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POWER SUPPLY TECHNOLOGY FOR ADVANCED WEAPON SYSTEMS

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Army Mobility Equipment Research and Development Center
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Certain weapon systems under consideration by the Army will require high power and/or high energy electrical inputs. Several technologies for power production are discussed with particular emphasis on military application. Rotating electrical machinery, fuel cells, and magnetohydrodynamic (MHD) power supplies are considered along with the supporting technologies of superconductivity, cryogenic refrigeration, and turbine engines.

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POWER SUPPLY TECHNOLOGY FOR ADVANCED WEAPON SYSTEMS

I. INTRODUCTION

1. **Subject.** Advanced weapon systems under study by DOD require large energy inputs. Certain classes of these devices require electrical energy at high voltage and/or high current. These requirements vary from high, continuous power to high-repetition-rate pulse generation. It is apparent that no single type source can satisfy all these requirements; however, a number of existing and developing technologies appear to offer practical solutions to the problem of supplying these needs. This report summarizes the status of the most promising methods of power production to support advanced weapon systems.

2. **Background.** The basic types of power source considered here are magnetohydrodynamic (MHD) generators, diesel- or turbine-driven rotating machinery, both normal and superconducting, and fuel cells. Methods of producing low-repetition-rate, high-power pulses from moderate-level sources are considered separately. The supporting technologies of refrigeration and superconducting materials are seen as overlapping a variety of systems and are therefore covered in detail. Briefly, the fundamentals of the referenced technologies are as follows.

MHD describes the behavior of electrically conducting fluids in the presence of electric and magnetic fields. In the present sense, it will be limited to the production of electric power through this means. The MHD generator is based on the Faraday effect: an induced electric field is produced in a conductor moving in a magnetic field. In the MHD generator, the moving conductor is an ionized fluid, frequently a gas which has been heated by chemical or nuclear fuel, which flows through the generator channel. The simplest geometry, and the one we will use as an example, is the linear MHD channel. In this configuration, the fluid flows through a linear duct with a magnetic field at right angles to the flow velocity (Fig. 1). This induces a Faraday field normal to both the magnetic field and the flow velocity; electrodes located on the sides of the channel and connected to a load allow a current to flow through the fluid, electrodes, and load. Other configurations are possible, along with variations on the linear scheme, but the principles are the same. The basic requirement is a component of the fluid velocity normal to the magnetic field so that a $\underline{v} \times \underline{B}$ field will be established. Interaction between this electric field and the charged particles (ions) in the fluid provides the driving force for currents in the plane normal to the magnetic field. Energy is extracted directly as electrical energy through the electrodes at the channel walls. This type of conversion eliminates the prime mover needed to drive the windings in conventional rotating machinery and is therefore referred to as a direct-conversion process.

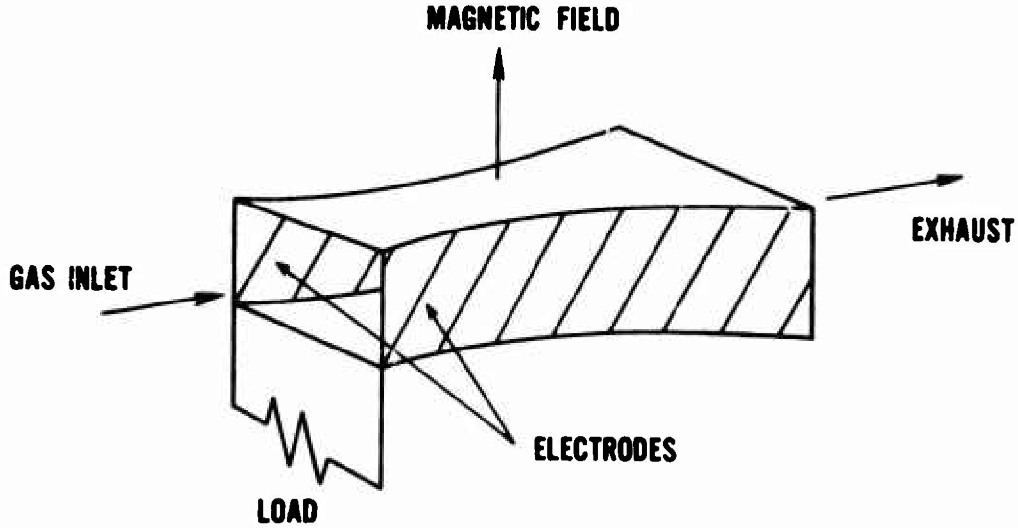

Fig. 1. Linear MHD channel.

Rotating machinery represents the most common type of energy-conversion device presently in use. Like the MHD generator, it is based on the Faraday effect; in this case, the electric field which drives the load circuit is produced by the relative motion between the armature windings and the magnetic flux produced by field windings or a permanent magnet. A prime mover, e.g., a diesel or turbine engine, is required to drive the rotating member. A simple example (Fig. 2) is the dc homopolar generator, or Faraday disc. Magnetic flux, generated by the solenoidal windings, passes through the metal disc. Rotation of the disc produces a Faraday electric field radially in the plane of the disc; contacts at the axis and circumference collect current which flows through the external circuit.

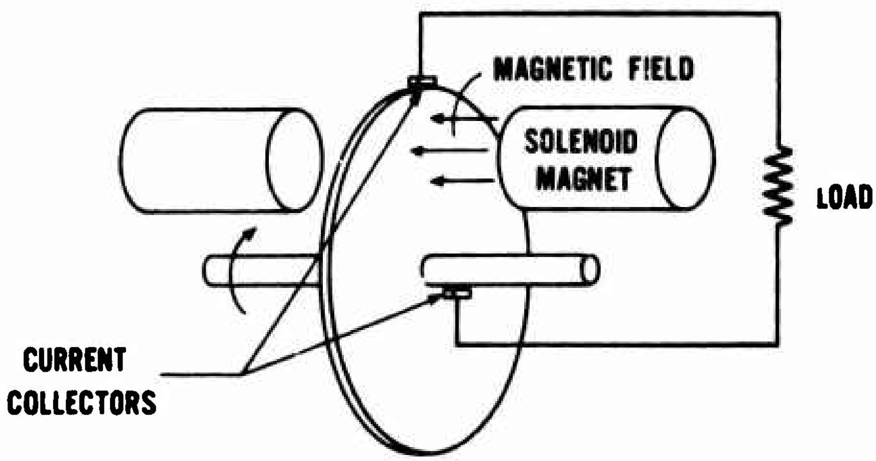

Fig. 2. Homopolar generator.

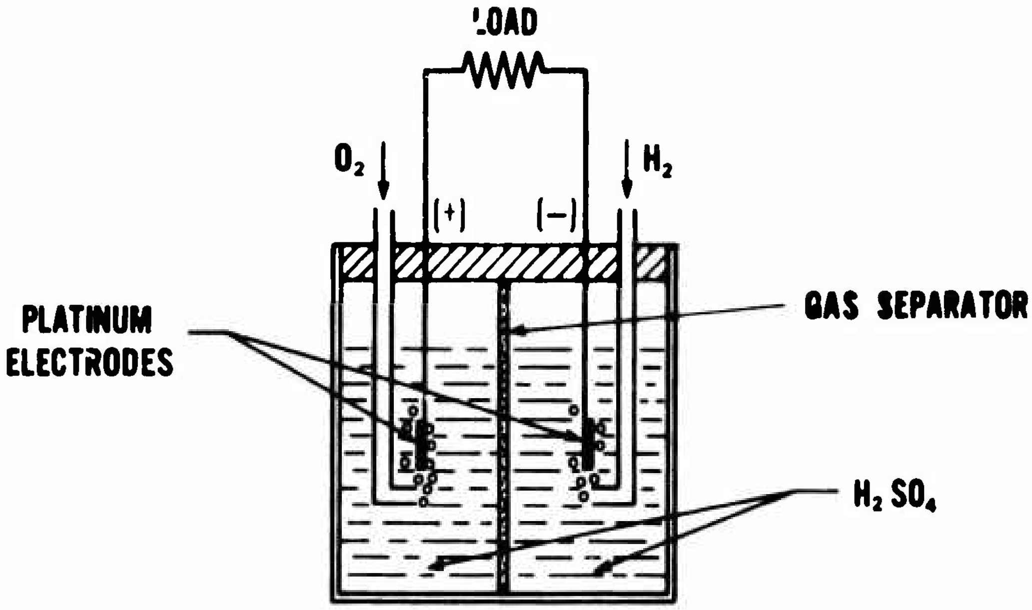

Fig. 3. Hydrogen-oxygen fuel cell.

The fuel cell is another example of direct conversion in which the energy of chemical fuel is converted directly to electrical energy without an intermediate step. In operation, fuel and oxidizer are supplied to the electrodes in contact with a suitable electrolyte. If the electrodes possess sufficient electrochemical activity, electrode potentials are established. The fuel and oxidizer electrodes become, respectively, the negative and positive electrodes of the cell; if the electrodes are connected through an external load circuit, electrons freed at the fuel electrode flow through the circuit to the positive electrode. As an example, let us consider the hydrogen-oxygen fuel cell. As illustrated in Fig. 3, platinum electrodes are immersed in an acid electrolyte, e.g., H_2SO_4, and supplied with hydrogen and oxygen. The reactant gases are separated by a permeable membrane. At the negative electrode surface, each hydrogen molecule dissociates into two atoms by catalytic action of the electrode surface. These go into solution as ions leaving two electrons at the electrode to pass through the external circuit. At the positive electrode, oxygen reacts with hydrogen ions in the electrolyte picking up two electrons from the electrode to give water. The emf is in the range 0.9 to 1.2 V. Many combinations of fuel, oxidizer, and electrolyte are possible, but, in general, the emf is of the order of 1 V so that usually it is necessary to connect a number of cells in series.

For this study, system power requirements are taken to be 0.5 to 25 megawatts (MW) for continuous applications and the same range of average power when designed for pulse systems. For the pulse-power requirement, pulse widths are taken to be 10^{-3} sec or less, with an energy of 10^3 J/pulse or higher. The repetition rate is considered to be on the order of 10's to 100's/sec. The energy is to be delivered at high voltage (10 to 300 kV).

For the continuous-power requirements, current designs and estimates indicate that below about 0.5 megavolt ampere (MVA) conventional alternators have specific weights below those of superconducting machines. From 0.5 to 1 MVA, superconducting machines (excluding refrigeration) begin to become competitive; while above 1 MVA they have a definite advantage in specific weight. Although the weights of superconducting alternators can be estimated with moderate accuracy, the weight estimates of helium refrigerators are not as firmly established. A recent survey indicates that operating refrigerators (with loads at about 4K) have a specific mass on the order of 100 $\frac{kg}{W}$ but with considerable scatter in the data. The refrigeration weight can be reduced at the site of the generator by the use of tanked cryogens, and this may be desirable for specific types of devices or types of mission; however, certain trade-offs must be made. Including integrated refrigeration, the superconducting machines as packages do not appear to offer specific weight advantages over conventional machines below about 5 MVA.

MHD devices are still under development, possibly to an even greater extent than superconducting machines; however, projections indicate specific weights comparable to superconducting devices at high (10 MW) ratings. Considerable research has been and is being done on MHD, particularly by the Air Force; the results indicate that for high ratings or some pulse applications MHD should receive consideration.

Although fuel cells offer power densities or specific weights in the same range as superconducting machines and are quieter, they tend to be limited in voltage output; thus, for the projected applications mentioned above, they are generally unsuitable without the addition of a significant weight in power-conditioning equipment.

Taking a specific system requirement, we may make a comparison between units utilizing each of the referenced technologies. The assumed requirement is a 10-MW, 400-Hz continuous power supply. At this level, 0.6 lb/kVA is considered achievable in conventional rotating machines so that the generator would have a weight of about 6000 lb. A superconducting generator is expected to have a specific weight of 0.2 lb/kVA which yields a weight of 2000 lb. In both cases, the weight of the prime mover must be added. In this range, gas turbines offer size-weight advantages over diesel power plants. To allow for generator efficiency and deratings imposed on military equipment by high altitude/ambient temperature requirements, an engine rated about 20,000 hp at standard conditions would be required. Based on aircraft practices, it is believed that an engine of this rating would be built with a weight of approximately

5000 lb, although such may not actually exist today. To this must be added the necessary refrigeration in the case of the superconducting machine. Westinghouse superconducting machine experience indicates a total heat load of 25 W for a 15 MVA machine. Taking 16 W for the case under consideration and using the refrigeration specific weight estimate quoted above yields 3250 lb for the refrigeration system. In addition, the refrigerator will consume power at about 1000 W per W of refrigeration, representing a drain of 0.16% on the system. The gas turbine will consume fuel at about .5 lb/hp-hr; for an assumed running time of 24 hours, 240,000 lb must be added for both systems.

By contrast, an MHD system at the 10 MVA level is projected to have a specific weight of 0.3 to 0.45 lb/kW (based on the assumption of combustion-type MHD) and includes a superconducting magnet, channel, burner, and dc to dc converter. The weight of refrigeration must be added although, as before, local weight could be reduced by cryogen tankage for certain applications. A conservative estimate of the heat leak for a magnet of this size is 2 W, so a refrigerator would add about 400 lb. If the MHD generator is of the dc type, an inverter will be required to satisfy our requirement for 400-Hz power. An inverter capable of handling 10 MW adds about 10,000 lb to the system weight (using a projection of 1 lb/kVA, a factor of ~ 6 down from present hardware). Fuel consumption is ~ 6 lb/kWh, so fuel for 24 hours of operation adds 1.4×10^6 lb.

If we base estimates of fuel cell systems on a requirement for using logistically available fuels and extrapolate from current development, specific mass of fuel cell systems will be about 100 lb/kW. A 10-MVA system would weigh about 1,000,000 lb which is not competitive for this application even without considering the extra weight of power conditioners. If we allow operation from hydrogen and oxygen rather than from hydrocarbon fuels, the specific weight becomes more favorable. A development program underway has 0.5 lb/kW as its goal; using this figure, we get ~ 5000 lb for the module plus ~ 10,000 lb for the power conditioner. Reactant consumption is ~ 0.44 lb/kWh so that 105,600 lb of fuel would be necessary. The weight of equipment for production of hydrogen and oxygen is not included here, nor is the efficiency of a process to convert hydrocarbon fuels.

For the example assumed above, the weight of consumables dominates the fixed weight of the system by a large margin, as expected for a system supplying continuous power. If we now consider a requirement for bursts of "continuous" power separated by periods of no demand, the situation changes. Let us take the requirement to be 10 MW at 100 kV dc for 2 minutes occurring at some unspecified time during a no-load period of several hours; rapid startup is required. A conventional generator for this application will have to be sized for approximately the full-load output; therefore, its size will be about the same as in the previous case (down by perhaps a factor of 2). A superconducting machine has more favorable overload characteristics due to its low internal impedance; it is estimated that for times of ~ 1 to 2 min, given adequate cooling, the superconducting machine could be overloaded by about a factor of 5. This would make itself felt in fixed weight; the conventional machine would weigh ~ 3000 lb while the superconducting machine would weigh ~ 500 lb. Refrigeration required during the full-load period could, to a certain extent, be averaged over the no-load period so as to bring the average load down. Taking ~ 4 W as an average adds about 800 lb for the refrigerator. To obtain the high-voltage dc required, it will be necessary to transform and rectify the output of these alternators. A short-duty transformer adds about 2000 lb, while the rectifier adds about 600 lb at the 10 MW level. The totals are 10,600 lb for the conventional machine and 8900 lb for the superconducting machine, including 5000 lb for the prime mover. Fuel is a negligible contribution if rapid start-up and short idle time are assumed. The fuel-cell system would have approximately the same weight as in the previous case if we allow operation from hydrogen and oxygen. A power conditioner having a weight of around 3200 lb must be included. The combination is ~ 8200 lb, not counting fuel (negligible) or the process of converting from hydrocarbon fuel to H_2 and O_2. An MHD system would offer rapid start-up (assuming the magnet is energized) and no fuel consumption on standby. The channel, combustors, magnet, and refrigeration would weigh ~ 4900 lb. The power conditioner converter adds ~ 3200 lb for a total of 8100 lb.

Table 1 contains a tabulation summarizing estimated weights and fuel requirements for the assumed examples. Included in this report are summaries for the various technologies considered applicable for high power/energies anticipated for advanced weapon systems. These summaries present more detailed information concerning background, current state of the art, and projected advancements for superconducting machinery, superconductors, MHD, fuel cells, helium refrigeration, and pulse power production. They also include a section on current state-of-the-art for turbine generator sets (400 Hz).

II. SUPERCONDUCTING GENERATORS

3. **Current Technology.** The technology of constructing electrical machines of significantly increased power density by employing superconducting elements is in its infancy. The announcement by researchers from Bell Laboratories in 1961 that the intermetallic compound Nb_3Sn (niobium-tin) was observed to carry a current density greater than 100,000 A/cm^2 in a magnetic field of 8.8 Tesla (T) (88 kilogauss) was the first real indication that the phenomenon of superconductivity could be applied to practical electric power devices. Discussion of the ensuing developmental efforts will separately consider ac and dc machines and will indicate possible applications for each.

a. **AC Superconducting Machines.** There have been six significant efforts aimed at building ac machines in the United States – all contributing to our current

Table 1. System Weight and Fuel Consumption Summary

	Turbine-Generator			
Parameter	Conventional (lb)	Superconducting (lb)	MHD (lb)	Fuel Cells (lb)
Continuous Operation				
Generator	6,000	2,000	4,500	5,000
Engine	5,000	5,000	–	–
Power Conditioner	–	–	10,000	10,000
Refrigeration	–	3,250	400	–
Total	11,000	10,250	14,900	15,000
Specific Fuel Consumption	.5/hph	.5/hph	6/kWh	.44/kWh
Total Fuel for 24 Hours	240,000	240,000	1,400,000	105,600
Intermittent Operation				
Generator	3,000	500	4,500	5,000
Engine	5,000	5,000	–	–
Power Conditioner	2,600	2,600	3,200	3,200
Refrigeration	–	800	400	–
Total	10,600	8,900	8,100	8,200

technological base. An early effort was undertaken by Dynatech Corporation under the sponsorship of the Aeropropulsion Laboratory, WPAFB. In a series of contracts, Dynatech performed a feasibility study, specific problem area R&D, and the design, construction, test, and evaluation of a 50-kW, laboratory-model superconducting generator. Overall emphasis was directed toward determining the feasibility of a 1000-kVA power supply for space applications. The test machine specifications demanded a 24,000 rpm, 2-pole, 400-cycle machine having a rotating, superconducting field coil and a 3-phase superconducting armature. Mechanical problems associated with high-speed operation and resulting electrical contact difficulties proved too severe for definitive test results to be obtained on the machine. The machine was operated at 7500 rpm at extracted powers less than 1 kW. Total Air Force funding on this project over the 1963-67 time frame covered by these contracts was $591K.

Though the results of this effort were not all that was anticipated, the considerable heat-transfer analysis and the demonstration of the feasibility of operating a superconducting winding in a rotating, vacuum-insulated vessel were significant contributions from this program.

A second early effort was initiated at MERDC (ERDL) in 1963 with Avco Everett Research Laboratories as the prime contractor. This effort concentrated on electrical design analysis and resulted in the construction of an 8-kW test machine. The machine employed a stationary, central superconducting field coil and an annular ambient temperature armature; this configuration minimizes cryogenic cooling system problems. The 4-pole device had a 3-phase air core armature rotating at 12,000 rpm, delivering the 8 kW at 400 Hz via a set of slip rings and brushes. This was the first successful demonstration of a superconducting machine of significant power rating. Later (1969-70), an iron-core armature was designed, built, and tested; it delivered in excess of 16 kW from an identical armature envelope. The results of the effort verified the design equations for iron-free and iron-core machines, demonstrated that the electromagnetic torques experienced by the field coil would not result in the loss of superconducting properties as some early investigators feared, and lucidly demonstrated the thermal advantages (as well as electromagnetic improvement when magnetic saturation is avoided) of using a ferromagnetic stator core with teeth. Total Army funding on the contractual part of this effort was $80K.

Another Army sponsored effort was conducted by Avco for AAVLABS–Fort Eustis (AVCO–Eustis) in 1967-68. This resulted in a 2-pole, 12,000-rpm, 15-hp design-rated test rig having a rotating, superconducting field winding and a 3-phase armature which could be either superconducting or cryogenically cooled. The object of this effort was to provide a demonstration of the feasibility of a rotating, cryogenic field coil system and to determine experimentally the losses in superconducting windings due to alternating currents and to rotating magnetic fields. This test rig suffered a seized bearing in early testing and the resultant mechanical damage limited the rotor to speeds less than 3000 rpm. The primary results of this effort were the clear demonstration of high swept-field losses in unshielded superconducting stator windings and a good transient response analysis based on application and removal of a short circuit or of a resistive load. This test rig is now at MERDC where the rotor is being assessed for possible utilization in a demonstration device employing a conventional stator.

More recently, investigators at MIT have been pursuing the demonstration of the feasibility of superconducting alternators for power station applications under the auspices of the Edison Electric Institute. Their first demonstration device was a vertical shaft, rotating field coil machine in which mechanical design of the rotor and a rotating liquid helium transfer coupling were the predominant features. The 2-pole, 3600-rpm, 3-phase machine was rated at 45 kVA on the basis of open-circuit voltage and short-circuit current tests.

A follow-up effort has resulted in the design and construction of a 2000 to 3000 kVA machine operating at 3600 rpm, 60 Hz. This machine is iron-free in the rotor and stator windings and employs either an aluminum eddy current shield (2000 kVA) or an iron shield (3000 kVA) to reduce stray magnetic fields outside the machine envelope. Construction is complete, but no tests have yet been reported on this device.

Westinghouse Electric Corporation has two superconducting .lternators under development – one under Westinghouse internal funding and one as an Air Force sponsored development. The Westinghouse-Air Force (WAF) machine is to be a 4-pole, 3-phase, 400-Hz device producing 5000 volts line-to-line and rated at 1000 kVA continuous with a 10-second overrating of 5000 kVA. This machine has been designed, and a test rotor is in the construction phase. This rotor is subject to more severe requirements than those of the commercial power frequency machines because of its 12,000 rpm rated speed.

The Westinghouse internal (WEC) machine program was intended to show the feasibility of developing superconducting generators for central station use and to identify technical problems not initially apparent in the design and operation of a substantially rated machine. The machine is a 2-pole, 3600-rpm, 3-phase device having a 5000 kVA rating and operating at 4160 V. The machine rating was verified experimentally by open-circuit voltage and short-circuit current tests but was not loaded to 5000 kVA. The only problem known to have existed was a vacuum leak in the rotating field coil dewar, and this has apparently been remedied.

A diagram of a typical altenator is shown in Fig. 4.

b. **DC Superconducting Machines.** There have been only two significant efforts in the development of dc machines in the U.S., both related to naval applications. General Electric built and tested an acyclic generator using a superconducting field as part of a theoretical and experimental study of the performance of a liquid metal (NaK), current-collection system. This test device used a simple solenoid for the field coil; the Nb_3Sn ribbon pancake-coil arrangement could produce up to a 5.7 T central field at 500 A. Operating at 3000 rpm and 2 T, this device delivered about 5 kW at 7000 A, 0.72 V; the generator was nominally rated at 20 kW, 2 V, 10,000 A, 4000 rpm, 4 T. The main contributions from the experimental effort were the demonstration of collector current densities to the range of 2000 $A/in.^2$ and verification of the theoretical predictions of the loss characteristics of liquid metal collectors in high magnetic fields.

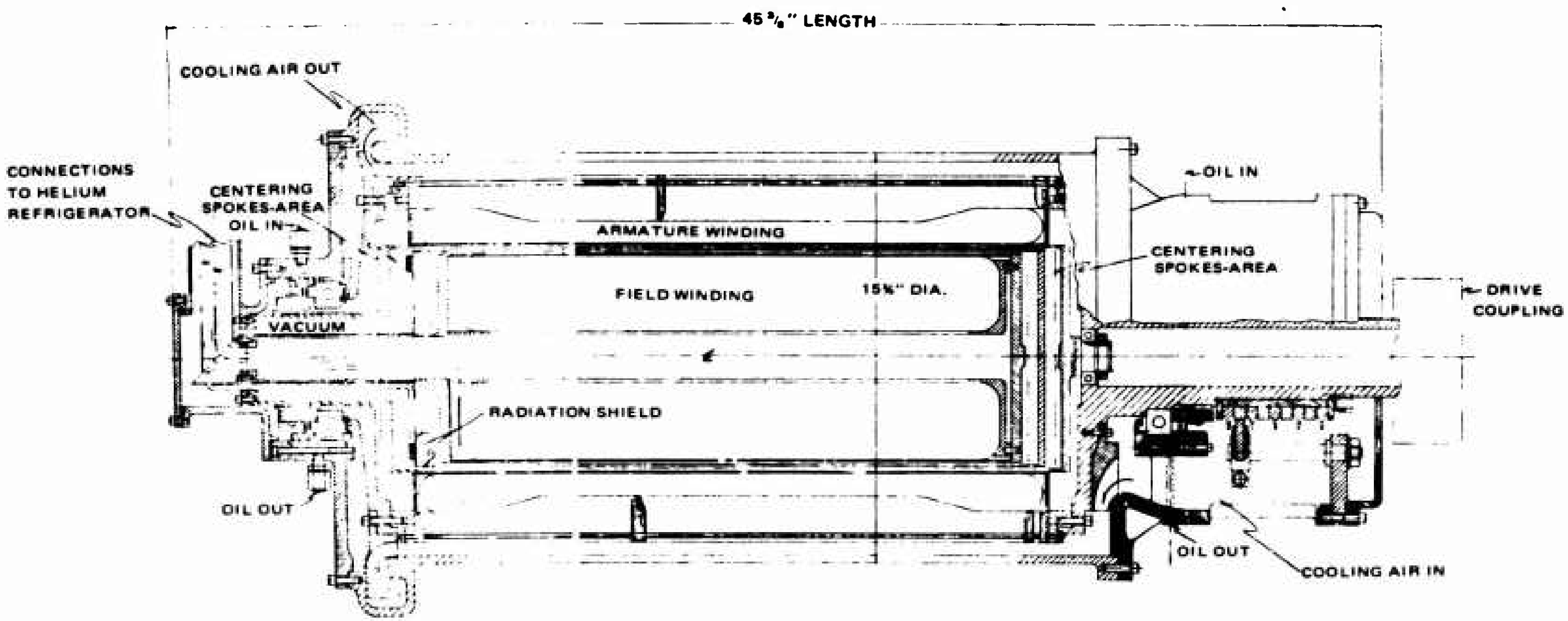

Fig. 4. Cross-section of typical superconducting alternator.

The Navy's second effort is an in-house program at NSRDC-Annapolis to develop "shaped field" superconducting motors and generators. This concept uses stationary superconducting field coils (solenoids) and an appropriate iron field shaping and shielding layout for either disk or drum type homopolar machines. Liquid metal current contacts are used. Design and test data have not been published, but an initial laboratory test machine is designed to be rated near 400 hp (300 kW) with anticipation of up to 1000 hp output.

Based upon the performance of the machines discussed, we can summarize the status of our current basic technology of superconducting machinery in the U.S. In the realm of ac machines, two configurations have been investigated, viz., the superconducting, stationary central field-rotating, ambient temperature, annular armature (AVCO-MERDC) machine; and the superconducting, rotating central field-stationary ambient temperature annular armature (AVCO-Eustis, MIT I&II, WAF, WEC). The design equations have been verified for both configurations. Electrically, no problems exist which cannot be accommedated by proper design, including increases in the field current under transient conditions. Superconducting ac machines can be constructed to be either high-voltage or high-current devices; thus, they are applicable to either capacitive or inductive energy storage systems. With appropriate development, such machines, including the cryogenic refrigeration system required, promise to be smaller and lighter than conventional machines of equivalent ratings for high-power applications (megawatts average power level).

Superconducting dc machines are inherently low-voltage, high-current machines. They are generally simplest from the cryogenic system standpoint but require efficient current-collection means. These devices are best suited for high-current, inductive-energy storage systems.

4. **Limitations of Existing Technology.** It is clear from past and present programs that superconducting electrical machinery can be built and operated satisfactorily. Since such devices operate at cryogenic temperatures, a compact, lightweight cryogenic refrigerator is required for all but short-term (several hours) military missions. Development of such a refrigerator with a long life and high reliability has been a major part of MERDC's cryogenic efforts. All machines investigated in the U.S. to date have relied on open-cycle cooling. Development of superconducting machinery will be best accomplished by having not just a closed-cycle refrigerator system but an integrated refrigerator – refrigerator-load system; this has not yet been attempted by anyone.

The high-current, stationary-field ac machines and the dc machines require efficient current-collection means. The liquid metal collector systems are the most promising for greatly increasing current-collection densities but add system complications and require additional auxiliary equipment. Losses associated with liquid metal collectors can be quite high. British developments on more conventional brushes indicate that significant improvements in solid brush, current-collection densities can be obtained as will be discussed later.

The rotating, superconducting field ac machines require careful mechanical design of the rotor in order to provide adequate structural integrity while minimizing the heat leak to the lowest temperature regions and accommodating the differential contraction experienced as the rotor is cooled to liquid helium temperatures. A rotating shaft seal for helium gas must also be incorporated in these designs. Such seals have been designed and tested, and satisfactory operation has been achieved. These are pointed out as limitations simply because there is not a widespread experience in designing such components in the electrical equipment industry.

The larger ac machines under development are iron free in the armature winding area, employing iron as a shield at a larger diameter. Such construction required the use of phenolics, fiberglass, and epoxies to support windings. This leads to higher eddy current losses in the windings, lower armature heat capacity, and lower heat-rejection capability. Until the armature loss and cooling requirements data become available for the larger machines, it will not be clear if such construction is really desirable. Tests at MERDC indicate that a more conventional toothed ferromagnetic lamination structure is preferable if magnetic saturation of the laminations can be avoided.

5. **Pacing Problems.** The primary problem retarding the development of superconducting machines for high-power, landmobile applications is the lack of a compact, highly reliable cryogenic refrigeration system. Superconducting machinery is certain to be applicable to utility power sized fixed installations and ship propulsion type applications (high-power, low-speed dc motors; high-power, moderate-speed dc generators) where higher ratings in a given frame size are achievable and ship design flexibility is significantly enhanced.

For some short-duration missions, it may be acceptable to provide cryogens by tankage from a central or remote liquefier. In these cases, open-cycle cooling designs will be required, and such machines would be similar to laboratory test versions being studied. Generally, closed-cycle cooling is assumed to be preferred, and MERDC's primary emphasis in this regard has been toward development of the refrigeration system with the superconducting devices given a lower priority at this time.

The dc machines require additional development of current-collection means—either solid brushes or liquid metal contacts. Improving collector current densities will have a signficant impact on the general range of application of dc machinery.

6. **Current DOD Programs.** There are four existing DOD programs which could impact on the development of superconducting machines as power sources for pulsed-power supplies. The three-phase program being performed by Westinghouse at Lima, Ohio, for the Air Force is aimed at developing a superconducting generator for airborne, high-power application. The three-phase program is as follows: (1) analyses, preliminary design, and critical component tests, including full-scale rotor tests, seal tests, and superconductor tests; (2) extended seal and rotor testing, detail design, machine fabrication, and checkout; and (3) performance verification tests of 1 MVA continuous and 10-second pulses of 5 MVA with 1 minute between pulses. This cost-plus contract was initially estimated to have a cost of $564,000; reported FY71 and 72 obligations total $315,000.

The development program is a reasonable and necessary step; the objectives of each phase represent a logical grouping of efforts which must be successful to warrant continuing to the next phase. The requirements of emerging high-power weapon systems will demand power sources with the capability achievable in machines of the type being developed. The optimum power source for the specific applications and mission profiles for each of the Services may be quite different even though the basic technology is identical.

A second Air Force program is aimed at the development of lightweight transformers for airborne, high-power supplies. Thermal Technology Laboratory of Buffalo, New York, has contracted to establish design criteria and techniques for transformers having specific weights less than 0.4 lb per kVA at power ratings of 1 to 100 MVA. Electrical, magnetic, and thermal characteristics are being modeled, and final design of a to-be-specified transformer will be undertaken. Estimated funding over FY72-74 is $70,400. The program is apparently aimed at providing high-power, step-up transformers for high-voltage applications. Minimizing weight is desirable for airborne, land-mobile, and seafaring applications; and an analytical and experimental program which considers electrical, magnetic, and thermal characteristics with emphasis on heat-rejection capabilities is worthwhile. The results of the effort will likely be applicable to high-power weapons technology for all Services in systems where an ac generator is the prime power source.

The Navy's in-house machine development program being conducted at NSRDC-Annapolis would, if successful, provide a means to design high-current, dc generators for supplying current to inductive energy storage devices. The shaped-field concept is as yet unproven, and the liquid metal, current-collection system requires further development. Program costs were earlier estimated at $1,000,000 per year for 10 years. The primary objective of the effort is to provide electric generators and motors for ship propulsion (20 MW and up) which would yield enhanced shipboard design flexibility.

A fourth DOD sponsored effort which could impact on the development of dc power sources for inductive energy storage devices is being performed by Westinghouse for ARPA. The program calls for the development of a Westinghouse conceived segmented-magnet, homopolar torque converter (SMHTC); the largest part of the experimental effort will be aimed at the study of liquid metal, current-collection systems. A segmented-magnet, homopolar generator would have low-voltage, high-current capability; such a machine might be considered as a power source for inductive energy storage devices. In any case, further development of liquid metal current collectors should result from this effort.

7. **Other Programs.** Three utility power type efforts also could impact on the development of ac superconducting machines for high-power applications. The details of the Westinghouse and MIT efforts have been described earlier. The Westinghouse 5 MVA rated machine seems to have been deliberately overdesigned mechanically as insurance against first-time oversights which might cause difficulty, and the MIT 2-3 MVA machine has not yet been tested. The machine conceived for utility power applications may not be ideal for military applications, but the success of these programs will further establish the feasibility of developing superconducting machines as power sources for high-power applications.

A third development which is apparently underway is being pursued by General Electric in Schenectady, New York. Indications that a substantially rated (10's of MVA) machine probably of the utility power variety is under development can be inferred from recent publications, though no direct mention of such a program exists.

8. **Foreign Technology.** The most significant total effort in the development of superconducting machines for a variety of high-power applications has been undertaken by the International Research and Development Company, Ltd. (IRD), Newcastle-upon-Tyne, England. Funding is primarily through the British Ministry of Defense-Navy (MOD-N) and the National Research and Development Corporation (NRDC), a "seed money" company for promising commercial endeavors. IRD has had a team of some 40 people working on the development of high-power superconducting machines since 1963. Their 50-horsepower Faraday-disc type motor completed in 1966 was the first operable motor of significant rating employing superconducting windings. Subsequent development led to the design, construction, and test of a 3,250 horsepower (2.4 MW) motor designed to direct drive a 200-rpm cooling-water-pump at the Fawley Power Station. The motor employs the segmented disc principle developed by IRD as a means to increase the voltage and reduce the current requirement of homopolar motors; solid brushes are employed. The segmented-disc principle allows operation at 430 V, 5,800 A as compared to a single solid disc device requiring 21.5 V and 116,000 A in the same size machine. Technological advances during the development time of this motor would allow the rating to be boosted to about 6 MW in the same machine size. IRD is currently

building a superconducting generator-motor set designed for marine propulsion. Present plans are for land tests only.

As an element in the development of high-power machines, IRD conducted extensive investigations of solid brushes. A metal-plated, carbon fibre brush construction resulted which promises to increase brush-current collection densities to the range of 300 to 600 A/in.^{2} as compared to 100 to 150 A/in.^{2} generally achievable for conventional brushes. This brush development will have significant impact on the design of high-power dc machines and could extend the range of applicability of rotating-armature ac machines.

Since the devices developed by IRD are equally useable as generators and the status of development is relatively complete by now, it is prudent to use this source for the supply of high-power dc machines where such sources are required. Output voltages up to a few thousand volts might be achievable. Such machines could be used to charge a capacitor bank where parallel-to-series switching or pulse transformation is employed to obtain the final output voltage or to power inductive-energy storage coils at high dc currents.

This developmental program and other foreign efforts are reasonably well documented in the final technical report prepared by Westinghouse Electric Corporation for the U.S. Navy–Office of Naval Research. The report on Contract #N000 14-70-C-0246 is entitled, "Survey of the State-of-the-Art of Superconducting Electrical Machinery"; it includes summaries of all significant efforts and an international bibliography of papers and reports on the subject. Developmental activities were reported in England, France, Germany, Sweden, Japan, Switzerland, and Russia. As an example, a 100-kVA alternator has been built (and now tested) in Russia and a 1000-kVA machine with a rotating, superconducting field winding is reportedly under construction.

9. Technology Forecast. The technology forecast for cryogenic refrigeration systems is included in the discussion of refrigeration developments. Solid brushes capable of 300 to 600 A/in.^{2} are under development in the U.K. (see Foreign Technology Section); at present the British will not sell these brushes. The technology of liquid metal contacts might be sufficiently developed in 3 to 5 years to warrant their employment in high-current machines, depending upon the progress of Navy and ARPA programs.

Results of the MIT and Westinghouse MVA range alternator tests are expected to be available in the next 1 to 2 years. The iron-free armature losses and cooling requirements determined in these programs might have a significant impact on optimum designs for machines in the 1 to 20 MVA range.

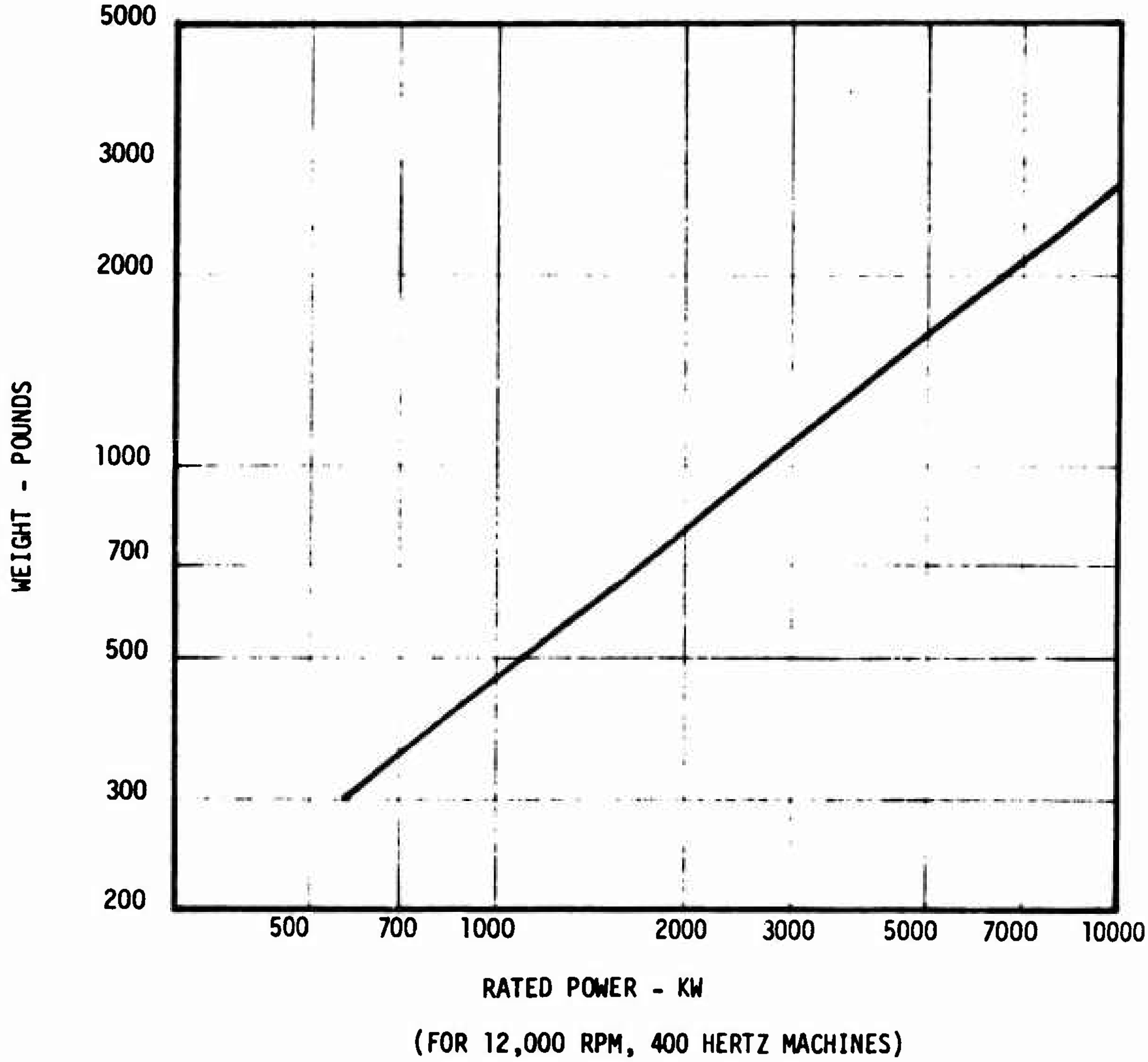

Fig. 5. Estimated weight vs. rated power for iron-core superconducting alternators.

Insofar as the forecast for superconducting machines regards potential size and weight vs. power ratings, estimates for a 1/MW-rated 12,000-rpm, 400-Hz alternator include 0.5-1 #/kW for the alternator alone (Fig. 5), 0.8-2 #/kW for alternator with closed-cycle refrigerator, and 3-5 #/kW for a complete package including alternator, refrigerator, gas turbine, and auxiliaries. Power density for the alternator alone should be in the range of 20 W/cc or higher.

10. Priorities. The best approach to providing the high energy and high power required by weaponry under development will depend on the operational characteristics of the weapons and on land mobility/transportability requirements. Since these characteristics are not well defined at this stage of development, many possible alternatives to supplying the power required need to be considered at this time so that a more optimum combination of device and power supply can be selected at the appropriate point in the system development cycle.

Both ac and dc superconducting machines promise to be more compact and lighter than conventional machines at sufficiently high power ratings. The design and construction technology for dc machines has been sufficiently advanced by the British so that it is prudent to license from that source for systems where such a dc supply is the optimum. The dc machine technology for propulsion drives being developed by the U.S. Navy should be followed with an eye to the high-power weapons applications, but it is not essential to providing a good dc source for energy-storage systems.

For ac systems, it is preferable to develop the rotating-field-coil configuration for ultimate use at high power because this configuration is most amenable to being developed into machines having ratings of 10's of MVA in transportable sizes. With the advances in solid brush technology pioneered by IRD, the limits of the extension of the power range of stationary central field superconducting machines need to be established. To do this it is desirable to design, construct, test, and evaluate the performance of a full-scale rated machine (500 to 1000 kW) and base performance extrapolations and limitations on such data.

In considering the development of rotating, superconducting field coil ac machines, the primary problems to be faced are the rotating, vacuum insulated dewar and the rotating helium transfer coupling. The primary helium transfer seal configuration investigated to date relies on surface contact of a face seal; the ferrofluidic rotating shaft seal seems to be much more reliable and should be investigated for its range of applicability with varying ambient temperature.

The rotating, vacuum insulated dewar requires good mechanical and thermal design. A simple three-walled dewar with an intermediate temperature electrothermal shield and a sealed vacuum space is currently used. An interesting MIT design for large systems would employ a stationary outer wall with rotating vacuum seals; this configuration would allow the use of multilayer superinsulation to reduce radiative thermal losses and sealed or continuous pumping of the vacuum space and to eliminate windage losses by virtue of rotor operation in the high vacuum. Again, ferrofluidic shaft seals are good candidates for the rotating vacuum seals.

The weapons applications of the power supplies discussed will be somewhat similar for the three services, but the final installed configurations are likely to be quite different because of the variation in mobility/transportability and mechanical requirements. Of the devices discussed, only the British dc machines can be considered to have essentially completed the exploratory development stage, and even these will need a detailed evaluation to determine their applicability to weapon systems power supplies as currently conceived.

AC machines of both stationary and rotating field coil configurations need to be further investigated, and a development which in some ways parallels the current Air Force program, but which is specifically geared to Army requirements, is worthwhile. This would allow a redundancy in general development which is desirable in the event of difficulties in either program and a sustained effort directed at an optimum power supply for Army weapons system applications.

III. CONVENTIONAL TURBINE GENERATOR SETS

11. **Background.** Turbine generator sets in the exact configuration suitable for Advanced Weapons Systems (AWS) have never been built. Turbine generator sets used by the Military have characteristics that generally are suitable but have never been attempted in the large ratings anticipated for AWS; most have a capability of less than 100 kW. Turbine generator sets used by industry have generally been emergency power plants (in the order of 1500 kW or smaller) or "peaking power" units (in ratings to about 20,000 kW) used by electric utility companies as a means to handle peak power demands for relatively short periods of time (hours per day). Industrial turbine generator sets will not be suitable for AWS because of excessive size and weight; the equipment is 60 Hz which results in large, massive generators; and the engines, while often derived from aircraft designs, have stressed low cost and long life resulting in versions of the engines in which both weight and bulk are inconsistent with AWS requirements.

12. **Current Technology.** The above discussion should not be taken to mean that existing turbine generator set technology is hopelessly inadequate and does not warrant consideration for AWS. Relatively small, lightweight equipment is believed possible by extending aircraft practice to larger ratings and by accepting compromises in life, cost, and noise level of the equipment (as compared to industrial machinery). MERDC is currently involved in the design of an 885-kW generator set which will weigh

approximately 2900 lb—not including fuel. While this power density is still not adequate for AWS, it is indicative of progress being made. It is expected that turbine generator sets will employ high-speed (up to 12,000 rpm) alternators at frequencies of 400 Hz or higher driven by engines running at higher speeds and higher turbine inlet temperatures than is acceptable for industrial equipment. The larger ratings are anticipated to be van or trailer mounted while smaller sets could be skid mounted. In some cases, several smaller engines would be "ganged" to provide capability to power a generator set of intermediate capacity. "Ganging" of engines is an attractive consideration since it could allow declutching of one or more engines to conserve fuel during periods of low power demand. Starting of turbine generator sets is relatively simple and quick. Even the larger sets can be started and loaded at full output within 2 minutes; in an emergency, this time could be reduced to as little as 45 seconds. Turbine generator sets can be built to accept a wide variety of fuels, both gaseous and liquid, with relatively good efficiency (heat rates in the order of 12,500 Btu/kWh).

Table 2 is a chart indicating weight and fuel comsumption for turbine generator sets utilizing generators and engines which can be derived from current technology based on comparatively long-life considerations. By accepting compromises in life, noise, and cost, it should be possible to do substantially better than the weights shown in the table.

Table 2. Conventional Turbine Generators for AWS Anticipated Weights

KW Rating	Weight (lb) Generator	Engine	Set	Generator Speed (rpm)	Fuel Cons (Gal/Hr)	Engines Possibly Suitable Make and Model
1,000	920	1,000	3,500	8,000	145	Lycoming Model TF 25B
2,000	1,430	1,100	4,000	8,000	230	Lycoming Model TF 40
5,000	2,600	3,300	7,300	8,000	585	Lycoming Model TF 35A (Three)
10,000	5,000	7,500	50,000*	6,000	1070	GE Model 3142
20,000	7,800	14,000	86,000*	6,000	1960	Pratt & Whitney Model FT 4

* Includes weight of van or trailer.

IV. FUEL CELLS

13. Current Technology. Fuel cells are basically still in a development stage. They offer the advantage of low-noise-level operation. Currently available stacks exhibit power densities in the range of 25 lb/kW. Militarized systems (as opposed to stacks) operating from hydrocarbon fuels are in the range of 100 to 200 lb/kW. Development programs underway have goals of 0.5 lb/kW (excluding power conditioners) for megawatt size devices using H_2, O_2.

Efficiencies of ~ 70% starting with H_2 and O_2 are achievable; counting production of H_2 and O_2, the efficiency drops to ~ 40%. Militarized versions mentioned above are about 10% efficient. Reactant consumption is about 0.2 to 0.3 (kg/kWh). Although the fuel cell is not particularly sensitive to on-off switching of the output line, it nevertheless would cause an inefficiency in that the reactant flow would continue during the off time. Pulsed operation is not physically damaging, and fuel cells have been operated significantly above rated power in a pulsed mode.

14. **Limitations.** The position of technology, as demonstrated by H_2, O_2 fuel cell employment in the space program, can be regarded as satisfactory for certain applications both in regard to working life and electrical characteristics. Improvements in the areas of electrode structure to increase limiting current density and in cathode catalysts to improve efficiency are needed.

Volumes and weights of stack elements are relatively low, but overall density is limited by auxiliary equipment. The output voltage of fuel cell batteries tends to be low due to the electrochemical reaction involved which limits, to a certain extent, high-voltage application.

15. **Pacing Problems.** For this application, development of high power densities is critical. Programs such as those of Pratt and Whitney, sponsored by Air Force, are defining constraints at present.

16. **Technology Forecast.** Fuel cells for fixed applications, e.g., consumer power, such as the 12½ kW modules being developed by Pratt and Whitney, should become available in the near future. Given adequate funding, programs underway will provide units suitable for Army applications in the 5- to 10-year time frame. A high-power-density system (goal: 0.5 lb/kW) capable of supplying megawatts for minutes is currently being developed.

17. **Current Programs.** The Air Force (Wright-Patterson Air Force Base) (WPAFB) has a contract ($200K, FY73) with Pratt & Whitney for developing high-power-density fuel cells for airborne applications. The goal is to obtain megawatts for seconds to minutes at a power density of 0.5 lb/kW.

Army, Navy, and Air Force have supporting programs in areas such as electrode processes, catalyst recrystallization, advanced developments, improved matrix materials, and low-cost electrodes.

NASA's program is fairly broad covering basic research as well as fuel cells for space craft but is not directed toward high-power applications.

18. Priorities. The Air Force-Pratt and Whitney effort should be followed. Modules should be obtained and tested if warranted.

V. MHD

19. Current Technology. The generation of electricity by MHD generally falls into three classes:

a. Open-cycle plasma generators.

(1) Combustion generators.

(2) Detonation or explosive generators.

b. Closed-cycle plasma generators.

c. Closed-cycle, liquid-metal generators.

Plasma and liquid metal MHD generators are often confused with each other because of the coincidence that the alkali metals such as potassium, cesium, and lithium are used as the working fluid in the liquid metal MHD systems; and these same alkali metals are also used as seed materials to enhance the conductivity of the plasma in the plasma MHD systems.

At the 5th International Conference on MHD Electrical Power, April 1971, Munich, it was concluded that all three classes of MHD generators are technically proven concepts and promise the generation of highly efficient electrical power. MHD power generation possesses the following attractive features: relative simplicity, high power to weight and volume ratios, favorable scaling characteristics, continuous and pulsed power, and instantaneously available power. In a rapidly growing electrical market, the increased power output for given fuel costs, air pollution, and thermal pollution could be important factors in favor of MHD power generation. Although MHD power generation has been technically proven, it has not been demonstrated that MHD power generation can compete economically with conventional, central-power generation.

Open-cycle combustion MHD systems have now reached the prototype stage. Several countries, particularly the USSR, have programs in open-cycle MHD and are developing systems capable of overall efficiencies between 48% and 53%. By comparison, central commercial power plants have overall efficiencies between 40% and 43%. Economic studies on large-scale, open-cycle MHD power stations for continuous operation on base load indicate that these systems in conjunction with conventional generating systems could be made economically attractive, even considering the requirements for minimizing air pollution due to sulfur oxides. However, the economic usefulness of open-cycle MHD systems, whether for base- or peak-load operation, must differ from country to country due to the large variation in costs of fossil fuels and the nuclear generation of power.

In the field of open-cycle explosive MHD, the Soviets recently succeeded in obtaining useful power from explosion of hydrocarbon fuels and oxygen. Explosive MHD appears promising for the direct generation of pulsed dc.

Small, closed-cycle plasma MHD experimental generators in a number of countries have been operated successfully. The results of these experiments indicate that is is possible to predict the performance and characteristics of multi-megawatt generators. As of April 1971, the West German facility "ARGAS 2" is the only MHD device to employ a superconducting magnet.

Experimental liquid metal MHD generators in the 1 kW range have been demonstrated in a number of countries including the United States. The goal of liquid metal MHD is the development of very reliable generators which would be suitable for space applications and submarine propulsion systems. Liquid metal MHD does not appear practical for commercial power applications because of its limited output.

In general, military technology of MHD is not related to commercial power plant technology. Only in the field of peaking power plants do the technologies overlap. For emergency sources of central power, peaking power plants will be required to provide megawatts of power "almost instantaneously" and to operate at these power levels for short periods of time. These requirements are similar to military requirements for high-power-density power supplies with short duty cycles and can be supplied by open-cycle plasma MHD. Explosive MHD appears to be attractive for pulsed-power applications because of the direct application of pulsed dc power.

Superconducting magnet technology has advanced to the point where superconducting magnets of various designs can be incorporated into MHD systems.

20. Limitations. Plasma MHD generators are restricted to the generation of dc power due to the comparatively low electrical conductivity of the plasmas. Typically, the conductivity is between 10 mho/meter to 100 mho/meter. This low electrical conductivity results in low voltage generation, and, consequently, ac power cannot be efficiently produced because the magnetic field cannot be efficiently varied to induce ac voltages. On the other hand, the electrical conductivity of liquid metals is about 10^6 mho/meter which is only about 100 times smaller than the conductivity of copper at room temperature. Liquid metal MHD generators offer the capability of generating either dc or ac power, with a wide range of frequencies, at selected voltages.

An important limitation of existing open-cycle combustion MHD generators is their expenditure of fuels which are not readily available in the Army's logistical system. Ordinarily, these devices are fueled with a liquid fuel (typically a hydrocarbon), an oxidizer (usually gaseous oxygen), and a seed compound (potassium or cesium carbonate). Present-day combustion MHD generators have to use oxygen or nitrogen-oxygen mixtures as the oxidizer no matter what fuel is employed. Future MHD devices may be able to use air as an oxidizer, and the logistic problem of supplying tanked oxygen will be eliminated. Fuels which yield plasmas with significantly higher electrical conductivities than JP4 are not presently available in the Army's logistical system. An example of such a "high conductivity" fuel is cyanogen (C_2N_2). The logistical problem of supplying seed material can be minimized with the development of an effective seed recovery device.

The lifetimes of the major components of plasma MHD generators such as channel, nozzle, and burner will be limited due to the erosion effects of high-temperature and high-velocity plasmas flowing through these components. Lifetimes of these components are further shortened due to erosion and spalling caused by thermal shocks that occur each time the generator is run.

The efficiency of explosive MHD generators is presently limited to 1.5%. The inefficiency of the conversion of explosive chemical energy to electrical energy means that relatively large amounts of explosives per pulse will have to be detonated to achieve usable power levels for pulsed operations. In addition, the containment of the comparatively large explosions per pulse will cause the generator itself to become bulky. The lifetime of explosive MHD generators will be severely limited by the erosion caused by the passage of the explosive products through the channel.

21. Limitations of Existing Devices. The current upper limits of operation for MHD systems are:

a. Continuous combustion MHD for low-duty cycles:

Power	10 MW	
Specific Fuel Consumption	$\frac{1\ \text{kg/sec}}{\text{MW}}$	$\frac{7.92\ \text{lb/hr}}{\text{kW}}$
Specific Weight (less fuel and oxidizer)	$\frac{0.2\ \text{kg}}{\text{MW}}$	$\frac{0.45\ \text{lb}}{\text{kW}}$
Output Voltage	≤ 30kV	

b. Pulsed explosive MHD:

Power	10 MW
Pulsed Energy	50 kJ
Pulse Duration	100 μ sec
Pulse Rate	$\leqslant$ 10 pulses/sec
Efficiency	1.5%
Current Rise Time	10 μ sec
Output Voltage	10's of kV

22. Pacing Problems.

a. A summary of critical technical problems for open-cycle combustion MHD is as follows:

(1) Channel and electrode erosion due to high temperature and high velocity plasma.

(2) Insulation breakdown.

(3) Recovery of alkali seed material.

(4) Current distribution in the plasma.

(5) Reduction of component size and weight.

b. A summary of critical technical problems for pulsed explosive MHD is as follows:

(1) Improved conversion of explosive chemical energy to electrical energy (higher efficiency).

(2) Multi-shot capability.

(3) Reduction of component size and weight.

c. A summary of critical problems for liquid metal MHD is as follows:

(1) Flow channel erosion due to velocity of liquid metal.

(2) Reduction of friction losses in the generator and liquid metal flow components.

(3) Thermal and electrical insulation of the generator from the liquid metal.

(4) Control of slip losses and shock losses in the two-phase flow.

(5) Corrosion and handling problems of liquid metals.

23. Current DOD Programs.

a. Overall DOD Effort. Current DOD MHD efforts are listed in Tables 3 and 4.

Table 3. Current Navy MHD Efforts

Pic No.	Agency	Contractor	Completion Date	Funds (K$)* FY-73	FY-74	Title
562	ONR	GE	CONT	199.9		MHD Gen Study
2669	ONR	GE	CONT	92.3 (ARPA)		MHD Laser
2670	ONR	Argonne Nat Lab	CONT	350.0		Two-Phase MHD Gen
2587	ONR	Argonne Nat Lab	CONT	130.0		Liquid Metal MHD
2020	ONR	Colorado State U.	CONT	32.99		MHD Plasma Investigation
2174	ONR	Argonne Nat Lab	CONT	(FY-72:35.0)		Evaluation of Liquid Metal MHD for Power Gen

*These figures are based upon data taken from the latest PIC sheets available in the Electrical Equipment files (Jan 1974). In some cases, the PIC sheets have not been kept up to date. Supplemental ARPA funds are shown where these figures were available.

b. Air Force. The Air Force Aero Propulsion Laboratory (AFAPL) has an extensive MHD program (over 900 K dollars in FY73) aimed at developing high-power pulsed and continuous MHD generators suitable for airborne applications. They have two pulsed explosive MHD contracts (Avco and Hercules) whose common objective is to demonstrate operation of a 50 kJ/pulse, 100 μsec pulse width, and at least 10 pulses/sec explosive device. Avco's explosive MHD generator will use a liquid explosive and Hercules will use a solid explosive. Hercules has already obtained a single pulse of 25 kJ using a seeded mixture of a military explosive (C-4) and cesium. In the field of continuous combustion MHD, the AFAPL's high-power density combustion generator effort at AVCO has been successfully completed. A specific power output of 0.5 MW/(kg/sec) (400 kW output at 0.8 kg/sec total mass flow) was obtained using a seeded conventional hydrocarbon (toluene)-oxygen fuel. In MHD magnet technology, AFAPL

Table 4. Current Air Force MHD Efforts

Pic No.	Agency	Contractor	Completion Date	Funds (K$)* FY-73	Funds (K$)* FY-74	Title
1214	AF Cambridge Rsch Lab	In-House	CONT	(FY-71:1.3m yr)		Transport Phenomena of Thermionic & MHD Converters
1518	AF Office Scient Rsch	Stanford U.	CONT	(FY-71:68.6)		Non-Equil Phen in Flowing Plasmas for MHD Pow Gen
2182	AF Office Scient Rsch	Air Vehicle Corp	CONT	35.0		Theory of Plasma Flows for Pow Gen
2183	AF Office Scient Rsch	Goetel, Inc.	CONT	65.0		Energy Transfer Mech in Plasmas Jet
2185	AF Office Scient Rsch	TRW, Inc.	CONT	66.7		Mag Field Annihilation in Plasmas
2354	AF Office Scient Rsch	Avco Corp	CONT	67.2		High-Density Uniform Plasmas for Adv MHD Gen
2355	AF Office Scient Rsch	NY State U. Rsch Found	CONT	(FY-72'36.1		Interact of Forced Convect Mag Fields with ARC Plasmas for Adv MHD Gen
2356	AF Office Scient Rsch	Std Rsch Corp	CONT	60.0		Non-Linear Time Dep Phen Applicable to Adv MHD Pow Gen
2352	AF Aero Prop Lab	In-House & Stanford U.	1975	0.3m yr 95.0	90	Limiting Mechanisms in Aircraft Gen Performance
2492	AF Aero Prop Lab	Hercules, Inc.	1974	106 (191 ARPA)	176.0	Explosively Driven MHD for Short Pulse Aircraft High Power
2493	AF Aero Prop Lab	Avco Corp	1974	194.0 (150 ARPA)	168 (300 ARPA)	Explosively Driven MHD for Short Pulse Aircraft High Power
2683	AF Aero Prop Lab	MCA	1973	30.0	35 overrun 40	SC Mag Test (Mag built by Ferranti-Packard-See PIC 2309).
2684	AF Aero Prop Lab	Systems Rsch	1974	185.0		Extended Duration MHD Power

* These figures are based upon data taken from the latest PIC sheets available in the Electrical Equipment files (Jan 1974). In some cases, the PIC sheets have not been kept up to date. Supplemental ARPA funds are shown where these figures were available.

has a program to develop and test a lightweight (1000 lb), 4 T superconducting magnet. Superconducting magnets were built at the Magnetic Corporation of America (MCA) and Ferranti-Packard, Ltd. The MCA magnet produced a peak field of 3.8 T, but the problem of excessive conductor movement has not yet been eliminated. Currently, APAFL has a contract with MCA to test the Ferranti-Packard magnet.

Finally, the Air Force has a spectrum of research contracts in MHD with universities and research companies. These efforts are funded primarily by AFAPL and AF Office of Scientific Research.

c. **Navy.** The Office of Naval Research (ONR) has a program in liquid metal MHD for power generation. Currently, ONR is funding an effort at Argonne National Laboratory to design and construct a two-phase MHD generator; ONR is also funding a study on the possible Naval applications of liquid metal MHD at Argonne, a liquid metal generator study, and an experimental study to determine the feasibility of an MHD laser at GE.

d. **Army.** The Army has a small surveillance program in MHD.

24. Foreign Technology. The USSR has the largest MHD research program in the world. The Soviets have major efforts in three areas: open-cycle and closed-cycle plasma MHD, and liquid metal MHD. The largest effort has been in open-cycle MHD and has led to the construction (1971) in Moscow of a pilot MHD plant (U-25) with a power rating of 25 MW. The U-25 is being slowly brought up to full power. Valuable data on the service life of the basic components of MHD plants is being obtained. A significant effort in liquid metal MHD is the construction of a model plant with a thermal input of 300 KW.

The Japanese have the second largest MHD program in the world, and their major goal is the building of a complete model of an open-cycle power plant. A previous effort has resulted in an open-cycle generator (ETL-Mark-II) which has produced a mega-watt. Presently, a generator (ETL-Mark-V) with a superconducting magnet and a model power plant (ETL-Mark-VI) have been constructed and preliminary tests are underway. The Japanese have excellent capabilities in applied superconductivity – especially in materials and magnets, and they can be expected to employ superconducting magnets with their MHD generators.

The Federal Republic of Germany had an extensive program in MHD but has recently terminated these efforts for economic reasons. The FRG Government felt that it would be cheaper to buy the technology rather than pay for the development. Some of the MHD workers are now working on controlled fusion; the rest have been scattered throughout West Germany. The Italians are also phasing out their excellent, but small, effort in closed-cycle MHD in favor of fusion research. The French effort in liquid metal MHD is slowly being shut down. The only West Europeans to have a viable large MHD effort at present are the Dutch. They have recently put an open-cycle plasma installation rated at 5 MW thermal input into operation. Other European countries with small research efforts in MHD are Austria, Czechoslovakia, Poland, Sweden, and Switzerland.

The Canadians are doing research in non-equilibrium MHD and are building a large thermal blow-down experiment having a thermal input of 10 MW. They are also planning the development of a small, open-cycle facility (2 MW electric). Initially, this facility will have a conventional magnet. Future plans call for replacing the conventional magnet with a superconducting magnet. The Australians also have a small research MHD effort at the University of Sidney.

25. Priorities. Two classes of MHD generators are attractive candidates for specific military high-power-supply requirements. The military's requirement for a lightweight, multi-megawatt generator with short duty cycles can be satisfied by an open-cycle combustion MHD generator with a superconducting channel magnet. Such a generator could use a seeded conventional hydrocarbon fuel and gaseous oxygen as the oxidizer. The Air Force has previously demonstrated a prototype of this variety with a conventional channel magnet. This combustion generator had an output of 400 kW and an attractive specific power output of 0.5 MW/(kg/sec).

The military's requirement for a pulsed power supply capable of supplying multi-kJ pulses could be filled in the future by an explosive MHD generator with a superconducting channel magnet. The Air Force has successfully demonstrated an explosive MHD generator. A solid explosive (C-4) generator (Hercules) has produced a 25-kJ pulse to date. Multi-shot capabilities are currently being investigated by Hercules.

The extensive Air Force programs in MHD should be closely monitored. The results of their investigations could lead to MHD generators suitable for Army requirements for high-power, pulsed and continuous power supplies.

VI. PULSE POWER

26. Current Technology. Some weapon systems under current consideration require high-energy pulses of electrical energy. For this type of application, rotating machines are generally not satisfactory. In many cases, it is not practical to size a machine for the peak power required or to design for overload. In any event, it is difficult to supply pulses of 10^5 J or greater having widths of < 1 msec directly from the machine. However, MHD generators offer this capability. (See Section V.) In such instances, pulse production may be obtained through discharge of circuit elements. Both capacitors and inductors can be used as the energy storage element in these circuits and each offers special characteristics.

At lower energy level ($<10^5$ J) and for fixed installations where size (or weight) is not of primary importance, capacitors are presently the best choice. Present capacitor devices offer energy densities of about 500 kJ/m^3 or 275 J/kg for the storage element alone at the 5 kV level. In terms of specific weight, i.e., weight per unit energy stored, 275 j/kg is about $3.6 \times 10 \frac{3\text{kg}}{\text{MJ}}$. Capacitors offer the advantage of relatively easy switching using previously developed techniques. Low jitter spark gap switching is presently available for fairly low repetition rates. For higher repetition rates, the clearing time of the spark gap switch limits the application to ~ 10 pps. Ignitrons permit higher repetition rates (~ 400 Hz) but are relatively expensive (~ $10K not counting control circuits) and bulky.

Although the specific weight of capacitors is dependent upon voltage level, it is not a function of energy level. This can be seen by noting that the plate separation is determined by breakdown strength; thus both the energy stored and the weight are proportional to plate area and, therefore, specific weight is constant to a first approximation. For inductors, however, the weight is approximately proprotional to the number of turns as is the field strength. Since the stored energy is proportional to the square of the field, the specific weight is inversely proprotional to the number of turns. Therefore, the specific weight is inversely proportional to the square root of the energy. This reasoning is borne out by the energy-weight relationships for existing systems: typical values are ~ 2 to 3×10^2 kg/MJ (coil and structure) at the 1 MJ level, decreasing with increasing energy.

The favorable specific weights for inductors indicated above are promising; however, utilization at present is limited for several reasons. The use of inductors to supply pulses of power at high energy levels requires opening a high-current switch in an inductive circuit. No suitable solid-state switches are presently available. High voltage/high current mechanical switches have been used as interrupters but are designed for use in ac lines where a "natural" current-zero will occur within ½ cycle. To use similar switches for the dc application entails the addition of a counter pulse circuit to force a current-zero in order to avoid high losses in the switch. Such circuits require capacitive storage of a percentage of the total system energy; this depends on system energy level but is estimated at ~ 10% for the megajoule level. Some schemes would allow recovery of this energy in the load.

Mechanical stress will be a significant consideration in any high-energy system in the range of interest. In this respect, both capacitive and inductive storage share similar problems. The high electromagnetic fields associated with these elements and with the transmission of large currents at high voltages exert large forces on the leads and support structure as well as on the elements themselves. It is also possible for non-negligible forces to be exerted on surrounding materials. An estimate for a particular solenoid storing $\sim 10^5$ J indicates (under static conditions) stresses on the order of the yield strength of copper (a major constituent of some conductors). The problems of winding movement and similar effects can be minimized at the expense of system weight by careful design.

Superconducting inductors have generally been maintained below the superconducting transition temperature by immersion in a bath of helium liquid. Such a technique is convenient for some purposes, but integrated refrigeration is more desirable from an efficiency standpoint as well as from a consideration of the difficulties inherent in making a two-phase system a self-contained unit while retaining mobility. Cryogenic refrigerators are available, but some development is necessary to make them sufficiently mobile and reliable for field use. (See Section VIII.)

Great progress has been made in materials development in the decade since the first high-field superconductors were discovered. Materials are now available which remain superconducting during charge or discharge rates of 5 to 10 T/sec. Such material appears to be marginal, at best, for pulse rates of 5/sec, assuming deep discharge. Improvements in materials with the goal of practical application are required. (See Section II.)

Voltages of the order of 10's to 100's of kV will be developed across the storage element during discharge. Insulation capable of withstanding this voltage at low temperature is required.

The external field of an inductor in a solenoid configuration is quite high: this presents a problem in shielding neighboring equipment. Even if no electronic equipment is located nearby, the surrounding metal structures can be subjected to significant forces by the magnetic field. A shield would therefore be required for many applications. Active shielding seems to be a possible method of accomplishing this. An inherently low external field can be achieved with a toroidal configuration; this would considerably reduce the shield required. For convenience of construction, a torus can be approximated as closely as desired by pancake or short, cylindrical segments. Other configurations with low field at a distance are also possible.

The preceding discussion has been devoted principally to high-energy pulses. For systems requiring lower energy pulses at the same average throughput of power, different techniques may be used. Pulsed MHD, for example, appears attractive for pulse energies in the 10's of kJ and repetition rates in the 10^2 Hz range (see Section V).

More conventional techniques are based on the use of a pulse-forming network (PFN) fed by a voltage or a current source. Some form of energy buffer, for example, an inductor or a flywheel-generator combination, may be used to ease the demand on the source of prime mover. Flywheel technology, in particular, has been investigated for transportation systems. Consideration has been given to the use of the field windings of generators (MHD, especially) as an inductive portion of the PFN.

27. **Limitations.** Principal limitations of existing capacitor banks and normal machinery are related to size and weight. In addition, the number of components required may be large, adding to the complexity and reducing the reliability of the system. Capacitors themselves are limited by achieved energy density. Systems using capacitors moreover require either the production of high voltages for charging or a large number of switch elements. It appears, however, that an inductive system can be made in a reasonable size-weight configuration for the application and that the number of circuit components could be reduced as compared to an equivalent capacitor system. The limitations to such an inductive system are in the switchgear and in cooling the energy-storage device. High voltage/high current switching is being developed as is refrigeration, but improvements in reliability and capacity are essential. For superconducting inductors, material properties impose special limitations: for example, the maximum dB/dt which can be tolerated.

28. **Pacing Problems.** The development of reliable refrigeration for use in the field will be a controlling factor in the development of systems utilizing superconducting or cryogenic devices. Capacitor development to increase energy density will control capacitor-based systems. Refinement of switching systems will be necessary in either case, but for low-repetition rates solutions appear to be available.

29. **Current Programs.** Air Force (Aero Propulsion Lab, Wright-Patterson Air Force Base) (WPAFB) has several programs underway at this time relating to inductive-energy storage. In FY's 71 and 72, contracts with AVCO and Magnetic Corporation of America (MCA) for inductive-energy storage investigations totalled $389.2K. This led to the FY73 contract with MCA for $177K to build the 100 kJ, 5 pps coil. Additional contracts with Westinghouse ($154K, FY73), MCA ($26K, FY73), Hughes ($145K, FY73), and Purdue ($17K, FY73) treat the switching problem separately.

NASA-Lewis has programs in capacitor improvement, notably for high-energy-density, thin-film capacitors and polycarbonate capacitors. Army (MERDC) has shown that some improvements in VA rating are possible using heat pipe cooling. In industry, Lawless at Corning Glass has shown high-energy-density storage to be possible at 77 K using Corning titanate-glass-ceramic materials. In addition, increased energy density appears possible through development of carbon capacitors.

The French have an active program for investigating superconducting, inductive-energy storage and have made some progress as evidenced by publications in the open literature.

Publications by Soviet bloc scientists indicate considerable interest in inductive storage and pulse production. The extent of the program is not known.

VII. SUPERCONDUCTING MATERIALS

30. Current Technology. Currently, there are several alloys used to make commercial superconductors. The most common are niobium titanium (NbTi) and niobium tin (Nb_3Sn) which are integrated in a matrix of a good normal conductor, usually copper. An enlargement of the cross section of a typical conductor is shown in Fig. 6. This matrix is essential to produce a stable, current-carrying wire. Each superconductor has intrinsic limitations in magnetic field and in temperature. The magnetic field limitation is called the critical field. If a superconductor is subject to a magnetic field greater than its critical field, it will become a normal conductor. The temperature limitation is called the critical temperature, and above this temperature a superconductor reverts to its normal conducting state.

Niobium titanium, which has a critical temperature of 10°K and a critical field of 12 T (120 kilogauss), has the advantage of being very ductile so that fabrication is easier and the superconductor cheaper. Reducing the size of the current-carrying, superconducting filament reduces hysteresis losses and thus leads to more stable characteristics under transient field conditions. Because of its high ductility, NbTi can be easily manufactured in multi-filament conductors. These are wires with many small superconducting filaments imbedded in a matrix of copper. The NbTi filaments have diameters typically in the range of 1 to 30 microns, and over 1000 filaments can be incorporated in one wire approximately 0.015 inch in diameter. In the most recent materials, these filaments are twisted inside the matrix so that they spiral along the length of the conductor with a twist pitch of 1 to 10 per inch.

Twisting is especially important in applications involving large transient magnetic fields because it eliminates induced cross currents flowing in the matrix between filaments. A matrix of relatively high resistivity copper-nickel alloy (cupronickel) is sometimes used to impede these cross currents. Typical matrix to superconductor ratios are between 1 to 1 and 2 to 1. The major disadvantage of NbTi is that it has a much lower critical field than Nb_3Sn which must be used in high field applications.

Niobium tin which has a critical temperature of 18°K and a critical field of 25 T is used in applications where fields of 7 T or more are required. However, Nb_3Sn is extremely brittle and cannot be drawn into wire form. Currently, Nb_3Sn is available

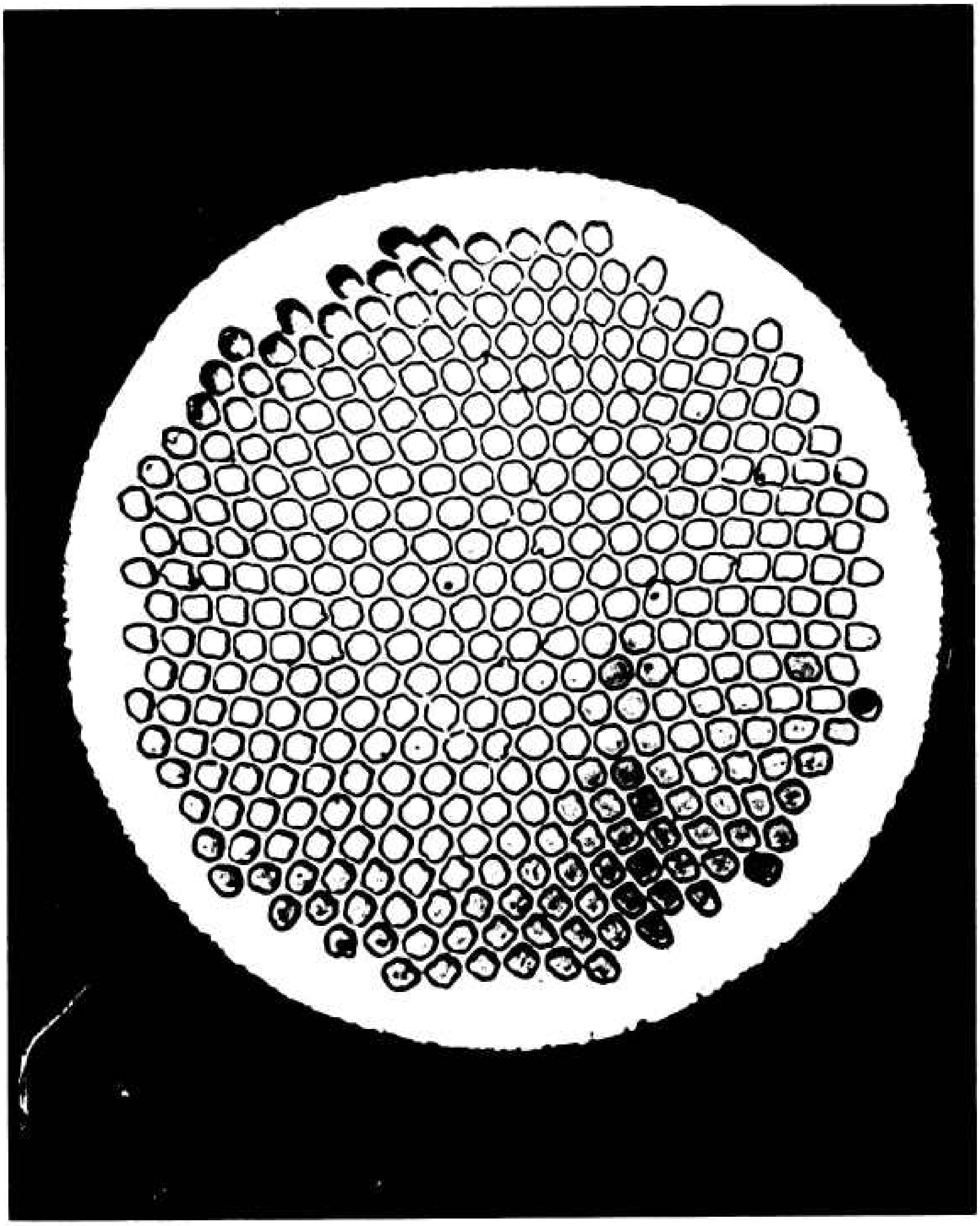

Fig. 6 Enlargement of the cross section of a typical conductor

only in rectangular cross section tape or ribbon. This ribbon consists of a deposit of Nb_3Sn a few microns thick laid on a metallic substrate with a normal stabilizer as the outside layer. This construction allows the composite to be bent without damaging the superconductor. Coils made fron Nb_3Sn tape are usually of the pancake variety. A pancake is simply a length of tape wound on a spool just as a roll of scotch tape. Many of these pancakes are stacked on top of one another and connected in series to make a solenoid. Solenoids made from Nb_3Sn tapes have good high-field performance; but, not having the advantages of small filamentary twisted conductors, their transient-field behavior is generally not as good as that of NbTi.

A vanadium – gallium alloy, V_3Ga, is the most recent commercially available superconductor and has even better high-field performance than Nb_3Sn. It is also very brittle and thus available only in ribbon form. Since it is relatively new on the market, V_3Ga has not been used in many applications.

Recently (1973) a new record high critical temperature of 23.2°K was reported for an alloy of niobium and germanium (Nb_3Ge). Even though it is not presently known that this material will be commercially practical, its discovery represents a significant advancement since its critical temperature is almost 3 degrees above the boiling point of hydrogen. This means that future applications of Nb_3Ge could utilize liquid hydrogen as a coolant rather than liquid helium. Nb_3Ge also has outstanding high magnetic field characteristics.

31. Limitations of Existing Technology. Present superconducting materials are severely limited by their operational temperature which is less than 9°K for NbTi and 18°K for Nb_3Sn.

There are several other limitations for practical superconductors. Niobium-titanium filaments can presently be no smaller than a few microns, and there is a coupling limitation on the number of filaments in a composite. Twist rates cannot exceed 10 twists/inch due to material strength. In practical applications, NbTi is also limited to magnetic fields below approximately 7 T. Above this field, superconducting NbTi has a low current density.

Due to brittleness, Nb_3Sn and V_3Ga cannot at this time be commercially produced in the form of wires. This is a very severe limitation for if these alloys could be manufactured in wire form they would offer the advantage of a high-field, high-current density conductor with the transient-field advantages of twisted, multifilament conductors. The higher operating temperature of Nb_3Sn greatly reduces the problem of removing the heat generated in coils.

32. Technical Forecast. Several American companies have current research programs aimed at a flexible wire conductor of Nb_3Sn, and development is possible in the next few years.

There is considerable effort in the development of higher temperature superconductors. This work is performed in many countries, in universities, industry, and government. There are no indications of major breakthroughs in the foreseeable future.

New conductors with smaller and thus more superconducting filaments of NbTi have appeared on the market the last few years and this trend is likely to continue.

A Japanese Company has recently marketed V_3Ga in ribbon form. This material is useful in coils which generate over 10 T and its use is likely to increase in the future, especially if multifilament wires can be commercially produced at a competitive price. Small lengths of multifilament V_3Ga have been produced in the laboratory by a new solid-state diffusion process.

There is some interest in the development of high-field superconductors of alloys in porous glass. Although some success has been experienced, it is very questionable that these materials will be able to compete with the more established superconductors in the near future.

Other materials with potential future use in superconducting coils are $Nb_3(Al_{.08}Ge_{.08})$ and $NbAl_3$, both brittle compounds, and the proprietary alloy of NbTi-Hf which can be easily drawn into wire form.

33. Current Programs. While there are many DOD sponsored programs in the field of superconductivity, there is currently very little effort directed toward the development or improvement of superconducting materials.

The following American Companies are engaged in research, development, and production of high-field superconductors:

Norton Co., Supercon Division: NbTi single- and multi-filament copper stabilized conductors. Up to 400 filaments/conductor. Filament diameter .0005 in. twisted or untwisted.

Magnetic Corporation of America: NbTi alloy embedded in high-conductivity copper. Single and multi-filament conductors up to 360 filaments/conductor, twisted 1-5/inch or untwisted. They also have a research program in multifilament Nb_3Sn composite conductors.

Intermagnetics General Corp: Nb_3Sn tape for high-magnetic-field applications. The tape consists of a niobium-tin strip bonded to strips of copper. If greater strength is needed, stainless steel strips can be laminated to the conductor.

New development in which Nb_3Sn is clad with very high purity aluminum. This also includes a stainless-steel member. This is the only American based company presently marketing Nb_3Sn conductors and they have a research program in Nb_3Sn multifilament composite conductors.

Supertechnology Corporation: NbTi single- and multi-filament copper cladded conductors. Up to 20 filaments/conductor twisted or untwisted are available. This is a very small company with limited resources.

Brookhaven National Laboratory: Considerable R&D on superconducting materials has been done in-house and on contract. Small lengths of multi-filament V_3Ga and Nb_3Sn have been prepared and tested at BNL.

34. **Foreign Programs.** Foreign programs are as follows:

Great Britain: Great Britain has a very advanced and versatile program in NbTi wires. Imperial Metal Industries (IMI) in conjunction with the Rutherford High Energy Laboratory are continually developing improved materials for alternating current applications. They were pioneers in the concept of filament twisting to improve ac characteristics. Currently, a wide variety of NbTi conductors are available from IMI. A cupronickel lining is applied around each filament to impede cross currents, and coil protection is provided by incorporating copper in the matrix. Conductors are produced with filaments as small as 10 microns; the number of filaments per conductor ranges from 61 to 1045; and there has been limited production of a 9000-filament conductor. The twist rate varies with the application.

Japan: Several Japanese companies produce superconducting materials for high-field applications. NbTi superconducting wire is produced in single- and multi-filament form with copper cladding. The Japanese are also doing developmental work in a proprietary NbTi-Hf alloy and in Nb_3Sn conductors. A tape of V_3Ga is produced in Japan and is the only V_3Ga conductor commercially available in the world.

Canada: The Canada Superconductor and Cryogenics Company Limited (CSCC) has acquired the complete production facility formerly owned by RCA Corporation. They produce a wide variety of vapor deposited niobium-tin ribbon including very-high-current-capacity conductors.

USSR: The standard superconducting material in the Soviet Union is NbTi. It is produced in single- and multi-filament of up to 400 filaments/conductor and is copper cladded. Although Nb_3Sn conductors are available, they are not being produced on a large scale. According to available information, the USSR Nb_3Sn ribbon is similar to that produced in the Western World. The Soviets are interested in V_3Ga but apparently produce none of their own.

35. Priorities. Applications of superconductivity such as electrical machinery and energy storage in superconducting coils greatly benefit from research programs, either to discover new materials with improved performance or to modify existing materials so that their performance is improved.

Of the existing R&D programs, the efforts to produce Nb_3Sn and V_3Ga multi-filament wire promise to have the most immediate impact on superconducting technology. Presently, two American Companies – Magnetic Corp. of America and Intermagnetics General Corp. – have research programs investigating Nb_3Sn multi-filament conductors. Both of the companies are technically competent, but they are small and it is doubtful they can bear the entire cost of the research. Many foreign manufacturers, however, are generously subsidized by their respective governments in support of high-risk industrial efforts. This allows these manufacturers to maintain a high level of effort thus increasing the likelihood of discovering new materials or methods. The outcome of this situation could be to put the United States in a position of lagging behind many foreign countries in the development of superconducting materials; and, as the market for these materials increases, we would become dependent on foreign countries for our supply of the materials.

Based on recent laboratory success, there is little doubt that with sufficient funding (several hundred thousand dollars/year) a successful program to develop commercial multi-filament Nb_3Sn type superconductors could be established by any one of several American companies within 1 or 2 years.

VIII. HELIUM REFRIGERATION TECHNOLOGY

36. Current Technology. The scope of cryogenic machinery in use today is extensive including such commercial applications as food processing and the production of liquid natural gas. The bulk of these cryogenic cooling applications is at temperatures where the use of helium is not mandatory, and helium is generally not used. For superconducting applications, helium temperature refrigeration is mandatory where, in the present context, helium temperature refrigeration will be understood to be refrigeration at temperatures below the boiling point of hydrogen: 20.4 K. A distinction will be made between liquefiers and refrigerators. A liquefier is a machine that produces liquid helium (for any purpose) while a helium refrigerator is a machine that maintains some item (e.g., a superconducting winding) at a temperature below 20 K with or without the production of a liquid. This distinction will assume added importance as superconducting materials near 10 K become available for practical designs. A typical refrigerator schematic for high-current power applications is shown in Fig. 7.

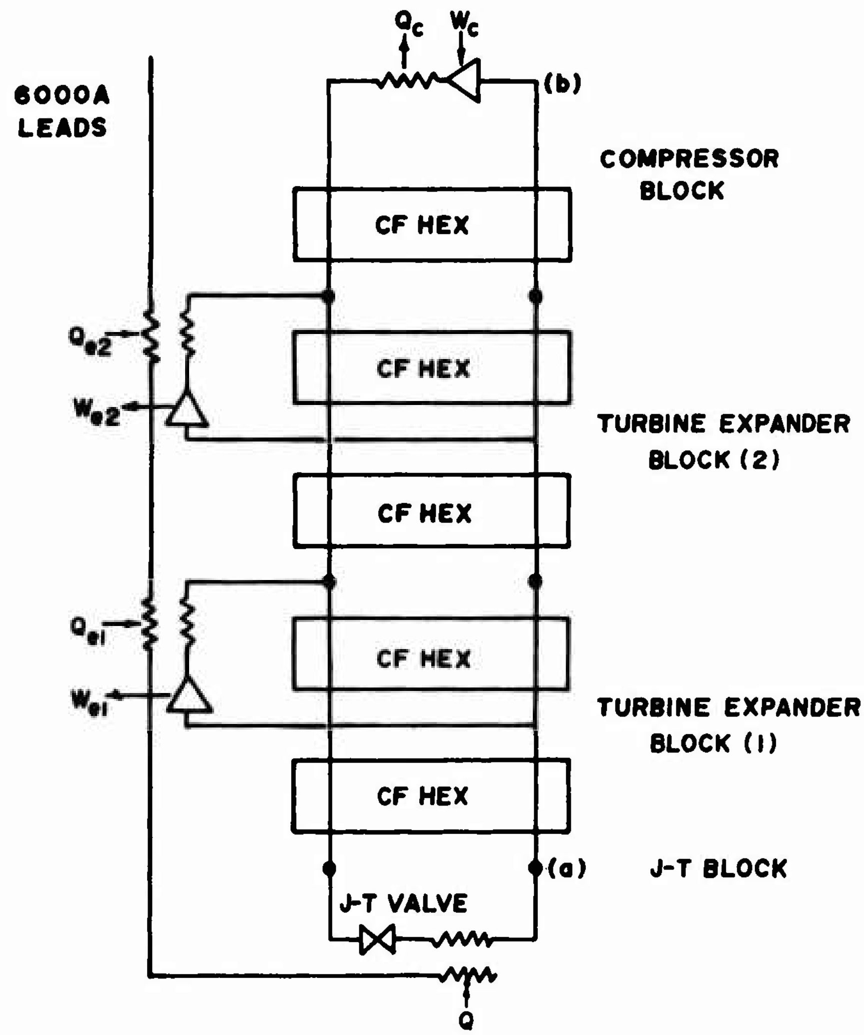

Fig. 7. A typical refrigerator schematic for high-current power applications.

Considerable experience is available on helium liquefiers for low-temperature research and for cooling, in a liquid bath, of large superconducting magnets being used in high-field research. The liquefier technology provides a solid basis for present high-reliability refrigerator development work. Present-day helium refrigerators are used in a variety of applications such as vacuum chambers for space simulation, and there is increasing development activity. However, at present, reliable helium refrigeration for the load profiles characteristic of superconducting power equipment is not available.

37. Limitations of Existing Technology. Military refrigeration equipment for pulsed superconducting coils, MHD magnets, or rotating energy converters using superconducting excitation will have special requirements. It is in the area of engineering for military requirements that many limitations exist (e.g., compressor technology, transportability, final heat rejection to air). Equipment must be mobile and reliable, without the need for complex field maintenance. Integration of the design of the refrigerator with the equipment being cooled will be essential to meeting military needs; however, little, if any, experience is available in the area of integration. For the majority of applications where high current must be conducted to a low-temperature region, integration of equipment which allows interception of thermal loads at intermediate temperatures will be important to size and efficiency. Factors of 5 to 10 are involved as regards bulk and power input. Cool-down times and overload performance of such systems cannot be easily estimated and design procedures need to be developed.

Size, weight, or input power of refrigeration equipment may offset the advantage of using cryogenics in some cases. Existing refrigerators having their main load at 4.5 K can be roughly sized using the following rules:

a. 100 kg/watt refrigeration.

b. 0.15 cubic meter/watt refrigeration.

c. Input power approximately 1000 W per W of refrigeration. Since cool-down time restrictions, heat rejection temperature, reliability requirements, and upper stage loads can result in order of magnitude errors, the above rules should be applied with caution. In many applications, it will be possible to circumvent apparent size and efficiency limitations when integrated design procedures are developed.

Another current limitation is reliability. Present technology is based on minimum capital cost for fixed-site installation. The primary application of the refrigerators is in high-technology environments where regular maintenance is almost universally performed in an expert manner, and continuous operation of equipment is not essential. For these reasons, components suitable for long-life and reliable field refrigerators have not been needed and have not been developed. Military development support is required to fulfill the special military needs for transportability, long life, and low maintenance.

38. Pacing Problems. There is no single paramount problem impeding development of refrigerators to meet Army requirements; indeed, there appear to be several viable alternative approaches. However, effort will have to be expended to uncover and solve a myriad of problems caused by the specific needs of the military. Important areas in which exploratory development is needed are integration of refrigeration equipment into overall designs; provisions for upper stage loads and transient loads; and development of compact, reliable components for long-term operation with minimum maintenance. Ambient temperature helium compressors represent the component area most in need of development. The compressor and associated heat rejection equipment account for a large part of the bulk of the entire refrigeration system. Piston compressors are commonly used and are bulky. Non-lubricated piston compressors have a mean time between maintenance (MTBM) of about 2500 hours, while labyrinth seal oil lubricated compressors have about 8000 hours MTBM. To meet size and weight requirements for military applications, more compact compressors will be needed. Depending on power level, helical screw compressors and turbomachine compressors have to be evaluated. Screw compressors are extrapolated to operate 40,000 hours MTBM, and turbomachinery combines compactness with potential reliability.

39. Technology Forecast. Applied superconductivity is rapidly coming of age, bringing with it the need for helium refrigeration technology. During the next decade, the commercial pressure to improve existing equipment, introduce new items, and realize cost savings will accelerate the introduction of superconductivity and the pace of refrigerator development. Superconducting systems will be designed to operate at temperatures above the critical point of liquid helium, and integrated refrigeration will replace tanked cryogens within 10 to 12 years.

40. Current DOD Programs. The discussion will be limited to helium refrigeration as defined in paragraph 36 and will not treat higher temperature cryogenic cooling of sensors. The Army at MERDC has an ongoing program of turbomachinery development for helium refrigeration, started in 1968, with a total funding level to date of $1,000K. Other Army interest has been limited to classified paper studies of helium refrigeration applied to special non-power equipment. The Navy sponsored an Industry-Government conference on cryogenic refrigeration in April 1972 to discuss their needs and to announce an intention to start a refrigerator program. Such work is an essential part of the Navy's planned development of superconducting electric drives for ships' propulsion. An in-house effort is now in progress at NRL and NBS. ARPA has initiated a program with General Electric which, to date, has been limited to a paper study and which will support the Navy's plans in superconducting machinery. Initial reports are not yet available. The Air Force is sponsoring low-power helium refrigeration work for unattended sensor applications. The Air Force work includes Vuilleumier development by Hughes and North American Philips; rotary free piston development by Arthur D. Little; and turbomachinery development at General Electric. The latter effort is being terminated, after an expenditure of $2000K, apparently due to funding limitations. It is understood that plans have been made for in-house completion and evaluation of this equipment, including low-temperature tests.

41. **Other Programs.** NBS has an ongoing in-house effort in helium refrigeration as well as a substantial background in hydrogen work. Both England and Japan have reported work on turboexpanders for helium refrigeration in the open literature; however, the details of their current refrigeration development programs are not known. The British Navy has reported in-house work on a multi-stage regenerative turbocompressor for helium using a single wheel. The present state of this development is not known.

42. **Priorities.**

a. Include integrated refrigeration in future superconducting equipment development.

b. Build a system to provide operating experience with turborefrigeration component and intermittent loads and heavy upper stage loads.

c. Fund component development of ambient temperature helium compressor equipment.

d. Develop refrigerator interface and heat-transfer techniques for vapor cooling of superconducting windings.