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POWER OPTIONS FOR LUNAR EXPLORATION

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Abstract

This paper presents an overview of the types of power systems available for providing power on the moon. Lunar missions of exploration, in situ resource utilization, and colonization will be constrained by availability of adequate power. The length of the lunar night places severe limitations on solar power system designs, because a large portion of the system mass is devoted to energy storage. The selection of the ideal power source hardware will require compatibility with not only the lunar base power requirements and environment, but also with the conversion, storage, and transmission equipment. In addition, further analysis to determine the optimum operating parameters for a given power system should be conducted so that critical technologies can be identified in the early stages of base development. This paper describes the various concepts proposed for providing power on the lunar surface and compares their ranges of applicability. The importance of a systems approach to the integration of these components will also be discussed.

INTRODUCTION

Future space missions will require much higher power levels than previous missions. The required power levels of a lunar base will be approximately 100 kW for the initial base, growing to 1 MW with the implementation of resource mining facilities. Large amounts of power will need to be transmitted over distances ranging from 1 to 5 km. The loads will include a habitat, a launch/landing facility, surface transportation, a science and research facility, and a resource mining facility. Design considerations will include operational, safety, environmental, and reliability issues. Ultimately, however, the establishment of a lunar base will become a reality only if the cost can be met within the political and socioeconomic structure responsible for the program. Elements of the lunar power system that need to be addressed include the power source, the method of power conversion, energy storage requirements and methods, and the power distribution system.

POWER SOURCES

The energy used to supply power to lunar base loads could be derived from one or more of three sources: solar radiation, nuclear, or electrochemical energy. The primary energy needs can be met using either solar or nuclear reactor technology. Secondary energy requirements, such as remote and transitory loads, may use an electrochemical power source or an isotope generator.

Solar

Power can be derived from solar energy through the use of photovoltaic cells that convert radiation directly into electricity, or by converting thermal energy to electric energy. Solar photovoltaic systems are composed of solar cells electrically configured in series and parallel combinations to produce the desired voltage and current output. The output current is a function of the magnitude and angle of the incident radiation, while the output voltage is inversely proportional to temperature. Potential solar cell candidates include gallium arsenide, silicon, and indium phosphide. An evaluation of these candidates should be based on their cost, efficiency, temperature sensitivity, ease of manufacturing, and overall long-term

stability in the lunar environment. The solar panels on which the cells are mounted can either be fixed in position or track the movement of the sun to maintain maximum power generation. Although a tracking configuration will increase the cost and complexity of the system, it will also ensure that excess power can be generated for electrochemical storage recharging during the lunar day.

The lunar environment will affect the design of solar photovoltaic systems in a number of ways. In particular, the temperature extremes (100 K to 380 K) and the possibility of contamination by dust will affect the operating characteristics of lunar photovoltaic sources. Because the efficiency of solar cells decreases linearly with increases in temperature, a radiator design that ensures that cell temperatures remain at reasonable levels to maintain efficient operation will be required. Electrostatically charged dust particles may gather on exposed electrodes, which could initiate electrical breakdown, mechanical failure, or at the least decrease the thermal characteristics of the system. As a result, regular maintenance will be required to maintain system reliability. These maintenance procedures could have a significant effect on the cost, reliability, and safety of the power system.

An alternative method of extracting energy from the sun involves the use of solar concentrators. The thermal energy captured by such devices can be converted into electrical power. A study comparing solar concentrators with regard to mass, specific power, volume, and operating temperatures of the conversion system was conducted by Systems Development Corporation (1986). Solar dynamic systems will require less maintenance, slower performance degradation, and, if a dynamic conversion method is employed, a higher efficiency than photovoltaic systems. However, because they are an immature space technology, solar thermal systems will have significantly higher development costs. Until such systems have been developed and tested on a much broader scale, the solar source of choice for the lunar base is the proven and reliable photovoltaic system.

Nuclear

The primary advantage of nuclear power systems is that they are able to supply a constant power output independent of the time of day or their orientation to the sun. They will also be less affected by the harsh lunar environment than photovoltaic systems. Nuclear sources fall into one of two basic categories: isotope generators and nuclear reactors. Radioisotope Thermoelectric Generators (RTG) and Dynamic Isotope Power Systems (DIPS) have been used extensively as power sources for low-power space missions. Possible lunar applications include remote, transitory, and backup power supplies. RTGs have a history of long life, high reliability, and stability in hostile environments. With a power capability of several hundred watts and a performance level of 7 W/kg, their use in the lunar power system will be limited. DIPS have higher efficiencies, lower unit costs, and greater flexibility than RTGs. Output power levels of 1 to 10 kWe at 8 W/kg make DIPS an attractive power option for remote science applications.

Power demands ranging from hundreds of kilowatts to one megawatt can be best supplied by nuclear reactor systems. Even though nuclear reactors have seen little use up until this time (primarily because of the political difficulties associated with launching such a system), reactor systems offer durability, long operating life, and little vulnerability to hostile environment conditions. Characteristics unique to the lunar environment further increase the benefits associated with a nuclear reactor power source. A reactor that is placed at a safe distance from the base would require little to no shielding. However, if directed energy transmission (power beaming) is not used, the distance would have to be such that the mass decrease because of the elimination or decrease in shielding is greater than the conductor increase resulting from increased transmission distance. Another method of decreasing shield mass would be to use the lunar soil as a radiation shield. The heat rejection system associated with such a design would need to compensate for the poor thermal conductivity of the lunar soil. A conceptual design of a SP-100 reactor power system for use on the lunar surface is discussed by Upton et al. (1991).

CONVERSION METHODS

Solar thermal and nuclear sources require some form of conversion device to convert the thermal energy into electric energy so that it can be more easily transmitted to the loads. Conversion methods can be either static or dynamic. Specific design issues include peak operating temperatures, heat rejection temperatures, working fluid properties, operating lifetime, vibration and torque effects, power range, modularity, startup and shutdown characteristics, and radiation resistance. How these affect the mass, efficiency, and reliability will determine which form of conversion is the most cost-effective for a specific application.

Static

As the name implies, static energy conversion methods have no moving parts. A working fluid, heated by the source, transports thermal energy to cells (either thermoelectric or thermionic) that convert the heat into electric energy. As in a photovoltaic system, the desired output characteristics can be obtained by arranging the thermionic cells in series and parallel. The output voltage is typically around 200 V. The efficiency of thermoelectric systems falls between 4 and 8%. Thermoelectric techniques have been in widespread use since the 1960s. As a result, thermoelectric power conversion has been established as a proven and reliable technology. Although their use is limited to relatively low power applications, their power level could approach a hundred kilowatts if used in conjunction with a reactor source. An alternative static conversion method uses thermionic cells to produce electric energy. Some benefits of using a thermionic system are its ability to achieve a higher fraction of Carnot efficiency and its higher heat rejection temperature. If the conversion is conducted in-core, this method can achieve higher operating efficiencies because of the higher temperatures. As the temperature of the thermal energy input into the conversion system increases, so does the efficiency and power density of the device. In-core conversion results in an efficiency of approximately 9 to 15%, almost double that of thermoelectric methods. In-core conversion, however, has not yet been demonstrated to an extent to qualify it as space-ready technology. Therefore, development costs can be expected to be substantially higher than those for thermoelectric conversion. Efficiencies of out-of-core conversion are on the same level as that of thermoelectric, making the only real advantage of presently available thermionic technology the reduction in radiator area associated with the higher heat rejection temperature.

Dynamic

Lunar base power requirements (estimated to be less than 100 kW) initially could be supplied with a nuclear reactor/static conversion system. Because of technical and reliability limitations associated with high-temperature operation of static devices, a dynamic method of conversion will be necessary as power levels approach 1 MW. A dynamic conversion device converts thermal energy to electric energy through the use of an alternator. Dynamic conversion systems that show particular promise for lunar base applications are the Brayton and Stirling heat engines (Rankine is not considered because of its low operating efficiency). Engine selection should be based not only on design and equipment costs, but also on maintenance and reliability issues such as wear modes of the parts, the number of welds, cycle temperatures and pressures, and equipment tolerances. A closed-cycle technique would be desirable because of the high cost of transportation which would be incurred with supplying replacement fluids. The efficiency of dynamic systems is about 40% greater than that of static devices.

A Brayton engine operates by heating a single-phase, inert working fluid, which then flows to a turbine-alternator-compressor assembly. The mechanical energy derived from the turbine wheel drives an alternator rotor and compressor. To increase the efficiency, a recuperator is used to recover a significant portion of the turbine waste heat. Brayton systems are compact, efficient, and inherently reliable because of the minimal use of moving parts. In addition, the systems will be unaffected by low gravity conditions and can be easily started and restarted at low temperatures. There are no significant technology barriers to the application of a Brayton system with heat sources in the range of 1100 to 1500 K. System efficiencies of 16 to 18% are expected with systems in the 10 to 100-kWe range. If used with isotope

generators, Brayton cycle efficiency increases to 25 %. Hunt and Rovang (1991) examined the potential use of a 2.5-kWe portable Brayton DIPS for the lunar and Mars missions.

There are two forms of Stirling engines. The kinematic engine converts the reciprocating movement of the piston into a steady rotating motion by means of a crankshaft or equivalent device. The effectiveness of such a kinematic Stirling engine with a parabolic dish solar concentrator source has been demonstrated by Systems Development Corporation (1986). A free-piston Stirling engine eliminates the frictional losses associated with the crankshaft by applying the oscillatory linear motion of the piston to a piston rod, which is then directly coupled to a reciprocating load such as a linear alternator. Not only does the free-piston Stirling engine operate at the highest efficiency of all known heat engines, but the configuration also allows hermetic sealing of the entire system, eliminating the need for high-pressure shaft seals and lubricants. Single engines have been designed for up to 100 kWe. A 1993 design goal for an SP-100 Stirling system is to achieve a system-specific power of 40 W/kg. This is almost twice the system-specific power of the SP-100 thermoelectric, which is estimated at 22 W/kg. Higher power outputs can be achieved by placing multiple engines in parallel. This technique, however, is still in the development stage.

ENERGY STORAGE

Regardless of the power source, an energy storage system will be a necessary element of the lunar base power system. If a solar source is implemented, storage systems will be needed to supply power needs during the lunar night. These storage systems will have a discharge time of approximately 375 hours. The length of the nighttime operation and the subsequent demands on the energy storage system make such a system the major mass contributor of a solar powered system. A nuclear source will also require a minimal stored energy supply to provide power during emergency conditions or to meet the demands during peak load conditions. Electrochemical energy storage devices may be used on a lunar base; they produce electric energy by inducing a chemical reaction in the presence of an electrolyte. Because of their low specific energy, efforts to improve the energy density and cycle life of such devices are critical. The design life is a function of the device duty cycle, operating temperature, and depth of discharge. Electrochemical energy storage technologies considered for space applications are battery and regenerative fuel cell technologies.

Batteries can be either primary (require resupply) or secondary (rechargeable). For primary batteries to be cost effective, they must be capable of deriving their replacement fuel from lunar materials processing efforts. Secondary batteries would eliminate the transportation and/or processing costs associated with fuel resupply, but their energy densities are significantly lower than that of primary batteries. Even the specific power of primary batteries is low enough to result in significant mass penalties. Regenerative fuel cells (RFCs) have better operating characteristics and will require less resupply than primary batteries. For these reasons, the use of batteries in the lunar power system should be limited.

The fuel cell particularly attractive for use with a lunar base is the alkaline electrolyte cell, which uses hydrogen and oxygen as fuel (both of which are anticipated products of lunar mining operations). This fuel cell system can be designed to be closed cycle (regenerative) by separating the water produced as a by-product back into its hydrogen and oxygen elements through electrolysis. An RFC system consists of a fuel cell stack, an electrolyzer, reactants, and storage facilities for the reactants and water. The reactants and storage have the greatest effect on the overall system mass. Harris et al. (1991) developed a computer model of a proton exchange membrane RFC that, given power level, operating time, and life requirements, optimizes the design and generates operating conditions and mass of the RFC system. Development goals are to achieve a specific power of 7 kW/kg and a specific energy of approximately 810 kJ/kg.

POWER TRANSMISSION AND DISTRIBUTION

There are essentially two options for transmitting power from one site to another across a lunar base; directed-energy transmission or the use of electric transmission lines. Characteristics that should be considered include mass, efficiency, and heat generation. In particular, an analysis of electric transmission lines should examine characteristics such as material selection, line geometry, line configuration, location, the operating voltage, waveform, frequency, and number of phases. Power beaming studies should identify the most suitable power source, operating frequency, antenna designs, and location of the transmitting antenna (orbital or surface-based). The potential of using power beaming techniques to supply power to a lunar base is examined by Bamberger (1992). The use of transmission lines in the lunar environment is discussed by Gordon and Gaustad (1991).

The selection, design, and limitations of power conditioning equipment will have a significant impact on the overall design of the lunar base power system. Kraus et al. (1990) have estimated that between 30 and 60% of the mass of the space station can be attributed to the power conditioning equipment. Although the lunar base power conditioning equipment mass will probably not account for so large a portion of the total system mass, proper design and planning could provide significant cost savings. In addition, the limitations of a single component could affect the operating parameters of the device and the system. The transmission system will be particularly affected by these limitations. For example, the output voltage of most of the power sources is approximately 200 V, while transmission lines will need to operate at a minimum of 1 kV and may require up to 5 kV to optimize conductor mass. Other possible applications include altering the operating frequency and/or waveform at the source and loads as required. The technological status of space-qualified high voltage/high current power-conditioning equipment needed to perform such functions is not very advanced. As a result, system operating parameters such as operating voltage, frequency, and waveform should be selected based not only on the physical ramifications of the decision (that is, mass), but also on whether or not the technology exists to produce and maintain the desired values.

In addition to the fundamental elements of the power system such as sources, loads, transmission system, and power-conditioning equipment, additional devices to ensure safe and continuous operation will be required. Protection equipment will be necessary to maintain operations during fault or overload conditions, and isolation, monitoring, and control equipment will be needed to enhance safety, track operating parameters, and regulate the operation of the system as a whole. Little research has been conducted to develop equipment that will perform such tasks under the environmental conditions and anticipated power and voltages levels of the lunar base.

CONCLUSIONS

Terrestrial power systems have traditionally been designed in a piecemeal fashion. The standardization of frequency and waveform and the design criteria of terrestrial systems allow this technique. The design of a lunar power system will not permit this luxury. Costs (the primary driver of both systems) associated with lunar power development and operations will be determined primarily by system mass and by development costs as opposed to equipment and construction costs (the determining factors in terrestrial designs). Safety and reliability requirements will also differ. The nature of these differences will force the source selection, load requirements, transmission parameters, power conditioning equipment, and protection and isolation needs to be simultaneously considered for optimum lunar base planning and design. Although individual component analysis is necessary throughout base design, the results of such studies should be gathered and an integrated system study conducted to determine the ideal lunar base design. A system constructed using the optimum components as determined solely from individual component analysis may prove to be neither the most cost-effective nor most efficient design. For example, a three-phase transmission system will have a lower conductor mass than a single-phase system. However, a three-phase system will require more control and monitoring devices. Therefore, a comparison of the conductor mass savings with increased mass of power-conditioning equipment should

be conducted before any conclusions can be made. Many of the proposed technologies are in the early stages of development, and many of their operating characteristics are vague or undefined. Current knowledge does allow us to determine which of the components are competitive for certain applications. For example, it is safe to assume that if the power source is surface-based, high power level requirements during the lunar night can be best served by a nuclear reactor source. Initial power requirements can be met with a static device, but development of a resource mining facility will require a dynamic conversion method. To further narrow down the candidate power system components and operating parameters, it will be necessary to define other requirements such as start/stop capability, level of fault protection, required load following, and smoothing. Identification of the operating characteristics of the loads will be vital to the selection of lunar base power equipment and its operating parameters. Obviously, the power required by the loads will determine the size and, along with environmental conditions, the nature of the power sources. The electrical profile of the loads will also have a profound affect on lunar power system design, particularly the transmission and distribution system. Because of the impact the mass of the power conditioning equipment has had on previous space missions, operating requirements of the load such as its voltage level and waveform may play a large role in determining the operating parameters of the transmission system.

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