulsion-engine drive as

<i>Configuration</i>	<i>Continuous Output</i>	<i>Dry Weight*</i>	<i>Input Speed</i>	<i>Output Speed</i>	<i>Efficiency</i>
Cartridge	85 hp	57 lbs	3000-9000 rpm	6000 rpm	77-90%
Sandwich	50	65	2800-6500	6000	75-88
Package	85	85	2800-8500	6000	72-88

*Parallel operation requires additional drive components weighing approximately 11 pounds per drive.

a sandwich between the drive and the generator; or it may be a separately-mounted package driven by a constant-ratio transmission.

The cartridge-type drive is probably the most desirable, for it actually results in an engine with a constant-speed power takeoff for generator operation. The cartridge-type drive is presently confined to turbo-jet engines, and generators are mounted directly on the output end of the cartridge which is in reality a portion of the engine rear section. It is doubtful whether generators of the size normally required for constant-frequency systems could be directly mounted on a cartridge-type drive incorporated into a reciprocating engine because of weight and overhang problems under the vibration conditions encountered; however, a constant-ratio transmission might be used to operate a generator remotely from the cartridge. The sandwich-type drive can be used as a substitute for the cartridge when engine design cannot be changed and when total overhang of the drive and mounted generator do not exceed engine limits. This latter limitation usually eliminates consideration of the drive for use in reciprocating-engine installations; however, the use of a constant-ratio drive to operate the generator remotely from the sandwich will considerably reduce the overhang moment. The package-type drive is the predominant type in use and can be used with any type of engine; however, it is the heaviest of the unit-type configurations because it is necessarily self-sufficient rather than relying on the engine for some services such as oil cooling, pressurization and sealing.

523.12 In split-type constant-speed transmissions the functions of a constant-speed and a remote transmis-

sion are combined into one system, usually consisting of one or more hydraulic pumps mounted on the main propulsion engine(s) connected by hydraulic lines to one or more hydraulic motors which drive generators. Either the engine-mounted pump(s) or the hydraulic motor(s) driving the generator(s) must be of the variable displacement type, and both may be in some systems. The use of a variable-displacement engine-mounted pump, rather than a fixed-displacement pump, results in more efficient utilization of hydraulic system components due to operation at approximately the same maximum pressure at all input speeds. However, variable-displacement pumps are larger and heavier than constant-displacement pumps. In addition, output-speed governing by means of controlling the displacement of input pumps in a multiple-pump installation is a rather complex problem.

The split-type transmission may also be used as a starting system either by introducing hydraulic power into the system and operating the system input pumps as hydraulic starting motors or by operating the generator(s) as starting motor(s) and reversing the hydraulic cycle.

The advantages of a split-type hydraulic drive are most apparent in the following situations:

- Space limitations prohibit use of a unit-type transmission.
- A combination starting and generator-driving system can be utilized.
- A multiple-pump installation will enable a reduc-

tion in the number of generators without a sacrifice in the number of prime movers available for generation of electric power.

The following are typical split-type transmissions:

<i>Continuous Output</i>	<i>Dry Weight*</i>	<i>Input Speed</i>	<i>Output Speed</i>	<i>Efficiency</i>
35 hp 70	120 lbs 206	2500-9000 rpm 2500-9000	6000 rpm 6000	75-83% 75-83

*This dry weight includes all components such as intercoolers, reservoirs and valves; however, it does not include fluid or lines. In a typical installation having 10-foot separation between pumps and motors, the working weights would be approximately 45 pounds and 80 pounds above the dry weights for the 35- and 70-horsepower transmissions respectively.

The 70-horsepower transmission comprises two separately-mounted 5-inch mounting-flange input pumps connected hydraulically to two hydraulic motors geared together and driving two 10-inch diameter generator mounting flanges.

On present split-type hydraulic transmissions, a gear box is incorporated into the hydraulic pumps and motors, as it is not possible to operate them at the high speed required for good generator design. The hydraulic components are being improved with regard to high-speed operation, and an appreciable weight saving will be gained when the gearing is eliminated.

523.2 Constant-Ratio Transmissions

523.21 The simplest method for driving a generator remotely from a main propulsion engine, not capable of mounting it directly, is by the use of a drive shaft. When a shaft is to be used, space must be found for both the shaft and the large generator in close proximity to the engine. The design of the shaft must be such that it will allow for engine movement but at the same time neither introduce nor amplify torsional vibrations. These two requirements add up to the necessity for the use of constant-velocity universal joints in most applications. The engine movement and installation allowance is usually of the order of 1.50 inches for axial variations and 10 degrees for misalignment between input and output ends of the shaft. The torsional requirement indicated above dictates that the natural frequency of the shaft must be low, and it is usually below 15 cycles on shafts designed for driving generators from reciprocating engines. This natural frequency is established under the condition that the shaft be mechanically loaded with the smallest polar inertia it will be driving when installed.

Several types of constant-velocity joints have been used in various shaft designs, such as spherical gears (Barcus), floating balls (Rzeppa) and diaphragms. It is necessary to provide oil circulation and cooling for some of the more complex types of joints because of their losses. Typical weights of remote shafts incorporating two diaphragm-type joints and having a

5-inch bolt-circle input flange and a 10-inch bolt-circle output flange are as follows:

<i>Horsepower</i>	<i>Speed</i>	<i>Length</i>	<i>Weight</i>
180	4000-9000 rpm	18 in.	25 lbs.
180	4000-9000	36	30
250	4000-9000	18	30
250	4000-9000	36	35

523.22 When engine limitations prevent direct mounting of a generator, and space limitations preclude the use of a remote shaft, it is possible to drive generators remotely using a system similar to that described above through split-type constant-speed transmissions, except that all pumps would be of constant-displacement type. This saves weight and gains simplicity in applications when constant speed is not essential. A typical hydraulic constant-ratio transmission delivers 30 horsepower continuously over an input and output speed range of 4000 to 8000 revolutions per minute, and has a dry weight of 100 pounds, with an efficiency of 78 to 86 percent.

In a typical installation having a 10-foot separation between pump and motor, the working weight would be about 45 pounds more than the dry weight.

523.23 In many installations it is necessary to provide gear boxes to alter the engine drive configuration to suit the aircraft requirements. These gear boxes may be used in conjunction with a transmission of some sort or may be in the form of a sandwich between the engine and generator(s). If they are of the latter type, particular attention should be given the weight and overhang-moment limitations of the engine which cannot be exceeded by the resultant combination of generator(s) and sandwich gear box. In particular installations, however, it may be possible to exceed the recorded engine limitation in those instances where the airframe G limitations are less than those for which the engine limitation was established (usually 10G). In the design of gear boxes, the effect of torsional vibrations, either introduced or amplified by the gearing, should be considered, as they may have detrimental effects on the generator. If the gear box requires external lubrication, consideration should be given to providing an individual lubricating system rather than possibly compromising the integrity of the main engine lubrication system by utilizing it for the gear box. The efficiency of a gear box can be approximated by assuming one percent loss of power per gear mesh.

523.24 On certain aircraft applications, particularly helicopters, the only apparent means for driving generators has been by the use of belt drives. In such installations, it is essential that the generator be installed so that radial belt load is not applied directly to generator bearings unless the generator is specifically designed to withstand such loads. In addition, the effect of various service conditions on belt performance should be evaluated, as should the effect of torsional vibrations in the system comprising the drive, the belt, and the generator.