POWER AND ENERGY FOR POSTERITY

By Robert F. Barthelemy and Robert F. Cooper

Robert F. Cooper
Air Force Aero-Propulsion Laboratory
Wright-Patterson AFB, Ohio

Abstract

During the past 20 years, the increasing electrical and thermal energy demands of aerospace vehicles have led to the development of highly sophisticated energy generation and storage systems. High-efficiency solar arrays, very reliable batteries and fuel cells, highly efficient turbogenerators, zero-loss superconducting energy storage devices, promising magnetohydrodynamic (MHD) power systems, high-energy density solar collectors, and reliable thermionic and thermoelectric electrical converters have all been developed to satisfy our aerospace needs. Since one of 20th century man's greatest needs is for usable energy, application of this technology to benefit the general public was considered. The utilization of these systems for pollution-free generation of energy to satisfy mankind's future electrical, thermal, and propulsion needs was of primary concern. Ground, air, and space transportation; commercial, peaking, and emergency electrical power; and metropolitan and unit thermal energy requirements were considered. Each type of energy system was first analyzed in terms of its utility in satisfying the requirement, and then its potential in reducing the air, noise, thermal, water, and nuclear pollution from future electrical and thermal systems was determined.

Introduction

During the past two decades, the increasing electrical and thermal energy demands of aerospace vehicles have required the development of highly sophisticated and unique energy generation and storage systems. For the megawatt aircraft electrical power requirements, MHD generators, and high-performance turboalternators have been investigated and are being constructed. The need to achieve lightweight MHD generators led to the study of superconducting magnets, which opened the way for the development of lightweight, low-temperature, and superconducting electrical energy storage systems. On the other end of the power and energy scale, electrical and thermal energy conversion and storage systems had to be developed in an extremely lightweight form to satisfy manned spacecraft and satellite energy needs. Since fuel and oxidizer systems for the long lifetime space missions would be very heavy, energy conversion systems for these applications concentrated on using free solar energy or lightweight nuclear energy. Solar cells, solar collectors, thermoelectrics, and thermionic conversion devices were developed to use these energy sources.

Although the development of higher performance energy systems for aerospace application is a continuing process, it seems appropriate, at this time of ecological awareness, to reflect upon the benefits that man might derive from the recent developments in this area. In particular, the great care taken during the evolution of these systems to either utilize natural energy sources or operate at very high efficiencies suggests that their applicability might be toward reducing pollution from our major energy generation and conversion processes. With this in mind, we have reviewed the technology and recent developments in aerospace energy systems in order to assess their potential promise for reducing the various forms of pollution associated with energy generation processes. All of the new energy systems seem to have some merit in this area. Although several interesting applications were found and are conceptually discussed, a detailed analysis to determine their payoff was not carried out. In addition, the cursory investigation carried out in this paper is by no means exhaustive. It is the authors' hope that this discussion of aerospace energy systems will lead to new ideas on their applicability in solving some of the world's energy problems.

Solar Arrays

Solar arrays have been developed by the Air Force and NASA to provide electric power for space satellites. The advantage of solar arrays is that they utilize solar energy for power generation, and hence, no heavy fuels and oxidizers need be launched for their operation. The disadvantage of arrays is that they operate only in sunlight. In order to satisfy the spacecraft's need for continuous electrical power, energy storage systems, such as batteries or fuel cells, must be employed for dark-time power.

Solar arrays have been developed to the point where they can be launched in a rolled-up configuration and deployed into flat plates in space. They are efficient, lightweight, and last for as long as 7 years in space without maintenance. Their main performance disadvantage is their cost, which could be substantially reduced with greater usage and increased production.

They are ideally suited as a pollution-free method of generating electrical power. They generate no air or water pollutants, and are noiseless and nonnuclear, using nothing but sunlight for power production. Commercial solar power plants could be designed in two ways. Long lifetime systems could be placed in an orbit around the earth where electrical power would be produced by the array and converted into microwave energy, which could be beamed down to earth and reconverted into electrical power. While such a system would have a very high initial cost (because of launch), its operating cost would be negligible. A typical system might be a 5-square mile array at synchronous orbit which could supply 10 million kilowatts of power for 23 hours a day. An earth-based battery storage bank would be needed to cover the remaining hour. The alternative system would be a ground-based array/battery complex. In this case, the initial cost is low but the operating cost is high (replacement, damage). In addition, the storage system would be much larger (8-12 hours versus 1 hour), and weather would greatly affect the system's operation.

Although solar array power production is essentially pollution free, application of this approach is being delayed because of the economics.

Solar Collectors

Solar collectors can be used to convert solar energy into highly concentrated thermal energy. Until last year, spacecraft engineers were primarily interested in using solar collectors as a heat source for electrical power generation turbogenerators or thermoelectric devices were used to convert the thermal energy to electrical power. Recently, requirements for large amounts of heat on spacecraft have led to renewed interest in solar collectors and programs to develop these solar to thermal conversion systems are currently underway.

Solar collectors have been built in a wide variety of sizes. For space systems, collectors capable of delivering several hundred kilowatts of thermal energy have been constructed. The collectors operate at very high efficiencies (~ 90 percent), are extremely lightweight ($0.2\ lb/ft^2$), and have long lifetimes (5-10 years) in space.

They could be used to provide both thermal and electrical power for either small units, such as homes, or large industrial complexes. Like solar cells, collectors are noiseless, nonnuclear and use nothing but sunlight for energy production. Although it would be possible to place solar collectors in orbit and transfer the collected energy to the earth, a more practical approach would be to utilize ground-based collectors. Heat storage systems, using the energy stored during the phase change of an alkali metal (like sodium) from the liquid state to the vapor state, could be employed to maintain constant heat output during dark periods. These heat storage systems have been built using heat pipe technology and have lifetimes of several years.

Housing and industrial complexes built around central solar-collector systems, providing both thermal and thermally converted electrical power, should be considered. The electrical conversion systems could be either centrally located or placed appropriately within the using subunits. Approximately 100 ft^2 of collector would be required for thermal input to a single family unit. In order to reduce costs, very large solar collectors could be used for inputs to several units.

The major disadvantage of ground-based solar-collector thermal heating and conversion is its performance dependence on weather. Heavy cloud cover virtually destroys the collector's ability to deliver thermal energy. There are several approaches which could compensate for this disadvantage. Collectors could be used primarily in areas where bad weather is rare. Oversized units with large storage systems could be employed in marginal areas. Auxiliary nonsolar power systems could be used with solar collectors to cover these blackout periods. Finally, solar collectors could only be utilized to provide auxiliary power for specific applications, such as air-conditioning, when heavy cloud cover is not a problem.

Batteries/Fuel Cells

The conversion of chemical energy directly into electrical energy can be accomplished in either a battery or a fuel cell. The only difference between the two lies in the state and physical relationship of the chemical reactants going into the reaction. Both fuel cells and batteries can be made to operate in a primary mode where they are never recharged, such as flashlight batteries, or in the secondary mode, where recharging is used to extend their useful lifetime. Batteries and fuel cells which can operate for many years with thousands of charge/discharge cycles have been developed for aircraft satellites. Since most batteries and fuel cells are modular, there is really no limit to the power levels one can achieve using them. In order to reduce launch costs and increase aircraft payload fractions, a very large development effort has been underway to reduce the weight of batteries and fuel cells. Primary batteries, with excellent reliability, have been developed with power densities of 100 W-h per pound for 100-hour applications. Secondary batteries and fuel cells, with 5-year continuous use lifetimes, have achieved power densities of 10 W-h/lb.

Although the use of batteries for special applications in industrial and household applications has been considered, and in some cases, utilized, the general use of these storage systems is now being studied. Battery-driven electric automobiles, where lifetime, weight, and volume are premiums, are very attractive from a pollution-control viewpoint. Automobiles designated primarily for short mileage use could operate on secondary batteries with recharging accomplished via commercial power during nonuse periods. Family and commercial unit electricity could be supplied with fuel cells operating on natural gas. These fuel cells could be combined with a natural-gas heating system to supply thermal energy to the units. Finally, the application of fuel cells or batteries to commercial transportation, via electrically driven land or sea systems, should be studied to determine the economic feasibility of these low-pollution systems.

Superconductivity

A decade ago, a discovery was made in materials which has provided a basis for revolutionizing energy conversion and energy transmission processes. This discovery, referred to as high magnetic strength superconductivity, has led to materials having zero resistance, under extremely low temperatures, to electric currents. This, of course, leads to the design and construction of high electric current conductors and very high strength magnets. The use of these magnets has further led very efficient power generation schemes - either previously unavailable or of low efficiency. Superconductors were first applied to large bubble chambers for high energy physics. Now, in less than 10 years from discovery to application, superconductors are being applied to compact and efficient rotating generators and motors, under ground energy transmission, as well as one of the most promising of direct electrical power generation schemes, MHD. Both the rotating machines using superconductors as well as MHD will be discussed in more detail in the following paragraphs.

Considerable detail could be given on the other uses of superconductivity alluded to above - such as high-speed trains, energy storage, underground electrical power transmission, medical research, plus general industrial applications. However, only the electrical power generation applications will be discussed.

Superconducting Rotating Machinery

The use of superconductors (instead of water-cooled copper) in electrical rotating machinery allows the increase of 10-100 times the current through a given area of conductor. This leads to a dramatic reduction in physical size, volume, and weight of rotating electrical machinery. Thus, one can either obtain a much smaller unit of fixed power or can produce 5-10 times more power for the same volume and weight of conventional machinery. Not only does this size advantage turn out to be of value for aircraft and ship power, but for commercial power as well — either steady-state (base load) or emergency (portable) power systems of multimegawatt capability. The additional advantages of high voltage (better for transmitting long distances) and high overload capability (intermittent power pulse demands) are some other attributes of this type of generator/motor.

In this area of superconducting rotating machinery, there have been programs sponsored by private industry and various governmental agencies to provide for engineering evaluations. The support for general superconducting technology has come from many governmental organizations and laboratories. This support has provided a strong basis for the rapid development of this area of power generation. But today, the technology is here. Machines do exist and the power levels, megawatts, and learning curves are rapidly growing as new goals are continuously being achieved.

For as this country doubles its power production capability in the next decade, the location, efficiency, and physical size of the power plants become increasingly important and costly. What advantages has the new area of superconducting electrical machinery? The answers are high efficiency, compactness, and lower costs - costs from power generation, plus fewer and more compact facilities.

MHD Power Generation

A great leap forward would be to have a type of energy conversion which could directly extract large amounts of electrical power from a thermal energy source. Such a technique does exist. It is called magnetohydrodynamics or MHD.

MHD is an energy conversion process which directly generates power from a very hot gas while it is moving through a magnetic field. In general, the higher the temperature one can work with for energy extraction, the higher the efficiency of the process. The limitation is generally set by materials, which in rotating machinery is the very high stress caused by spinning at high speeds and at high temperatures. The MHD energy conversion process requires no moving parts, and thus, can be operated at a much higher temperature and efficiency than rotating machinery. Higher efficiency can then be equated to reduced pollution, better use of resources (conservation), and higher power per fixed unit leading to fewer plant sites.

The MHD process can be used with any thermal energy source, which is hot enough, to either couple directly with the energy source or to complement a conventional powerplant system. The thermal energy sources primarily being considered today are hydrocarbon fuels where the MHD system may increase the overall plant efficiency from 40 percent to 50-60 percent. This could result in a reduction of the thermal pollution by over 200 percent for the same electrical power output. In addition more efficient utilization of our limited natural resources would be possible.

The marriage of MHD with a nuclear energy source could also be realized in a number of ways — each of which requires high temperature reactors. The higher temperatures are essential to make the MHD conversion process work efficiently. Operating temperature of above 4000°F, for example, are required for direct coupling of MHD to a gaseous cooled reactor. By using regenerative techniques, cycle efficiencies of 60-70 percent are feasible for commercial MHD power generation. This represents a doubling of today's nuclear powerplant efficiencies and a reducing of thermal pollution by over 300 percent.

Today, development programs are considering MHD plus nuclear energy combinations for electrical power in space. Efficiencies for near-term systems are much lower, but still attractive, in order to provide long life and to use lower temperature reactors.

MHD power generation technology has been supported in the past mainly by the Department of Defense (DOD) and NASA, until recently when the Department of the Interior entered the support picture for commercial power. NASA's major emphasis has been on nuclear MHD systems, while DOD's has been on hydrocarbon-fueled (combustion driven) MHD for short time operation. The advantages of instant on-off of combustion-driven MHD systems make it very attractive for emergency power and other very high-level pulsed power uses. The startup and shutdown mechanisms for MHD do not involve the dynamic loading of many precision components, such as in conventional rotating machinery. MHD has the added advantage of becoming more efficient with a larger power size as well as higher temperatures.

The output of most MHD systems of interest is direct current power which could be directly used in applications, such as wind tunnels, metal refining, and chemical industry which require very large amounts of power over short time periods. (Short times may range from millisecond pulses to running times of seconds to minutes, perhaps even hours.) The technology is directly applicable to emergency power plants, portable megawatt (1000 kW) units with fast, online responses and minimal water and air pollution systems. The attractiveness of portable power units, each modeled to a particular application, exists. MHD would provide not only a new capability in today's modern society, but the drastic lowering of thermal, air, and solid pollution coupled with resource conservation. This area of pulsed MHD power can differ significantly from commercial baseload MHD power, where economics still dominate the choice. However, as the pulses become longer the two will approach common technological goals, areas of development, and technological problems.

An obvious question is the cost per kilowatt — in fact, does it cost more for MHD units than conventional power? But what is really meant by costs? If you mean dollars per unit of electricity, the answer may be yes for the early MHD plants, because of the development required. However, costs must not only be gaged in economics. To many of us it costs dearly to add more thermal and air pollution; to waste valuable needed land for less efficient (more real estate) power plants; when a 50-percent increase in electricity could be obtained from each pound of fuel but is not being accomplished!

In summary, since the MHD process can work at much higher temperatures, and since the process eliminates a complete step in the direct conversion of thermal energy to electricity, MHD power systems should indeed by considered a 21st century energy conversion process that is available today!

Conclusion

The necessity for compact, efficient energy sources for aerospace vehicles has led to the development of high performance energy generation, conversion, and storage systems. Because of their unique operating characteristics, these systems could be applied to significantly reduce air, thermal, noise, and waste pollution, which are generated during the commercial and private production and consumption of useful energy. Some of these applications have been discussed in this paper; hopefully more can be found.

The staggering ecological problems caused by our energy utilization necessitate the use of the very best technology to reduce this effect. Fortunately, this technology can be made available as a result of pioneering aerospace programs.