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DEVELOPMENT OF REGENERABLE ENERGY STORAGE FOR SPACE MULTIMEGAWATT APPLICATIONS

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ABSTRACT

A program has recently been initiated as a part of the national Strategic Defense Initiative (SDI) to develop energy storage technology for space power applications. This program is jointly conducted by the Department of Energy and the Department of Defense. It is focused on the development of advanced technologies in regenerable energy storage that will be required for generation of multimegawatt levels of sprint power for SDI space missions. Energy storage technology considered in the program relate to devices that have a high specific capacity for energy storage, which can provide high levels of electric power on demand, and which may be recharged with electric power. The devices of principal interest are electrochemical batteries, chemical fuel cells, and electromechanical flywheels (the latter includes the motors and generators used to provide the electrical to mechanical coupling).

The intent of the program is to resolve technical feasibility issues associated with an electrically regenerable energy storage system satisfying SDI needs. Specifically, energy storage technology will be developed through the proof-of-concept stage within the next six years that provides a specific power greater than 2.5 kW/kg with an energy storage density of at least 450 kJ/kg.

BACKGROUND

Energy storage can play a critical role in meeting space power needs for a number of diverse applications. This includes sprint (also known as burst) and alert mode applications where relatively high power levels are required for short periods. In addition, energy storage is a requirement when coupling an intermittent energy source (such as the sun) with a user that requires power input on a continuous basis.

Energy storage systems for sprint power provide an alternative to sprint power concepts that generate prime electric power directly from thermal energy. These energy storage systems, of which flywheel motor/generators, regenerable fuel cells, and batteries are leading contenders, are capable of being charged electrically at relatively low power, storing the energy for a suitably long period between recharges, and discharging the energy when needed at very high power levels. These systems, because they are regenerable, have the capability for repeated charge/discharge cycles. Also, since they operate in a closed cycle, they do not discharge gases that can fog external devices or cause undesired propulsion of the space platform. Thus, they are more suitable for testing of end use devices and supplying of alert mode power than are propellant charged open cycle systems.

When a constant power output is required but the primary energy source is periodic, as in solar dynamic power cycles, an energy storage component in the power supply is necessary. During the daylight portion of the orbit, excess energy is stored. During the night portion, energy is withdrawn from storage to meet the platform's power needs.

To meet the newly emerging needs for power sources in the multimegawatt range for space applications, a program has been initiated to develop the required power system technology. The program is jointly sponsored by the Department of Energy and the Department of Defense and is composed of ten program elements. These elements range from energy conversion and storage to materials and include nuclear and non-nuclear technologies. This paper focuses on the energy storage element of the Multimegawatt (MMW) Technology Development Program and describes the rationale for selecting the technology to be developed and gives an overview of the development effort required.

MMW ENERGY STORAGE PROGRAM OVERVIEW

ONLY REGENERABLE ELECTRICAL energy storage is considered in this program. Further, the program is focused on sprint power needs for Strategic Defense Initiative (SDI) applications. Energy storage technology considered in this program relates to devices that have a high specific capacity for energy storage, which can provide high levels of electric power on demand, and which may be recharged with electric power. The devices of principal interest are electrochemical batteries, chemical fuel cells and electromechanical flywheels (the latter including appropriate motors and generators that are used to provide the electrical to mechanical coupling). As will be discussed later other types of electrical energy storage devices, such as magnetic inductors and capacitors, do not have specific energy storage capability that is high enough to be of interest. Thus, they are considered a component of power conditioning rather than energy storage and they are not included in this program.

The intent of the energy storage program is to resolve technical feasibility issues associated with an electrically regenerable energy storage system for SDI applications. Specifically, energy storage technology will be developed through the proof-of-concept stage within the next six years that has specific power greater than 2.5 kW/kg with a specific energy of at least 450 kJ/kg.

The current energy storage technology base is not capable of providing multimegawatt levels of sprint power for SDI missions. Although each of the technologies included in the program has been used in space applications, the system demands have been quite modest when compared to SDI sprint power

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needs. Thus, the current technology level (e.g. NiCd batteries) for each option is not directly applicable. Each of these technologies, however, has been advanced by research directed at different applications. For example, flywheel energy storage densities were doubled in a DOE program focused on automotive uses of flywheels. At present, the applicability of the storage options to SDI missions varies. In the case of flywheels, specific power levels are sufficient, but specific energy levels must be raised. For fuel cells and batteries the reverse is true. Using the most recent advances in materials and concepts, it appears reasonable to expect the development of regenerable energy storage systems that will be able to provide electric power levels of hundreds of megawatts for time periods approaching a thousand seconds.

The program is conducted through the Oak Ridge National Laboratory (ORNL) and the AeroPropulsion Laboratory (APL) at Wright-Patterson Air Force Base. Responsibility for the flywheel and fuel cell activities resides at ORNL while the battery development program is conducted through APL. The following section of this paper will explore, in summary fashion, those technologies not included in the storage development program to indicate the reasons for their exclusion. This section will also give a brief overview of battery technology to indicate why it has been included in the program. Subsequent sections will deal, in greater detail, with the technologies for which ORNL has responsibility.

ENERGY STORAGE OPTIONS

Regenerable energy storage that can be charged electrically can be accomplished using electric fields (capacitors) or magnetic fields (inductors). In addition, energy can be stored inertially (flywheels), chemically (and converted using fuel cells), or electrochemically (batteries). The specific energies of flywheel, fuel cell, and battery systems are substantially higher than those for capacitors or inductors. Thus, these technologies are the leading contenders for space power applications.

CAPICATORS - Capacitor technology is relatively mature and capacitors are available in a wide range of voltages up to 100 kV. (1)* Their modular construction allows them to be connected in series or parallel and makes them versatile building blocks for providing short-term (normally < 1 sec) pulses of very high power. However, their specific energy is relatively low, ranging from 0.1 to 50 kJ/kg (1, 2), with values at the lower end of the range being typical. Specific energies at the higher end of the range have been achieved only by sacrificing reliability. Recent advances in capacitor technology, however, indicate that reliable capacitor storage systems will be available with storage densities of 30 kJ/kg. (3)

INDUCTORS - Inductors have higher specific energy values than capacitors but typically have shorter time constants. To obtain storage times suitable for multimegawatt applications of interest to this program will require the use of a superconducting magnet. Systems in the 10 GJ range have been examined for space applications (4). The specific energy for these superconducting magnet systems is expected to be about 110 kJ/kg. However, quenching problems (hence, loss of superconductivity) during rapid discharge and maintenance of cryogenic conditions with a temperature sink substantially above 5 K could reduce operational energy storage densities to about 50 kJ/kg.

Because capacitor and inductor energy storage densities are an order of magnitude lower than those required for the SDI applications, they were not included in the energy storage program. They were instead considered to be a part of the power conditioning program being conducted by the Air Force.

BATTERIES - Batteries have been a baseline energy storage system for most space applications to date. The mission requirements have been modest and the NiCD and NiH_2 batteries (currently considered the state-of-the-art technology) are unsuited to the more demanding requirements imposed by the SDI missions.

The most developed of the advanced battery concepts is the NaS concept. It can have a system specific energy as high as 360 kJ/kg. However, at this specific energy the specific power is only 120 W/kg. Several new battery concepts have been suggested that, conceptually, could improve battery performance to the point where they would be competitive for SDI applications. Two such concepts are the sodium/glass/sulfur cell (4) and the lithium-aluminum/iron disulfide bipolar cell (5). Both concepts theoretically offer specific energies on the order of 700 kJ/kg with specific power of about 2 kW/kg. Another concept being examined is the dynamic power cell. This concept uses an alkali metal anode (lithium), an acid electrolyte and a rotating cathode (drum or disk). Demonstrated laboratory cell performance has been impressive; achieving an energy density of 3600 kJ/kg with a specific power of 12 kW/kg (6). Although these are cell only figures, they do indicate that the concept has substantial potential for meeting the SDI requirements. Because the promising developments in storage and power densities for batteries put them in a position where they are approaching the storage requirements outlined for the program, they have been included as a storage option to be developed. As previously indicated, responsibility for this development will reside with the Air Force.

FLYWHEEL SPRINT POWER MODULE

Flywheels have seen limited use in space. Primarily, they have been used in the attitude control system (e.g. control moment gyro systems) for spacecraft. Since the energy storage requirements have been minimal, low performance metallic rotors have been used.

A flywheel sprint power module storage system would have three major subsystems: rotor and containment, suspension, and power components. Composite rotor technology, which enabled the specific energy of rotors to be increased by more than a factor of two, was developed during the early 1980s in the DOE Mechanical Energy Storage Technology (MEST) Program. This program, managed by ORNL, raised the allowable specific energy from 70 kJ/kg (typical of metallic rotors) to 145 kJ/kg by using S-glass,

*Numbers in parentheses designate References at end of paper

Kevlar, and graphite/epoxy composite materials (7). Recent advances in fiber strength have permitted further increases in the operational storage density of rotors. Maximum rotor performance had previously been achieved using Kevlar fibers having an ultimate tensile strength of 300 ksi. The high-strain graphite fibers now available have tensile strengths in the range of 750-820 ksi range. Thin rim rotors using this material have achieved an operational specific energy of 625 kJ/kg with an ultimate value of 880 kJ/kg in a program being conducted by ORNL.

The specific power of a flywheel system is primarily determined by the generator. Recent advances in homopolar generators and permanent magnet generators enable power densities in the range of 2-3 kW/kg to be achieved. An air-core homopolar generator, using two 115-MJ flywheels for energy storage, is currently being developed by the University of Texas and ORNL. This machine will deliver a peak power of 32 GW and weigh 2500 kg, thus yielding a specific power of 13 MW/kg.

Magnetic bearings will be used for suspension of the flywheels in order to provide long lifetime and reliable operations. Magnetic bearings have been developed by SNIAS (France), TELDIX (Germany), Draper Laboratories, and NASA for suspension of flywheel rotors and have proven to be reliable (8, 9,10). The use of electromagnets can provide for an adjustable stiffness. Because they can be designed to produce almost zero jitter, magnetic bearings have been recommended for use on the space telescope platform.

Flywheel systems tested in space have used metal rotors which limited the usable specific energy to less than 70 kJ/kg. To achieve the performance levels required for SDI applications, this technology base must be advanced by improving performance levels for the major system components. Rotor performance must be improved by using the newest fibers. This will require design studies of rotor configurations and the development of fabrication methods. Active magnetic bearings will require development to minimize power consumption. Generators with high specific power levels will be required for specific end uses. Since a flywheel module will consist of two counter-rotating rotors, the control technology to match the speeds of the two wheels and to produce a zero net momentum vector must be investigated.

REGENERABLE FUEL CELLS

Regenerable fuel cells have been used for energy storage in space applications. Although specific energy is acceptable for these systems, the specific power, at about 100 W/kg, is much too low to be useful for SDI applications. The latest generation of fuel cells used for space missions were alkaline fuel cells with a current density of 116 mA/cm^2 and a voltage of 0.84 V (11). Performance for these cells is limited because of the liquid electrolyte. A large mass is required for the inert container to hold the liquid in place. Concerns also exist involving electrolyte vaporization and carryover.

A new fuel cell concept employing a ceramic monolith structure has promise for achieving substantially improved power densities (12). This concept uses a solid zirconium oxide electrolyte with hydrogen and oxygen. Use of the solid electrolyte in a corrugated pattern provides a high surface area to volume ratio. The high operating temperature (1000 C) results in the use of thin electrode layers minimizing electrical resistance. The use of a solid electrolyte permits an order of magnitude reduction in cell height (about 1 mm, as compared to more conventional designs using a 1 cm cell height) which reduces resistance in the electrical path. With this concept it may be possible to develop a regenerable storage module with a specific energy of 1580 kJ/kg and a specific power of 3.2 kW/kg.

The monolithic fuel cell concept has been under development by Argonne National Laboratory since July 1983. This effort is to produce an array of cells and demonstrate power production capability. In January 1985, a cell was run for 75 hours at 0.6V. The current density was 600 mA/cm^2. A three-layer array was successfully operated in July 1985.

Although the concept holds promise, development work has occurred essentially only on the cell level. Technical development of the cell will be required to obtain the necessary voltage and current density. Once the cell power performance has achieved desired levels, the electrolysis operation must be demonstrated. All testing of the monolith cells to date has occurred at atmospheric pressures. Operation of the monolith array at pressure must be demonstrated. The ability of the monolith to come up to power from a hot standby condition must also be verified.

SUMMARY

The energy storage activity within the MMW Technology Development Program will develop advanced technology for electrically regenerable energy storage systems that potentially can provide electric power in the range of 100 MW for several hundred seconds in a space environment. Typical performance requirements include a specific power of at least 2.5 kW/kg with a specific energy of at least 450 kJ/kg. Flywheel and fuel cell technology will be developed through ORNL while battery development will be managed by the Air Force. The current state of the technology is approximately as follows: (1) flywheel motor/generators can meet the specific power goal but with only 30 to 50% of the required specific energy; (2) regenerable fuel cells can provide much higher specific energy, but only with much lower specific power; and (3) batteries can provide the specific energy, but with only about 10% of the required specific power.

FLYWHEEL MOTOR GENERATOR - The technology base for this technology is the most advanced in terms of meeting the program goals. The technology development program will address principle concerns related to rotor design, suspension systems for minimal platform jitter, and speed matching for rotor pairs to obtain a zero net momentum for the flywheel module.

REGENERABLE FUEL CELL - An advanced monolithic fuel cell offers the potential for high specific power and regenerable operation. This effort will build upon a parallel DARPA program. At present, this technology has operated in only the power production mode and only at the cell level. Technical issues include development of cell arrays, electrolysis operation, pressurization, and reliability.

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