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ANALYSIS OF HOMOPOLAR GENERATORS AND SUPERCONDUCTING INDUCTIVE ENERGY STORAGE SYSTEMS AS POWER SUPPLIES FOR HIGH-ENERGY, SPACE-BASED LASERS

by

J. S. Gilbert and E. A. Kern

ABSTRACT

The operating characteristics of homopolar generators and superconducting inductive energy storage systems are summarized. A survey is made of possible prime power sources for space-based homopolar generators. Free-World state-of-the-art electrical pulse power technology is evaluated. An analysis is made of the possible uses of homopolar generators and superconducting inductive energy storage systems in power supplies for high-energy, space-based lasers. Overall system mass is of primary importance in the analysis. These types of power supplies are evaluated for possible application to Controlled Thermonuclear Reactor (CTR) experiments.

I. INTRODUCTION

Capacitive energy storage systems are employed in the power supplies of pulsed lasers. However, as lasers become larger (laser energies greater than 10 kJ per pulse), the cost and size of the required capacitive energy storage systems may be prohibitive, particularly for space-based laser applications. Investigations into alternative pulse power systems appear warranted at this time. The homopolar generator combined with a superconducting inductive energy storage system appears to be a power supply which overcomes the cost and mass disadvantages of capacitive energy storage. The report summarizes the results of a feasibility study of employing this type of power supply for high-energy, space-based laser applications.

II. HOMOPOLAR GENERATORS

A. Description

The homopolar generator, the unipolar, or acyclic generator, is basically a dc machine which can develop large currents, up to 1.6 MA, at moderately low voltages, usually in the 50- to 800-V range. A homopolar machine may be used as either a generator or a motor.

A cutaway view of a typical homopolar generator is given in Fig. 1.[1] Magnetic flux, produced by the two field coils, generates a voltage in the spinning rotor proportional to the rate at which the flux is cut. The voltage generated in the rotor causes a current to flow between the two current collectors. The homopolar generator derives its name from the fact that the flux is always cut in the same direction. Because the rotor has no windings, the homopolar generator is able to withstand much higher transient loadings than the conventional ac or dc generators. To facilitate the collection of the large dc currents in the machine, the entire rotor

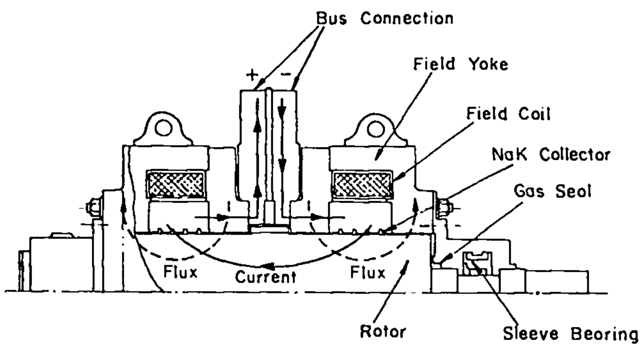

Fig. 1. Homopolar generator (from Ref. 1).

is frequently bathed in a circulating NaK liquid-metal solution.

The homopolar generator shown in Fig. 1 has the spinning rotor mounted inside the stationary field coils. An alternative arrangement would have the field coils rotate around a fixed center conductor in which the voltage is generated. This would greatly simplify the current collection procedures because the current-carrying conductor is now stationary. However, for large homopolar generators with rotating field coils the problems associated with mechanical stability and strength of the rotor have been too formidable to be overcome with present technology.[2] Hence, practically all homopolar generators incorporate the inside spinning rotor arrangement.

The voltage generated by the homopolar generator is directly proportional to the rate at which the magnetic lines of flux are cut. Hence, for a rotor of given diameter, the output voltage can be increased by increasing either the rotor flux density or the speed of the rotor. However, the amount of flux that can be passed through the rotor is limited by the saturation-flux density of the rotor material, which, for an iron rotor, is ~ 1.7-2.1 T. In addition, the rotor mechanical strength and current-collector requirements limit the rotor peripheral velocity to ~ 200 m/s.[3] A 3 600-rpm, 1-m-diam rotor would have a peripheral velocity of 188.5 m/s. From the above considerations it can be concluded that the maximum output voltage of a homopolar generator is determined by the rotor diameter.

The homopolar generator operates at a relatively high mechanical-to-electrical energy conversion efficiency (90-94%). Because of its simplicity it requires little maintenance and has a long use life with a relatively low initial cost per kilowatt of power produced. In addition, the homopolar generator delivers a pure, direct current that is practically ripple free.

Most of the homopolar generators currently in use do not employ superconductivity in either the rotor or the field circuits. The performance of homopolar generators may be significantly improved through the use of superconducting techniques. A superconducting rotor does not appear practical because either the superconducting circuit must include sliding contacts or suitable heavy current leads must be provided from the superconductor to the contacts at higher temperature. In the first case the refrigeration losses at the sliding contacts would be intolerably high, whereas the second alternative would introduce considerable complication as well as high refrigeration losses.[4] Superconducting field coils for homopolar generators appear more attractive. Such coils would increase the rotor flux densities and thus the output voltages while at the same time significantly reducing generator mass. Most mass savings would be realized through elimination of the heavy magnetic core required to handle the field flux outside the rotor. However, certain technical difficulties must be overcome before superconducting field coils become a reality on high-speed homopolar generators. The major difficulty appears to be a serious magnetohydrodynamic interaction between the superconducting field and the NaK liquid-metal used in the current collection in high-speed machines.[5,6]

The homopolar machine can also be operated as a dc motor requiring high amperage at relatively low voltage in the rotor circuit. The speed of the motor is controlled through changes in field excitation. For certain applications the homopolar machine can be brought up to its rated speed in the motor mode and then used as a generator to convert the mechanical energy of the rotor into electrical energy.

The NaK liquid-metal current-collector system has made higher amperage outputs from homopolar generators possible, and also provides cooling of the generator rotor. The low density and high electrical conductivity of NaK keep the hydraulic and contact losses to a minimum. However, NaK oxidizes rapidly in air; therefore, the rotor is usually enclosed and kept in pure, dry nitrogen. Seals are provided around the rotor shaft, and a slight positive gas pressure is maintained to ensure that no oxygen or water enters the system.

Before the technology of NaK current collectors was developed, sliding contacts of various materials were used. Although simpler, these contacts limited the performance of homopolar machines.

B. System Configurations

As indicated above, the homopolar generator is basically a low-voltage, high-current machine. In the conventional ac and dc generators a broad range of output voltages can easily be achieved by connecting in series a given number of armature conductors.

However, in a homopolar generator it is impossible to vary the voltage in this manner because the homopolar generator has basically only one armature conductor. As mentioned earlier, the rotor diameter and the maximum stress capability of the rotor material set the maximum output voltage of the homopolar generator, whereas the output current is limited primarily by considerations of maximum rotor heating and allowable current densities across the current collectors. Therefore, a given homopolar generator is limited both with regard to its output voltage and current. However, a limited amount of current and voltage control can be achieved through a series and parallel arrangement of several generators.

The total energy stored in the rotor of a homopolar generator is limited by the maximum rotor peripheral velocity. Additional stored energy is available by coupling high-speed flywheels to the generator rotor shaft.

The operating characteristics of a modern, high-speed, nonsuperconducting homopolar generator are presented in Table I.

With a superconducting coil, the total system mass could be reduced by ~ 40% to around 15 000 kg and the output voltage would increase to ~ 200 V.

The variation of total energy stored as a function of generator total mass is shown in Fig. 2. These energy-vs-mass characteristics were generated by linear extrapolation of the data presented in Table I and by assuming a 40% mass reduction through the use of superconducting coils.

C. Applications

The homopolar generator can be operated in

TABLE I

OPERATING CHARACTERISTICS OF A MODERN, NONSUPERCONDUCTING, HOMOPOLAR GENERATOR

Rotor diameter, m	1
Speed, rpm	3 600
Rotor mass, kg	5 000
Total mass, kg	25 000
Rotor flux density, T	1.27
Efficiency, %	95
Output voltage, V	120
Maximum current, A	0.5×10^6
Maximum stored energy, J	42.0×10^6
Mass-to-energy ratio, kg/kJ	0.595

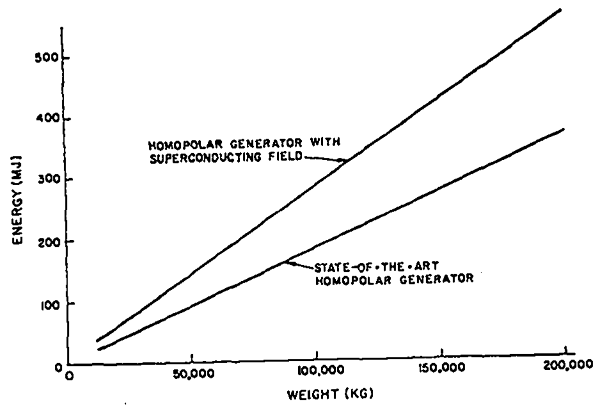

Fig. 2. Energy vs mass for homopolar generators.

either the continuous mode or in a pulsed mode. In the continuous mode of operation the input mechanical energy to the generator essentially balances the electrical energy output plus losses, whereas in the pulsed mode large electrical energies are extracted from the generator in exchange for mechanical energy of the rotor. During the pulsing phase, the rotor will slow down significantly.

The homopolar generator can be employed in a continuous operating mode in any application requiring a ripple-free source of large dc currents at low voltages, for example, to satisfy electrolytic power requirements in the electrochemical industries. However, in applications of this type the motor-driven homopolar generator must compete on the basis of cost and reliability with the modern static diode-type rectifier.[1] On the basis of cost, the homopolar generator system appears to compare favorably with the diode rectifier. Also, the output of the generator is much smoother. However, because the diode rectifier has no moving parts and can be more quickly repaired in case of breakdown, practically all electrolytic power requirements as well as other similar power requirements are being satisfied by diode rectifiers. Hence, not many application possibilities seem to exist for homopolar generators operating in a continuous mode.[7]

The homopolar generator can store up large amounts of mechanical energy at a relatively low cost per joule and then efficiently convert this mechanical energy into electrical energy in a short time interval (0.1-10 s). In addition, because the homopolar generator has essentially no windings, it is able to withstand much higher transient loading conditions than the conventional ac or dc generators.

Therefore, the homopolar generator is an attractive source of large electrical energy pulses. Many present and future applications exist for the homopolar generator operating in a pulsed manner. In some applications a pulse-shaping network centered around an inductive coil can be employed in conjunction with the homopolar generator to provide higher voltages and shorter pulse times than are available directly from the homopolar generator. The output from the inductive storage device can be used to satisfy a number of applications requiring high voltages, high currents, and short pulse times. These applications, as well as other applications in which the homopolar generator pulse can be utilized directly to drive a given load, will now be considered in more detail.

1. Inductive Storage. The low output voltages (50-800 V) of the homopolar generator and the time intervals (0.1-10 s) required for it to discharge its energy impose a limitation on the types of loads that the generator can drive directly. When higher voltages and shorter pulses are required, a pulse-shaping network between the generator and the load is necessary. Such a network that incorporates a large inductive storage device appears particularly well suited for shaping the high-current, low-voltage output of the generator.

As shown in the Appendix, the homopolar generator for electric circuit modeling purposes, behaves like a capacitor charged to some given voltage. Hence, the homopolar generator along with the inductive storage device and load can be represented by the idealized circuit shown in Fig. 3.

The load in Fig. 3 is supplied with the desired input pulse in the following sequence of events. With switch S_1 closed the homopolar generator is brought up to its rated speed. The field circuit of

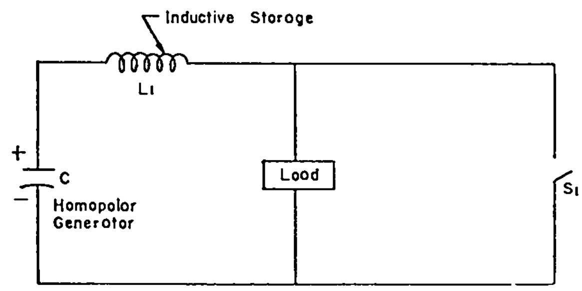

Fig. 3. Homopolar generator connected through a pulse-shaping inductive storage device to a load.

the generator is excited, allowing the homopolar generator to discharge through the inductive storage device. At the instant when maximum current is attained in the inductive device, switch S_1 is opened, thus diverting the coil current through the load. With a properly designed inductive storage device along with the associated switching, the load voltage will be higher than the homopolar generator voltage, and the duration of the load pulse will be shorter than the discharge time of the generator. In practice the circuit shown in Fig. 3 would not perform very effectively because of the large current arc that would be encountered during the opening of switch S_1. This circuit is introduced to show in a simplified manner how the homopolar generator can be utilized in conjunction with an inductive storage device. A more detailed discussion of inductive storage along with the associated switching circuitry will be presented in Sec. IV.

Not all the energy stored in the homopolar generator can be delivered to the inductive device. Because the stored inductive energy is proportional to the square of the current, the maximum energy that can be stored in the inductive device is a function of the peak current that can be delivered by the homopolar generator. As shown in the Appendix, the peak current and, hence, the maximum energy that can be delivered are a function of the generator stored energy, the generator initial voltage, and the resistance of the charging circuit. For an average installation it is estimated that the required generated energy storage will be at least double the energy delivered to inductive storage. However, only a fraction of the nondelivered energy will be consumed in resistance heating losses, because a significant amount of energy will remain as rotational energy in the generator.

It is possible to drive a number of different types of loads with a homopolar generator in conjunction with an inductive storage device. The largest known homopolar generator/inductive storage system in this country was built by General Electric Corporation in 1961 for the Air Force Development Center, Tullahoma, Tennessee, to provide the power for an arc-type hypersonic wind tunnel facility. Another promising application of homopolar generator/inductive storage technology appears to be in the pumping of high-powered laser systems. The pumping times and voltages for most high-powered lasers under consideration are such that the homopolar generator could not be used directly. An inductive storage system would be required to provide the proper pulse shaping for laser applications.[8] These laser-type applications will be discussed in greater detail in Sec. VI and Sec. VII.

2. Other Applications. For many high-current (10^5-1.5×10^6 A), low-voltage (50-800 V) applications, the output of a homopolar generator operating in a pulsed mode can be coupled directly to the load. A simplified circuit representing the homopolar generator driving the load is shown in Fig. 4. In this case the homopolar generator is brought up to rated speed with the field circuit open. The field circuit is energized simultaneously with the closing of the switch to discharge the generator into the load.

Operating in the pulsed mode without an inductive storage device, the homopolar generator can be employed as an energy store in the production of very high magnetic fields for use in experiments in plasma and solid-state physics. A large homopolar generator at the Australian National University, Canberra, Australia, was originally designed to provide energy to the main magnet of a large proton synchrotron accelerator.[3] Although the accelerator project was abandoned, the homopolar generator was completed and is being used in the laboratory to generate high-intensity magnetic fields. Smaller homopolar generator installations at the NASA Lewis Research Center in Cleveland, Ohio, and the Lawrence Livermore Laboratory in Livermore, California, have been employed to explore the characteristics of high magnetic fields and to test the capabilities of the generator as a possible power source for nuclear studies. In all three of these installations the generator is brought up to its rated speed by using it as a motor with the power being supplied from the electric mains.

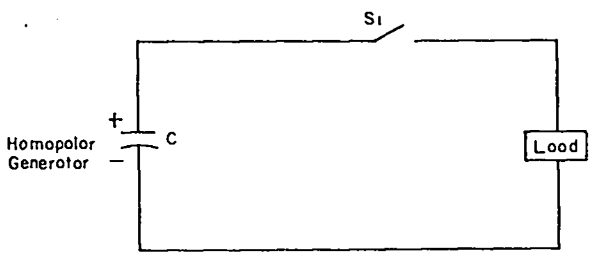

Fig. 4. Homopolar generator with direct load coupling.

Other applications of homopolar generators could include their use as welding machines to resistance weld very thick plates, or to accelerate small masses to high velocities in the study of missile reentry problems.

D. United States and Other Free-World Technology

Homopolar generators throughout the United States and the Free-World are being used primarily as a source of pulsed power for experimental research. Very little, if any, commercial use of homopolar generators is being made.

The Free-World's largest homopolar generator is the Mark II Canberra Machine in the Department of Engineering Physics at the Australian National University, Canberra, Australia, mentioned previously. This machine has two rotors which rotate in opposite directions so that no net torque is transmitted to the machine foundations. The performance and physical characteristics of the Mark II Canberra Machine are given in Table II.

The machine is brought up to its rated speed in about ten minutes by using it as a motor supplied from the electric mains. The cost of energy storage in the machine is estimated to be ~ 0.25 ¢/J. A NaK liquid-metal current collector system was originally employed. However, after an explosion during an operation involving the handling of NaK away from the machine it was decided to replace the NaK systems with carbon brushes.

The largest known homopolar generator system in the United States was built by General Electric in 1961 to provide an energy store for an arc-type hypervelocity wind tunnel at the Air Force Development Center, Tullahoma, Tennessee.[2,5] In this application the homopolar generator system was used to discharge through a large inductance coil for pulse shaping

TABLE II

CHARACTERISTICS OF MARK II HOMOPOLAR GENERATOR AT THE AUSTRALIAN NATIONAL UNIVERISTY, CANBERRA, AUSTRALIA

Rotor mass (2 each), kg	40 000
Rotor diameter, m	3.6
Rated speed, rpm	900
Peak current, A	1.6×10^6
Maximum voltage, V	800
Maximum energy storage, J	576.0×10^6
Discharge time, s	1

purposes. An NaK current collector system was employed. The operating characteristics and physical properties of the generator used in this installation are summarized in Table III.

Four of these homopolar generators were employed in a series-parallel connection to provide for a peak current output of 10^6 A at a voltage of 90 V. The generator rotor shafts were coupled together in pairs, and each pair of generators was driven by a 746-kW motor to form a motor-generator set. A 22 700 kg, 1.8-m-diam flywheel was coupled to the shaft of each motor generator set to increase the energy storage of the system. Hence, the entire motor-generator system consisted of two motors, two flywheels, and four homopolar generators with a maximum stored energy capacity of 371 MJ. This system was used to charge a 50 000-kg, 2-mH copper inductance coil to an energy level of 121 MJ in 8 s. Approximately 15 min were required to bring the system up to rated speed.

Allis Chalmers Manufacturing Company has installed smaller homopolar generator systems for arc-type hypervelocity wind tunnel applications at the Air Force Development Center, Tullahoma, Tennessee, and the University of Michigan.[1] They have also provided homopolar generator installations primarily for magnet power supplies at the Lawrence Livermore Laboratory, Livermore, California, and at the NASA Lewis Research Center, Cleveland, Ohio. At present Allis Chalmers is not engaged in any homopolar generator activities.

Westinghouse Electric Corporation is building, under contract to Advanced Research Project Agency (ARPA), a small, 3 600-rpm homopolar machine with a rotor diameter of 0.33 m.[6] The maximum output voltage of this machine is estimated at ~ 20 V.

TABLE III

OPERATING CHARACTERISTICS AND PHYSICAL PROPERTIES OF GENERAL ELECTRIC HOMOPOLAR GENERATOR USED IN TULLAHOMA HYPERVELOCITY WIND TUNNEL

Generator mass, kg	22 727
Rotor mass, kg	5 700
Rotor diameter, m	0.812
Rated speed, rpm	1 800
Peak current, A	0.5×10^6
Maximum voltage, V	45
Maximum energy storage, J	8.34×10^6

General Electric appears to be the only organization in this country which is attempting to build a homopolar generator with a superconducting field circuit.[5] General Electric is under contract with the Navy to build a superconducting homopolar generator. As mentioned previously, the primary difficulty which must be overcome with superconducting homopolar machines is the serious interaction of the field with the NaK liquid-metal current collecting system.

III. POWER SYSTEMS FOR HOMOPOLAR GENERATORS

In this section we will survey the possible power source for space-based homopolar generator systems and single out those that appear most attractive. A very important consideration will be that of system mass. For laser applications we will assume a pulsed mode of operation wherein the homopolar generator is brought up to speed in some manner and then allowed to discharge rapidly into an inductive storage device over a time interval of 0.1-10 s. As a criterion in the consideration of various types of power sources, we will assume that the homopolar generator is brought up to its rated operating speed by either the shaft work of an electric motor, or by a turbine, or by a low-voltage (50-200 V), high-current (10^5-10^6 A) source, which provides the power to drive the generator as a motor.

A. Power System Survey

We will first consider briefly the various power supplies and their suitability as power sources for space-based homopolar generator systems.[9,10]

1. Thermoelectric Systems. These systems provide direct conversion of heat energy into electric energy. Their major advantages are high reliability, long lifetime, and low development costs. The primary disadvantage is their relatively low electrical conversion efficiency. Consequently, at any appreciable power level, these systems are very massive and, therefore, not attractive for homopolar generator space-power applications.

2. Thermionic Reactors. Thermionic reactor systems provide a direct source of electric energy by means of thermionic emission. The thermionic system appears attractive as a possible power source for homopolar generators because of its inherent low voltage (50-150 V) and high-current capabilities in the 1-10 MW power range. This would allow the

thermionic reactor to output directly into the homopolar generator without the need for power-conditioning equipment. Thermionic reactors are also attractive from the standpoint of specific mass vs power output. It is predicted that relatively long-life (tens of hours) thermionic reactors having specific masses of ~ 1.44 kg/kW can be built with advanced technology for a 10-MW system.

The closed-cycle mechanical power system can be utilized to produce rotating shaft output energy by supplying nuclear heat energy to a working fluid which then passes through a thermodynamic cycle. With this type system the homopolar generator would be brought up to speed through direct coupling with the output turbine shaft. Using advanced technology projections, optimistic forecasts indicate that a closed mechanical power system in the 10-MW power range could be built with a specific mass of around 15 kg/kW. This high specific mass makes the closed-cycle mechanical power system very unattractive as a space-based prime mover for the homopolar generator.

3. MHD Systems. The magnetohydrodynamic (MHD) generator produces direct electric energy by forcing an ionized gas through a magnetic field. MHD power systems may be of the closed cycle, open cycle, or explosive types. The electrical energy output from either the open- or closed-MHD system could be used to bring the homopolar machines up to speed while operating as a motor. However, power-conditioning equipment would be required to reduce the MHD generator voltages from the 5-kV region to the 50-200 V range. Because the open MHD system uses an expendable working fluid, the specific mass is dependent upon total operating time. Specific masses at the 10-MW power level for an open-cycle MHD system with an operating time of 4 h and for a closed-cycle MHD system are both about 5 kg/kW.

Explosive MHD power systems do not appear attractive for homopolar generator applications because of the discontinuous nature of the output power from these systems.

4. Explosive-Driven Magnetic-Field Compression Generators. This power-generating device uses an explosion-driven metallic conductor to decrease the inductance, L, of a magnetic energy storage system. Because the magnetic flux, which is a product of the inductance, L, and current, I, must remain constant throughout the explosion, the decrease in L causes an increase in I. In this way it is possible to convert explosive energy into electric energy.

These explosively-driven magnetic-field compression generators are very impressive from a system mass standpoint. Output energies approaching 1 MJ have been achieved from a generator weighing 10 kg.[11] In comparison it is estimated that an explosive MHD generator at the 1-MJ energy level would have a mass of ~ 5 000 kg. The main constraint upon explosive-driven magnetic field compression generators is that the load must be purely inductive.

The explosive-driven generator does not appear to hold much promise as a power system for homopolar generators because such a generator, when used as a motor, behaves like a resistive load. Also, a continuous power source is better suited for charging up the homopolar generator.

5. Open-Cycle Liquid-Hydrogen Nuclear Reactor System. In this type of system liquid hydrogen (LH_2) is heated by a nuclear reactor and then expanded through a turbine. Because of the expendable working fluid, specific mass for this system is a function of the desired operating time. At a 10-MW power level and at an operating time of 4 h, the specific mass for this open-cycle LH_2 system is estimated at ~ 1.7 kg/kW.

The homopolar generator would be coupled directly to the turbine shaft. The low specific mass of this system makes it a feasible source of power for the homopolar generator.

6. Open-Cycle Chemical Reaction System. The open-cycle chemical system consists of a working fluid which, through a chemical reaction, provides its own source of heat. After heating, the fluid is expanded through a turbine in a manner similar to that of the open-cycle LH_2 system.

The chemical reactants that make up the working fluid may be divided into two classes: (1) those that must be stored in space as cryogenics, and (2) those that may be stored in space at ambient earth surface temperatures and pressures. Liquid hydrogen (LH_2) and liquid oxygen (LO_2) are cryogenic reactants with good performance characteristics; noncryogenic reactants with good performance are monomethylhydrazine (MMH) and nitrogen tetroxide (N_2O_4).

Specific mass estimates for these open-cycle chemical systems at the 10-MW power level and at an operating time of 4 h are 2 kg/kW for the LO_2/LH_2 system and 7 kg/kW for the N_2O_4/MMH system. This low specific mass makes the LO_2/LH_2 system attractive as a power supply for the homopolar generator.

B. Conclusions

One of the most important considerations in the selection of a power system for space-based homopolar generators is a low specific mass (kg/kW). In addition, where the power system serves as a direct source of electric energy (as, for example, in the thermionic and MHD systems), this source must be of continuous nature.

From a power level standpoint, a 10-MW system would be adequate for most homopolar generators. Even if only 50% of this power could be delivered as torque to the homopolar generator rotor, it still would be possible to store 50 MJ of energy in the homopolar generator over a time interval of 10 s. A generator at this energy level with a superconducting field would have mass of around ~ 18 000 kg.

It is difficult to classify space power systems as acceptable or unacceptable purely on the basis of specific mass for a 10-MW system, because, among other things, the mission requirements are not defined, and the specific mass estimates themselves are speculative. However, with these deficiencies in mind, an attempt has been made to classify the power systems under consideration: Those having a specific mass of 2 kg/kW or less will be classified as "attractive," those in the 2- to 8-kg/kW range as "marginally attractive," and those with specific masses greater than 8 kg/kW as "unattractive." In addition, several power systems will be classified as unattractive because of incompatibility with homopolar generator requirements. The specific mass values associated with each of the power systems below correspond to a 10-MW system and are based on advanced technology estimates. For open-cycle systems an operating time of 4 h was used in computing the specific masses.

- Attractive
  - Thermionic Reactors (1.44 kg/kW)

    The power output of these systems is directly compatible with homopolar generator requirements.
  - Open-Cycle, LH_2, Nuclear/Turbine (1.7 kg/kW)

    A disadvantage to this system as well as of the thermionic reactor system is the need to place a nuclear reactor into space.
  - Open-Cycle, LO_2/LH_2/Turbine (2.0 kg/kW)

    This is the only nonnulcear system with an attractive specific mass. However, handling of cryogenics is required.

- Marginally Attractive
  - Open-Cycle, LH_2, Nuclear, MHD (5.0 kg/kW)

    The MHD systems require power conditioning of the output to be compatible with homopolar generators.
  - Closed-Cycle, Nuclear, MHD (5.0 kg/kW)

    For operating lifetimes of more than 4 h, this system would have a lower specific mass than the open-cycle MHD system.
  - Open Cycle, N_2O_4/MMH Turbine (7.0 kg/kW)

    This system has the advantage of being nonnuclear and noncryogenic.

- Not Attractive
  - Closed-Cycle Mechanical (15 kg/kW)

    These systems include conventional thermodynamic cycles with their associated nuclear reactors, turbines, and heat exchangers. They appear very unattractive from a standpoint of system mass.
  - Thermoelectric

    No specific mass estimates were available for this system. However, because of their inherently low efficiency, it is expected that the specific mass would be greater than 15 kg/kW.
  - Explosive MHD

    The pulsed output from this system is not compatible with homopolar generator requirements.
  - Explosive-Driven Magnetic-Field Compression Generators

    This system requires an inductive load and hence is not compatible with the homopolar generator.

IV. MAGNETIC ENERGY STORAGE IN SUPERCONDUCTING COILS

A. Description

If a current is flowing through a coil of wire, the coil is capable of storing a large amount of energy in its magnetic field. For pulsed power applications this stored magnetic energy seems very attractive because it can be converted into a high-current (10^5-10^6 A), high-voltage (10-100 kV) pulse, with a minimum pulse duration in the 10-100 μs range. Pulses of this magnitude and duration may be necessary to satisfy the pumping requirements of pulsed laser systems. A relatively low-voltage (50-200 V), high-current (10^5-10^6 A) electric source, could energize the magnetic storage coil; the power requirements could be satisfied by the homopolar generator discussed in Sec. II.

The development of more compact and efficient storage systems has gained great impetus through recent advances in superconducting materials technology. A superconductor offers essentially zero resistance to the flow of current, so that very high energy densities can be achieved in the magnetic field of a superconducting coil. Because resistive losses are absent in superconducting materials, energy can be stored and later transferred with high efficiency. To achieve superconductivity, the conductor must be fabricated of special materials and these materials must be cooled to temperatures in the range from 5-20 K. Liquid helium at 4.2 K is currently the most practical coolant. A more detailed discussion of superconducting materials is presented in Sec. V.

Although large magnetic energy storage systems employing normal (nonsuperconducting) low-resistance windings of, e.g., copper have been employed successfully in the past, superconducting coils offer the promise of much larger energy storage per unit volume with zero coil resistance heating losses. For example, in a large 150-MJ normal copper coil built by General Electric, the energy density was ~ 10 MJ/m^3. However, in a superconducting magnetic energy storage system energy densities of 40 MJ/m^3 are easily attainable, with much higher energy densities expected in the future. The energy losses in a normal copper storage coil due to resistance heating are significant. For example, it is estimated that in energizing a normal copper coil to its rated energy level in a time interval of 0.1 s or more, an amount of energy at least equal to that stored in the coil would be dissipated due to coil resistance.

Also, the specific mass (kg/MJ) of superconducting magnetic energy storage systems seems more attractive than those of a capacitive system. Specific masses of capacitors are compared in Fig. 5 with inductive storage systems having current state-of-the-art superconducting coils.[12] The specific mass for capacitors is essentially independent of stored energy and is shown in two bands, one for relatively heavy units with unlimited lifetime in terms of number of charges and discharges, and the other for

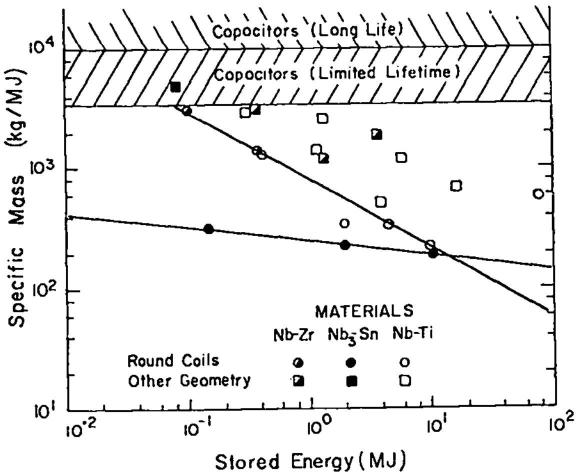

Fig. 5. Comparison of specific mass for capacitors (shaded) and current state-of-the-art superconducting coils (circles and squares).

relatively light high-performance units with limited lifetime. The specific mass for capacitors is not a function of energy level because the main limitation is dielectric strength. The data points in Fig. 5 are given for existing inductors with superconducting coils. Even though the coils were not built for energy storage, they have considerably lower specific mass than the capacitors, and also show a generally decreasing specific mass with increasing energy.

In terms of cost per unit energy stored, the superconducting magnetic energy storage system also appears to have a decided advantage. For example, the 395-MJ superconducting magnetic energy storage system at the National Accelerator Laboratory bubble chamber was built at the cost of 0.5¢/J, a value which is at least an order of magnitude lower than capacitive storage.

In spite of the obvious advantage in terms of mass and cost over capacitive systems, important questions remain to be answered before superconducting magnetic energy storage systems can replace capacitive systems in many pulsed power applications. First, the switching problems associated with magnetic energy storage systems are more difficult than with capacitive systems. Magnetic energy storage devices are basically current sources making it necessary to switch large currents from the input circuit to the output circuit. On the other hand, capacitive systems are inherently voltage sources, with an easier switching problem.

Due to the rapidly changing magnetic field upon discharge, there is strong evidence to suggest that the superconducting coil will be normalized. Hence, before it could be re-energized, the coil would have to be restored to the superconducting state. It is uncertain as to how much time and how much liquid helium would be required to restore superconducting conditions. This could be a limiting factor in maximizing the pulse repetition rate of the system.

It is estimated that the laser input voltage requirements will be around 300 kV. Preliminary calculations indicate that these voltages will be attainable since the storage coils will have only a few turns making it relatively easy to insulate the coil to prevent voltage breakdown.

The minimum pulse width that can be achieved with a discharging superconduting coil is in the range of 10-100 μs. This pulse-width limitation is imposed primarily by the switching circuitry and by the maximum allowable discharge rate of the superconducting coil. Additional pulse shaping circuitry would be required for pulse widths less than 10 μs.

B. System Configurations

In the following we will describe a typical dewar and storage coil assembly and will discuss how a superconducting magnetic storage coil can be utilized in a pulse power system.

1. Dewar and Storage Coil Assembly. For space applications with their relatively short mission times and high refrigeration loads during operation, a power system using stored cryogen (LHe) is much lighter and more compact than a closed-cycle refrigeration system. The mass of stored LHe required to remove heat at ~ 4.2 K for total operating times of 10 min is only ~ 3 kg/W utilizing just the latent heat of boiling. Therefore, stored cryogen appears to be a satisfactory means of refrigeration. In contrast, even the smallest available helium refrigerators (~ 1 W capacity at 4.2 K) weigh well over 50 kg.

A typical storage dewar and coil dewar assembly is shown in Fig. 6. Liquid helium is maintained under pressure in the storage dewar at 4.2 K and flows into the coil dewar as required to maintain superconductivity within the storage coil. The inner wall is usually fabricated from plastic to eliminate eddy current heating and to prevent arcing.

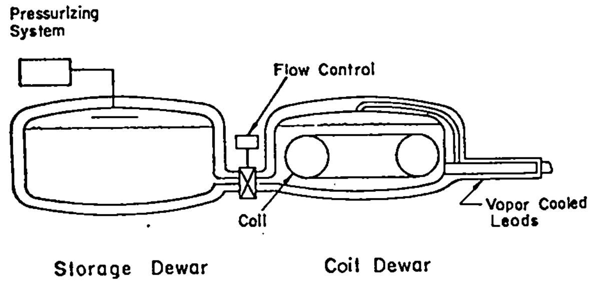

Fig. 6. Schematic of coil dewar and storage dewar.

2. Application to Pulse Power Systems. A major problem associated with the application of magnetic or inductive storage devices to pulsed power systems is that of efficiently removing the energy from storage into the load so that the electric pulse is of the required length and magnitude. As mentioned previously, a magnetic or inductive storage device is basically a current source. The energy stored in the coil is proportional to the square of the current flowing through the coil. To transfer this energy into a load it is necessary to switch this large coil current. This results in severe arcing problems at the switches leading to such undesirable effects as limited switch lifetimes, high transfer energy losses, pulse repetition rate limits, and minimum pulse-length limits. Significant advances in high-current switching technology must be made before magnetic energy storage can be considered attractive for future high-energy pulsed power systems.

As an example of how the switching requirements may be satisfied while minimizing the losses and maximizing switch lifetime, consider the circuit shown in Fig. 7. The magnetic storage coil is represented by L_1; for a laser, the load would be primarily resistive. Capacitor C_1 is used to limit the maximum coil voltage. The energy source could be a homopolar generator. The main purpose of this circuit is to allow the magnetic storage coil to discharge through the load without causing a severe arc across the main switch S_1. The sequence of events that would occur in a normal charge-discharge operation is as follows. With switches S_1 and S_2 open, switch S_3 is closed and capacitor C_o charged to a predetermined voltage with the polarity shown. Switch S_3 is then opened and S_1 closed, allowing L_1 to take on a charge from power supply P_1. Upon reaching the desired current level, S_1 is opened and

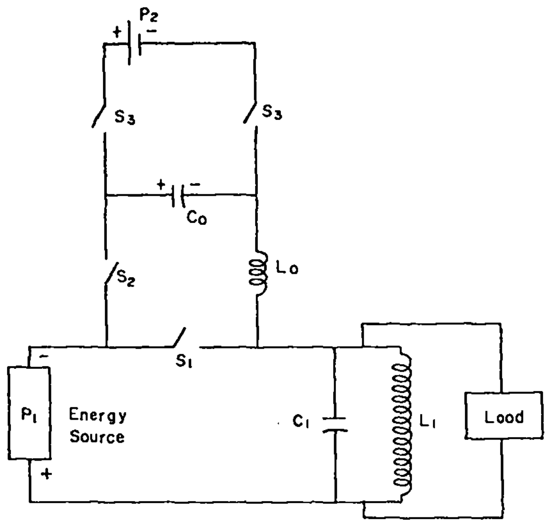

Fig. 7. Simplified circuit for producing a zero current in main switch S_1.

an arc is drawn across its contacts. When these contacts are fully parted, switch S_2 is closed and capacitor C_o is discharged through switch S_1 with a current in opposition to the main power supply current. If the capacitor C_o, its charge, and the inductor L_o are properly chosen, a zero current can be established in S_1. The system current will then be diverted to the three parallel paths containing L_o and C_o, C_1 and the load. Assuming switch S_2 remains closed, C_o will be charged up to the peak system voltage with a polarity opposite to that shown, and, after reaching a peak, it will discharge through the load. If the cycle is to be repeated, switch S_2 is opened and capacitor C_o is again charged from power supply P_2.

The magnitude and duration of the input pulse to load can be regulated to a certain extent through choice of the capacitor C_1. However, the lower limit on pulse duration appears to be in the range 10-50 μs. If, as is the case for certain lasers, a shorter pulse is required, additional pulse-forming networks would have to be incorporated.

C. United States and Other Free-World Technology

In discussing superconducting inductive energy storage technology we will consider only those coils that have been designed specifically for magnetic energy storage. Three coils with a storage capacity of 100 kJ or more each are the only existing ones of significant size known to the authors.

The first U.S.-built superconducting magnetic energy storage coil in the 100-kJ range was designed and built by AVCO Corporation for the U.S. Army Missile Command, Redstone Arsenal, Alabama. The general requirements for this 100-kJ coil were that it be capable of releasing its energy into a resistive load at a maximum voltage of 5 kV with an approximate time constant of 2 ms.[13] From these criteria it can be established that: the coil inductance must be 500 μH; the load must be 0.25 Ω; and the maximum coil current must be 20 000 A. To minimize the dewar costs it was decided to wind the coil as a long solenoid. Additionally, to minimize superconducting costs, it was wound with a stablized NbZr conductor rather than with a higher field strength Nb_3Sn conductor. These two decisions necessitated the construction of a coil that was not optimized for minimum volume and weight. This system was operated in the superconducting mode up to a maximum energy level of 86 000 J with a linear resistive load. The charge time was 3.0 s and the discharge time constant was 4.0 ms. During these tests the coil operated satisfactorily. However, considerable difficulty was experienced in the switching circuit. As a consequence, it was decided to operate the coil for economic reasons at liquid-nitrogen temperature to investigate the switching circuit. The switch selected to release the energy stored in the coil to the load was a high-vacuum switch. To make this switch effective in an inductive circuit a charged capacitor was used to provide a countercurrent pulse during switching. This counter pulse forced the current through the switch to zero, allowing the arc to break and the stored energy to be released to the load. The poor performance of the switch in the first test was attributed to the lack of knowledge about the recovery time of the switch after the arc break. Additional circuit elements slowed down the discharge of the counter-pulse capacitor and effectively overcame this deficiency. The system was then successfully operated up to a maximum current level of 6 300 A (its limit of operation as a cryogenic coil) with a linear resistive load. The load was then changed to a nonlinear resistor (flash lamp), and successful operation of the system was again demonstrated.

The Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, has for several years been engaged in a multifaceted program to develop airborne, superconducting, inductive energy storage systems for pulsed laser applications. A 100-kJ superconducting coil, built by Magnetic Corporation of America, is the largest Aero Propulsion Laboratory coil to date. The first phase of a three-phase program to design, build, and test this 100 kJ energy storage system has been described elsewhere.[14] Coil characteristics are summarized in Table IV.

A 300-kJ superconducting magnetic energy storage system has been designed by the Los Alamos Scientific Laboratory (LASL) and is under construction. This experiment should prove out concepts to be used in a 0.6-1.5 MJ module which, when assembled as one of approximately 150 to 500 like units, will provide a 300-MJ energy storage system for a controlled thermonuclear reactor feasibility experiment. Related details of possible experiments have been described.[15-18] The characteristics of this coil are given in Table V.

Superconducting coils provide the magnetic fields in bubble chambers of high-energy physics research. Because of the large field volume and high magnetic fields required, a large amount of energy is stored. Table VI lists characteristics of a few of these bubble chamber magnets. Similar large magnets are in use in the USSR.

TABLE IV

CHARACTERISTICS OF 100-kJ ENERGY STORAGE COIL
(Built by Magnetic Corporation of America for Air Force Aero Propulsion Laboratory)

Inner winding radius, m	0.292
Outer winding radius, m	0.328
Winding length, m	0.320
Coil mass, kg	29.3
Central flux density at operating current, Wb/m^2	1.04
Peak flux density at operating current, Wb/m^2	1.58
Operating current (primary windings), kA	1.94
Inductance, mH	53.4
Stored energy at operating current, kJ	100
Primary windings	
Number of layers	10
Number of turns	300
Maximum voltage, kV	60
Secondary windings	
Number of layers	12
Number of turns	50
Maximum current, kA	11.6
Maximum voltage, kV	10
Turns ratio, primary/secondary	6

TABLE V

LOS ALAMOS SCIENTIFIC LABORATORY 300-kJ EXPERIMENT

Storage Coil (single layer, edgewound)	
Energy stored, kJ	300
Inductance, mH	6
Current, kA	10
Number of turns	133
Inner diameter, cm	57
Length, cm	70
Conductor dimensions, cm	0.51 x 1.02
Central field at 10 kA, T	1.8
Maximum field at conductor, T	2.0
Critical current of conductor at 2T, kA	13
Switches	
Normal state resistance, Ω	2 to 4
Peak voltage generated, kV	20 to 40
Transformer Secondary Winding (Room Temperature)	
Inner diameter, cm	76.8
Length, cm	76
Thickness, cm	1.27
Number of turns	1
dc resistance, μΩ	6
Coupling constant	0.74
Peak current, kA	280
Peak voltage, V	~ 140
Load Coil (Room Temperature)	
Mean diameter, cm	19.7
Length, cm	76
Number of turns	3
dc resistance, μΩ	11
Peak field, T	1.4
Energy at peak field, kJ	21

V. SUPERCONDUCTING MATERIALS TECHNOLOGY

To achieve superconductivity in a suitable superconductor the material must be cooled to 5-20 K. Considerable effort is being expended to improve the technology, and significant advances are anticipated.

A. Important Properties

In applying superconducting materials to an inductive energy storage coil operating in a space environment the following factors are of particular importance.[13,14]

TABLE VI

CHARACTERISTICS OF LARGE SUPERCONDUCTING SOLENOIDS FOR HIGH-ENERGY PHYSICS

Facility	Magnet ID, m	Central Field, T	Maximum Field, T	Overall Current Density, A/cm^2	Stored Energy, MJ
3.7-m bubble chamber (Argonne National Laboratory	4.8	1.8	1.8	775	80
Bubble chamber (National Accelerator Laboratory)	4.3	3.0	5.1	1 885	395
BEBC (Organisation Europeenne pour la Recherche Nucleaire)	4.7	3.5	5.1	1 100	800
Omega Project (Organisation Europeenne pour la Recherche Nucleaire)	3.0	1.8	3.5	1 400	50

- High Current Density

  This factor is important to minimize the mass and volume of the coil.

  High Stability

  Superconductor stability is a measure of how well the superconductor remains in the superconducting mode. A high degree of stability is important because the required fast coil discharge will have a strong tendency to drive the conductor normal. While it may be impossible (and even undesirable) to design the coil to remain superconducting during discharge, it is extremely important that the conductor recover rapidly enough to be superconducting during subsequent charging.

- Low Eddy Current and Hysteresis Losses

  Hysteresis losses in the superconductor are the result of a changing magnetic field in the conductor, which causes heat to be generated within the superconductor. Eddy currents within the superconductor are caused by magnetic flux lines cutting the conductor during a changing magnetic field. If, as is generally expected, the superconductor is normalized during discharge of the coil, then the eddy currents created would result in additional I^2R losses in the normalized superconductor. Inherently low eddy current and hysteresis losses are important because under expected operating conditions (repetitive charging and discharging), these losses will be much larger than others and must be minimized to reduce both mass and volume of the liquid helium (LHe).

- High Critical Field

  For a given superconducting wire at some low temperature there is a maximum field which the conductor can withstand without being driven normal. This maximum or critical field is a function of the current density and the temperature of the material. Higher field densities imply higher energy storage capabilities and hence lower weight and volume requirements.

For a space environment the desirable conductor property of high critical temperature is of lesser importance. The critical temperature is the temperature above which the superconductor becomes normalized. However, in order to achieve a reasonably high field density, it is necessary to operate the superconductor at a temperature of at least 3 K below the critical temperature. For present superconducting materials the critical temperature lies in the approximate range of 8-20 K. If a superconductor were chosen with a critical temperature near the lower limit of this range, then for high field density a temperature of around 5 K would be required. Since coolant in the form of LHe at a temperature of 4.2 K is readily available, the use of a superconductor with a critical temperature of 8 K can be reasonable. This would not be the case if continuous closed-loop refrigeration were involved. However, because of the relatively short mission time, the use of bulk LHe to cool the coil results in a significant mass saving over a system with a closed-loop refrigerator and is therefore the preferred cooling means.

B. Fabrication Geometry

High current density, high stability, and low eddy current and hysteresis losses are thus the most important considerations in the choice of a superconducting material and in the design of the coil. To a certain extent current density is dependent upon the type of superconducting material. However, for a given amount of superconductor material, a higher current density can be obtained in an ac coil employing numerous smaller wires rather than a few larger ones. This phenomenon is due to the "skin-effect;" i.e., to the fact that all the current in a superconducting wire is carried on the outer surface of the wire. In addition, eddy current and hysteresis losses can be minimized by employing a large number of small wires which are twisted together with a twist pitch that is a function of the rate of change of the magnetic field and the dimensions of the superconductor cross section. Wires on the order of 2.54E-05 m (0.001 in.) appear feasible for superconductor application. Superconductor stability is commonly achieved by combining a good normal conductor with a superconductor to form a composite in which filaments (or a thin ribbon) of superconductor are encased in a jacket or substrate of the normal material. If a superconducting wire tends to go normal, a parallel path for the current through the substrate is thus available. This reduces the heat buildup in the superconductor and makes a quick return to superconducting conditions possible.

C. Material Characteristics

Although the number of superconducting materials is very high, up to now only the alloy system NbTi and the compound Nb_3Sn have been used extensively in coils. The NbTi system is ductile and can be made into conductors by standard metal-working techniques. Compounds such as Nb_3Sn, on the other hand, are brittle and special techniques are necessary in fabrication. Recently, a V_3Ga conductor has become available commercially, which, like Nb_3Sn, is also formed by a diffusion process. Small coils have been constructed from this material, and its future use is expected to increase. Other intermetallic compounds with potential future application in superconducting coils are $Nb_3(Al_{0.8}Ge_{0.2})$ and Nb_3Al.

Table VII summarizes the useful (or potentially useful) critical fields and critical temperatures for some of the more popular superconducting materials.

TABLE VII

SUPERCONDUCTING PROPERTIES

Material	Critical Temperature, K	Critical Field at 4.2 K, T
NbTi	9.5	12.2
Nb_3Sn	18.2	24.5
V_3Ga	16.8	21.0
$Nb_3(Al_{0.8}Ge_{0.2})$	20.7	41.0
Nb_3Al	17.5	30.0

Of the two most readily available superconductors, Nb_3Sn has the advantage of a higher critical temperature and a higher critical field. However, Nb_3Sn is a very brittle material making it extremely difficult to form into the fine wire or filament-type superconductor which is essential for minimizing the hysteresis and eddy current losses. On the other hand NbTi can be easily formed into filament-type wires. Although the 9.5 K critical temperature of NbTi dictates an operating temperature at about 6 K, this low temperature is attainable in space application where the superconductor will be cooled by direct application of LHe at 4.2 K. The choice of a superconductor would therefore depend primarily upon the desired maximum field intensity. If field intensities greater than 10 T are required, then it would be necessary to employ Nb_3Sn. For field intensities below 10 T it would be possible to utilize the more readily machinable NbTi.

VI. SPACE APPLICATIONS OF HOMOPOLAR GENERATORS AND INDUCTIVE ENERGY STORAGE

A. General

In this section we will present a preliminary design study of a homopolar generator superconducting inductive energy storage pulse-power system to satisfy the pumping requirements of a space-based, short-pulse, 1-MJ laser module. We have chosen a 1-MJ laser only for purposes of illustration. Many possible space applications would require larger output; the weights for other systems can be derived by using the approach and information given herein. Overall power supply weight is of prime importance because the cost per unit weight of the orbiting payload is very high. We will first define the laser load requirements and will then work backwards through the pulse power system considering in sequence the inductive energy store, the homopolar generator, and the basic source of energy or power supply.

B. Definition of Laser Load

For purposes of this analysis we assume a 10% efficient laser which produces a 1-MJ output pulse every 60 s for a total of 300 pulses. Hence, a 10-MJ pulse is required as the laser input. In addition, we assume an input pulse width of 10 μs with a voltage of ~ 300 kV, resulting in an input current of ~ 3.3 MA.

C. Inductive Energy Storage System

We will first establish the feasibility of employing an inductive energy storage system to satisfy the above laser input requirements and we will then estimate the weight of such a system.

1. Inductive Storage Feasibility Analysis. For purposes of this analysis the laser can be considered a resistive load. Dividing the required laser voltage (300 kV) by the required laser current (3.3 MA) yields an equivalent laser resistance of 0.009 Ω. The energy, E, stored in a coil of inductance L carrying a current I is

$$E = \frac{1}{2} LI^2, \tag{1}$$

the coil voltage is

$$V_o = L\frac{dI}{dt}, \tag{2}$$

and the current emanating from the coil into a pure resistive load with resistance R is governed by

$$I = I(t_o)e^{\frac{-R}{L}t}, \tag{3}$$

where,

t = time, and

$I(t_o)$ = current at $t = o$.

An iterative procedure can be employed to find an inductive storage system that satisfies Eqs. (1-3). If we assume that 15% of the 10 MJ delivered to the load is consumed in the switching circuit, then the total energy delivered by the coil in 10 μs must be 11.5 MJ. Some energy will ordinarily remain in the coil at the end of 10 μs. The iterative approach to finding an inductive system that satisfies the pulse requirements and Eqs. (1-3) requires that we guess a suitable current time history and energy E. We obtain a reasonable solution with an energy of 22.5 MJ and a current time history that varies linearly from an initial value of 4.0 MA to 2.8 MA at the end of the 10 μs pulse. This gives an average current of 3.4 MA over the pulse interval, compared with the 3.3 MA required. The inductance L can then be found by using Eq. (1) with an E of 22.5 MJ and an initial current of 4.0 MA; the resultant inductance then is 2.81 μH.

The time required for the current to change from an initial value of 4 MA to a final value of 2.8 MA can be found by solving Eq. (3) for t, and using R = 0.009 Ω and L = 2.81 μH. We thus obtain t = 11.0 μs, which compares favorably with the required pulse width of 10 μs.

An approximate value for the voltage developed across the load can be found from Eq. (2). With L = 2.81 μH and using the approximation

$$\frac{dI}{dt} = \frac{I - I(t_o)}{(\text{pulse width})} = \frac{1.2 \times 10^6}{11.0 \times 10^{-6}} \tag{4}$$

we calculate a voltage of 305.8 kV, which compares favorably with the required voltage of 300 kV.

At the end of the pulse period the current will be 2.8 MA. Hence, from Eq. (1) with L = 2.81 μH, the energy remaining in the inductive system at this time will be 11.02 MJ. Because the initial energy was 22.5 MJ, the net energy extracted from the coil was 11.48 MJ. After subtracting the switching-circuit loss of 1.5 MJ, we have 9.98 MJ delivered to the load, which is close to the desired value of 10 MJ.

The above preliminary analysis leads us to conclude that an inductive storage system with an inductance of 2.81 μH, a stored energy of 22.5 MJ, and an initial current of 4.0 MA will satisfy the laser input-pulse requirements.

2. Inductive Storage System Weights. The weight of the inductive system including the dewar and switching circuitry may be estimated from Fig. 5. A specific mass of 100 kg/MJ at the 22.5-MJ level appears attainable if we assume a round coil with NbTi superconducting material and take into consideration the fact that we are designing the coil for a limited-life space application. Thus, the total inductive system weight will be 2 250 kg.

D. Homopolar Generator System

As a result of the inductive storage system analysis, the homopolar generator system will be required to deliver 22.5 MJ to the inductive storage system with a peak current of 4.0 MA. In the following analysis we will derive a minimum weight homopolar generator system to satisfy the above requirements. We shall first develop some fundamental relations that are applicable to a minimum weight space-based homopolar generator.

1. Equations for Maximum Current, Voltage, and Energy. The current, voltage, and stored energy requirements are the three most important factors that must be considered in the design of a homopolar generator. In the following paragraph we will develop expressions for the maximum values of these three factors as functions of generator parameters.

The voltage and stored energy can be increased by increasing the peripheral velocity of the rotor. However, the rotor peripheral velocity is limited by the maximum allowable stress in the rotor material. For a given rotor with peripheral velocity v, composed of a material with density ρ and Poisson's ratio μ the maximum tangential stress σ_t is given by[19]

$$\sigma_t = \frac{\rho \ v^2 \ (3 + \mu)}{4} \ . \tag{5}$$

Solving for v gives

$$v = \left[\frac{4 \ \sigma_t}{\rho \ (3 + \mu)}\right]^{1/2} . \tag{6}$$

Currently, one of the strongest materials for rotors is HP-9-4-45 steel (Republic Steel), which has an allowable design strength of 0.965 GPa (140 000 psi). For medium lifetime space applications it is estimated that the maximum stress of this material could be extended to 1.37 GPa (200 000 psi). Using this stress in Eq. (6) along with a Poisson's ratio of 0.3 and a density of 7 900 kg/m^3 (0.285 lb/in.^{3}) results in a maximum rotor peripheral velocity of

$$v = 450 \text{ m/s.}$$

For space applications of a homopolar generator we shall therefore consider 450 m/s to be the maximum peripheral velocity.

The energy E_r (see Appendix) stored in a homopolar generator

$$E_r = 0.25 \ m_r \ R^2 \ \omega^2, \ J \tag{7}$$

where

m_r = rotor mass, kg
R = rotor radius, m
ω = rotor angular velocity, rad/s,

because

$v = R\omega$ it follows that

$$E_r = 0.25 \ m_r v^2, \ J \tag{8}$$

or

$$\frac{E_r}{m_r} = 0.25 \ v^2, \ J/kg. \tag{9}$$

Using the maximum peripheral velocity of 450 m/s in the above equation gives

$$\frac{E_r}{m_r} = 50.625 \ \frac{kJ}{kg} \ . \tag{10}$$

Thus, a rotor weighing 1 000 kg will have a maximum energy capacity of 50.625 MJ.

The homopolar generator voltage V_o (see Appendix) is given by

$$V_o = \frac{\pi \ n \ d^2 \ B}{120} \ , \ V \tag{11}$$

where

n = rotor speed, rpm
d = rotor diameter, m
B = rotor flux density, T.

Because $v = R\omega$ it follows that

$$V_o = \frac{d \ v \ B}{2} \ , \ V. \tag{12}$$

With a superconducting field coil the maximum flux density B that can be attained is governed by the saturation flux density of the rotor. A reasonable upper limit for B is ~ 2 T. Using this value for B and a velocity of 450 m/s we obtain from Eq. (12)

$$V_o = 450 \ d, \ V. \tag{13}$$

Therefore, in a homopolar machine with a rotor diameter of 1 m, the maximum output voltage will be 450 V.

On the basis of Eq. (13) it may be tempting to conclude that for a given mass of the rotor we could obtain practically any higher voltage by increasing the rotor diameter d and decreasing the rotor length ℓ. However, for the cylindrical rotor generator the rotor must be of sufficient length to provide adequate magnetic flux paths. For the applications being considered here the minimum rotor length-to-rotor diameter ratio is

$$\frac{\ell}{d} = 2. \tag{14}$$

The energy storage capacity for a homopolar generator can be increased by coupling a high-speed flywheel to the generator rotor. Important advances in flywheel technology are being made and it is estimated that a superflywheel[20] built from a PRD-49 fiber composite material will have an energy density of ~ 1.26 MJ/kg, i.e.,

$$\frac{\text{Flywheel Energy}}{\text{Flywheel Mass}} \sim 1.26\ \frac{\text{MJ}}{\text{kg}}\ . \tag{15}$$

Hence, the energy density of the flywheel is ~ 25 times larger than that of the homopolar generator rotor, [Eq. (10)].

The maximum current that can be delivered by a homopolar generator is limited by the maximum allowable current density in the liquid-metal current collectors. The current collectors consist of rings that encircle each end of the generator rotor. With present technology the maximum current density these current collectors can withstand is ~ 5 000 A/cm^2. For space applications this maximum current density can probably be increased to ~ 7 500 A/cm^2. Therefore, for a current collector with a width of 5 cm, the maximum current capability of the generator with a rotor diameter d (in meters) will be $I = \pi d(5)(7\ 500)\ (100)$ or

$$I = 11.781\ d,\ \text{MA}. \tag{16}$$

Therefore, a generator with a 1-m-diam rotor will be capable of supplying a current of 11.78 MA.

2. Minimum Weight Design Philosophy. The generator energy, voltage, and current for a minimum weight system are given by Eqs. (10), (13), and (16), respectively. A more usable form for Eq. (10) can be obtained through elimination of the rotor mass m_r. Because

$$m_r = \frac{\pi}{4}\, d^2\ \ell\rho,\ \text{kg} \tag{17}$$

it follows with $\ell/d = 2$ and $\rho = 7\ 888.77$ kg/m^3 that

$$m_r = 12\ 391\ d^3,\ \text{kg}. \tag{18}$$

Substituting the above expression for m_r into Eq. (10) gives

$$E_r = 627.327\ d^3,\ \text{MJ}. \tag{19}$$

Examination of Eqs. (13), (16), (18), and (19) reveals that voltage and current vary linearly with diameter d, whereas the rotor mass and energy vary as the cube of the diameter. Because the main objective in the design of the homopolar system is to minimize the mass, the best way to satisfy the voltage, current, and energy requirements is by using several smaller homopolar generators. For example, suppose we wish to double the current I or the voltage V for a given machine. We can do this either by doubling its diameter or by coupling two of the original machines. According to Eq. (18) doubling the diameter will increase the system mass by a factor of 8 whereas using two of the original machines will require only 2 times the mass. Of course, the stored energy will be increased by a factor of 8 when the diameter is doubled [Eq. (19)], whereas it will be doubled if two of the original machines are used. However, if the system is short of energy, the additional required energy can be more optimally included by means of flywheels. This is evident from a comparison of Eqs. (10) and (15) for rotor and flywheel storage, which shows that flywheel storage is about 25 times more efficient than generator rotor storage.

The above considerations indicate that the minimum weight homopolar generator system should consist of several smaller coupled generators rather than of one large generator. Obviously, there is a limit to how small a generator can be. A reasonable lower limit for a rotor diameter is ~ 0.2 m.

Hence, with the size of the basic generator rotor established at 0.2 m, the maximum current and voltage requirements of the load can be satisfied by coupling in parallel and series a sufficient number of homopolar generator units. If the energy requirements are not satisfied by these units, flywheel storage should be added.

3. Design of Minimum Weight Generator and Flywheel System. For this application the homopolar generator system must deliver 22.5 MJ to the inductive storage with a peak current of 4.0 MA.

Let us consider the current requirements first. The maximum current capacity of a homopolar generator with diameter d is expressed by Eq. (16). As pointed out previously, it is from a weight standpoint more efficient to use several smaller homopolar generators rather than one large unit. The smallest practical generator was assumed to have a rotor diameter of 0.2 m. Applying Eq. (16) for a set of N parallel connected generators gives

$$I = 11.7810 \, dN, \text{ MA}. \qquad (20)$$

With d = 0.2 m and I = 4 MA, we can solve the above equation for N;

$$N = 1.7 \text{ generators}.$$

Therefore, to remain above the minimum rotor diameter of 0.2 m, only one homopolar generator should be employed. In space application an even number of generators with counterspinning rotors should be employed to balance the reaction torques on the space vehicle. Because more than one laser module will most likely be in a given application, the problem of using one generator per module is not considered important in this analysis. With N = 1 and I = 4 MA we can solve Eq. (16) for

$$d = 0.34 \text{ m}.$$

Thus, one homopolar generator with a diameter 0.34 m will satisfy the current requirements.

The maximum generated voltage can be found from Eq. (13) with d = 0.34 m to be

$$V_o = 152.8 \text{ V};$$

and, similarly, the maximum generator energy storage capability can be found from Eq. (19) to be

$$E_r = 24.6 \text{ MJ}.$$

Because the generator is required to deliver 22.5 MJ to the inductive load, it may appear that a maximum storage capacity of 24.56 MJ is adequate for the task. However, as pointed out previously, the maximum energy is delivered to the inductive load at the time of peak current. At this instant, the generator must have sufficient voltage, V_o, to equal the voltage drop across the resistance of the charging circuit. However, because generator energy is proportional to V_o^2 (see Appendix) , some energy must remain in the generator when the inductive load is fully energized. Therefore, a generator energy of 24.56 MJ may be inadequate and flywheel energy may have to supplement the generator energy.

To determine the amount of stored rotational energy required, we must perform an analysis similar to the one outlined at the end of the Appendix. If we use the previously computed inductance L_L of 2.81 μH and an assumed charging resistance R_L of 20 μΩ, then, by this analysis for a generator voltage V_o of 152.8 V, the required generator energy will be 70.1 MJ. Because only 24.6 MJ can be stored in the generator, flywheel energy storage must account for the remaining 45.5 MJ. The time required to energize the inductive system is computed to be 0.16 s, as outlined in the Appendix.

Not all the total flywheel and generator energy of 70.1 MJ will be consumed during the discharge. To determine how much energy will remain in the flywheel-generator system when the inductive system is fully energized, we make use of the fact that at the time of peak current the voltage across the coil will be zero ($\frac{dI}{dt} = 0$), and therefore the generator voltage must be equal to the voltage drop across the circuit resistance. With a peak current of 4 MA and a circuit resistance of 20 μΩ the generator voltage will be 80 V. Equation (12) can then be solved for the rotor velocity with V_o = 80 V, d = 0.34 m, and B = 2 T to give

$$V = 235.3 \text{ m/s}.$$

Because energy is proportional to the square of velocity, the energy corresponding to a velocity of 235.3 m/s will be

$$E = 70.1 \, \frac{235.3^2}{450^2} \text{ MJ} = 19.2 \text{ MJ}.$$

Therefore, at the end of the generator discharge phase 19.2 MJ will remain in the flywheel-generator storage system. The difference between the initial energy of 70.1 MJ and the final energy of 19.2 MJ, i.e., 50.9 MJ, must be provided by the power supply.

4. Weight Computation for Generator and Flywheel System. We have determined in the above analysis that the energy storage requirements for the flywheel and homopolar generator are 45.5 and 24.6 MJ, respectively. With a flywheel energy density of 1.26 MJ/kg [Eq. (15)] the mass of the flywheel system will be 26.1 kg, and with a generator rotor energy density of 60.5 kJ/kg [Eq. (10)] the mass of the rotor will be 486.2 kg. If we assume that the mass of the field circuit and supporting structure is twice the rotor mass, then the total generator mass will equal 1 458.6 kg. For the flywheel with a rotor mass of 36.1 kg we estimate that the associated support structure and gear box will bring the total flywheel system mass to ~ 100 kg.

E. Basic Power Supply

Because of its low specific mass and simplicity we have chosen a LO_2/LH_2 turbine power supply to energize the flywheel and generator system. The flywheel and generator rotors are coupled directly to the turbine shaft.

As a result of the previous analysis we conclude that the power supply must deliver 50.9 MJ to the flywheel and homopolar generator system prior to every laser pulse. A 0.85-MW power supply will be sufficient to satisfy this energy input because the interval between laser pulses is not expected to be less than 60 s. With a system designed for 300 pulses, the total power supply operating time will be 18 000 s (5 h). For an open-cycle LO_2/LH_2 turbine power supply at this power level and operating time the specific mass will be ~ 5.5 kg/kW.[10] Thus, at the 0.85-MW level the total power supply mass will be 4 675 kg.

F. Total Mass of Pulse Power System

The mass of the total pulse power system for a 10% efficient 1-MJ pulse laser delivering 300 pulses at 60-s intervals is summarized in Table VIII.

TABLE VIII

SUMMARY OF PULSE POWER SYSTEM MASS

Subsystem	Mass, kg
Inductive storage	2 250
Homopolar generator	1 459
Flywheel	100
Power supply	4 675
Total	8 484

VII. APPLICATION OF HOMOPOLAR GENERATORS AND INDUCTIVE STORAGE TO CONTROLLED THERMONUCLEAR REACTORS

Homopolar generators and/or inductive storage devices may play a significant role in future Controlled Thermonuclear Reactor (CTR) development, both with the magnetic-confinement (MCTR) and the laser pellet-fusion (LCTR) concepts.

A theta-pinch MCTR experiment is in progress at the Los Alamos Scientific Laboratory. In this experiment a large amount of electric energy must be delivered to a compression coil to magnetically compress the plasma. The current LASL theta-pinch Scyllac facility employs charged capacitor banks and associated switching circuitry to energize the compression coil. About 10 MJ of stored capacitive energy are required. After completion of the Scyllac experiment, LASL's MCTR effort will be dedicated to the development of an advanced, much larger theta-pinch facility called the Scientific Feasibility Experiment (SFX), in which superconducting magnetic storage will replace capacitive storage. It is estimated that ~ 250 MJ of stored magnetic energy will be required to energize the compression coil. To satisfy these requirements a large number (150-500) of smaller superconducting magnetic energy storage coils will be employed, with each coil having a storage capacity in the 0.6-1.5-MJ range. For each coil the peak voltage will be around 60 kV and the peak current ~ 25 kA with a pulse width of around 1 ms. Cost for the magnetic energy storage and its associated switching is estimated at 5¢/J,[15] whereas, the cost of an equivalent capacitive system is estimated at ~ 40¢/J.[21] At the 250-MJ level, it is therefore, obvious why LASL has chosen superconducting magnetic energy storage for its theta-pinch Scientific Feasibility Experiment. No firm decision has been made as to how the magnetic storage coils will be energized; homopolar generators have been considered but, because of the relative low maximum current requirements (25 kA) for the storage coils, conventional dc generators are presently favored.

Laser Controlled Thermonuclear Reactors (LCTRs), as they are being conceived, will also require large pulsed power systems, in this case for electrically pumping the lasers.[22] The use of lasers for Controlled Thermonuclear Reactor (CTR) concepts is a recent development, in contrast with magnetic confinement techniques. Primary efforts have been dedicated to assessing the feasibility of laser compression and heating of DT pellets to thermonuclear ignition and burn conditions. Because laser research and development is advancing rapidly, it is not possible to predict the specific type or types of lasers that will be most advantageous for application in LCTR power systems. Calculations indicate that a total laser pulse of ~ 1 MJ with a pulse width of ~ 1 ns and a pulse repetition rate of 30-50 pulses per second will be required. The laser system that is developing most rapidly and shows promise of achieving the required performance at reasonable cost and operating efficiency is the CO_2 system or a similar electrically pumped laser using some other gas as the lasing medium.

Electrical pumping of a 10% efficient CO_2 laser system of this type would require an electric pulse of ~ 10 MJ with a duration of ~ 10 μs, a voltage of ~ 300 kV, and current of 3.3 MA.[23] Superconducting magnetic energy storage coils would, as in the case of the theta-pinch MCTR system, be considerably less costly than capacitive storage. However, the relatively short pulse width (10 μs), high current (3.3 MA), high voltage (300 kV), and high pulse repetition rate (30-50 pulses per second) may be difficult to attain with superconducting magnetic energy storage systems. Additional studies would be needed before magnetic energy storage could be recommended for LCTR applications.

If magnetic energy storage were employed, homopolar generators could provide the energizing power, because of their high current-carrying capabilities. The generator would be coupled through flywheels to turbines in the steam power plant. A major limitation to the use of homopolar generators appears to be their incapacity of satisfying the required pulse rate of 30-50 pulses per second. Because a homopolar generator can probably not discharge its energy in less than 0.1 s, and because at least some seconds are required to bring the generator back to its rated operating speed after a discharge, the number of generators required to satisfy the high pulse rate would be prohibitively large. However, in experimental LCTR systems where high pulse rates are not required, the homopolar generator may be an attractive energizer for magnetic energy storage systems. Capacitive storage is currently used to store and to condition the electric energy for experimental LCTR laser systems.[23]

APPENDIX

HOMOPOLAR GENERATOR THEORY

I. VOLTAGE AND TORQUE RELATIONS

For simplicity a homopolar generator may be considered as a disk spinning on its axis in a magnetic field.[2] Consider a disk of radius R rotating with angular velocity ω in a magnetic field $\vec{B}$ as shown in Fig. A-1. A voltage V will be induced in the rotor proportional to the rate at which flux lines are being cut. The voltage developed in the disk can be derived through the following arguments.

Consider a unit charge located at a distance r from the center of the disk. Then the magnetic force $\vec{F}_m$ on the unit charge is given by

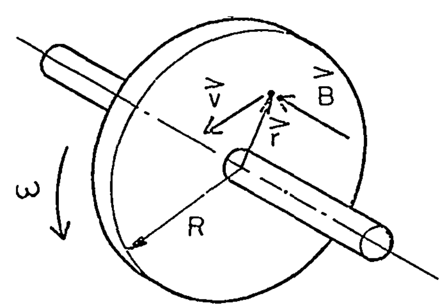

Fig. A-1. Homopolar generator rotor.

$$\vec{F}_m = \vec{v} \times \vec{B} \qquad \text{(A-1)}$$

where

$\vec{v}$ = vector velocity of the unit charge due to the disk rotation.

With the velocity $\vec{v}$ and the magnetic field $\vec{B}$ as shown in Fig. A-1, the vector $\vec{v} \times \vec{B}$ will be equal in magnitude to vB and will be directed along a radial line from the charged particle to the center of the disk, i.e.,

$$\vec{v} \times \vec{B} = -v\, B\, \vec{i}_r \qquad \text{(A-2)}$$

where

$\vec{i}_r$ = unit vector directed along r.

Combining Eqs. (A-1) and (A-2) gives

$$\vec{F}_m = -v\, B\, \vec{i}_r. \qquad \text{(A-3)}$$

The voltage rise V from the center of the disk to the rim of the disk is defined as the amount of work required to move a unit charge from center to the rim. Let $\vec{F}$ be the force to move the unit charge. Then this force must be equal and opposite to the magnetic field force $\vec{F}_m$ tor

$$\vec{F} = -\vec{F}_m \qquad \text{(A-4)}$$

and from Eq. (A-3) it follows that

$$\vec{F} = v\, B\, \vec{i}_r. \qquad \text{(A-5)}$$

The work dW required to move a unit charge through a distance dr along a radial line defined by the unit vector $\vec{i}_r$ is by definition

$$dW = \vec{F} \cdot \vec{i}_r\, dr. \qquad \text{(A-6)}$$

Because work on a unit charge is equivalent to voltage,

$$dV_{disk} = dW. \qquad \text{(A-7)}$$

Combining Eqs. (A-5), (A-6), and (A-7) and substituting rω for y gives

$$dV_{disk} = r\omega B\, \vec{i}_r \cdot \vec{i}_r dr. \qquad \text{(A-8)}$$

Integrating the above equation from the center of the disk (r = 0) to the disk rim (r = R) gives

$$V_{disk} = \frac{\omega B\, R^2}{2}, \qquad \text{(A-9)}$$

where V_{disk} is the voltage rise from the center of the disk to the rim of the disk. Let

n = rotor velocity in rpm

d = rotor diameter.

Because

$$\omega = \frac{2\pi n}{60}$$

and

$$R = d/2,$$

it follows from Eq. (A-9) that

$$V_{disk} = \frac{\pi\, n\, d^2\, B}{240}. \qquad \text{(A-10)}$$

The voltage V_{disk} in the above equation represents the voltage induced in a rotating disk. Most modern homopolar generators have a cylindrical rotor with field coils at each end. From an induced voltage standpoint the cylindrical rotor would be equivalent to two disk rotors of the type considered in the above derivation. Letting V be the voltage induced in the cylinder, it follows that

$$V = 2V_{disk} \qquad \text{(A-11)}$$

and from Eq. (A-10) we have

$$V = \frac{\pi\, n\, d^2\, B}{120}. \qquad \text{(A-12)}$$

If in the above equation we use the rotor speed n in rpm, the rotor diameter d in meters, and the flux density B in W/m^2 (Tesla) then the rotor voltage V will be in volts. (For an iron-type rotor the saturation flux density is ~ 2.5 T.)

If a current I flows in the rotor of the homopolar generator, a torque T will be developed on the rotor as a result of the interaction between the magnetic flux lines. If, for example, a pure resistance R_L is placed across the generator, then the current I will be given by

$$I = \frac{V}{R_L} , \tag{A-13}$$

and from Eq. (A-12) it follows that

$$I = \frac{\pi\, n\, d^2\, B}{120\, R_L} . \tag{A-14}$$

As a result of the rotor current I, a magnetic interaction torque T will be exerted upon the rotor. For purposes of deriving an expression for T, assume that the rotor consists of a disk in which a current I is flowing. In addition it can be assumed that all the current is concentrated in a narrow sector of the disk as shown in Fig. A-2.

By Ampere's Law the force exerted upon the infinitesimal volume located at a distance r from the disk center will be

$$d\vec{F} = B \times I\, dr . \tag{A-15}$$

Because the vector torque $d\vec{T}_{disk}$ is given by

$$d\vec{T}_{disk} = r \times d\vec{F} \tag{A-16}$$

it follows from Eq. (A-15) that

$$d\vec{T}_{disk} = \vec{r} \times \vec{B} \times \vec{I}\, dr . \tag{A-17}$$

Because the vectors $\vec{r}$, $\vec{B}$, and $\vec{I}$ are all mutually perpendicular, Eq. (A-17) reduces to

$$dT_{disk} = B\, I\, r\, dr . \tag{A-18}$$

Integrating the above equation from r = 0 to r = R gives for the total disk torque

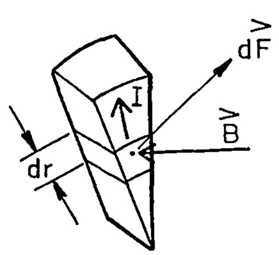

Fig. A-2. Segment of rotor disk.

$$T_{disk} = \frac{B\, I\, R^2}{2} . \tag{A-19}$$

For a cylindrical rotor the braking torque will be twice that of a disk rotor. If we let T be the braking torque associated with a cylindrical rotor it follows from Eq. (A-19) that

$$T = B\, I\, R^2 . \tag{A-20}$$

With R = d/2 the above equation becomes

$$T = \frac{B\, I\, d^2}{4} . \tag{A-21}$$

For a purely resistive load we have from Eq. (A-14)

$$T = \frac{\pi\, n\, d^4\, B^2}{480\, R_L} . \tag{A-22}$$

II. EQUIVALENT CAPACITANCE

For circuit analysis purposes, the homopolar generator can be replaced by an equivalent capacitor. This can be proven in the following manner. Consider the capacitor C in Fig. A-3 with current I and voltage V. The basic voltage current relationship for a capacitor is

$$\dot{V} = \frac{I}{C} . \tag{A-23}$$

We now desire to develop a similar expression for the homopolar generator. With n = 30 ω/π we have from Eq. (A-12)

$$V = \frac{\omega\, d^2\, B}{4} . \tag{A-24}$$

Differentiating both sides of the above equation gives

$$\dot{V} = \frac{d^2\, B}{4}\, \dot{\omega} . \tag{A-25}$$

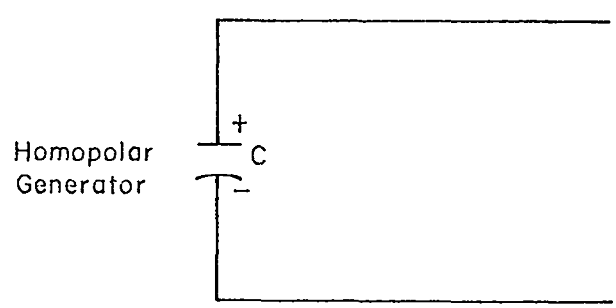

Fig. A-3. Homopolar generator represented by a capacitor.

For the generator rotor with moment of inertia J we have the following basic relation

$$T = J \dot{\omega} . \quad \text{(A-26)}$$

Solving Eq. (A-26) for $\dot{\omega}$ and eliminating T through the use of Eq. (A-21) gives

$$\dot{\omega} = \frac{BId^2}{4\ J} . \quad \text{(A-27)}$$

Substituting this expression for $\dot{\omega}$ into Eq. (A-25) yields for the homopolar generator

$$\dot{V} = \frac{d^4 B^2 I}{16\ J} . \quad \text{(A-28)}$$

Comparing Eqs. (A-28) and (A-23), we see that the homopolar generator behaves similar to a capacitor because the rate of change of the generator voltage is equal to the product of a constant and the current. The equivalent generator capacitance C can be determined by equating the right-hand sides of Eqs. (A-23) and (A-28) to give

$$C = \frac{16J}{d^4 B^2} . \quad \text{(A-29)}$$

Therefore, for circuit analysis purposes, the homopolar generator can be replaced by a capacitor whose capacitance is given by Eq. (A-29).

III. STORED ENERGY

The kinetic energy stored in the homopolar generator rotor with moment of inertia J is given by

$$E = 1/2\ J\ \omega^2 . \quad \text{(A-30)}$$

For a cylindrical type rotor of mass m

$$J = 1/2\ mR^2 , \quad \text{(A-31)}$$

and hence Eq. (A-30) becomes

$$E = 1/4\ mR^2\ \omega^2 . \quad \text{(A-32)}$$

Because $\omega = \frac{\pi n}{30}$ and $R = \frac{d}{2}$, it follows that

$$E = \frac{1}{4m} \left(\frac{\pi n\ d}{60}\right)^2 . \quad \text{(A-33)}$$

The energy stored in the homopolar generator can also be computed by considering the energy stored in the equivalent capacitor which is given by

$$E = \frac{1}{2} C\ V^2 . \quad \text{(A-34)}$$

The energies given by Eqs. (A-30) and (A-34) must be equivalent if the homopolar generator is correctly modeled by a capacitor. To show the equivalence of these two equations, we solve Eq. (A-24) for ω and substitute the resulting expression in Eq. (A-30) to give

$$E = \frac{8J\ V^2}{d^4\ B^2} . \quad \text{(A-35)}$$

Equating the right-hand sides of Eqs. (A-34) and (A-35) and solving for C gives

$$C = \frac{16\ J}{d^4\ B^2} . \quad \text{(A-36)}$$

This is the identical expression for C given in Eq. (A-29) and hence the energy relations given by Eqs. (A-30) and (A-34) are equivalent.

If the energy and output voltage of a given homopolar generator are known, the equivalent generator capacitance can be found by solving Eq. (A-34), i.e.,

$$C = \frac{2E}{V^2} . \quad \text{(A-37)}$$

IV. APPLICATION TO INDUCTIVE LOAD

When a homopolar generator is employed to energize an inductive load, not all of the stored generator energy can be converted to electrical energy and delivered to the load. Since inductive energy is proportional to the square of the current, maximum energy coincides with maximum current. At the instant of maximum current the generator voltage must be sufficient to balance the sizable voltage drop developed across the resistance of the charging circuit. Since generator energy is proportional to the square of the voltage [Eq. (A-34)], a significant portion of energy must be present in the generator after the coil is fully energized. Some energy will be dissipated in the circuit resistance, and this energy will be significant even for rapid (0.1-1 s) charging systems. The amount of generator energy which cannot be delivered to the inductive load is heavily dependent upon the generator voltage and the resistance of the charging circuit. This will be shown in the following development.

Consider the circuit of Fig. A-4 in which a homopolar generator, represented by the capacitor C, is shown discharging through a load of inductance L_L and resistance R_L. Initially the switch is open while the homopolar generator is brought up to its desired operating speed. The switch is closed when the generator output voltage equals V_o, and the generator, behaving like a capacitive element, discharges through the load. The differential equation describing the circuit behavior is

$$\dot{I} + \frac{R}{L} I + \frac{1}{C}\int I dt = 0 \tag{A-38}$$

with boundary conditions

$$I(t = 0) = 0$$

$$\int_{-t}^{o} I dt = V_o \ .$$

Equation (A-38) along with the associated boundary conditions can easily be solved via Laplace Transforms to give for the current

$$I(t) = V_o \sqrt{\frac{C}{L_L}} \frac{\omega_0}{\omega_d} e^{-\alpha t} \sin \omega_d t \tag{A-39}$$

where

$$\omega_o = 1/\sqrt{L_L C}$$

$$\alpha = \frac{R_L}{2L_L}$$

$$\omega_d = \sqrt{\omega_o^2 - \alpha^2} \ .$$

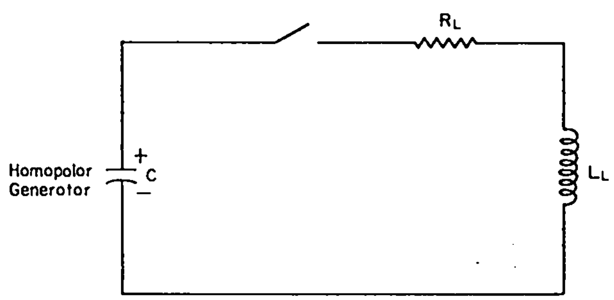

Fig. A-4. Homopolar generator charging lossy inductive load.

Differentiating Eq. (A-39) setting I(t) equal to zero and solving for t gives the time t_p at which the current is at maximum, i.e.,

$$t_p = \omega_d \frac{1}{\omega_d} \tan^{-1}\left[\frac{\omega_d}{2}\right] \ . \tag{A-40}$$

The peak current I_p can be found by substituting this expression for t_p into Eq. (A-39). This gives

$$I_p = V_o \sqrt{\frac{C}{L_L}} \ e^{-\alpha t_p} \ . \tag{A-41}$$

The magnetic energy stored in the inductive coil is given by

$$E_{coil} = \frac{1}{2} L_L \ I^2 \ . \tag{A-42}$$

Hence, from Eq. (A-41), the maximum energy stored in the coil will be given by

$$E_{coil}^{max} = \frac{1}{2} C \ V_o^{\ 2} \ e^{-2 \ \alpha t_p} \ . \tag{A-43}$$

Let E_{hg} be the initial energy stored in the homopolar generator or, equivalently, the initial energy stored in the capacitor. Then

$$E_{hg} = \frac{1}{2} C \ V_o^{\ 2} \ , \tag{A-44}$$

and it follows from Eq. (A-43) that the

$$E_{coil}^{max} = E_{hg} \ e^{-2 \ \alpha t_p} \ . \tag{A-45}$$

If we define the system efficiency η as the ratio of the peak coil energy to the original energy stored in the generator, i.e.,

$$\eta = \frac{E_{coil}^{max}}{E_{hg}} \ , \tag{A-46}$$

then, from Eq. (A-44), it follows that

$$\eta = e^{-2 \ \alpha t_p} \ . \tag{A-47}$$

The significance of the above development can be appreciated by considering the following numerical example in which it is desired to energize an inductance coil to a maximum level of 10^6 J, i.e.,

$$E_{coil}^{max} = 10^6 \ J.$$

It is desired to determine what effect the initial generator voltage V_o has upon the required energy storage, E_{hg}, in the generator. For the example consider a circuit in which

$$R_L = 5 \times 10^{-4}\ \Omega$$

$$L_L = 5 \times 10^{-5}\ H$$

$$I_p = 2 \times 10^{5}\ A.$$

For these values of inductance and peak current it follows from Eq. (A-42) that the maximum coil energy will be 10^6 J.

The following steps are then taken to find the required generator energy storage as a function of the initial generator voltage.

1. Choose a value of capacitance C.
2. Compute ω_o, α, ω_d, t_p, and η.
3. From Eq. (A-37)

$$V_o = \sqrt{\frac{2\ E_{hg}}{C}}\ . \tag{A-48}$$

Because from Eq. (A-46)

$$E_{hg} = \frac{E_{coil}^{max}}{\eta} \tag{A-49}$$

or

$$E_{hg} = \frac{10^6}{\eta}\ , \tag{A-50}$$

it follows that

$$V_o = 10^3 \sqrt{\frac{2}{\eta C}}\ . \tag{A-51}$$

The desired values for the generator energy E_{hg} and the corresponding generator voltage V_o are computed from Eqs. (A-50) and (A-51). Repeating the above steps for different values of capacitance will provide sufficient values for the plot of E_{hg} vs V_o shown in Fig. A-5.

The complete set of values that lead to Fig. A-5 are shown in Table A-1.

From Fig. A-5 it is obvious that higher generator voltages lead to smaller stored energy requirements. This can be explained through the following reasoning. Complete energization of the coil

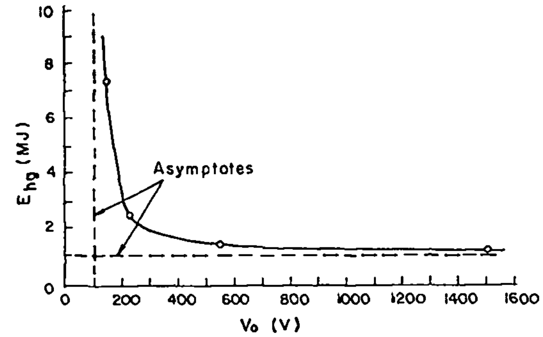

Fig. A-5. Voltage and stored energy for homopolar generator charging a practical 10^6 J inductance to 200 kA.

coincides with the time of peak current. At this time the voltage across the coil is zero because $\frac{dI}{dt} = 0$, and hence the generator voltage must equal the voltage drop across the circuit resistance. Thus, the only useful energy which can be extracted from the generator takes place as the voltage drops from its initial value V_o to the voltage at the time of peak current. Since generator energy is proportional to V_o^2 [Eq. (A-34)], the energy which cannot be delivered by the generator comprises a smaller percentage of the total generator energy as the value of the initial voltage is increased significantly above the voltage at peak current.

From Fig. A-5 it is also evident that there is a limiting generator voltage, V_o = 100 V, below which it is impossible to energize the inductance coil to the desired level. This minimum voltage level represents the voltage drop across the resistance $R_L = 5 \times 10^{-4}\ \Omega$ when carrying the peak current of 200×10^3 A, i.e.,

$$V_{limit} = R_L\ I_p \tag{A-52}$$

or

$$V_{limit} = 100\ V.$$

TABLE A-1

SUMMARY OF CALCULATIONS FOR FIG. A-5

C (F)	ω_d (s^{-1})	t_p (s)	η	E_{hg} (MJ)	V_o (V)
1	140	1.1×10^{-2}	0.89	1.11	1 500
10	44.5	3.3×10^{-2}	0.72	1.4	526
100	13.2	9.1×10^{-2}	0.40	2.5	220
800*	0	0.2	0.135	7.4	136

*Critical damping values.

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