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MEGAWATT SOLAR POWER SYSTEMS FOR LUNAR SURFACE OPERATIONS

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Lunar surface operations require habitation, transportation, life support, scientific, and manufacturing systems, all of which require some form of power. Nuclear thermal power is often considered to be the only type of power system which can provide a lunar base with power on the megawatt level, but political and technological obstacles may severely limit the application of nuclear power in space. As an alternative to nuclear power, this report focuses on the development of a modular, one-megawatt solar power system, examining both photovoltaic and dynamic cycle conversion methods, along with energy storage, heat rejection, and power backup subsystems. For photovoltaic power conversion, two systems are examined. First, a substantial increase in photovoltaic conversion efficiency is realized with the use of new GaAs/GaSb tandem photovoltaic cells, offering an impressive overall array efficiency of 23.5%. Since these new cells are still in the experimental phase of development, a currently available GaAs cell providing 18% efficiency is examined as an alternate to the experimental cells. Both Brayton and Stirling cycles, powered by linear parabolic solar concentrators, are examined for dynamic cycle power conversion. The Brayton cycle is studied in depth since it is already well developed and can provide high power levels fairly efficiently in a compact, low mass system. The dynamic conversion system requires large scale waste heat rejection capability. To provide this heat rejection, a comparison is made between a heat pipe/radiative fin system using advanced composites, and a potentially less massive liquid droplet radiator system. To supply power through the lunar night, both a low temperature alkaline fuel cell system and an experimental high temperature monolithic solid-oxide fuel cell system are considered. The reactants for the fuel cells are stored cryogenically in order to avoid the high tankage mass required by conventional gaseous storage. In addition, it is proposed that the propellant tanks from a spent, prototype lunar excursion vehicle be used for this purpose, therefore, resulting in a significant overall reduction in effective storage system mass. Emergency backup power is supplied by a nickel-hydrogen battery system derived from the energy storage system to be used on Space Station *Freedom*, in order to save on development costs and to provide one of the most reliable systems available. Structural elements for the entire power system are made of composites and aluminum, keeping system mass to a minimum. All components of the system are designed for transport to low Earth orbit in modular units aboard the Shuttle-C launch vehicle.

INTRODUCTION

Plans for lunar development will ultimately require a large power system to support all of the planned activities. Nuclear energy has usually been the assumed power source due to the high power densities offered, yet nuclear power is far from ideal. There are many problems, including startup of the plant, the large amounts of radiation produced and the need for a large area set aside permanently as a result, the impossibility of maintenance, and very low efficiency. The Space Systems Design Course at the University of Washington has, therefore, performed this design study on the harnessing of solar power for use on the Moon as a cleaner, safer alternative to nuclear power.

This study looks at two basic methods of converting solar energy into electrical power, with the objective of providing one megawatt of electrical power. The first method is the use of direct electrical conversion of solar energy using a new, highly efficient solar cell developed by the Boeing Corporation. The second method is the use of a dynamic cycle operating on energy supplied by a solar concentrator system. The Brayton cycle was chosen for this study for its relatively high efficiency and its availability in the timeframe of the lunar base as a proven and reliable unit. This cycle will also require an extensive heat rejection capability provided by one of two systems examined in this study: an advanced technology heat pipe radiator, or a liquid droplet radiator.

Neither of these power sources will, of course, provide power during the lunar night and, thus, energy is stored using a fuel cell system. Fuel cells similar to those used on the space shuttle, along with cryogenic hydrogen and oxygen stored in the tanks of a spent lunar lander, are employed as the energy storage system. Energy storage is relatively massive, so in order to keep the overall mass of the lunar power system from becoming excessively large, the nighttime energy storage system will provide just 50 kW, rather than a full megawatt. This nighttime power reduction may be offset by adding more photovoltaic arrays or dynamic cycle units, which are far less massive, for increased daytime power production.

The entire power system is designed to be modular, configured in such a way that no single point failures are possible. In the rare event of catastrophic failure, however, emergency power for repair and evacuation procedures is provided. For development, cost, and reliability reasons, the energy storage system from the Space Station *Freedom* was reconfigured to provide the required emergency backup power.

SOLAR PHOTOVOLTAIC POWER SUPPLY SYSTEM

As mentioned above, one of the power generation systems considered makes use of direct conversion via photovoltaic cells. Typical photovoltaic cells used in space and terrestrial applications are made of gallium arsenide (GaAs) or silicon (Si) and convert only part of the available radiation spectrum into electrical power. These cells usually attain a solar energy conversion efficiency between 14% and 21%. A new tandem cell (Fig. 1) being developed by Boeing Aerospace is used in the present design and consists of two cells of different materials, mechanically stacked on top of one another[1]. The upper cell, made of GaAs, absorbs photons with energies above 1.42 eV and has been made transparent to infrared radiation. Infrared radiation passes through the upper cell to a lower cell made of gallium antimonide (GaSb), which absorbs photons with energies as low as 0.72 eV. GaSb was chosen as the infrared sensitive booster cell because it is a direct bandgap material that generates higher currents, its bandgap is significantly lower than that of GaAs, and the voltage produced is nearly one-third that of the GaAs cell[2], allowing it to be voltage matched with GaAs in a 3:1 ratio series-parallel arrangement to produce a 1.0 V triplet[3], as shown in Fig. 1.

Individual cell efficiencies are enhanced by the addition of prismatic cover slides that fit over the upper gridlines on each cell and direct light toward the cell surface, away from the gridlines. This minimizes reflection losses and increases efficiency by 10% per cell[4]. When tested at a light concentration ratio of 100 times solar intensity (100 suns) in air-mass-zero (AM0) conditions, the individual performance of the GaAs cell was 23.9%, and that of the GaSb cell was 6.9%, for a total of 30.8% solar energy conversion[4].

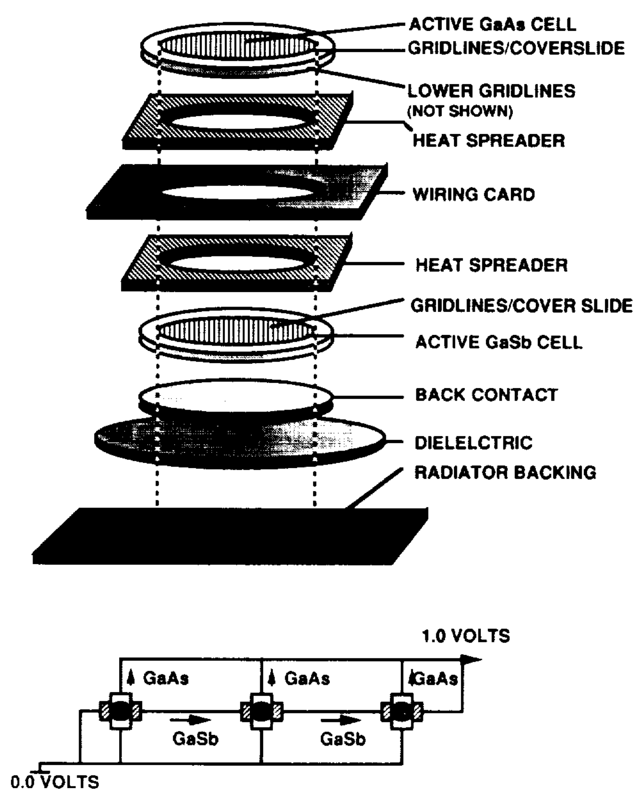

Fig. 1. Cell Assembly and Triplet Formation

To concentrate incoming sunlight to 100 suns, domed Fresnel lenses made by Entech, Inc. are used. These lightweight silicone lenses have a prismatic undersurface, designed to focus light at the center of the cell. A layer of protective microglass is laminated directly to the curved upper surface of the lens to protect it from solar proton flares and micrometeorite damage. Together, the microglass and silicone comprise 27.8% of the total panel mass[5].

The lenses (which have a 3.75-cm-square cross-section) are fitted into a square aluminum honeycomb housing, so that the lenses lie below the top of the housing. The honeycomb housing is made of 0.15-mm-thick aluminum, 4.05 cm high, with small extensions in the corners to support the lenses[5]. The photovoltaic cells and wiring are attached to a thin aluminum backing, which is placed underneath the honeycomb and lens assembly, as shown in Fig. 2. This backing, coated with alumina for high emissivity, acts as a thermal radiator, rejecting excess heat. When wired into triplets and placed under the concentrating lenses, the entire assembly converts solar radiation to electricity with an overall efficiency of 23.5%, operating at a temperature of 80°C[3].

To size the array using the above efficiency, it is necessary to determine what power the lunar base requires and what other subsystem inefficiencies apply. This design was configured for a baseline output of 1.0 MW_e during the day and 50 kW_e at night, provided to the users. During the day, power will be channeled directly through transmission lines which have an efficiency of 94.4%. During the night, energy must be provided from a storage facility which, along with transmission and power conditioning, has an efficiency of 43.2%. Therefore, 1.175 MW_e are needed from the array during the day.

The cells are arranged in panels, 12.5 m × 3.0 m each. Individual panel dimensions are determined by structural and maintenance considerations. In the event of a breakdown, the panels will need to be repaired by an astronaut on site. A width of 3.0 m was chosen, therefore, to allow an astronaut to reach each half of the panel. The panels are supported close to the ground by a central truss, and rotated 0.54° per hour to track the sun, using single-axis tracking. A panel length of 12.5 m

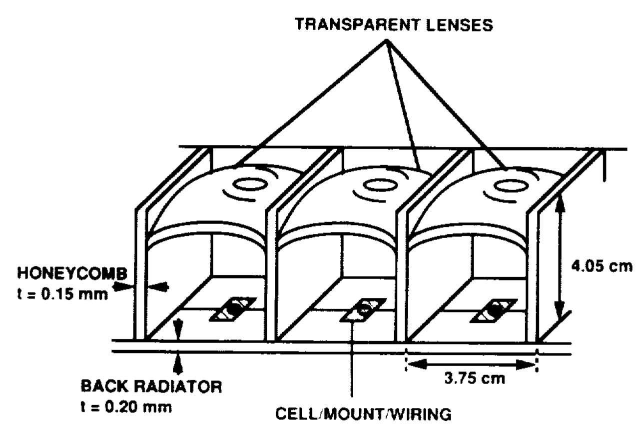

Fig. 2. Honeycomb Section Dimensions

was chosen to minimize structural weight. Two panels are mounted on a support structure with a motor in the center to form a panel set producing 23.85 kW_e at a mass of 183 kg (not including structural members).

Fifty panel sets are required to provide the baseline power output of 1 MW_e. These are arranged in 5 rows of 10 sets each, at a spacing of 15 m to minimize mutual shading effects. When panels are placed in rows facing sunrise or sunset, all panels behind the front row are partially shaded until the sun reaches a certain angle above the horizon. For a total of 50 panels arranged in 5 rows, the minimum is calculated to be 15 m. In this arrangement, the total array has a mass of 9,150 kg (not including structures) and requires a land area of 19,748 m^2 (4.9 acres).

Since the tandem cell developed by Boeing Aerospace has not been fully tested, an alternative array was also configured using an unconcentrated, single cell produced by TRW. This is intended to provide a comparison using existing technology. The alternative cell is made of GaAs deposited on a germanium substrate and offers an efficiency of 18%[(6)]. The cells are rectangular (2.0 cm × 4.0 cm × 0.2 mm thick) and require no concentrating lenses or extra housing. They can simply be secured to a radiative backing, placed close together, and wired in series.

The GaAs cells have roughly the same mass as the tandem cells (170 kg/panel set), but due to their lower efficiency, 65 panels are required to provide the same amount of power. Panel sizes are the same as for the tandem cell array: 12.5 m × 3.0 m. This means 15 extra panels are required, which is an addition of 1900 kg to the total system mass (not including structures), or an increase of 21% over the GaAs/GaSb cell array. The panels are arranged in 8 rows of 8 sets each, with one additional panel in the front, at a row spacing of 17 m to minimize shading effects. The total array mass is 11,066 kg (not including structures) and uses a land area of 27,171 m^2 (6.7 acres).

A comparison of the two alternative arrays is shown in Table 1. Note that the difference in efficiencies of the two cells significantly affects the power density. While the single GaAs cells are appealing in terms of simplicity and availability, the tandem cells, with a higher efficiency, require less mass. Mass is at a premium when all system components must be lifted to orbit, and the lighter weight tandem cell array is recommended.

Table 1. Cell Comparison Summary

	Tandem Cell	GaAs Cell
Array Efficiency	23.5%	18.0%
Concentration Ratio	100	1.0
Power/Area (W_e/m^2)	318	243.3
Total Required Area (m^2)	3750	4825
Number of Panel Sets	50	65
Cell Mass (kg/m^2)	2.44	2.27
Mass/Panel Set (kg)	183	170
Power/Panel Set (kW_e)	23.85	18.26
Total Array Mass (kg)	9150	11066
Power Density (W_e/kg)	130.3	107.3

BRAYTON DYNAMIC POWER SUPPLY SYSTEM

The second power unit considered in this study is the Brayton dynamic cycle conversion system powered by solar radiation concentrated by a parabolic trough collector. The total conversion system is composed of five modules, each with a 250 kW_e output. As shown in Fig. 3, each conversion module is made up of three main elements: the solar collection unit, the dynamic power module, and a heat rejection system. The system configuration was determined by manipulating the Brayton cycle parameters to obtain a system of minimum mass.

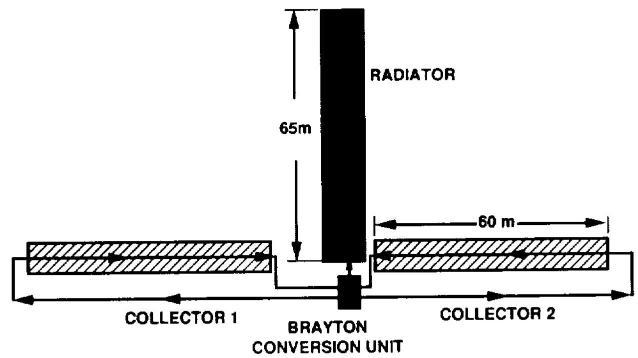

Fig. 3. Dynamic Conversion System Layout

The solar collection unit is designed to concentrate solar radiation onto a receiver through which the system working fluid passes. This fluid is thus heated for delivery to the turbine of the dynamic power module. The solar collection unit consists of two parabolic trough collectors, each 60 m long. Each collector processes half of the required mass flow rate of the system working fluid. The trough collectors are made up of a parabolic reflector surface and a receiver duct mounted at the line focus of the reflector. The reflector consists of a rigid structure that supports a reflective surface of aluminum foil. The reflector has an aperture of 7.0 m and a focal length of 1.0 m. For this design a reflectivity for aluminum foil of 86% was used[(7)].

The receiver consists of a 5-cm-diameter duct made of UDE MET 700 alloy with a spectrally selective coating of cobalt oxide that is electroplated onto the duct. It serves to reduce the reradiative loss from the receiver by providing a low surface emissivity at the receiver operating temperature of 780 to 1000 K. The selective nature of the cobalt oxide coating is such that it has a high emissivity for radiation of wavelengths below 3 μm and a low emissivity at longer wavelengths[(8)]. This provides a solar absorptivity of 95%, with an effective emissivity from 18% to 32% over the entire length of the collector. This allows an efficiency of 63% to be achieved by the collector.

The dynamic power module consists of a regenerative Brayton cycle conversion unit. The cycle parameters used for the optimization of the system were the compressor and turbine inlet temperatures and the compressor pressure ratio. The operating temperature range is determined by considering system mass versus overall cycle efficiency. The compressor inlet temperature was made as low as possible (330 K) without pushing the radiator mass to extremely high levels. The turbine inlet temperature is driven by two opposing factors. This temperature should be as high as possible to give a high cycle efficiency. However, the efficiency of the collector decreases as its average operating temperature increases. This suggests that there is an optimum turbine inlet temperature. As Fig. 4 shows, this optimum temperature occurs at ~1000 K. Based on the selection of the compressor and turbine inlet temperatures, the Brayton cycle efficiency is then maximized with respect to the compressor pressure ratio. The optimum pressure ratio was found to be 1.85 and resulted in a cycle efficiency of 36%.

For the dynamic power module, the compressor and turbine are mounted on the same shaft along with an alternator to produce the electrical power. The turbomachinery chosen for this study consists of a radial compressor and a radial turbine. This choice was made because of the low mass flow rate of the working fluid. Radial compressors require fewer stages than axial flow compressors to obtain the same pressure increase. Also, radial flow components are lighter and more rugged than axial flow components.

Several factors affect the choice of the working fluid: the extreme cold experienced during the two-week lunar night, the need for a noncorrosive gas to limit erosion and breakdown of system components, and the need for a high specific heat to minimize the mass flow rate. Helium was chosen as the working fluid because it does not become liquid at the temperatures reached during lunar night, and it has a high specific heat. Heat engines have higher component efficiencies using working fluids of higher molecular weight, however, any gases heavier than helium will condense out of the mixture at the low temperature of 116 K reached during lunar night.

Two different heat rejection systems were considered for this study. The first is a heat pipe radiator and the second is a liquid droplet radiator. Each requires a different heat

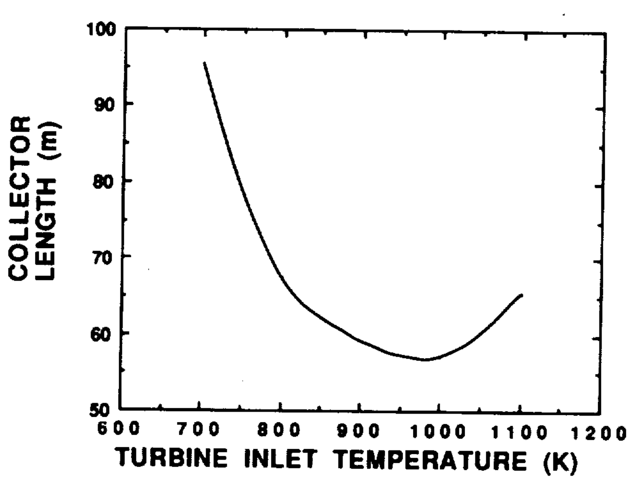

Fig. 4. Variation of Collector Length With Turbine Inlet Temperature

exchanger for the heat rejection from the dynamic power module working fluid. The heat pipe radiator requires a heat exchanger consisting of tubes immersed in the heat pipe fluid through which the helium passes. The liquid droplet radiator requires a heat exchanger that allows the helium to flow around tubes containing the liquid droplet radiator fluid.

The dynamic power conversion system has an overall efficiency of 23% of the incident solar energy. The mass of various components of the cycle, including the waste heat exchanger is given in Table 2, and will be used later to compare the dynamic conversion system to the photovoltaic system.

Table 2. Brayton Engine Mass Breakdown

Component	Mass, kg
Brayton Conversion Unit	
Turbomachinery	234
Regenerator	207
LDR Heat Exchanger	206
HPR Heat Exchanger	148
Gas Supply	8
Total Mass (LDR)	655
Total Mass (HPR)	597
Solar Collector	
Reflector Material	2808
Receiver Duct	15
Piping	105
Support Structure	7977
Total Mass	10,905

THERMAL MANAGEMENT

In any power generating system there will be a requirement for the disposal of a certain amount of waste heat. In the design of a lunar power system, additional complications arise from the lunar environment. The only viable method of heat rejection in the lunar environment is radiation, since the lack of an atmosphere precludes the use of convection and evaporation as methods of rejecting the waste energy. Also, the thermal conductivity of the Moon is very poor, which eliminates the use of conduction of waste heat to the lunar regolith. The waste heat rejection system must take into account any additional background radiation given off by the lunar surface. In addition, the radiator must have a high radiated power-to-mass ratio to minimize its mass, since all the material for the first generation lunar base must be transported from Earth.

The amount of waste heat to be rejected by the radiator varies dramatically between the two power generation systems. The photovoltaic power system is able to reject its own waste heat via the aluminum backing plate on each array, as noted earlier, and does not require a separate heat rejection system. On the other hand, the radiator for the dynamic cycle will be required to radiate away a significant percentage of the incoming solar energy due to the thermal efficiency of the cycle. In order to reject this heat, two possible radiator concepts are considered in this study: the Heat Pipe Radiator (HPR) and the Liquid Droplet Radiator (LDR).

HPRs have been under development since the late 1960s[9]. The device designed for the present purpose uses a horizontal "mother" heat pipe (MHP) to conduct heat to a series of vertical heat pipes (VHP) which are connected to it and aligned with the vertical, as shown in Fig. 5. The VHP units conduct thermal energy to the attached fins, which radiate the waste heat to space. Suitable shading and reflecting surfaces are employed to minimize background input to the radiator. The HPR makes use of low density materials (pyrolitic graphite and graphite epoxy) for weight minimization.

The heat pipe radiator system has many distinct advantages over other heat rejection systems. Heat pipes do not require the use of pumps or moving parts, since they operate via vapor flow and capillary action. The individual VHP sections are independent of one another as well as of the MHP and are, therefore, resistant to single point failure. Another important aspect of the HPR's unique design is its utilization of available technology, reducing the amount of research and development necessary before implementation of the system.

The LDR utilizes a sheet of freely falling liquid droplets to radiate the waste heat[10, 11]. A schematic of the LDR system is shown in Fig. 6. The working fluid receives the waste heat from the power cycle at the heat exchanger. The fluid is pumped up through pipes to an emitter, which sprays the fluid as a vertical sheet of small spherical droplets. The droplets are then captured by a collector at the base of the LDR, and the fluid is recycled through the system. The most attractive aspect of the LDR system is the high surface area to volume ratio of the small spherical coolant droplets, which results in radiating power to mass ratio of 250 W_e/kg for this design.

There are also a number of potential disadvantages with the LDR system. First of all, lunar dust may present a problem by plugging the emitter, which is designed with very small holes in order to form the desired size of droplets in the sheet. Due to the centralized nature of the fluid transfer system, the LDR is not resistant to single point failure in the fluid handling system and the entire radiator would have to be shut down in the event of a system failure. For this design the pumps for the LDR would consume about 10% of the usable power from the Brayton cycle engines, which decreases the total power to mass ratio of the lunar power system. A majority of the present research into the LDR is for space-based applications; however, additional research is necessary before this system becomes a viable alternative heat rejection system.

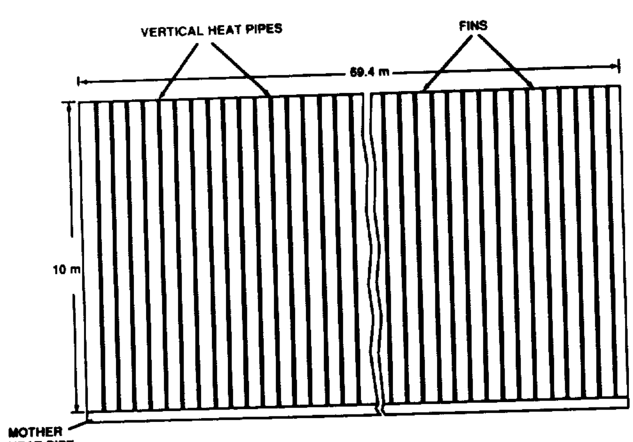

Fig. 5. Lunar HPR Configuration

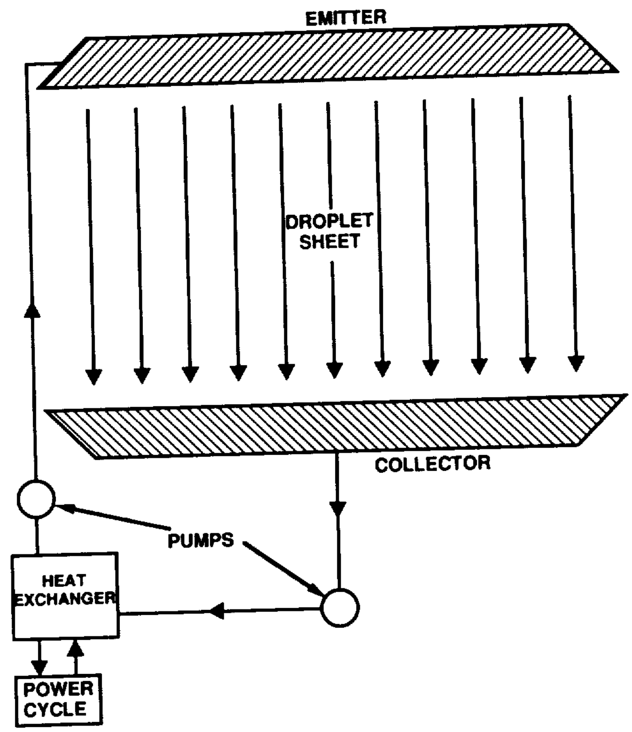

Fig. 6. Liquid Droplet Radiator Schematic

ENERGY STORAGE

Using solar energy to power a manned lunar outpost has one major disadvantage: keeping the outpost fully operational at a 1 MW_e level during the long night would require the storage of more than one trillion joules of energy. Since energy storage tends to be extremely heavy, nighttime operation is limited to 50 kW_e for life-support, astronomy, and reduced research activities.

Recent advances have made the regenerative fuel cell the prime candidate for high power, longterm storage systems[12]. Though fuel cells come in a variety of configurations and operate at various temperatures, each has a basic purpose: the generation of electrical power through the processing of chemical reactants. During the night hours the chemical reactants, H_2 and O_2, enter the fuel cell, where they react to produce electric power and water as a byproduct. During the day, the water produced in the fuel cell is separated back into H_2 and O_2 by electrolysis, which is basically a fuel cell run in reverse. This requires an external energy source (PV array or solar-dynamic cycle) to supply the voltage needed for dissociation of the H_2O.

A schematic drawing of the 50 kW_e system is shown in Fig. 7. It is comprised of two 25 kW_e units, each with separate reactant storage tanks. If one unit were to malfunction, the

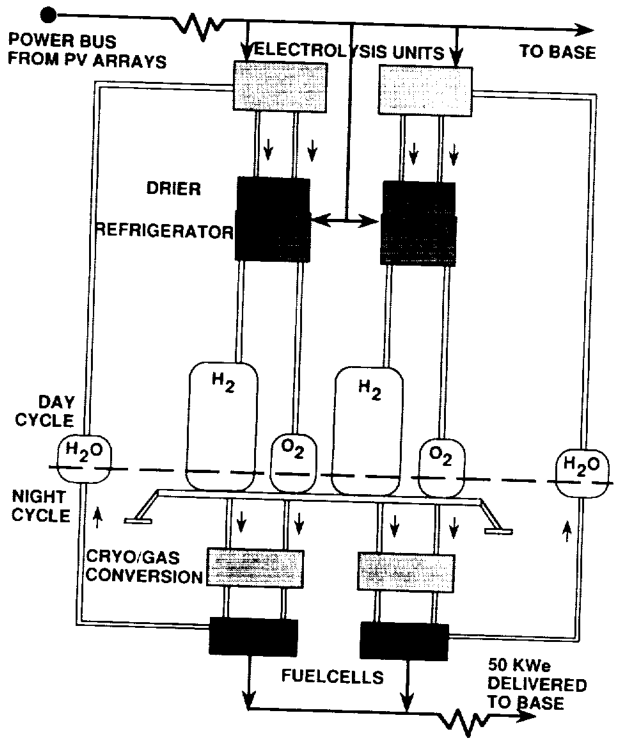

Fig. 7. 50 KWe Energy Storage Schematic

other is capable of providing life-support for the assumed base crew of 8 astronauts (1.5 kW_e/astronaut) plus 13 kW_e which can be used to repair the other unit or for reduced astronomy and research activities.

Two different fuel cells have been considered: the experimental high temperature, monolithic solid-oxide fuel cell (MSOFC)[13], and today's state-of-the-art low temperature alkaline fuel cell that is used on the space shuttle[14]. Table 3 summarizes the system properties associated with each type of fuel cell design. The system masses include the PV array necessary for the recharging of the cell along with the related structures, reactants, and the associated fuel cells. The table shows that the MSOFC does not have an advantage over the alkaline cell. The primary advantage of the low temperature fuel cell is the fact that its reliable operation has been proven and that it is currently in use. Development of MSOFC still faces problems with fabrication and processing of this sophisticated unit. The low temperature fuel cell, due to its availability and reliability, along with an adequate efficiency, was selected for the storage of energy on the Moon.

Table 3. Mass Summary for a 50 kW_e System

	Alkaline Cell	MSOFC
Chem. to Electrical efficiency	70%	60%
Round Trip efficiency	55%	40%
PV Array	1460 kg	2008 kg
Reactant Mass	7125 kg	8315 kg
Fuel cell and electrolysis	748 kg	6 kg
Total Mass	9333 kg	10,329 kg

In conventional energy storage systems, reactants are stored as gases in heavy, pressurized tanks. Satellites in low Earth orbit require storage periods of approximately 40 minutes. In these systems, using Inconel tanks, the tankage mass accounts for only 5.5% of the total system mass. Lunar missions, however, require storage for approximately 360 hours. Here, Inconel tanks account for 83% of the total system mass. Substituting lightweight filament-wound Kevlar 49/epoxy tanks reduces the fraction to 65%. However, by storing the reactants as cryogenic liquids, the tankage mass can be reduced significantly. In a report by L. Kohout of NASA's Lewis Research Center (LeRC), a conceptual design showed that tanks used in storing cryogenic reactants have a mass only 7.4% that of the Kevlar tanks used in the gaseous storage system[12].

Storing the reactants as cryogenic liquids does require the additional mass of drying and liquefaction plants, as well as additional energy to power them, which means an increase in PV array mass or Brayton unit mass. As the hydrogen and oxygen streams leave the electrolysis unit, they contain a small amount of water vapor that was not completely electrolyzed. This water vapor must be removed before the gases are liquified so that the water does not freeze and block the flow of reactants. Each dryer (one per 25 kW_e unit) has a daytime energy requirement of 0.3 kW_e and a mass of 28 kg. The liquefaction plants convert the reactants to a cryogenic liquid through a series of compressions and expansions. A reversed Brayton refrigeration cycle was chosen over Stirling, Vuilleumier, and other cycles because it has a lower mass and volume at higher refrigeration capacities. Each H_2 liquefaction unit (one per 25 kW_e unit) has a daytime energy requirement of 3.88 kW_e and a mass of 428 kg. Each O_2 unit has a daytime energy requirement of 1.84 kW_e and a mass of 136 kg[15]. However, even with these additional masses the total system mass is reduced by 50% due to the reduced tank mass.

Kohout proposes the construction of special, lightweight tanks for storing the cryogenic fluids, but an overview of the lunar development scenario reveals that there may be no need to design and build tanks especially for energy storage, as a variety of such tanks will be already available. In a conceptual report from Martin Marietta[16], the lunar transit and excursion vehicles (LTV and LEV) will undergo a series of unmanned flight tests from Space Station *Freedom*. On the fourth and final test flight, an LEV will be loaded with cargo and will then land and remain on the Moon while the LTV returns to Space Station *Freedom*. This LEV can provide the reactant tankage for the 50 kW_e energy storage system.

An LEV lands with two LH_2 and two LOX tanks. Each LH_2 tank is capable of storing 1.44 tons of hydrogen and each LOX tank is capable of storing 8.68 tons of oxygen. For the 50 kW_e nighttime power requirement, these tanks will be less than half full (396 kg H_2 and 3166 kg O_2). They remain attached to the LEV, which provides the necessary structural support.

In addition to the LEV tanks, tanks are needed to store the water formed in the fuel cell until it can be electrolyzed in the daytime. The same tanks that were used to transport the reactants (in the form of water) from Earth can be used. These tanks have a volume 110% of that required by the water to accommodate freezing during transportation. Once the energy storage system is engaged, there will be a constant influx of warm water from the fuel cell during the lunar night, and the water is not expected to freeze. The tanks are made from filament-wound Kevlar/epoxy, and the mass is found to be 148 kg by scaling from Kohout's system using the square-cube rule[12].

The present design is compared to systems storing the reactants as high pressure gases and Kohout's baseline system utilizing cryogenic storage. Where storing the reactants as cryogenic liquids cuts the total energy storage system in half, the design presented here has an additional 5% reduction in system mass. Using Boeing's tandem photovoltaic cell as the power source for the electrolyzer unit, the PV array mass is reduced. Replacing the pumped loop radiators in the liquefaction plant and storing the cryogenic liquids in the propellant tanks of a spent LEV further reduces the mass.

POWER TRANSMISSION

The storage and transmission of energy require different types of power. For transmission at reasonable voltage over long distances (greater than 200 m), the current must be alternating, at or below a few thousand Hz. For energy storage, the current must be direct. The photovoltaic panels in this study produce direct current at 200 V, which is ideal for the proposed electrolysis units, but not for long-distance transmission. The solar dynamic engines considered in the study produce alternating current at 50 Hz and can be fitted with generators yielding 200 V. This power must be converted to DC for storage, and to higher voltage for long-range transmission. Converting between DC and AC is accomplished with an inverter.

For this study, short (~100 m) transmission distances are used, as a simple power distribution system that operates at the voltage generated by the solar cells requires less mass than a more complicated arrangement that uses high voltage in the lines (see Fig. 8). Also, the only power conditioning required is an inverter between the solar array and the user, plus a smaller inverter downstream of the fuel cells for nighttime power. A 280-kg inverter will be needed between the solar array and the user, and a 14-kg inverter will be required to convert the 50 kW_e nighttime output of the fuel cells into AC for the base[17].

Aluminum cables were chosen for their superior conductivity per unit mass over copper cables (14,240 m^2/Ω-kg, compared to 6683 m^2/Ω-kg)[18], and it is suggested that the cables be buried in the lunar regolith to avoid any resistivity variations due to temperature changes during the day/night cycle.

For the 1.175 MW_e transmitted (direct power for the base plus charging power for energy storage), the power conditioning mass is roughly 300 kg, and the total mass of the transmission system is 950 kg. This is roughly 5% of the power generation system mass. Note, however, that a distance of only 1000 m between the solar arrays and the base would require a much more complicated system to transmit the power efficiently (see Fig. 9).

STRUCTURAL DESIGNS

The structural designs for the lunar base power system were developed with three primary characteristics in mind. These are that the structural supports for all systems should be easily assembled, they should require no maintenance, and they should be fabricated from materials with the highest specific strength and durability available. All designs take into account the size and mass capacity of the Shuttle-C cargo bay (25 m × 4.6 m diameter, 71-metric-ton payload capacity) on the

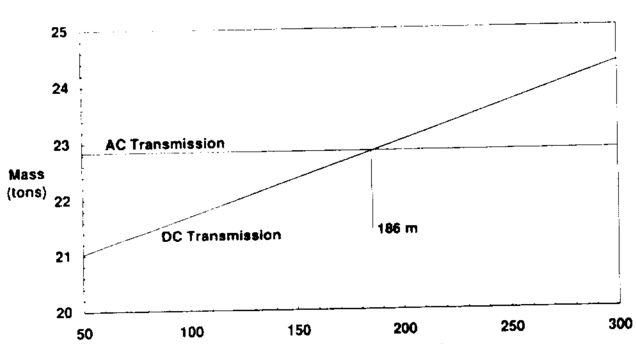

Fig. 8. Effect of Transmission Distance on Total System Mass for AC or DC Transmission

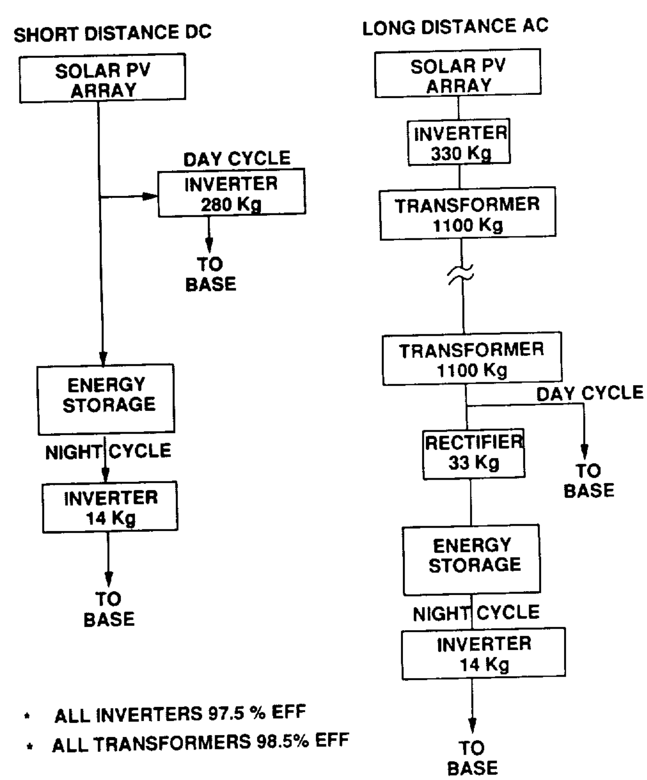

Fig. 9. Solar Photovoltaic Power Transmission

assumption that this is the vehicle that will be available for the delivery of large payloads to low Earth orbit (LEO). Another important criterion in developing the large truss structures was that as few different types of truss members as possible be used, so that a scheme of keeping track of each type (such as color-coding) can be made as simple as possible. Robotic assembly of large truss structures has not been researched in depth for this report, so it was assumed that much of the construction will be performed by astronauts. The four major design sections corresponding to the primary components of the lunar power station are: (1) solar photovoltaic array structural design, (2) solar dynamic parabolic trough collector structural design, (3) thermal management structural designs (including both the HPR and LDR), and (4) lunar concrete structural designs.

The support structure for the solar photovoltaic arrays consists of four different types of members, all fabricated of advanced composite materials. Approximately 3750 m^2 of Boeing high-efficiency cells are required for the lunar power system, indicating that 50 individual rotating arrays (2 panels × 12.5 m × 3 m) will be needed to achieve this surface area. The design concept is termed "backbone and rib" structure and is similar to a human backbone. The "backbone" is a solid, square graphite epoxy composite tube supported on both ends and in the center by rotating bearings (see Fig. 10). A row of graphite epoxy "ribs" filled with a honeycomb core are fitted through the "backbone" at constant intervals, and locked into place. A thin wire mesh is attached to the top of these ribs, and the cell housings themselves are supported by this mesh and the "ribs." This is then supported on each end by a tetrahedral truss structure and in the center by a triangular truss structure. A mass inventory for this design is given in Table 4.

The structural designs for the solar dynamic cycle centered on the design of the parabolic trough collector (see Fig. 11). Approximately 110 m of solar collector is required per engine. This length is divided into 5-m segments, and the basic structural unit is based on this length. Five meters was chosen to minimize unstable bending in the reflecting panels (four around the perimeter of the parabola) while being lifted into

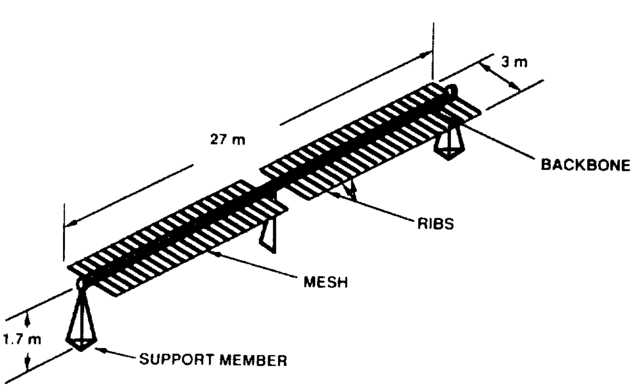

Fig. 10. Solar Array Structure

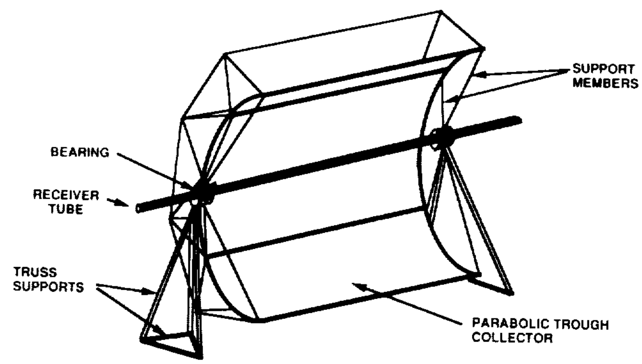

Fig. 11. Isometric View of Solar Trough Collector

position within the support framework. This framework is a system of trusses connected to two stiff graphite epoxy ribs and three support members. The framework holds the shape of the parabola and is strong enough to support the four reflecting panels. In addition, the framework was designed to place the center of mass of the 5-m segment at the point 1 m directly above the apex of the parabola, i.e., the focus. Thus, the concentrator has a mass distribution such that it can be easily rotated about the fluid duct. The reflecting surface will simply be a thin coating over the graphite epoxy honeycomb sandwich panels in order to minimize the mass of the system.

Table 4. Structural Mass Inventory for Solar Array

Member Type	Total Mass Per Array (kg)
Box Beam	70
Ribs	50
Supports	38
Bearings and Nodes	45
Total Mass	203

The four reflecting panels within each 5-m segment have a small space between them and there is a gap between each segment for support structure (a region in which the fluid temperature may drop slightly), both diminishing the system efficiency. To make up for this, two additional 5-m segments are added to the solar collector for each engine, resulting in a total length of 120 m per engine. Thus, twelve 5-m segments will lie on either side of each engine and be supported by tetrahedral trusses at the two ends and triangular trusses in between.

The heat pipe radiator, shown in Fig. 12, consists of four major components: (1) a v-shaped roof, (2) horizontal members that provide lateral stability, (3) vertical members that support the roof, and (4) base support brackets to hold the mother heat pipe and support members. All components are fabricated from advanced composite materials, and designed so that assembly is fast and efficient. The base support brackets are located every 17.5 m along the span of the radiator. The mother heat pipe is laid between these with the vertical heat pipes projecting out of it. The horizontal support members extend out of the bracket along the lunar surface and a guy wire is attached to each, running from the ends to

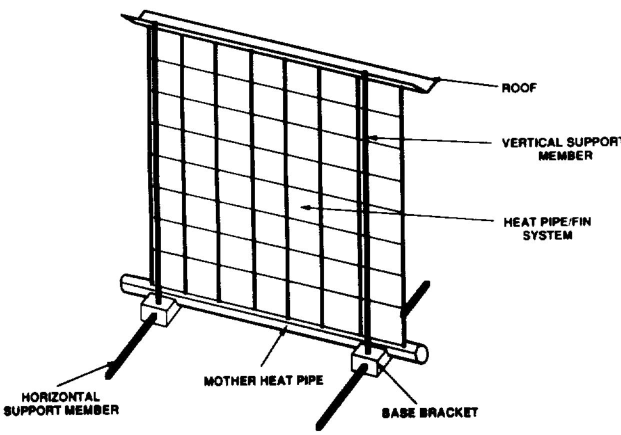

Fig. 12. Isometric View of Heat Pipe Radiator

the roof. Vertical support members project up out of the bracket and support the roof. The guy wires provide support, so that if any kind of lateral load should be applied, the force will be distributed to the horizontal support members on the opposite side and not to the heat pipes.

The liquid droplet radiator, if implemented, would be the largest structural design for the lunar power station (see Fig. 13). It stands 52 m tall and 15 m wide. Many of the major design features were adopted from a previous University of Washington study on nuclear power for a lunar base[11]. The structure consists of four major elements: (1) erectable masts, (2) a cable-pulley inter-tie system, (3) a longitudinal emitter support truss, and (4) a droplet collector.

On top of each mast a lifting extension truss is fixed. Due to the difficulties involved in the construction of large towers on the Moon, these masts will be built from the top down. This means that the extension truss must be assembled as the first unit to be raised, with each box truss erected beneath

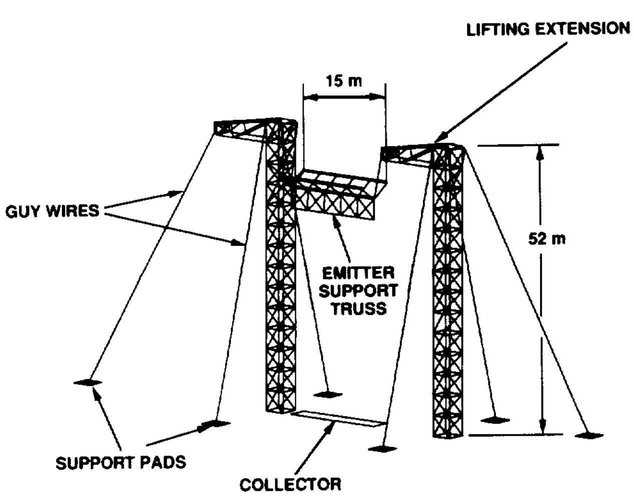

Fig. 13. Liquid Droplet Radiator Structure

it. Attached to each side of the lifting extension are an emitter support bracket and a cable-pulley inter-tie system used to hoist the emitter support truss. The emitter support truss consists of 2-m horizontal and vertical support members with diagonal members placed in between. The emitter will be mounted mechanically to the bottom of the truss before raising it, and the flexible feed line will be attached and allowed to hang freely as it is raised. The liquid droplet collector is placed directly below the emitter and the LDR fluid is pumped out of one end, through the heat exchanger loop and back up to the emitter.

The remainder of each mast consists of twelve 4-m × 4-m box trusses with guy wires to provide lateral stability. Each box truss is erected one at a time within a framework surrounded by four hydraulic jacks. When each box is assembled, it is raised 4 m by the jacks, allowing the next one to be assembled beneath it. In this way, the entire mast can be constructed on the ground quickly and with little effort.

The possibility of using lunar concrete produced by a method proposed by Shimizu Corporation of Japan was also examined[19]. Shimizu studies indicate that a vacuum environment maintained during the hardening of concrete significantly reduces its strength. Because of this and the large mass involved, it was decided that lunar concrete would not be used extensively in the lunar power system design. However, in some applications, such as pads placed beneath truss supports for stability and solid blocks to be used to anchor guy wires, this concept may be worthwhile.

EMERGENCY POWER BACKUP SYSTEM

The lunar power system presented in this report is a modular system with many levels of redundancy. Even so, there is still the chance of some kind of system failure; thus, the decision was made to provide an emergency backup power source. Several candidate power storage methods were examined, including fuel cells and several types of both primary and secondary batteries. After considering the pros and cons of each, nickel-hydrogen secondary batteries were chosen on the basis of their proven record of use in space and their moderately high power density. In order to decrease development costs, and to make use of existing technology, it was decided that a derivative of the power storage system to be used on the Space Station *Freedom* (SSF) be employed as the backup system for lunar operations[20].

The basic unit system for backup power is comprised of two 81 Ah, 95 V nickel hydrogen batteries wired in parallel, and the supporting electronics and thermal control equipment (see Fig. 14). After inefficiencies are considered, this is enough energy to supply two persons with 1.5 kW each for approximately 3.5 hours. The components used in the backup power system are designed in modular sections called Orbital Replacement Units for ease of repair. These components are mounted on two standard utility plates that provide structural backing, and coolant fluid pipes. The utility plates will simply be placed where necessary, as opposed to being rigidly connected as on SSF, in order to reduce unnecessary system mass. A modified fluid junction box connects the utility plates

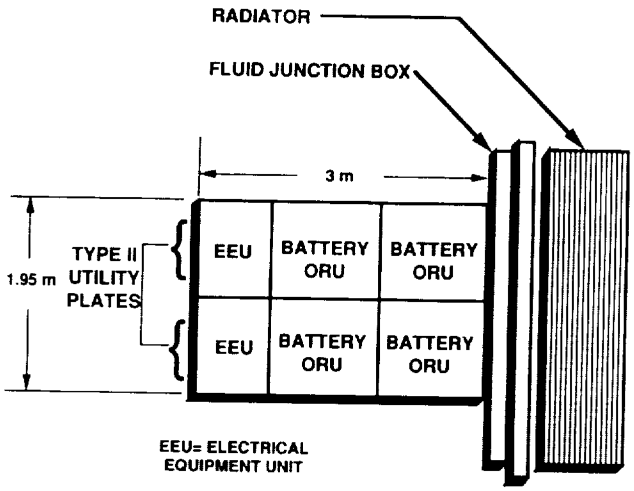

Fig. 14. Space Station *Freedom* Energy Storage System

with the pumped loop ammonia radiator, completing the thermal control loop, as well as the basic unit. These two-person-rated systems may be combined in sufficient quantities, once given the number of occupants at the lunar base.

This battery system turns out to be relatively massive (see Table 5) due to the relatively low energy density of batteries as opposed to fuel cell storage. As stated earlier, the nickel-hydrogen system was chosen because it will be extremely reliable. However, fuel cell systems, when configured in a highly redundant manner, may provide the same power as batteries at a great mass savings, but with increased complexity. When the lunar base is constructed, mission planners will have to decide whether the high mass of the batteries is justified or if some type of fuel cell system should be supplied for emergency backup.

Table 5. Lunar Emergency Backup Power System Components

Component	Mass (kg)	Parasitic Power (kW)	Energy (kWh)	Quantity
Battery ORU	146	-	3	4
EEU	76	0.140	-	2
Utility Plate	136	-	-	2
TCS Pump ORU	36	0.125	-	1
Fluid Junction Box	21	-	-	1
Radiator	125	-	-	1

CONCLUSION

The work presented here shows that a solar power system can provide power on the order of one megawatt to a lunar base with a fairly high specific power. The main drawback to using solar power is still the high mass, and, therefore, cost of supplying energy storage through the lunar night. The use of cryogenic reactant storage in a fuel cell system, however, greatly reduces the total system mass over conventional energy storage schemes.

As shown in Table 6, the advanced new tandem GaAs/GaSb photovoltaic cells provide a specific power nearly four times that of the dynamic cycle conversion scheme. This comparison takes into account all necessary structural, thermal control, and solar collector masses, and suggests that the photovoltaic system is the best system to use. Additionally, the solar cells are passive, with the only moving part being the solar-tracking motor, thereby increasing the system reliability. For these reasons, the photovoltaic array is recommended for use over the dynamic power system.

Table 6. Comparison of Solar Power Systems

	Photovoltaic Arrays	Brayton Cycle
Photovoltaic Array Mass	9,150 kg	-
Structural Mass (PV)	10,150 kg	-
HPR Brayton Engines (5)	-	2985 kg
Solar Collector (5)	-	54,525 kg
Radiator (HPR) (5)	-	17,450 kg
Total Power Supplied	1,175 kW	1,250 kW
Total Specific Power	61.7 W/kg	16.7 W/kg

Obviously, the solar cells produce no power during the night, and since energy storage for the lunar night is so massive when compared to daytime power, cutting back on power during the lunar night is highly recommended. In this system, 50 kW was chosen as the minimum nighttime power in order to greatly reduce overall system mass while still allowing enough power for scientific experimentation. Making use of the spent cryogenic tanks from a lunar excursion vehicle reduces the net mass of the storage system, but not enough to make high power at night economically feasible.

If the dynamic conversion system is used, thermal management should be provided by the heat pipe radiator system because of its fairly high specific thermal power dissipation, and because heat pipe radiator technology is well developed. The liquid droplet radiator is a very promising concept, and may one day surpass conventional systems in performance, but more research needs to be performed first.

If, for some reason, the power system is shut down, a modified version of the Space Station *Freedom* energy storage system is employed to provide the base inhabitants with enough emergency power to escape from the base. This system turned out to be quite massive, and so systems with slightly less reliability may be preferable to help reduce overall system mass.

In conclusion, technology has advanced to the point where a solar power system may now be seriously considered for high power applications on the Moon, as this report has shown. Given all of the problems, both political and technological, with nuclear power, it may be time to reexamine the old idea of using the sun to power the lunar base.

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