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CONTENTS

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SUMMARY

A space turboelectric generation system delivering 5000 volts, direct current, at a 1-megawatt power level is analyzed. This system employs a superconducting field as the stator with a 200° or 340° K rotor as the armature. Both alternating- and direct-current models of this generator are studied for possible spacecraft use.

A comparison with other rotating generation systems that might be used as alternatives shows that the superconducting magnet generator system holds promise of being lighter in weight and more efficient.

Consideration is given to the effects of refrigeration system weight and to the seal, bearing, and electric-contact problems in space. A parametric analysis of various rotating generator types is also made.

INTRODUCTION

In present spacecraft missions, only about 10 kilowatts of continuous electrical power are necessary. Quantities of the order of 1 megawatt of electrical power will be necessary, however, for future deep space missions. For this reason, all the types of energy conversion from thermal, nuclear, or solar energy to electrical energy which may be practical in the megawatt-power-level range should be analyzed. This report is an analysis of a conversion system of thermal to rotating mechanical to electrical energy with emphasis on the use of a superconducting magnet.

The prime energy source could be nuclear, chemical, or solar, but at the present time the nuclear source seems most attractive. One means of providing transformation to electrical energy is with a boiler, a condenser, and a turbine, which transduce the thermal energy to the mechanical energy of a rotating shaft, and a usual electric generator for the final conversion to electrical energy.

Shown in figure 1 is a comparison of space electrical power systems now operating or proposed. The parameter used for comparison is the ratio of system weight to power generated: the specific weight in pounds per kilovolt-ampere. As the fuel consumed by these systems is negligible compared with the total system weight, this parameter is pertinent for comparison.

The system of most interest in this figure is the SNAP-50 system. The SNAP-50 nuclear powerplant is expected to have a specific weight of 15 to 30 pounds per kilovolt-ampere and a life of 10 000 hours (ref. 1). Of this weight, 1 to 2 pounds per kilovolt-ampere has been assigned to the electric generator. This small specific weight dictates a lightweight generator design in addition to an efficient design.

Shown in figure 2 is a comparison of specific weights of various rotating electric generators in operation, designed, and proposed. The generator specific weight does not include power conditioning equipment; ac generators must thus assume an additional weight penalty of about 0.5 pound per kilovolt-ampere for ac to dc conversion when the required output is dc, such as for electropropulsion.

The purpose of this report is to compare nuclear pile systems that have various types of rotating electric generators with emphasis on ones which employ superconducting magnetic fields.

A superconducting-magnet generator is proposed which holds promise of being very efficient and lightweight. For such a system to be practical for space applications, however, a number of advances must be made in a number of fields. Among these are

(1) A 10-weber-per-square-meter superconducting magnet must be made with larger bores than those available at present.

(2) Cryogenic refrigerators of the efficiency and weight of those proposed for space in the literature must be made available.

(3) The material problems associated with the use of bearings, brushes, and commutator or slip rings in a space environment must be solved.

(4) Present-day, high-purity, high-strength ceramics must be made available in larger and more complex forms.

A superconducting generator configuration similar to that given herein was analyzed in reference 2. The analysis is for a ground-based, ac, gas-turbine-driven system, however, and does not include the reactor, radiator, or power conditioning equipment needed for an electropropulsion system.

In the present analysis, the electrical power desired is assumed to be 1 megawatt at 5000 volts, direct current, for an electropropulsion mission. The shaft supply system is designated as all the equipment necessary in the energy flow diagram previous to the electric generator shaft. Generator inefficiency or slow generator speed, since the turbine is less efficient at slow speeds, reflects itself as an increased shaft supply weight called the additional weight penalty. This additional weight penalty is properly charged to the generation systems under consideration. The weights of the scientific payload and the propulsion device are not included in this analysis.

BASICS OF POWER GENERATION

The basic design equation for all electric generators is (ref. 3)

$$P_g = \frac{(d^2\ell)nB_gA}{9\times10^3} \tag{1}$$

(All symbols are defined in appendix A.)

It is with this equation that comparisons of different speeds, fields, and sizes of generators may be made. To make a compact, lightweight generator for space use, the equation requires a high flux density and speed. In conventional generators, the flux density is limited to the magnetic saturation of steel, while the maximum speed is a mechanical consideration. For high-speed, lightweight operation, the 400-cycle generators and motors were developed for aircraft in the late 1930's.

Basic to any discussion of electric generators is the fact that common experience has shown that the generator with both the highest efficiency and the lightest weight for a given power output is the wound-pole alternator.

Brushless, Solid-Rotor Generators

The development of the brushless, solid-rotor generators is due to the graphite brush problems at high altitudes (refs. 4 and 5). Solid-rotor generators also offer a higher reliability, since the rotor conductors in the wound-pole alternator tend to creep and fail. In the solid-rotor generator, the main losses are in the stator, which can be easily cooled. Various types of these generators are now mentioned in the order of their importance.

The homopolar-inductor (pulsating flux) alternator has solid-rotor, high-speed construction and has found use in the SNAP-8 system and is proposed for the SNAP-50 system. It has a rotor length-to-diameter ratio typically of 3/4 to 5/4 as compared with about 2 for the wound-pole alternator.

The Lundell (reversing flux) generator also has a solid rotor and is brushless, but its construction requires a small length-to-diameter ratio (about 1/3 for minimum weight), which limits it to lower speeds than the homopolar-inductor alternator.

The inductor and Lundell alternators both have solid rotors which have higher hysteresis and eddy currents than a laminated rotor, such as in the wound-pole alternator, although laminated rotor poles are proposed in future inductor alternators. At the same speed and power, the solid-rotor generators weigh about twice as much as the wound-pole type. The complex flux paths in the solid-rotor generators give rise to many flux leakage paths which must be compensated for by additional field excitation.

Another type of solid-rotor alternator is the permanent-magnet generator. These generators are, unfortunately, limited to low-power generation (less than 1 kW), since large kilogauss permanent magnets, which will not disintegrate at high speeds, are not available.

Brushless, Wound-Pole Generators

The brushless, wound-pole generator has recently been used in high-altitude aircraft for lightweight operation. This type of generator utilizes the usual wound-pole alternator (ref. 6) with the exciter armature on the rotor, which thereby makes brushes unnecessary. The exciter is ac, and diodes are used on the shaft to excite the generator's wound-pole field.

Limitations to the use of this type of generator are a lower speed than the solid-rotor generator and a low-temperature rotor because of the silicon rectifiers and insulation. Typical characteristics and system configuration of a brushless, wound-pole alternator are given in table I. A 1-megawatt brushless generator design which is derived from the data of table I is given in appendix B.

Brush, Superconducting Generators

Since the discovery of superconductivity over 50 years ago, there has been a desire to put superconductors to work in motors and generators. It was only when the "hard" superconducting materials such as the compound niobium-tin came into being that technical applications became practical. Until recently, only small laboratory generators (less than 100 W) could be found which used the principle of superconductivity (refs. 7 and 8). Application of these principles to larger generators has been made, such as the superconducting induction generator (ref. 9) and a pancake generator (ref. 10). Present superconducting motors have been small and usually have a unique design (refs. 11 and 12).

A 1/2-kilowatt superconducting-field, ac generator has been tested, and the loading of the alternator caused no measurable effect on the value of the critical field (ref. 13). An 8-kilowatt superconducting-field, 400-hertz generator has been built which has excellent voltage regulation and transient response (refs. 14 and 15). A design of a 1-megawatt superconducting magnet generator is given in appendix C.

SUPERCONDUCTING MAGNETS

Superconducting magnets have been developed during the past few years in the 10 to 100 kilogauss range (refs. 16 to 19). At present, magnets have been developed which yield over 40 kilogauss with an 11-inch bore and 107 kilogauss with a 1-inch bore (refs. 20 and 21).

Once the field current is introduced to a superconducting magnet, the magnetic field lasts indefinitely, since no resistance is present in the superconducting coil. The only power necessary is the refrigeration power to make up for the radiation and conduction loss, which is considerably less than the power necessary for a high-flux-density electromagnet.

There are, however, limits to the use of superconducting magnets. Alternating currents cannot be made to flow indefinitely in a superconducting coil, since heating occurs and the critical field is lowered even at a few cycles per second (refs. 22 to 24). The generation of an ac field with superconductors is thus not profitable.

Hard superconductors have also exhibited critical current degradation when formed into coils. This degradation seems to be a coil-separation problem and can be lessened by a few mils of silver or copper coating on the coil wire (refs. 17, 25, and 26).

If superconducting magnets are to be used efficiently, high-flux-density operation must occur. If so, none of the present ferromagnetic material can be present in a superconducting generator, or a magnetically saturated condition would exist. It is this fact which makes the Lundell and homopolar inductor superconducting generators very unattractive, since flux paths must be provided by magnetic material paths to enable either to be a generator.

In the present analysis, it is assumed that there is no ferromagnetic material present in the region of high flux density. In future systems, the rare-earth elements, gadolinium and holmium, which have saturation values up to 100 kilogauss in pure samples (ref. 27), could be useful (ref. 2) as a means of shaping the magnetic field, but they are thought to have very low magnetic permeability.

REFRIGERATION

One of the major difficulties in using superconducting magnet generators in space is the added power consumption, weight, and decreased reliability because of the necessity of cooling components to temperatures below 15° K. In addition, in the present analysis, some components must be cooled to the temperature range of 100° to 350° K.

The refrigeration cycle to use for cooling is dependent upon the required temperature range (refs. 28 and 29). Above 170° K, the most efficient refrigeration process is vapor evaporation. Between 170° and 60° K, the most efficient method is the Stirling cycle. Below 60° K, the most efficient process is adiabatic gas expansion. Shown in figure 3 are the efficiencies (watts refrigerated/total wattage) of various ground-based systems (refs. 28 and 30 to 34) as a function of temperature. Also shown in this figure are two lightweight space refrigerators (refs. 35 and 36).

At the lower temperatures much of the loss is due to heat leakage. As a result, the efficiency is a function of the power level. Portions of the curve of figure 3 may conveniently be fitted by simple equations.

In the following analysis the efficiency of the cryogenic refrigerator (at 4.2° K) will be assumed to be

$$\eta = \frac{\text{Refrigerated power}}{\text{Power out}} \simeq \frac{(\text{Refrigerated power in kW})^{1/3}}{280} \tag{2}$$

wherein power out is rejected at 350° K. This functional variation agrees with the values for advanced systems given in reference 2.

For refrigeration in the range 100° to 350° K, the following functional variation in efficiency is assumed:

$$\eta \simeq \left(\frac{T}{350}\right)^{1.42} \tag{3}$$

where the power out is rejected at 350° K.

From 350° K to the radiator temperature, the thermal efficiency is assumed to be

$$\eta \simeq 0.8\left(\frac{T}{T_R}\right) \tag{4}$$

Although ground-based systems are low speed and thereby reliable, the specific weights of such systems are prohibitive at superconducting temperatures. Raising the speed can greatly reduce the weight. A 2-watt space Stirling cycle (77° K) refrigerator (ref. 36) has a specific weight of about 7000 pounds per kilowatt at 3600 cycles per minute. The 100-watt 20° K gas expansion system of reference 35 has a specific weight of 10 000 pounds per kilowatt, not including the radiator. This last system consists of a motor, a multistage compressor with interstage cooling, and a turbine expander (ref. 37) on a common shaft rotating at a speed of 100 000 to 200 000 rpm. Expander turbines have been used in cryogenic refrigeration for a long time, and miniature expander turbines have been built for refrigeration in space (ref. 38). In the following analysis a system similar to that of reference 37 will be assumed. The specific weight will be assumed to be equal to $35.7/\eta$ pounds per kilowatt refrigerated.

The specific weight for refrigeration between 100° and 350° K will be assumed to be equal to $25/\eta$ pounds per kilowatt refrigerated. Above 350° K the specific weight is equal to $8/\eta$ plus radiator weight.

The total weight penalty for using cryogenic refrigeration is comprised of the refrigerator weight plus the weight added because of the additional heat which must be radiated and the additional electric power which must be used. Shown in figure 4 is the total weight penalty which must be assumed for a typical reactor-powered system for heat generated at temperatures below the radiator temperature. This penalty may be approximately represented by the function

$$\frac{\Delta W}{H} \text{ (in lb/kW)} \simeq 12 + 19\left(\frac{500}{T}\right)^2 \tag{5}$$

One result of the large penalty for cryogenic temperatures is that superconducting magnet generators do not become competitive on the basis of weight and efficiency until power levels of 1 megawatt and above are reached (ref. 2). This result is due to the fact that the usual generator losses are proportional to the generator volume, thus, approximately to the generator power, while the major source of cryogenic heating is radiation from the rotor surface and magnet support conduction losses. This heat leakage is proportional to the generator area and thus approximately proportional to the two-thirds power of the generated power. The effect is further emphasized by the dependence of the refrigerator weight and efficiency on refrigeration level (eq. (2)).

The reliability of present ground-based refrigerator systems is about that which will have to be expected from the space-borne refrigerator, 10 000 hours between overhauls. The space system will have essentially one moving part, the high-speed rotating shaft. The reliability of the refrigerator will thus depend to a large extent upon the reliability of the shaft bearings and seals.

In the off-design analysis, the refrigerators are considered as a package, and no off-design analysis is made of the refrigerator components.

BEARINGS, SEALS, COMMUTATORS, AND SLIP RINGS

The major metallurgical problem of all the generating systems considered herein is that of the dependability of those parts in which a high-speed moving part is adjacent to a nonmoving part. All generators analyzed have bearings; all generators except one have seals for the passage of cooling fluid through the rotor shaft. The superconducting generators have the additional problem of the use of slip rings or a commutator. These problems are not unique to the systems of this analysis, and much work has already been done by NASA and others in attempting to find solutions (refs. 39 and 40).

In the present analysis, it is assumed that the bearings are ball bearings, solid lubricated (refs. 39 to 43) with a bore of from 2 to 4 inches. The losses in the bearings vary from 0.2 to 1.0 kilowatt, depending upon the loading, speed, and diameter.

Although in many cases the coolant seal could also be used as the shaft bearing (ref. 39), in the present analysis they are considered separate items for simplicity of analysis. Design of a rotating seal usually involves a compromise between small clearances with increased heat generation and large clearances with loss of coolant material. On a mission of 10 000 hours, material loss must be kept to a minimum. This is especially true of any superconducting system using shaft cooling, as the coolant would deposit on the magnet shell, where it would increase the emissivity of the shell and thus increase the heat leak to the cryogenic system.

In the present analysis, the coolant for rotors below 350° K is assumed to be silicone oil with a viscosity of 5 centipoises. Above 400° K the coolant is assumed to be liquid metal with a viscosity of 0.5 centipoise (ref. 39). The heat loss in the seals varies from 0.5 to 3 kilowatts, depending on the speed, viscosity, and seal clearances. The total weight of bearings and seals for all generators (not including refrigerators) is about 100 to 150 pounds.

While in the case of the superconducting generator the coolant seals are eliminated, there is the additional problem of commutator or slip-ring friction. Since the usual brush materials cannot be used in space applications, all generators now being used for high altitude and space applications are the brushless type. The research which has been done on bearing materials is now being extended to the brush problem, where there are the additional complications of brush arcing and contact resistance. Preliminary research at Lewis has uncovered promising materials and provided guidelines for the choice of materials (refs. 39 and 44 to 47). At present the most promising is a silver-rhenium combination; the silver is necessary to carry off the heat generated. The use of a commutator in the dc superconducting generator has the added complication that the locally melted brush material must not be deposited in the commutator slots. In the present analysis the heat generated by the commutator (or slip ring) is computed to be approximately 1.4 kilowatts, which includes friction, electrical-resistance, and contact-resistance losses.

Because the technological complexity of the friction problem does not lead to an accurate simple analysis, there is room for considerable error in the values used. For this reason an off-design analysis was made with the friction heat generated used as a parameter (appendix D).

The bearings and seals of the refrigeration systems will be either refrigerant-gas or liquid lubricated (ref. 39). The losses and the weight of these bearings and seals are included in the efficiency and specific weights of the refrigerators.

RADIATOR

All the heat generated by the system must be radiated to space. A great deal of thought has been given to the problem of the radiator configuration (refs. 48 to 51) in connection with the radiation of the heat of the thermal cycle ahead of the generator shaft. The values used herein were taken from reference 51 and can be given in the following functional form:

Below 540° K (aluminum radiator):

$$\text{Specific weight} \simeq 28.6\left(\frac{350}{T_R}\right)^4 \quad \text{(lb/kW)} \tag{6}$$

Above 540° K (beryllium radiator):

$$\text{Specific weight} \simeq 31.0\left(\frac{350}{T_R}\right)^4 \quad \text{(lb/kW)} \tag{7}$$

The optimum temperature of the radiator is obtained from a compromise between high-temperature lightweight radiators and the weight penalty associated with raising the generator losses to the radiator temperature (eq. (5)). The resultant optimum temperatures lie between 475° and 540° K for all systems considered. The variation of system weight with radiator temperature is considered in appendix D.

POWER GENERATION SYSTEMS

Alternating-Current, Solid-Rotor, Homopolar Inductor Generators

Two typical proposed space homopolar generator designs have been chosen (ref. 52) as models for the type of space system that could be used in a 1-megawatt powerplant. When the models were chosen, care was taken to choose 2.15-kilovolt line to neutral generators so that 5.0 kilovolts, direct current, could be obtained after rectification without the use of a 500-pound transformer. Both designs are below the rotor steel stress limits.

The homopolar system weight analysis is given in table II and the system schematic diagrams are in figures 5 and 6. In table II the weights are rounded to the nearest 10 pounds.

The circuit breaker, switch, voltage regulator, excitation, instrumentation and control, and rectifier systems are all typical systems chosen from reference 52. A shaft clamp has been added to provide shaft support during lift-off, and a dummy load has been added for testing. The same auxiliary equipment is considered in each system.

Alternating-Current, Wound-Pole, Brushless Generators

This system has been designed as indicated in appendix B and is a larger version of the wound-pole, brushless aircraft generator given in table I. The 1-megawatt, wound-pole, designed generator ratings are given in appendix B. A maximum peripheral speed of 77.5 meters per second determines the generator dimensions.

The losses for this machine are calculated from idealized models, and the true efficiency would undoubtedly be less. This design does show the high efficiency and light weight at a given speed of a wound-pole alternator. The design also acts as a calculated comparison for the superconducting generator systems.

Table II gives a system weight comparison for the brushless, wound-pole alternator, and the system schematic diagram is in figure 7.

Alternating- and Direct-Current Superconducting Generators

Sketches of the proposed superconducting magnet dc electric generator are given in figures 8 to 10. Since the field of a superconducting generator is approximately eight times that of a normal generator, the anticipated size or weight reduction at a given speed would be approximately eight. Unfortunately, this is not true because of the size of the cryogenic refrigerator.

Since wound-pole alternators are the lightest in weight, most efficient, and require no unusual flux paths, they seem the ideal choice as a superconducting generator.

In an ordinary ac alternator, the magnetic field is the rotor (ref. 53), but in a superconducting magnet generator many problems arise if the rotor is superconducting. The main problems are the heat from the turbine coming to the cryogenic rotor by means of the shaft and the problem of a rotating refrigeration and insulation system. The first necessary revision to usual alternator design, therefore, is to turn the machine inside out, like a dc generator, which makes the field the stator and the armature the rotor.

Since a nonmagnetic rotor is necessary, an increase in the wire cross section may be made to decrease the armature copper loss. As more wire is added, the eddy current loss is increased; the design, given later in appendix C, must thus take this increase into account.

An electrical insulating rotor material must be employed to prevent eddy current loss in areas of the rotor in which conductors are not present. If the eddy current loss in the rotor is minimized, it may operate at lower temperatures and will not radiate so much heat to the superconducting magnet. Since removal of the rotor heat is a necessary function of the rotor and the rotor shaft, a high-thermal-conductivity rotor and shaft material is desired. Also, a high-strength material is necessary to withstand the high rotor stress. High-grade alumina best fits these specifications, and one solid piece would be used for the rotor and the shaft. A very thin silver coating at the rotor surface would reduce radiation. No outside back iron is necessary on the stator, and actually some of the magnetic field lines would extend to infinity. This could create miniature Van Allen belts, but if this were bothersome, a thin covering sheet of magnetic material could be placed some distance away where the field is lower. The winding and hookup of this type of dc or ac generator would be conventional.

The generator size is determined by the ultimate tensile strength of alumina at 10 000 rpm. Above 10 000 rpm the brush and slip ring problem become extremely complex. The alumina rotor allows a high peripheral speed, since the conductors cannot creep out of the slots to the air gap.

The dc superconducting magnet generator is of more interest than the ac superconducting magnet generator because no conditioning equipment is necessary. The design of a dc and an ac superconducting magnet generator is given in appendix C. Both systems have a weight analysis in table II. The dc system schematic diagram is in figure 11, while the ac system schematic diagram is in figure 12.

Both the ac and the dc superconducting magnet generators have been designed for 150 watts of rotor loss. With this small loss the heat may be extracted through the alumina shaft and metallic bearings. If a coolant and shaft seals are used, about 400 pounds in system weight can be saved, but it seems more advantageous not to have seals at all. In all the other generation systems, the heat generated in the rotor dictates a coolant liquid with shaft seals.

The ac superconducting magnet generator is smaller than its dc counterpart and therefore requires about 1 watt less of refrigeration at superconducting temperatures. The complete dc superconducting magnet generator system from table II weighs approximately 400 pounds less than its ac counterpart, although slip rings in outer space would certainly be less difficult than commutating brushes.

EFFECT OF SHAFT SUPPLY WEIGHT AND PARALLELING GENERATORS

The thermal source, boiler, condenser, pumps, piping, turbine, and main radiator, that is, all the components necessary ahead of the electrical generator shaft, have been designated the shaft supply system. A specific weight W_{ss} in pounds per megawatt may be assigned to this system. The weight of this system will be raised by the generator inefficiency, as more than 1 megawatt of mechanical power will be necessary to deliver 1 megawatt of electrical power. Also, there is an additional weight penalty due to the speed of the generator; higher speed turbines are more efficient. The inefficiency and the speed penalty may be combined in an additional weight penalty factor α. The total systems weight is given by

$$W_T = W_{ss}(1 + \alpha) + W_{gs} \tag{8}$$

where the weight assigned to the generator is given by $W_{gs} + \alpha W_{ss}$.

Table II shows that the superconducting magnet generators have the lowest value of α. In this computation and all others which include α, it is assumed that the turbine efficiency is 84 percent at 20 000 rpm and that it decreases 1 percent for every drop of 5000 rpm; thus,

$$1 + \alpha = \frac{1}{X} \frac{84}{80 + 2N}$$

Expected values of SNAP-50 would be a shaft supply weight of 15 000 to 30 000 pounds for 1 megawatt of power on a 20 000 rpm shaft (ref. 1). Table III gives the total system weight with various generators for two shaft supply weights. This table includes the aforementioned additional weight penalty. Table III makes it clear that for lightweight shaft supply systems the superconducting generators are more attractive, because a larger percentage of the total system weight may be saved.

For larger amounts of power, the possible parallel operation of generators looks attractive, since the generation system reliability is increased. If a larger cryogenic refrigeration system is used, a lower specific weight for it may be taken. Figure 13 shows the effect on weight attributed to the generator, including the additional weight penalty, as 1-megawatt generation systems are paralleled, and one larger cryogenic refrigerator is employed.

OFF-DESIGN SYSTEMS

Five generator systems were considered in the parametric off-design analysis of appendix D:

(1) A 400-hertz homopolar generator (ref. 52)

(2) A 1000-hertz homopolar generator (ref. 52)

(3) A 400-hertz wound-rotor, brushless generator (appendix B)

(4) A dc superconducting magnet generator with a conduction-cooled shaft (appendix C)

(5) A dc superconducting magnet generator with a liquid-cooled shaft

The ac superconducting magnet generator was not considered, as the trends are the same for the dc systems with the weight difference a constant amount above the dc curves. The shaft supply system weight is taken as 17 000 pounds for 1 megawatt at 20 000 rpm. Four off-design parameters were considered:

(1) Rotational speed (fig. 14)

(2) Frictional heat generated (fig. 15)

(3) Copper and core heat generated (fig. 16)

(4) Radiator temperature (fig. 17)

In addition, a number of assumptions were made as to the functional variation of losses and weights with these parameters. These assumptions are listed in appendix D.

The variation of total system weight with generator speed is shown in figure 14. In addition, base weight, which is the weight for a 100-percent-efficient, zero-weight generator, is shown. Also shown are the maximum allowable speeds due to rotor stress limitations. The limitations were taken from extrapolation of data in reference 52 for the homopolar generators and from data in appendixes B and C for the other generators.

The variation of total systems weight with shaft friction is shown in figure 15. The values are shown over a wide range of this parameter, as the values calculated for design have a large margin of error. The curve for the conduction-cooled superconducting magnet generator rises more sharply than the others because of the effect of the commutator friction on the rotor temperature and the heat leakage to the superconducting magnet.

The variation of total systems weight with copper and core losses is shown in figure 16. The low values of these losses for the superconducting magnet generator are due to the fact that there is no iron or steel in the rotor or the rotor shaft. The very sharp rise of the conduction-cooled generator is due to the adverse effect of the rotor heating on the rotor temperature.

The variation of total systems weight with radiator temperature is shown in figure 17. All the curves have a shallow minimum in the range 475° to 540° K. The calculated points have a discontinuity at 540° K (smoothed in the figure) due to a change in design assumptions.

CONCLUDING REMARKS

Apparently, efficiency gains and weight reduction can be made by using a superconducting magnet generator system over usual turboelectric rotating generation systems.

The major problems of the superconducting magnet generator are (1) the necessity of refrigerating the superconducting components, (2) the use of brushes and commutators or slip rings in a space environment, and (3) the construction of a rotor shaft which is electrically insulating and thermally conducting. The weight reliability and efficiency of cryogenic refrigerators must reach the values of those proposed for future space use. All turboelectric rotating generation systems must employ high-speed, low-loss bearings in a vacuum and have rotors operating close to the maximum stress limit.

In the superconducting magnet generator, any loss which increases the rotor temperature and thus increases the radiation to the superconducting magnet must be minimized because of the high weight penalty for losses at cryogenic temperatures (figs. 4, 15, and 16).

The direct-current superconducting magnet generator has the potential of being the best electrical system of those considered for electropropulsion missions, since it is efficient, lightweight, and requires no power conditioning equipment and minimal turbine control. The oil-cooled rotor version of the superconducting magnet generator looks attractive, but the conduction-cooled rotor version is favored because of the removal of the shaft coolant seals. The proposed dc superconducting model in this report is 1 megawatt, 10 000 rpm, and 5000 volts, direct current. The generation system efficiency of the conduction-cooled-rotor, superconducting magnet generator is 96.5 percent. The preceding generator weight, including shaft, bearings, and commutator is 410 pounds, while the cryogenic refrigerator weighs 450 pounds. For a shaft supply weight of 20 000 pounds for 1 megawatt, the total system weight for 1 megawatt of electrical power is 22 750 pounds. The weight which may be attributed to the generator represents 13 percent of the total system weight. An ac superconducting generator is also attractive, but when dc power is required, additional weight is necessary (about 450 lb) for the conditioning and larger heat rejection system.

Table III indicates that as lower specific weights of shaft supply systems are reached, a greater percentage of the total system weight will be saved by using superconducting generators. Since cryogenic refrigeration specific weight is decreased for larger refrigeration requirements, the superconducting magnet generator looks attractive for parallel operation since the specific system weight decreases (fig. 13).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 17, 1965.

APPENDIX A

SYMBOLS

A ampere conductors per meter of stator bore periphery

a area, sq m

B flux density, Wb/sq m

B_g flux density in air gap, Wb/sq m

d rotor or stator diameter, m

E voltage, V

f frequency, Hz

H heat, kW

H_E electrical heat generated (copper and core loss), kW

$H_{E,0}$ design copper and core loss, kW

H_F frictional heat generated, kW

$H_{F,0}$ design frictional heat, kW

I current, A

I_{LN} line to neutral current, A

ℓ stator or rotor length, m

M number of series-connected active conductors per phase

m number of turns

N speed, revolutions/10^{-4} min

n speed, revolutions/min

P number of poles

P_{Cu} copper loss, kW

P_e eddy current loss, kW

P_f field power loss, kW

P_g generator power, kVA

P_h hysteresis loss, kW

r wire radius, m

s number of parallel paths

T temperature, $^{\circ}K$

T_e rotor temperature, $^{\circ}K$

T_R radiator temperature, $^{\circ}K$

t lamination thickness, m

V_{LN} root-mean-square voltage, line to neutral

W weight, lb

ΔW weight difference, lb

W_{gs} generation system weight, lb/MW

W_{ss} shaft supply weight, lb/MW

W_T total weight, lb/MW

X total electrical generation system efficiency

Z active number of conductors

α additional weight penalty factor

ϵ emissivity

η refrigeration efficiency

η' Steinmetz coefficient

ρ resistivity, ohm-m

φ flux per pole, Wb

APPENDIX B

DESIGN OF ALTERNATING-CURRENT, WOUND-POLE, BRUSHLESS GENERATOR

The first step in machine design is to use the following method to determine the machine size: Since

$$P_g = \frac{(d^2 \ell) n B_g A}{9\times10^3} \tag{1}$$

the following equation can be developed:

$$d_2^2 \ell_2 = \frac{P_{g,2}}{P_{g,1}} \frac{n_1}{n_2} \frac{A_1}{A_2} d_1^2 \ell_1$$

where the subscript 2 is the designed generator and the subscript 1 represents the generator in table I. The term $d^2\ell$ is proportional to the electromagnetic volume weight.

An 8000-rpm alternator is assumed where $A_1/A_2 = 0.72$ (ref. 54, p. 793). Since the rest of the data are presented in table I, a 1-megawatt machine design weight of 960 pounds and $d^2\ell$ of 2.95×10^{-2} cubic meter can be considered. A wound-pole machine has a maximum peripheral speed of about 77.5 meters per second, which yields a rotor diameter of 0.183 meter and a length of 0.88 meter. The ion engine load is considered resistive, and a power factor of 0.95 is assumed.

The ac wound-pole designed generator ratings are as follows:

Power (at 0.95 power factor), kW	1000
Speed, rpm	8000
Frequency, Hz	400
Poles	6
Total weight, lb	1060
Exciter, rectifier, and regulator weight, lb	50
Generator weight, lb	960
Rectifier efficiency, percent	>90
$d^2\ell$, cu m	2.95×10^{-2}
Rotor weight, lb	380
Wound stator weight, lb	310

Electromagnetic weight, lb	690
Voltage, V	2150

The next important design consideration is to evaluate the various losses in the generator.

The hysteresis loss P_h is computed as follows:

$$\frac{P_h}{\text{Magnetic volume}} = 2.5\times10^5 \eta' B^{1.6} f \qquad \text{(W/cu m)}$$

where $\eta' = 0.00046$ for silicon sheet steel (ref. 55, pp. 15 to 23). If $B = 1.2$ webers per cubic meter and $f = 400$ hertz,

$$\frac{P_h}{\text{Stator volume}} = 1.34\times10^5 \qquad \text{(W/cu m)}$$

$$P_h = 3.2 \qquad \text{(kW)}$$

The field power loss $P_{f,2}$ is

$$P_{f,2} = \frac{d_2^2 \ell_2}{d_1^2 \ell_1} P_{f,1} = 5.06 \qquad \text{(kW)}$$

The eddy current loss P_e is (ref. 54, p. 49)

$$\frac{P_e}{\text{Eddy current volume}} = \frac{(\pi t f B)^2}{6\rho} \qquad \text{(W/cu m)}$$

Steel with 4 percent silicon has a resistivity ρ of 51×10^{-4} ohm-meter, and laminations will be assumed 3.5×10^{-4} meter thick (ref. 55, p. 158).

$$\frac{P_e}{\text{Stator volume}} = 9.6\times10^4 \qquad \text{(W/cu m)}$$

$$P_e = 2.3 \qquad \text{(kW)}$$

The stray loss compensates for additional eddy current loss in stator teeth, the iron loss due to the stator current, the end finger loss, the rotor surface loss, and damper winding loss. This loss is proportional to the current squared of a generator; for example, for the designed generator (ref. 54, p. 685),

$$I_{LN} = \frac{10^6}{3V_{LN}} = 155 \qquad \text{(A)}$$

Therefore,

$$\text{Stray loss} \approx 2.1 \qquad \text{(kW)}$$

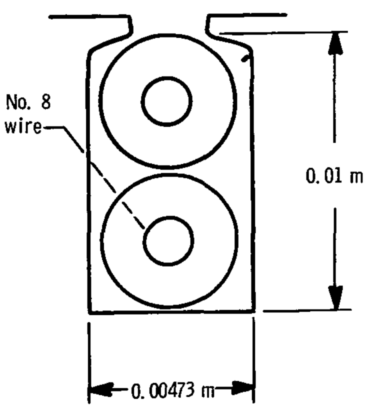
The copper loss can be computed as follows: The full-pitch voltage generation equation comes from reference 54 (p. 648):

$$E = 2.1\ f\varphi M$$

Pole area, sq m	0.0845
Pole strength, Wb	0.0707
Voltage, V	2150

Therefore,

Number of series-connected active conductors per phase, M	38
Actual turns	$38 \times 3 = 114$
Number of double slots	6 poles × 3 phases × 4 conductors/phase = 72



(a) Slot dimensions.

If a total slot width of 0.6 πd is assumed, slot dimensions can be constructed as shown in sketch (a). Polyimide insulation will be used on the windings for 270° C operation for 10 000 hours. Polyimide insulates at 300 volts per mil.

$$\text{Test insulation} = 2E + 1000 \qquad \text{(V)}$$

$$\simeq 6000 \qquad \text{(V)}$$

Insulation must therefore be 20 mils, and the wire size is 0.00345 meter in diameter (i.e., no. 8 wire), with a resistance of 2.1×10^{-3} ohm per meter. Resistance per phase is 0.235 ohm at 540° K, and P_{Cu} is 17.0 kilowatts.

The stray loss is split equally between the stator and the rotor. All the hysteresis and eddy current is attributed to the stator, which is nearly correct. All the copper loss is in the stator, while all the field loss is in the rotor.

The rectifiers on the shaft have rectification efficiencies above 90 percent and thereby present a 0.5-kilowatt loss, while the copper loss of the exciter is also near 0.5 kilowatt. The permanent magnet stator and exciter field have been given a loss of 1.0 kilowatts.

The calculated efficiency of this generator is from an idealized model. Eddy current loss in the conductors was not taken into account, as well as a few additional losses, and a practical generator at this speed and frequency would be less efficient. The purpose of this design is to act as a calculated comparison for the superconducting generator systems.

APPENDIX C

DESIGN OF ALTERNATING- AND DIRECT-CURRENT SUPERCONDUCTING GENERATORS

As in appendix B, the following equation may be developed from equation (1):

$$d_2^2\ell_2 = \frac{P_{g,2}}{P_{g,1}}\frac{n_1}{n_2}\frac{A_1}{A_2}d_1^2\ell_1$$

where the subscript 2 is the designed generator and the subscript 1 represents the generator in table I.

It is shown in reference 56 that the weight of a dc machine is 1.7 the weight of an ac machine. From this fact, the preceding equation is modified to

$$d_2^2\ell_2 = 1.7\frac{P_{g,2}}{P_{g,1}}\frac{n_1}{n_2}\frac{A_1}{A_2}d_1^2\ell_1$$

A 10 000-rpm dc generator is assumed where $A_1/A_2 = 0.72$ (ref. 54, p. 793). Since the rest of the data are presented in table I, a 1-megawatt electromagnetic machine design volume of 4.4×10^{-3} cubic meter can be considered. The rotor is made of alumina, and the rotor size is 0.190 meter in outside diameter. The average size of the winding is 0.153 meter in diameter and 0.190 meter long.

The dc superconducting designed generator ratings are as follows:

Power (at 0.95 power factor), kW	1000
Speed, rpm	10 000
Rotor weight, lb	90
Shaft weight, lb	90
Commutator weight, lb	30
Superconducting magnet weight, lb	150
Dimensions of rotor	
Outside diameter, m	0.190
Length, m	0.190
$d^2\ell$ of rotor, cu m	5.24×10^{-3}
Voltage, V	5000

If a conventional lap or wave winding is assumed, the generated voltage equation becomes (ref. 57, p. 56)

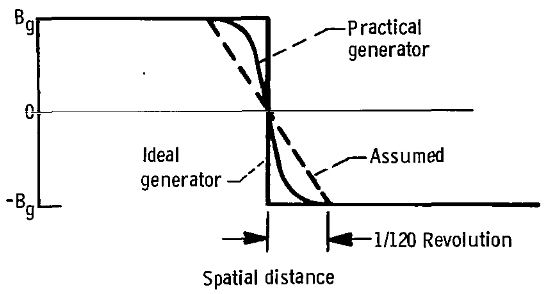
$$E = \frac{\varphi ZnP}{60s}$$

Since $B_g = 10$ webers per square meter and the pole area with an average winding is 0.0360 square meter, $\varphi = 0.36$ weber. With $E = 5000$ volts, P and $s = 2$; at 10 000 rpm, 67 armature conductors are necessary. In this design there are 35 slots, with 70 active conductors and 35 commutator bars.

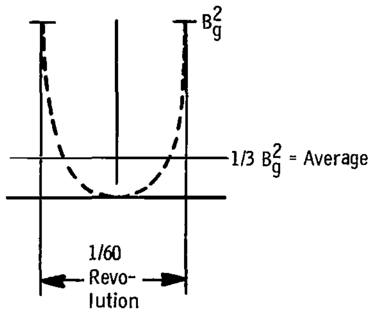
The slot cross section is shown in figure 9. The slot is assumed to be split into two equal 2.13×10^{-4}-square-meter areas, and a 0.8 winding factor is assumed. The eddy current loss in wire is given in reference 54 (p. 49) by

$$\frac{P_e}{\text{Rotor volume}} = \frac{(\pi r f B)^2}{4\rho} \qquad \text{(W/cu m)}$$

In a dc generator a flux switching action takes place, as shown in sketches (b) and (c). It is desired to calculate an effective eddy current loss due to this flux switching. The



(b) Spatial flux distribution.



(c) Varying squared flux.

value B is made with the assumption that the eddy circulating current is equal to the generated current during the flux transition period. The effective squared flux B^2 necessary in an eddy-current-loss calculation is 0.01 B_g^2 from sketches (b) and (c). Calculations assuming a 10-percent nonuniform field distribution yield a smaller effective B, and the previously calculated value is used. With a maximum gap field of 100 kilogauss,

$$\frac{P_e}{\text{Slot}} = 2.24\,\frac{r^2}{\rho} \qquad \text{(W/Slot)}$$

The copper loss is given by

$$\frac{P_{Cu}}{\text{Slot}} = 1.09\times10^{7}\,\rho \qquad \text{(W/Slot)}$$

The total eddy current and copper loss is

$$P_e + P_{Cu} = 156\,\frac{r^2}{\rho} + 7.65\times10^{8}\,\rho \qquad \text{(W)}$$

Investigation for the minimum total loss yields

$$\rho = 4.53\times10^{-4}\,r$$

For copper,

$$\rho = 2.8\times10^{-8} \qquad \text{(ohm-m)}$$

The total loss is kept beneath 150 watts with small diameter wires. With a loss of only 150 watts, no shaft seal for cooling is necessary, but all the heat loss may be extracted through the bearings. Actually, it is shown later that about a 400-pound weight saving may be made with shaft seals and a coolant, but the conduction-cooled model previously mentioned will be recommended because of its simplicity.

$$r = 0.000152 \text{ m}$$

The superconducting magnet design will now be considered (ref. 58, p. 588).

$$B = \frac{\varphi}{a} = \frac{4\pi\times10^{-7}\,mI}{\ell}$$

With the assumption that the flux density of typical superconducting cable, which at present has a critical flux density of 4 webers per square meter, will be extended to 10 webers per square meter, the magnet design may be made. The length of the magnet wire necessary is 1.5×10^{4} meters. The weight of the magnet and the required jacket is 150 pounds (fig. 10). The shielding jacket is stainless steel (ϵ = 0.048 at 76° K), while the rotor is plated aluminum with a 0.25-μ thickness of oxide (ϵ = 0.06 at 311° K)(ref. 59, p. 348).

Effective values of emissivity may be calculated by use of the following equations:

$$\epsilon_{\text{Parallel plates}} = \frac{\epsilon_i \epsilon_o}{\epsilon_o + (1 - \epsilon_o)\epsilon_i}$$

where the subscripts i and o denote inner and outer, respectively (ref. 59, p. 148).

$$\epsilon_{\text{Long coaxial cylinders}} = \frac{\epsilon_i \epsilon_o}{\epsilon_o + \frac{a_i}{a_o}(1 - \epsilon_o)\epsilon_i}$$

The emissivity ϵ of the shaft is assumed to be 1.0.

The radiated heat lost is calculated by application of the previous formulas to the rotor outside area, the rotor ends, and the shaft.

$$H \approx 9.4\times10^{-3} \left(\frac{T_e}{350}\right)^4$$

From this equation it can be seen that about 10 watts of heat are radiated at a rotor temperature of 350° K. The thermal conductivity of the outer insulation must also be calculated. Since 80-mesh perlite with a conductivity of 1×10^{-3} watt per meter - degree Kelvin (ref. 59) is used, a calculation of heat leak yields 0.75 watt for a temperature change of 300° K and a 0.1-meter perlite thickness.

The eight support wires (0.00127-m diam. or equivalent cross section) provide a heat leak of 0.5 watt. The total heat lost is the sum of these terms. The I^2R and contact loss for the required brushes is less than 0.5 kilowatt.

An ac, 166-hertz, 10 000-rpm superconducting alternator with slip rings will now be designed. From the sizing equation, it should be noted that the ac generator would be slightly smaller than the dc model, but the sinusoidal flux distribution results in a more complex superconducting magnet.

The ac superconducting designed generator ratings are as follows:

Power (at 0.95 power factor), kW	1000
Speed, rpm	10 000
Frequency, Hz	166
Poles	2
Rotor weight, lb	80

Shaft weight, lb	90
Superconducting magnet weight, lb	160
Dimensions of rotor	
Outside diameter, m	0.178
Length, m	0.178
Voltage (line to neutral), V	2150

The full-pitch voltage is, as in appendix B (ref. 54, p. 648),

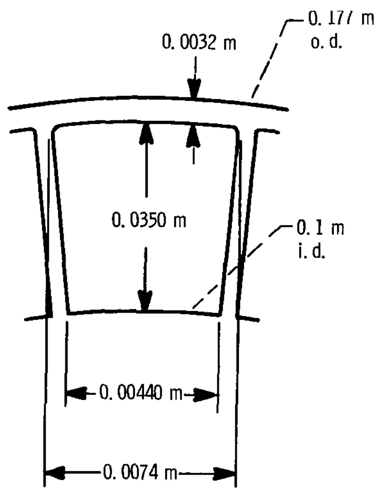
$$E = 2.1\, f\varphi M$$

Pole area, sq m	0.05
Pole strength, Wb	0.33
Voltage, V	2150

Therefore,

Number of series-connected active conductors per phase, M	17
Number of actual necessary turns	51
Number of slots	2 poles × 3 phases × 9 conductors/phase = 54

The slot detail is shown in sketch (d). The slot cross section yields an area of 0.000213 square meter. The same assumptions used in the dc machine are applied, and a 0.8 winding factor is assumed.



(d) Slot detail.

$$\frac{P_e}{\text{Slot}} = 2.2\frac{r^2}{\rho} \qquad (\text{W/Slot})$$

$$\frac{P_{Cu}}{\text{Slot}} = 2.5\times10^7\,\rho \qquad (\text{W/Slot})$$

$$P_e + P_{Cu} = \text{Total loss} = 119\frac{r^2}{\rho} + 1.35\times10^9\,\rho \qquad (\text{W})$$

$$r = 0.000167 \text{ m}$$

The smaller generator size results in about 1 watt less of cryogenic refrigerator power. The slip ring friction, resistance, and contact losses are about one-half the dc counterparts. In this ac superconducting model, again, design has been made by use of a solid alumina shaft and a rotor loss of 150 watts. The heat leak from the turbine is 80 watts. By using a coolant and shaft seals, about a 400-pound weight saving could be made when the additional weight penalty is included.

APPENDIX D

PARAMETRIC OFF-DESIGN ANALYSIS

Five generator systems are considered in the off-design analysis:

(1) A 400-hertz, 12 000-rpm homopolar generator

(2) A 1000-hertz, 20 000-rpm homopolar generator

(3) A 400-hertz, 8000-rpm wound-rotor brushless generator

(4) A dc 10 000-rpm dc superconducting magnet generator with conduction cooling of the rotor

(5) A dc 10 000-rpm dc superconducting magnet generator with liquid cooling of the rotor

Four off-design parameters are considered:

(1) Rotational speed

(2) Frictional heat generated

(3) Copper and core losses

(4) Radiator temperature

Assumptions

In order to simplify the analysis, certain assumptions were made as to the functional variation of the losses and the weights with the preceding parameters. Among these assumptions were the following:

(1) Turbine efficiency is approximately equal to $0.80 + 0.02\ N$, where N is speed in rpm/10 000.

(2) Refrigerator efficiencies are those given by equations (2), (3), and (4).

(3) Bearing loss is proportional to N.

(4) Seal, commutator, and slip-ring losses are proportional to N^2.

(5) Hysteresis and eddy-current loss is proportional to N/T.

(6) I^2R copper loss is proportional to T/N.

(7) Rotor temperature for conduction-cooled generator is approximately equal to

$$\text{Bearing temperature} + \frac{\text{Rotor heat} \times 10^3 - 10}{1.17} + 14 \times \text{Commutator loss}$$

(8) Rotor temperature for all other generators is approximately equal to bearing temperature.

(9) Loss to superconducting magnet in kilowatts is approximately equal to

$$9.4\times10^{-3}\left(\frac{0.75}{N}+0.25\right)\left(\frac{T_e}{350}\right)^4+10^{-3}$$

(10) Specific weight of 4.2° to 350° K refrigerator in pounds per kilowatt is approximately equal to $35.4/\eta$.

(11) Specific weight of 100° to 300° K refrigerator and piping in pounds per kilowatt is approximately equal to $25.0/\eta$.

(12) Specific weight of 350° K to radiator temperature heat pump in pounds per kilowatt is approximately equal to $8/\eta$.

(13) Specific weight of pump at radiator temperature in pounds per kilowatt is approximately equal to 5.

(14) Specific weight of radiator for $540^{\circ} > T_R > 350^{\circ}$ K is approximately equal to $28.6\,(350/T_R)^4$.

(15) Specific weight of radiator for $950^{\circ} > T_R > 540^{\circ}$ K is approximately equal to $31.0\,(350/T_R)^4$.

There are also temperature limitations which must be considered:

(1) The bearing temperatures are between 200° and 540° K.

(2) All controls, rectifiers, etc., are at 350° K or below.

(3) All generator parts are below 540° K.

Effect of Rotational Speed

The variation of system weights with rotational speed is shown in figure 14. Also shown are the theoretical rotational speed limits.

Generator data for the homopolar generators were taken from values in reference 52 for the speeds shown. To these values bearing and seal losses were added. The resultant forms for the equation are

For generator 1, at 8000 rpm:

ΔW = Added motor weight + Speed penalty + Penalty for generator losses

+ Bearing and seal loss penalty

$\simeq -320$ (lb)

The weight and losses at 8000 rpm were scaled from the 600-kilovolt-ampere generator of reference 52.

For generator 2:

ΔW = Added motor weight + Speed penalty + Penalty for generator losses

+ Bearing and seal loss penalty

$\simeq 365$ (lb)

The wound-rotor brushless generator data were taken from the system analysis given in appendix B. The resultant equation is

For generator 3:

ΔW = Added generator weight + Speed turbine penalty

+ Generator and seal loss penalty at 350° K + Generator loss penalty at 540° K

$$\simeq 910\left[\left(\frac{0.8}{N}\right)^{2/3} - 1\right] + 400(0.8 - N) + 93.1\left[\left(\frac{N}{0.8}\right)^{2} - 1\right] + 178\left(\frac{N}{0.8} - 1\right) + 831\left(\frac{0.8}{N} - 1\right)$$

The dc superconducting magnet generator data were taken from the system analysis given in appendix C. The resultant equations are

For generators 4 and 5:

$\Delta W \simeq$ Added motor weight + Speed turbine penalty

+ Generator bearing, seal, and electrical loss penalty at rotor temperature

+ Penalty for superconducting refrigerator loss due to magnet size change

and rotor temperature change

For generator 4:

$$\Delta W \simeq 122\left(\frac{1}{N} - 1\right) + 400(1 - N) + 166.6\left[2.56(N - 1) + 0.015\left(\frac{1}{N} - 1\right)\right]$$

$$+ 240\left[9.4\,\varphi(N)\left(\frac{T_e}{350}\right)^{4} + 1\right]^{2/3} - 1070$$

For generator 5:

$$\Delta W \simeq 122\left(\frac{1}{N} - 1\right) + 400(1 - N) + 166.6\left[1.95\,(N^2 - 1) + 1.78(N - 1) + 0.015\left(\frac{1}{N} - 1\right)\right]$$

$$+ 240\left[9.4\,\varphi(N)\left(\frac{200}{350}\right)^4 + 1\right]^{2/3} - 374$$

where

$$\varphi(N) = \frac{0.75}{N} + 0.25$$

and

$$T_e \simeq 200 + \left[150\left(0.90\,N + \frac{0.10}{N}\right) - 10 + \frac{20N}{\varphi(N)}\right]\frac{\varphi(N)}{1.17}$$

Effect of Friction

The variation of system weights with shaft friction is shown in figure 15.

With the exception of the conduction-cooled superconducting magnet generator, the formulation for variation of weight with frictional heat is straightforward, since it is the penalty for loss at the temperature generated. The resulting equations are

For generators 1 and 2:

$$\Delta W \simeq 28.0(H_F - H_{F,0})$$

For generator 3:

$$\Delta W \simeq 52.5(H_F - H_{F,0})$$

For generator 5:

$$\Delta W \simeq 112.9(H_F - H_{F,0})$$

where $H_F - H_{F,0}$ is the frictional heat difference from the design value.

The conduction-cooled superconducting magnet generator has a more complex form:

For generator 4:

$\Delta W \simeq$ Weight penalty due to frictional heat generated at shaft temperature

+ Weight penalty due to increased radiation to magnet due to increased rotor temperature (assumption (7))

$$\simeq 112.9\left(H_F - H_{F,0}\right) + 240\left[9.4\left(\frac{320 + 20\dfrac{H_F}{H_{F,0}}}{350}\right)^4 + 1\right]^{2/3} - 1070$$

Effect of Copper and Core Losses

The variation of system weights with shaft friction is shown in figure 16. Again, the formulation is simple except for the dc superconducting magnet generator with conduction cooling. The resulting equations are

For generators 1 and 2:

$$\Delta W \simeq 28.0\left(H_E - H_{E,0}\right)$$

For generator 3, since some heat is generated at 350° K and other heat is generated at 540° K:

$$\Delta W \simeq 28.0\left[7.1\left(\frac{H_E}{H_{E,0}} - 1\right)\right] + 52.5\left[23.6\left(\frac{H_E}{H_{E,0}}\right) - 1\right]$$

For generator 5:

$$\Delta W \simeq 112.9\left(H_E - H_{E,0}\right)$$

For generator 4:

$\Delta W \simeq$ Weight penalty due to increased rotor heat

+ Increased weight penalty due to increased radiation to magnet

$$\simeq 112.9(H_E - H_{E,0}) + 240\left[9.4\left(\frac{240 + 120\dfrac{H_E}{H_{E,0}}}{350}\right)^4 + 1\right]^{2/3} - 1070$$

Effect of Radiator Temperature

The variation of system weight with radiator temperature is given in figure 17. In the formulation of the effect of radiator temperature it is the equations for the first three generator systems at radiator temperatures below 540° K which become complex. This complexity is due to the temperature limitation of 540° K set on generator parts. Below this temperature those parts designed at 540° K will be assumed to be at the radiator temperature. The major terms in all equations are the weight penalty for the heat pump up to T_R (a term proportional to T_R) and the radiator weight penalty (a term proportional to T_R^{-3}). The resultant equations are

For generator 1, below 540° K:

$$\Delta W \simeq 2141\left(\frac{T_R}{540} - 1\right) + 676\left(\frac{540}{T_R} - 1\right) + 553\left[\left(\frac{540}{T_R}\right)^3 - 1\right] + 7.8\left[\left(\frac{540}{T_R}\right)^4 - 1\right] + 180\left[\left(\frac{540}{T_R}\right)^5 - 1\right]$$

For generator 1, above 540° K:

$$\Delta W \simeq 3240\left(\frac{T_R}{540} - 1\right) + 780\left[\left(\frac{540}{T_R}\right)^3 - 1\right] + 440$$

For generator 2, below 540° K:

$$\Delta W \simeq 971\left(\frac{T_R}{540} - 1\right) + 576\left(\frac{540}{T_R} - 1\right) + 239\left[\left(\frac{540}{T_R}\right)^3 - 1\right] + 8.6\left[\left(\frac{540}{T_R}\right)^4 - 1\right] + 271\left[\left(\frac{540}{T_R}\right)^5 - 1\right]$$

For generator 2, above 540° K:

$$\Delta W \simeq 1864\left(\frac{T_R}{540} - 1\right) + 549\left[\left(\frac{540}{T_R}\right)^3 - 1\right] + 390$$

For generator 3, below 540° K:

$$\Delta W \simeq 1434\left(\frac{T_R}{540} - 1\right) + 148\left(\frac{540}{T_R} - 1\right) + 297\left[\left(\frac{540}{T_R}\right)^3 - 1\right] + 6.9\left[\left(\frac{540}{T_R}\right)^4 - 1\right] + 34.4\left[\left(\frac{540}{T_R}\right)^5 - 1\right]$$

For generator 3, above 540° K:

$$\Delta W \simeq 668\left(\frac{T_R}{540} - 1\right) + 338\left[\left(\frac{T_R}{540}\right)^3 - 1\right] + 120$$

For generator 4, below 540° K:

$$\Delta W \simeq 845\left(\frac{T_R}{540} - 1\right) + 198\left[\left(\frac{540}{T_R}\right)^3 - 1\right]$$

For generator 4, above 540° K:

$$\Delta W \simeq 845\left(\frac{T_R}{540} - 1\right) + 216\left[\left(\frac{540}{T_R}\right)^3 - 1\right]$$

For generator 5, below 540° K:

$$\Delta W \simeq 1240\left(\frac{T_R}{540} - 1\right) + 290\left[\left(\frac{540}{T_R}\right)^3 - 1\right]$$

For generator 5, above 540° K:

$$\Delta W \simeq 1240\left(\frac{T_R}{540} - 1\right) + 317\left[\left(\frac{540}{T_R}\right)^3 - 1\right]$$

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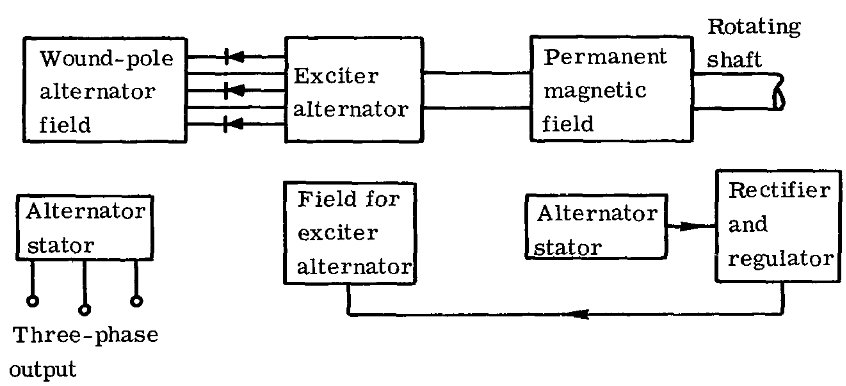
TABLE I. - ADVANCED HIGH-ALTITUDE, 400-HERTZ, WOUND-POLE, BRUSHLESS, AIRCRAFT GENERATOR RATINGS



Power (at 0.75 power factor), kW	60 (i.e., 80 kVA)
Speed, rpm	8000
Frequency, Hz	400
Total weight, lb	106
Case dimensions, m	
Outside diameter	0.228
Length	0.178
Rotor dimensions, m	
Outside diameter	0.152
Length	0.140
Electromagnetic value, $d^2\ell$, cu m	3.23×10^{-3}
Terminal voltage, V	120/208, three phase
Electromagnetic weight, lb	66
Field power (at 0.75 power factor), W	553
Efficiency at full load (at 0.75 power factor), percent	approx. 89
Temperature cooling oil, ^{o}K	approx. 425
Exciter winding temperature, ^{o}K	495
Generator winding temperature, ^{o}K	520

TABLE II. - SYSTEM WEIGHT COMPARISONS, NOT INCLUDING

WEIGHT PENALTY OF SHAFT SUPPLY SYSTEM

	Generator type				
	dc superconducting magnet (5 kV; 1 MW; 10 000 rpm)	ac superconducting magnet (2.15 kV line to neutral; 1 MW; 10 000 rpm; 166 Hz)	ac brushless wound pole (2.15 kV line to neutral; 1 MW; 8000 rpm; 400 Hz)	ac brushless homopolar inductor (2.15 kV line to neutral; 1 MW; 20 000 rpm; 1000 Hz)	ac brushless homopolar inductor (2.15 kV line to neutral; 1 MW; 12 000 rpm; 400 Hz)
Component weight, lb					
Rotor	90	90	------	------	------
Stator	150	150	1060	1090	3670
Shaft	90	90	60	60	60
Bearings and seals	50	50	180	140	140
Commutator or slip rings	30	30	------	------	------
Cryogenic refrigerator	450	420	------	------	------
Refrigerator, 200° to 350° K	90	70	310	------	------
Refrigerators and pumps, 350° to radiator temperature	100	130	120	450	600
Instrumentation and control	120	120	90	90	90
Battery for startup	50	50	------	------	------
Circuit breakers and switches	30	30	30	30	30
Exciter and voltage regulator	------	------	50	50	50
Dummy test load	10	10	10	10	10
Rectifier and shield	------	160	160	160	160
Radiator shield piping and deployment	210	280	380	460	650
Shaft clamp	50	50	50	50	50
Total weight of generation system	1520	1730	2460	2590	5510
Additional weight penalty factor, α	0.0616	0.0739	0.0990	0.0919	0.1593

TABLE III. - TOTAL SYSTEM WEIGHT FOR TWO SHAFT-SUPPLY-SYSTEM WEIGHTS

Shaft supply system, lb/MW	Generator type					
	dc superconducting magnet (5 kV; 1 MW; 10 000 rpm; oil-cooled rotor)	dc superconducting magnet (5 kV; 1 MW; 10 000 rpm; conduction-cooled rotor)	ac superconducting magnet (2.15 kV line to neutral; 1 MW; 10 000 rpm; 166 Hz; conduction-cooled rotor)	ac brushless wound pole (2.15 kV; line to neutral; 1 MW; 8000 rpm; 400 Hz; 350° K rotor)	ac brushless homopolar (2.15 kV line to neutral; 1 MW; 20 000 rpm; 500° K rotor)	ac brushless homopolar (2.15 kV line to neutral; 1 MW; 12 000 rpm; 400 Hz; 500° K rotor)
	Total system weight, lb/MW					
20 000	22 170	22 750	23 210	24 390	24 430	28 700
10 000	11 670	12 140	12 470	13 400	13 510	17 110
	Amount of total system weight attributed to generator, percent					
20 000	10	13	14	18	18	30
10 000	14	18	20	25	26	42

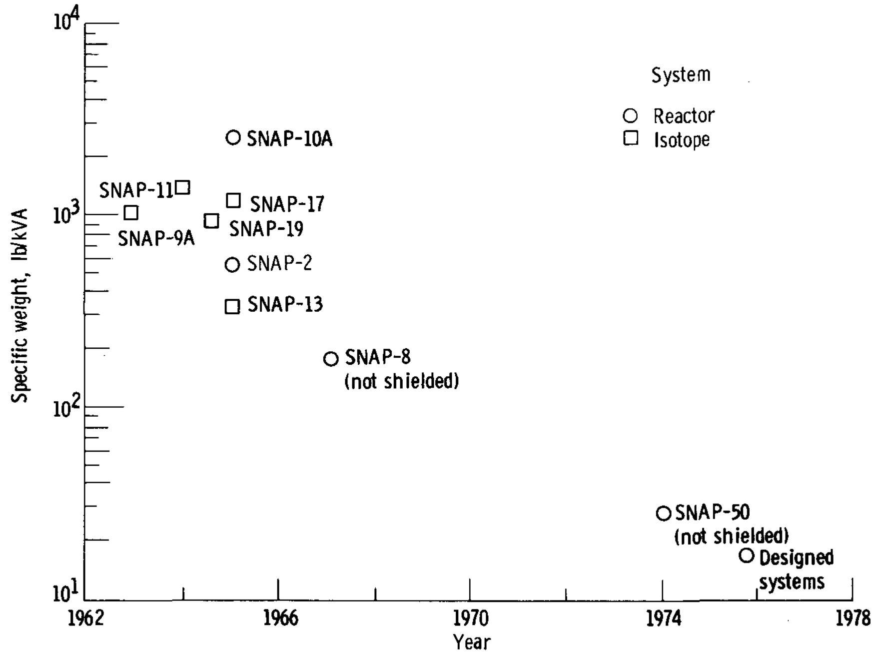


Figure 1. - Specific weight by year for nuclear-electric power systems.

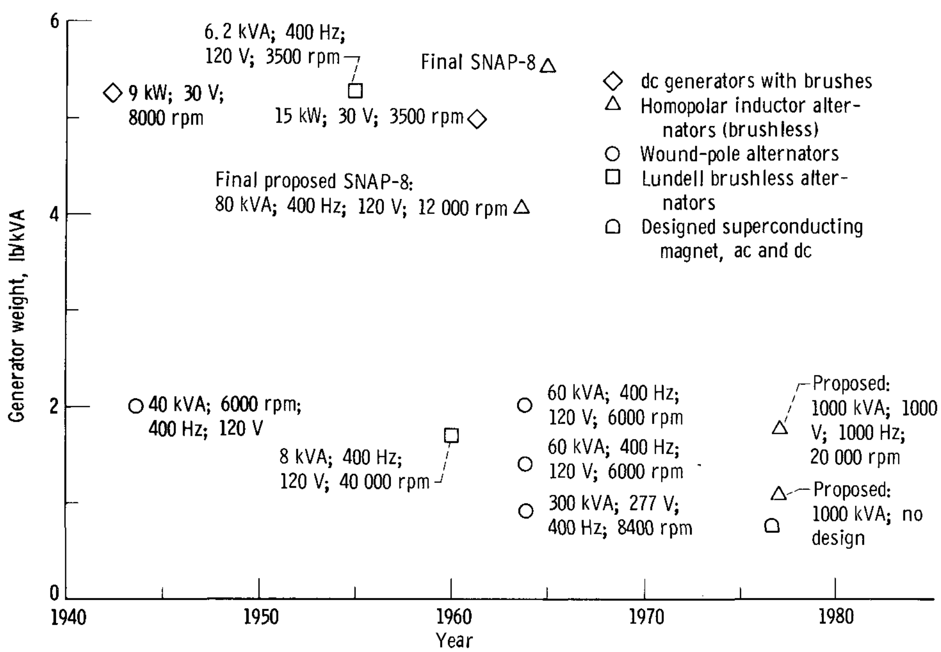


Figure 2. - Generator weight by year. Control and conditioning weight not included.

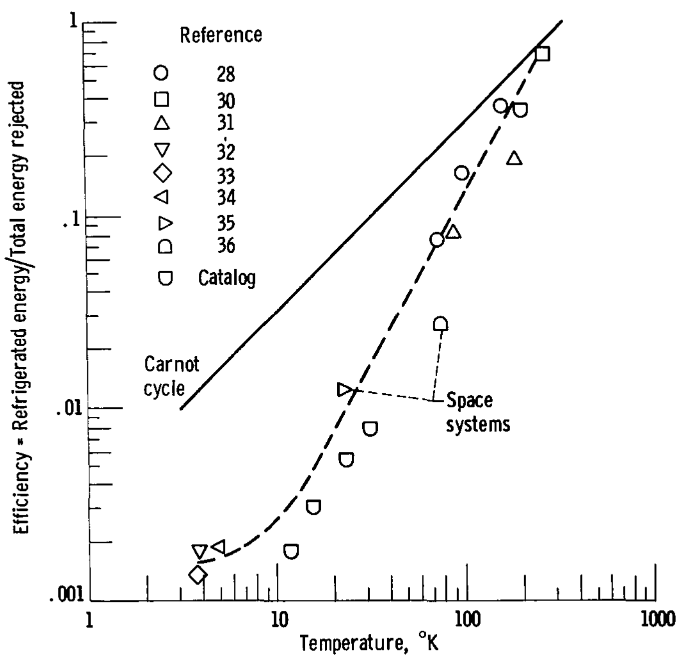


Figure 3. - Refrigeration system efficiency as function of temperature. Heat rejected at 350° K.

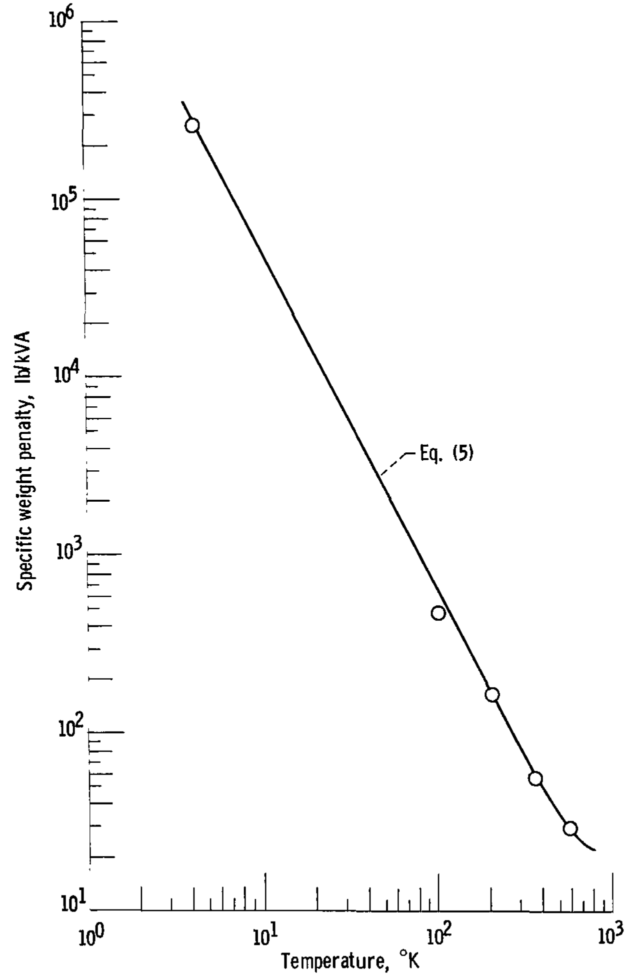


Figure 4. - Effect of temperature on specific weight penalty. Radiator temperature, 450° to 550° K; shaft supply weight, 17 400 pounds at 10 000 rpm.

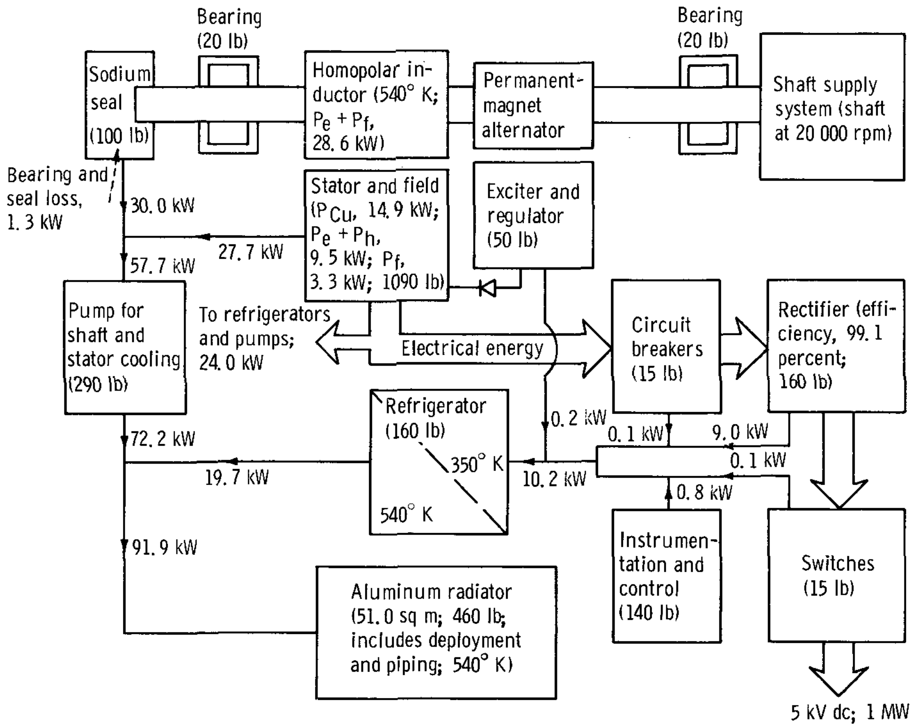


Figure 5. - One-line heat-flow diagram for electrical-generation system with typical homopolar-inductor, 20 000-rpm, 1000-hertz, 1-megawatt generator (ref. 52). Generation system efficiency, 91.5 percent.

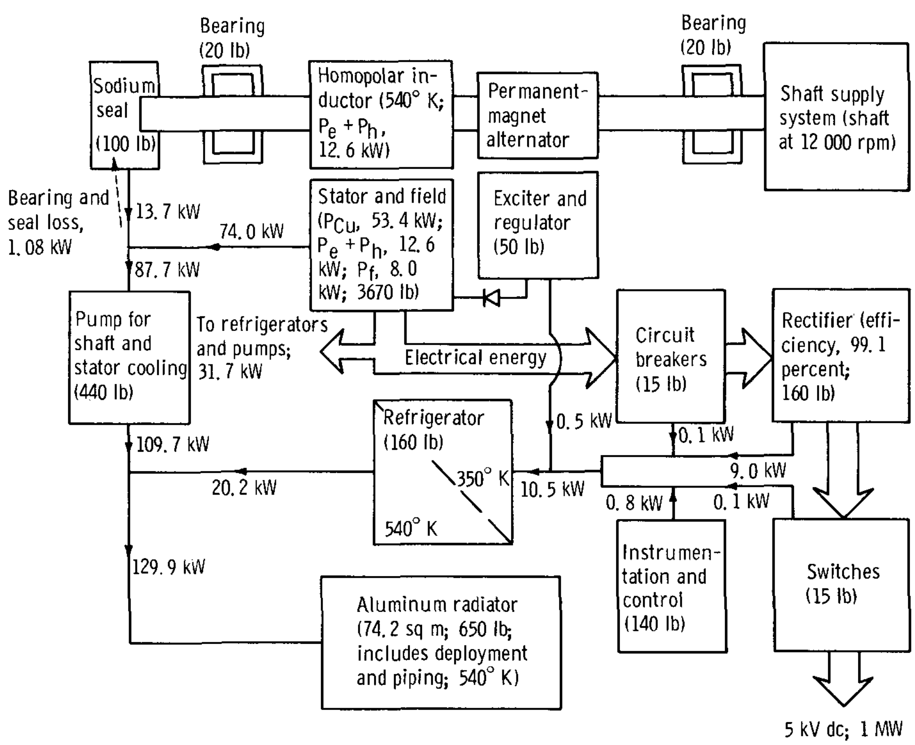


Figure 6. - One-line heat-flow diagram for electrical-generation system with typical homopolar-inductor, 12 000-rpm, 400-hertz, 1-megawatt generator (ref. 52). Generation system efficiency, 88.5 percent.

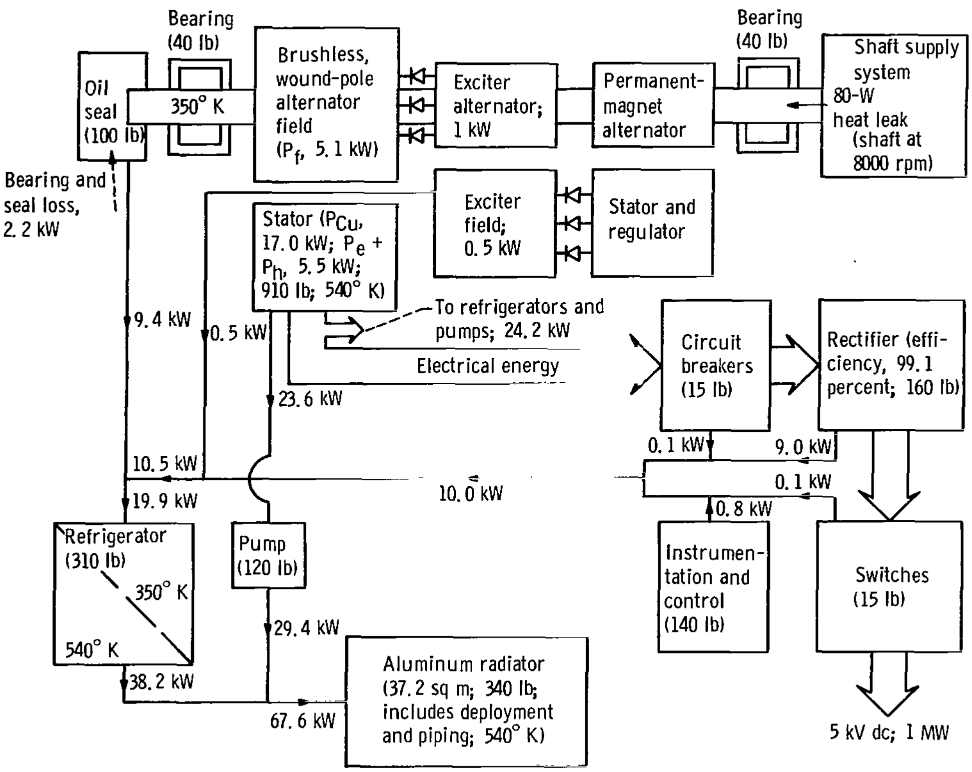


Figure 7. - One-line heat-flow diagram for electrical-generation system with brushless, wound-pole, 8000 rpm, 400-hertz, 1-megawatt alternator designed in appendix B. Generation system efficiency, 92.8 percent.

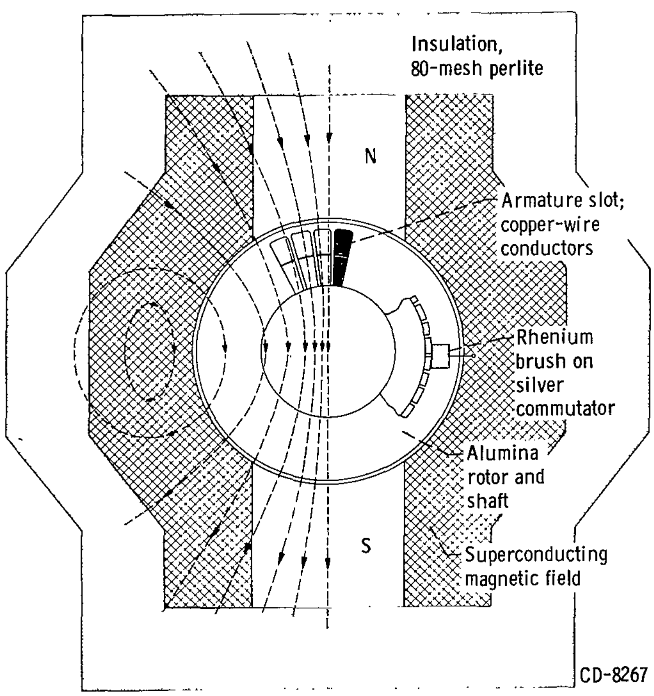


Figure 8. - Diagram of two-pole dc superconducting magnet generator. Field, 100 kilogauss.

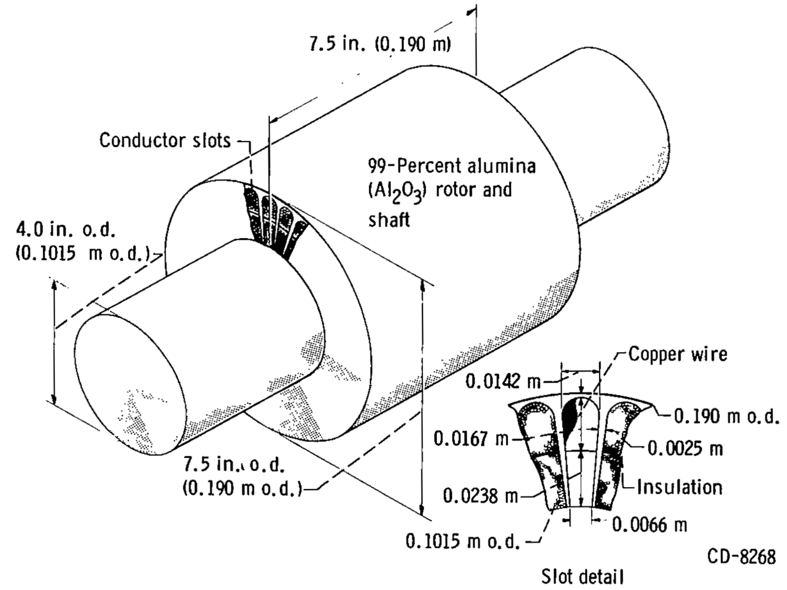


Figure 9. - Rotor construction of dc superconducting magnet generator.

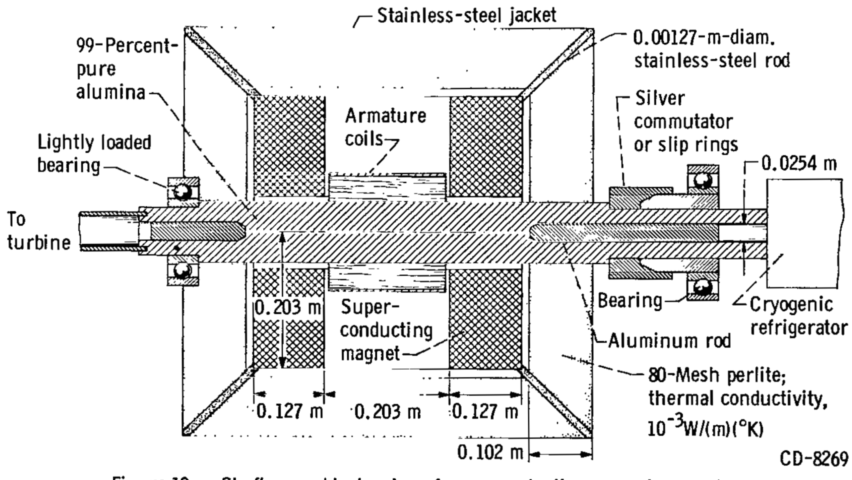


Figure 10. - Shaft assembly drawing of superconducting magnet generator.

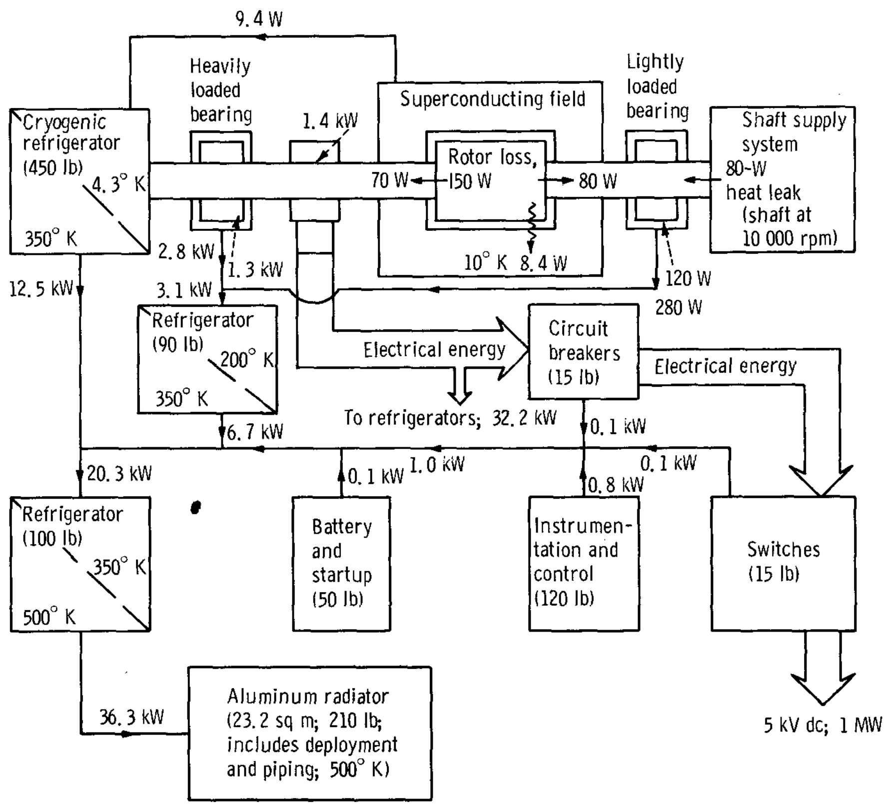


Figure 11. - One-line heat-flow diagram for electrical-generation system with brush-type-superconducting-magnet, 10 000-rpm, dc, 1-megawatt generator with conduction-cooled rotor. Generation system efficiency, 96.5 percent.

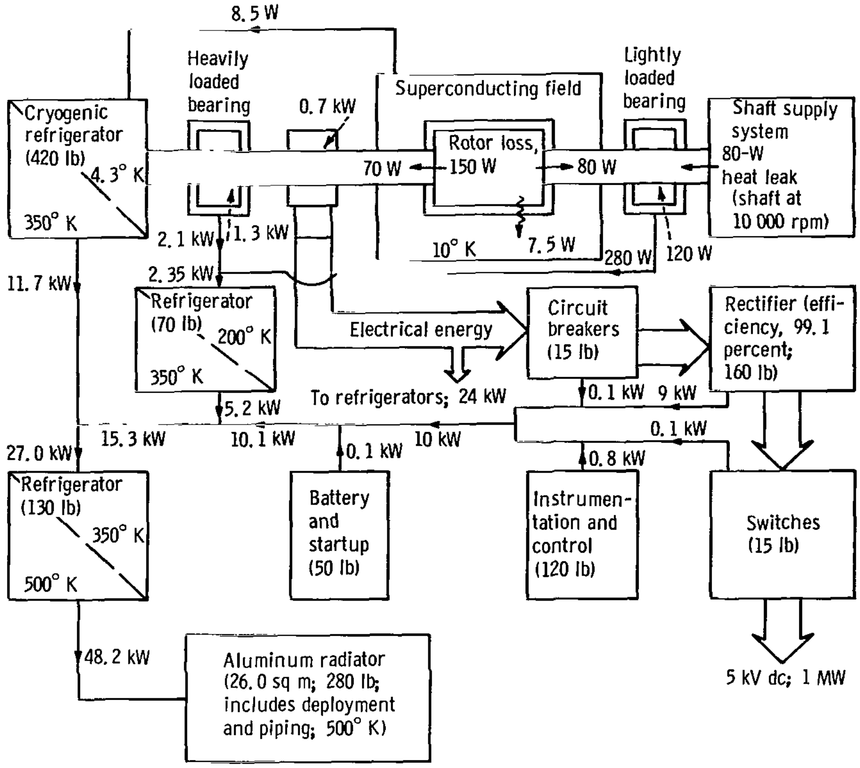


Figure 12. - One-line heat-flow diagram for electrical-generation system with brush-type-superconducting-magnet, 10 000-rpm, 166-hertz, 1-megawatt alternator with conduction-cooled rotor. Generation system efficiency, 95.4 percent.

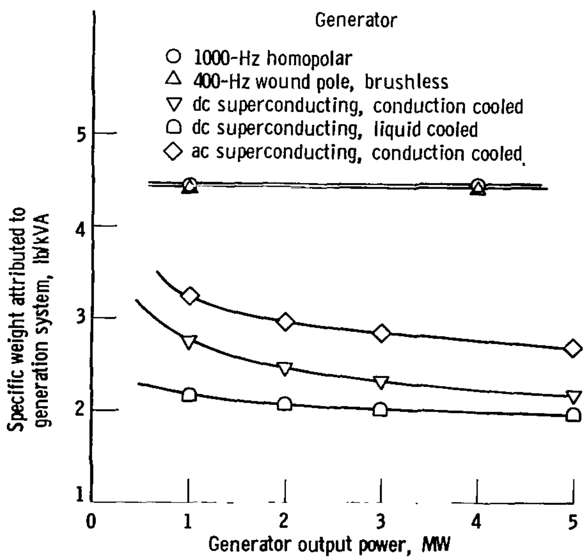


Figure 13. - Effect of parallel operation of generators with only one cryogenic refrigerator. Shaft supply weight is taken as 20 000 pounds per megawatt.

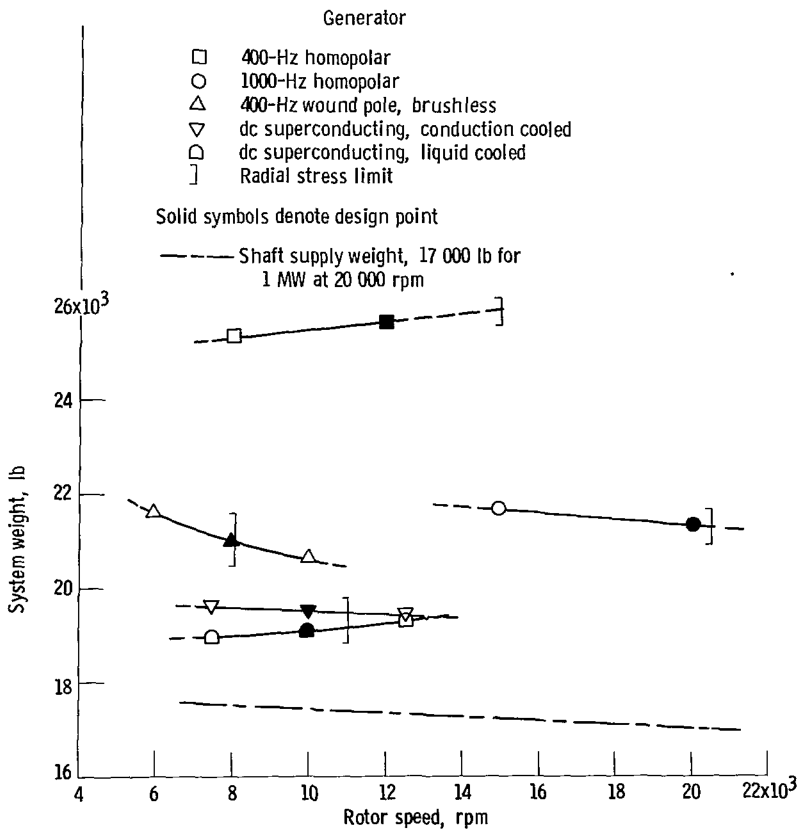


Figure 14. - Effect of rotor speed on system weight.

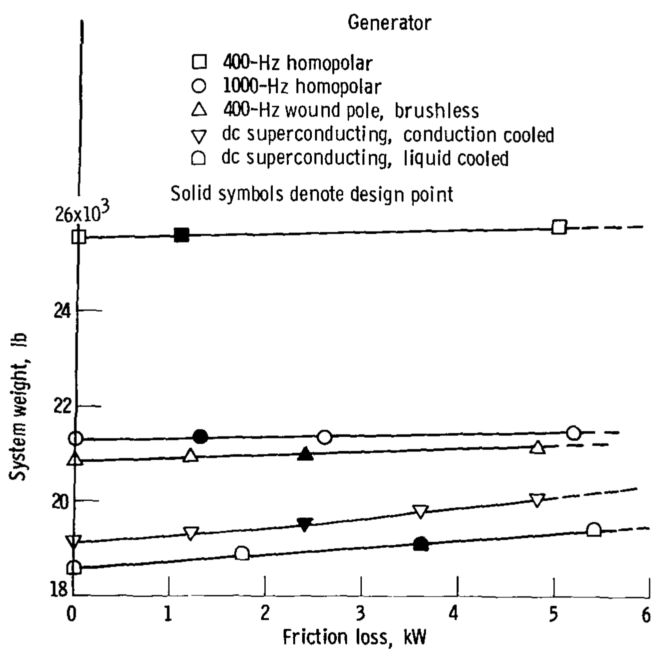


Figure 15. - Effect of friction loss on system weight. Shaft supply weight, 17 000 pounds for 1 megawatt at 20 000 rpm.

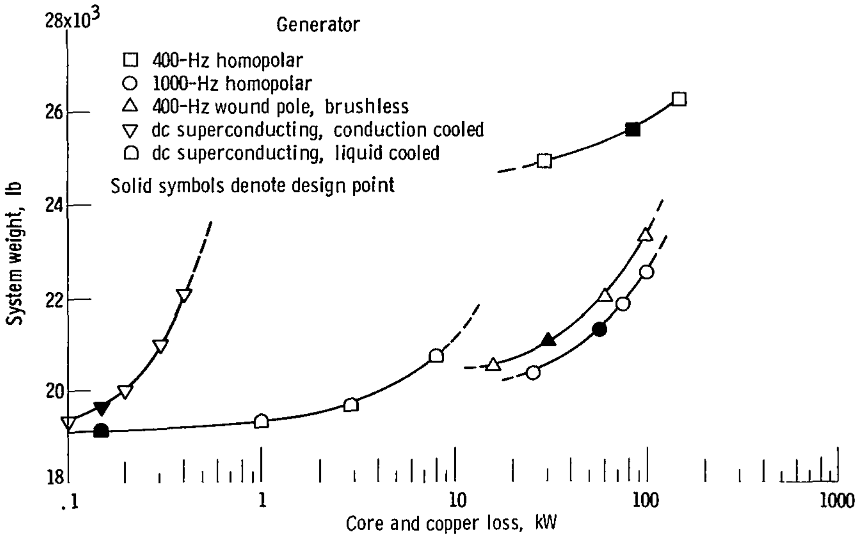


Figure 16. - Effect of core and copper loss on system weight. Shaft supply weight, 17 000 pounds for 1 megawatt at 20 000 rpm.

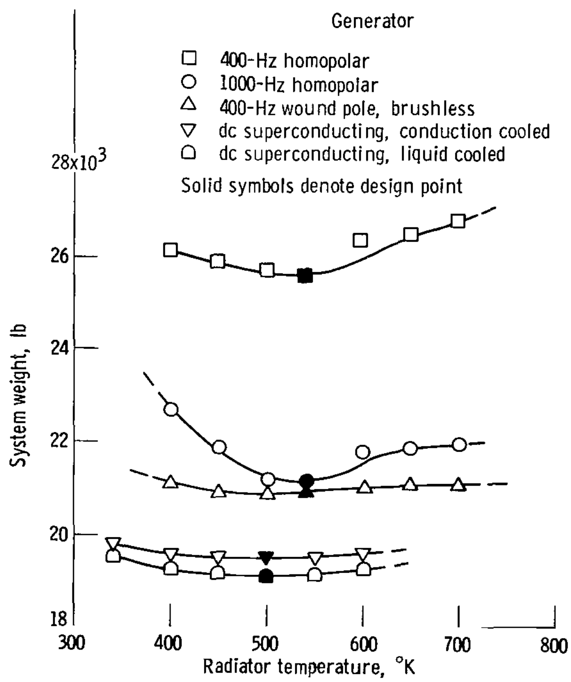


Figure 17. - Effect of radiator temperature on system weight. Shaft supply weight, 17 000 pounds for 1 megawatt at 20 000 rpm.

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