DarkSide Logistics – Lunar Spaceport Initiative

Vehicles: Power Source Analysis

1. Introduction

The Power schemes that we intend to use in our mission are Solar Power, rechargeable Li-ion or lithium thionyl chloride batteries and AMTEC cells.

Solar Power will be our primary source of ENERGY!

2. Solar Power Source

2.1 Introduction to Solar Arrays

Photovoltaic solar array systems are the most common method for providing spacecraft power generation. In a time period of less than four decades space solar arrays have grown in size from less than 1 watt to systems over 75,000 watts, such as the International Space Station Alpha (ISSA) solar array.

Advanced high efficiency GaAs/Ge solar cells are now being manufactured in large quantities and are being utilized on many spacecraft. Since the bare solar cell cost and efficiency is much higher than silicon cells, it is often difficult to determine the system cost advantages that are hard to quantify in terms of cost benefits.

We are now at a stage where the system advantages of high efficiency solar cells and arrays are being recognized. Many spacecraft missions have now incorporated GaAs/Ge solar cells in their designs because there are specific benefits that are achieved. At the array level, costs may be 50% higher, however, at the system level the costs of GaAs/Ge solar cell arrays can be shown to be 60 to 80% of the cost of a comparable silicon solar cell array design.

2.2 Limiting Factors

The dimensions of a solar cell for use in space applications are size, cost and weight.

2.2.1 Weight

Some of the contributors to the weight of a solar cell or solar panel are
- Weight of the cover glass used
- Cover Adhesive
- Interconnects
- Cell Adhesive
- Bus/Wire/Diodes
- Substrate

2.2.2 Cost

Some of the factors contributing to cost are
- Cover glass
- Fabrication
- Circuit Laydown
- Substrate/Integration
- Miscellaneous Mechanisms

2.3 What is a solar cell?

A solar cell or photovoltaic cell is a device that converts light energy into electrical energy by the photovoltaic effect.

2.4 Photovoltaic Effect!

The "photovoltaic effect" is the basic physical process through which a solar cell converts sunlight into electricity.

Some trivia!

In 1839, nineteen-year-old Edmund Becquerel, a French experimental physicist, discovered the photovoltaic effect while experimenting with an electrolytic cell made up of two metal electrodes. Becquerel found that certain materials would produce small amounts of electric current when exposed to light.

Sunlight is composed of photons, or "packets" of energy. These photons contain various amounts of energy corresponding to the different wavelengths of light. When photons strike a solar cell, they may be reflected or absorbed, or they may pass right through. When a photon is absorbed, the energy of the photon is transferred to an electron in an atom of the cell (which is actually a semiconductor). With its newfound energy, the electron is able to escape from its normal position associated with that atom to become part of the current in an electrical circuit. By leaving this position, the electron causes a hole to form.

Special electrical properties of the solar cell built-in electric field (thanks to a P-N junction) provide the voltage needed to drive the current through an external load (such as a light bulb).

3. More into Solar Cells!

3.1 Solar Cell Types

The different types of solar cell materials are

- Silicon (Si)—including single-crystalline Si, multicrystalline Si, and amorphous Si
- Polycrystalline thin films—including copper indium diselenide (CIS), cadmium telluride (CdTe), and thin-film silicon

- Single-crystalline thin films—including high-efficiency material such as gallium arsenide (GaAs)

3.1.1 Single Crystal Silicon

The most common material used in solar cells is single crystal silicon. Solar cells made from single crystal silicon are currently limited to about 25% efficiency because they are most sensitive to infrared light, and radiation in this region of the electromagnetic spectrum is relatively low in energy.

3.1.2 Polycrystalline Solar Cells

Polycrystalline ("many crystals") solar cells are made by a casting process in which molten silicon is poured into a mould and allowed to cool, then sliced into wafers. This process results in cells that are significantly cheaper to produce than single crystal cells, but whose efficiency is limited to less than 20% due to internal resistance at the boundaries of the silicon crystals.

3.1.3 Amorphous Solar Cells

Amorphous cells are made by depositing silicon onto a glass substrate from a reactive gas such as silane (SiH_4). This type of solar cell can be applied as a thin film to low cost substrates such as glass or plastic. Thin film cells have a number of advantages, including easier deposition and assembly, the ability to be deposited on inexpensive substrates, the ease of mass production, and the high suitability to large applications. Since amorphous silicon cells have no crystal structure at all, their efficiencies are presently only about 10% due to significant internal energy losses.

Aside from the various forms of silicon, a number of other materials can also be used to make solar cells -- gallium arsenide, copper indium diselenide and cadmium telluride to name a few. Note that solar cells are sensitive to different wavelengths of light (i.e., photons of different energies) as a function of the materials they are built from.

3.2 Cell Packaging

Solar cells also are available in a variety of packages. Most common are "raw cells," often with some cover sheet attached. One popular line of cells, the Panasonic Suncerams, consist of amorphous silicon cells, deposited on the back of a glass substrate (in this case, the glass functions as both substrate and cover sheet). These are durable and cost-effective cells, if a bit heavy due to the thickness of the glass. Encapsulated solar cells are also sold -- as the name implies, an enclosure (often plastic, often with some sort of concentrator lenses built into the cover sheet) contains a regular (generally multicellular) solar cell or cells. These are extremely durable, if heavy and none too efficient. Recently, flexible solar cells have become available. These are amorphous cells on a thin plastic substrate -- low efficiency, fairly high cost, but light and a very useful package for some applications.

3.3 Solar Cell Technologies

3.3.1 Introduction

A photovoltaic (PV) or solar cell is the basic building block of a PV (or solar electric) system. An individual PV cell is usually quite small, typically producing about 1 or 2 watts of power. To boost the power output of PV cells, we connect them together to form larger units called modules. Modules, in turn, can be connected to form even larger units called arrays, which can be interconnected to produce more power, and so on. In this way, we can build PV systems able to meet almost any electric power need, whether small or large.

By themselves, modules or arrays do not represent an entire PV system. We also need structures to put them on that point them toward the sun, and components that take the direct-current electricity produced by modules and "condition" that electricity, usually by converting it to alternate-current electricity. We might also want to store some electricity, usually in batteries, for later use. All these items are referred to as the "balance of system" (BOS) components.

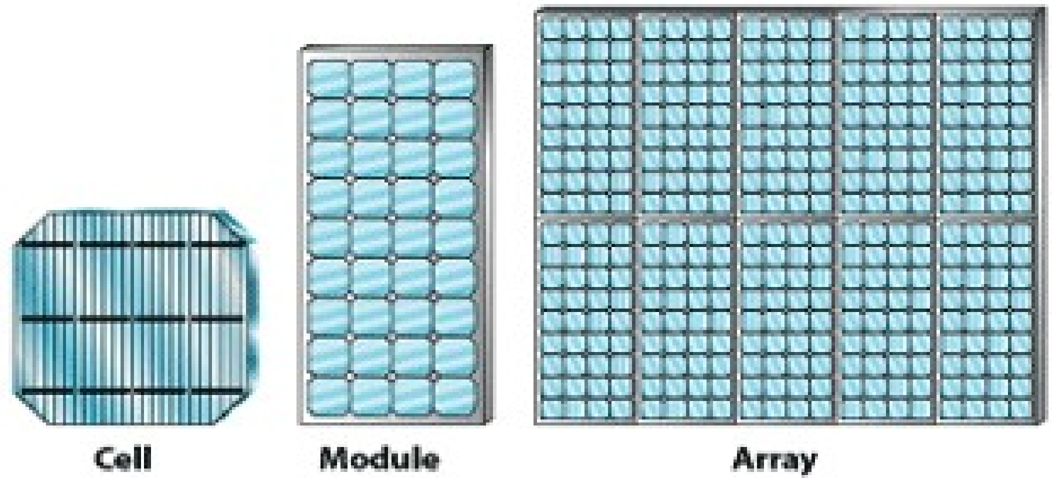

Figure-1-Solar cells, Modules and Arrays depicted

Some of the technologies that being currently researched are

3.3.2 Thin Film Technology

The high cost of crystalline silicon wafers (they make up 40-50% of the cost of a finished module) has led the industry to look at cheaper materials to make solar cells.

The selected materials are all strong light absorbers and only need to be about 1micron thick, so materials costs are significantly reduced. The most common materials are amorphous silicon (a-Si, still silicon, but in a different form), or the polycrystalline materials: cadmium telluride (CdTe) and copper indium (gallium) diselenide (CIS or CIGS).

Each of these three is amenable to large area deposition (on to substrates of about 1 meter dimensions) and hence high volume manufacturing. The thin film semiconductor layers are deposited on to either coated glass or stainless steel sheet.

The semiconductor junctions are formed in different ways, either as a p-i-n device in amorphous silicon, or as a hetero-junction (e.g. with a thin cadmium sulphide layer) for CdTe and CIS. A transparent conducting oxide layer (such as tin oxide) forms the front electrical contact of the cell, and a metal layer forms the rear contact.

Thin film technologies are all complex. They have taken at least twenty years, supported in some cases by major corporations, to get from the stage of promising research (about 8% efficiency at 1cm2 scale) to the first manufacturing plants producing early product.

Amorphous silicon is the most well developed of the thin film technologies. In its simplest form, the cell structure has a single sequence of p-i-n layers. Such cells suffer from significant degradation in their power output (in the range 15-35%) when exposed to the sun.

The mechanism of degradation is called the Staebler-Wronski Effect, after its discoverers. Better stability requires the use of thinner layers in order to increase the electric field strength across the material. However, this reduces light absorption and hence cell efficiency.

As before, thin film cells are laminated to produce a weather resistant and environmentally robust module. Although they are less efficient (production modules range from 5 to 8%), thin films are potentially cheaper than c-Si because of their lower materials costs and larger substrate size.

However, some thin film materials have shown degradation of performance over time and stabilized efficiencies can be 15-35% lower than initial values. Many thin film technologies have demonstrated best cell efficiencies at research scale above 13%, and best prototype module efficiencies above 10%. The technology that is most successful in achieving low manufacturing costs in the long run is likely to be the one that can deliver the highest stable efficiencies (probably at least 10%) with the highest process yields.

Amorphous silicon is the most well-developed thin film technology to-date and has an interesting avenue of further development through the use of "**microcrystalline**" silicon which seeks to combine the stable high efficiencies of crystalline Si technology with the simpler and cheaper large area deposition technology of amorphous silicon.

However, conventional c-Si manufacturing technology has continued its steady improvement year by year and its production costs are still falling too.

The emerging thin film technologies have yet to make significant in-roads into the dominant position held by the relatively mature c-Si technology. However, they do hold a **niche position** in low power (<50W) and consumer electronics applications, and may offer particular design options for building integrated applications.

Figure-2-Thin Film Solar Panels

3.3.3 Concentrators

Photovoltaic concentrator solar arrays for primary spacecraft power are devices, which intensify the sunlight on the photovoltaics. This design uses lenses, called Fresnel lenses, which take a large area of sunlight and direct it towards a specific spot by bending the rays of light and focusing them. Some people use the same principle when they use a magnifying lens to focus the Sun's rays on a pile of kindling or paper to start fires.

Solar concentrators put one of these lenses over every solar cell. This focuses light from the large concentrator area down to the smaller cell area. This allows the quantity of expensive solar cells to be reduced by the amount of concentration. Concentrators work best when there is a single source of light and the concentrator can be pointed right at it. This is ideal in space, where the Sun is a single light source.

Advantages
Solar cells are the most expensive part of solar arrays, and arrays are often a very expensive part of the spacecraft. This technology allows costs to be cut significantly due to the utilization of less material.

Trivia
Spectrolab's Earth-based concentrator cells currently hold the world's record for efficiency, 40.7 percent under concentrated sunlight.

Figure-3-Solar Concentrator Cells

3.3.4 Electrochemical PV-cells

Unlike the crystalline and thin film solar cells that have solid-state light absorbing layers, electrochemical solar cells have their active component in a liquid phase. They use a **dye sensitizer** to absorb the light and create electron-hole pairs in a nanocrystalline titanium dioxide semiconductor layer. This is sandwiched in between a tin oxide coated glass sheet (the front contact of the cell) and a rear carbon contact layer, with a glass or foil backing sheet.

Some consider that these cells will offer lower manufacturing costs in the future because of their simplicity and use of cheap materials. The challenges of scaling up manufacturing and demonstrating reliable field operation of products lie ahead. However, prototypes of small devices powered by dye-sensitised nanocrystalline electrochemical PV cells are now appearing (120cm2 cells with an efficiency of 7%).

3.3.5 Crystalline Silicon Solar Cells

Historically, crystalline silicon (c-Si) has been used as the light-absorbing semiconductor in most solar cells, even though it is a relatively poor absorber of light and requires a considerable thickness (several hundred microns) of material. Nevertheless, it has proved convenient because it yields stable solar cells with good efficiencies (11-16%, half to two-thirds of the theoretical maximum) and uses process technology developed from the huge knowledge base of the microelectronics industry.

Two types of crystalline silicon are used in the industry. The first is monocrystalline, produced by slicing wafers (up to 150mm diameter and 350 microns thick) from a high-purity single crystal boule. The second is multicrystalline silicon, made by sawing a cast block of silicon first into bars and then wafers. The main trend in crystalline silicon cell manufacture is toward multicrystalline technology.

For both mono- and multicrystalline Si, a semiconductor homojunction is formed by diffusing phosphorus (an n-type dopant) into the top surface of the boron doped (p-type) Si wafer. Screen-printed contacts are applied to the front and rear of the cell, with the front contact pattern specially designed to allow maximum light exposure of the Si material with minimum electrical (resistive) losses in the cell.

The most efficient production cells use monocrystalline c-Si with laser grooved, buried grid contacts for maximum light absorption and current collection.

Some companies are productionizing technologies that by-pass some of the inefficiencies of the crystal growth/casting and wafer sawing route. One route is to grow a ribbon of silicon, either as a plain two-dimensional strip or as an octagonal column, by pulling it from a silicon melt.

Another is to melt silicon powder on a cheap conducting substrate. These processes may bring with them other issues of lower growth/pulling rates and poorer uniformity and surface roughness.

Each c-Si cell generates about 0.5V, so 36 cells are usually soldered together in series to produce a module with an output to charge a 12V battery. The cells are hermetically sealed under toughened, high transmission glass to produce highly reliable, weather resistant modules that may be warrantied for up to 25 years.

3.3.6 Multi-junction Solar Cells

Multi-junction solar cells created from III-V semiconductor materials exhibit high efficiencies matched by no other existing photovoltaic technology. Multi-junction solar cells are composed of 3 layers of material that have different bandgaps. The top layer has the largest bandgap while the bottom layer has the smallest bandgap. This design allows less energetic photons to pass through the upper layer(s) and be absorbed by a lower layer, which increases the overall efficiency of the solar cell. One important design consideration is that the photocurrent generated in each layer must be the same since the layers are in series. In addition, the bandgaps of each layer should differ by approximately equal energies so that the spectrum of incident radiation is most effectively absorbed. Although multi-junction solar cells are very efficient, they are also very expensive. Due to their high cost, multi-junction solar cells are primarily used in systems in outer space and as collector cells where a large amount of sunlight is reflected onto the cell. The use of multi-junction solar cells made of III-V semiconductor materials appears to be restricted to limited applications while single crystalline silicon semiconductors have a wider application due to the lesser cost.

High-efficiency cells have been developed for special applications such as satellites and space exploration. These multijunction cells consist of multiple thin films produced using molecular beam epitaxy. A triple-junction cell, for example, may consist of the semiconductors: GaAs, Ge, and $GaInP_2$. Each type of semiconductor will have a characteristic band gap energy which, loosely speaking, causes it to absorb light most efficiently at a certain color, or more precisely, to absorb electromagnetic radiation over a portion of the spectrum. The semiconductors are carefully chosen to absorb nearly the entire solar spectrum, thus generating electricity from as much of the solar energy as possible.

GaAs multi-junction devices are the most efficient solar cells to date, reaching a record high of 40.7% efficiency under solar concentration and laboratory conditions. These devices use 20 to 30 different semiconductors layered in series. At the National Renewable Energy Laboratory, a new cell of area 0.26685 cm² will generate a power of 2.6 W. They estimate that this technology could eventually produce electricity at a mere 8–10 cents/kWh. This is similar to the price of electricity today. Thus, this breakthrough could ultimately result in increased consumer use of solar cells.

This technology is currently too expensive for large-scale commercial manufacture, but similar technology is being used right now on the Mars rover missions. The rovers have outlived their predicted life spans and have worked for over two years. Their success in the dust-ridden Martian environment is a strong testament to the durability and longevity of these types of solar cells.

Triple-junction GaAs solar cells were also being used as the power source of the Dutch four-time World Solar Challenge winners Nuna in 2005 and 2007.

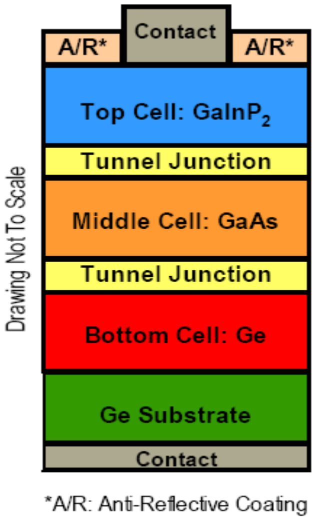

Figure-4-Structure of a Multi-junction Solar Cell

4. Power Specification and Budget Estimation

For the Lander and Rover the power requirements and the specifications are as follows

We got the price quotes for the Solar panels from Spectrolab, the world's leading manufacturer of space solar cells and panels. Spectrolab's product portfolio includes terrestrial concentrator solar cells and modules, searchlight systems, solar simulators and Photo detector products.

4.1 Solar Power Budget

4.1.1 Lander Solar Power Budget

For the Lander we will be using the Concentrator Solar Cell technology. This method reduces the cost per watt as it uses lesser number of solar cells. Solar cells are the most expensive constituents of a solar panel.

Power required = 100 watts

Price per watt = $2000

For 100watts, Price = $200,000

Non-recurring engineering = $150,000

Environmental Tests = $150,000

Lander Solar Power Budget = $500,000

4.1.2 Rover Solar Power Budget

For the rover we will be using thin film technology. This enables us to reduce the weight of the rover. But the cost per watt might be slightly higher than that of the Concentrator solar cell technology since it requires more number of cells to produce the same amount of power. But it is not going to very high as there are no Fresnel Lenses used in this case.

Power required = 50 watts

Price per watt = $2300

For 50 watts, Price = $115,000

Engineering Costs = $100,000

Rover Solar Power Budget = $215,000

4.1.3 Solar Array Technical Information

4.1.3.1 Solar array technical specifications of the rover

Solar Cells

Type - Gallium Arsenide or Germanium

Size - 2 x 4 cm, 5.5 mil thick

Coverglass – 3mil, CMG

Efficiency - >18% Efficiency

Solar Array

Configuration - 13 parallel strings, 18 series cells per string

Power - 45 watts

Operating Voltage - 14 to 18 volts

Substrate – Nomex Honeycomb

Weight - 0.340kg

Size – 0.22 m2

Solar Array Contractor

1. www.spectrolab.com
2. Applied Solar Energy Corporation (ASEC)

4.1.3.2 Solar array technical specifications of the Lander

Solar Concentration Ratio = 2.36/1 (Number of cells reduced by a factor of 0.424 relative to flat plate collector panels)

7.9" x 9.76" Modules, which can be combined into any size panel

Each module provides 16.8 VOLTS D.C. at greater than 25% efficiency

Power/Weight Figure of Merit greater than 150 watts/Kg.

Can use either EMCORE or SPECTROLAB Triple Junction, 26% efficiency, GaAs solar cells with 99% effective packing factor

("Egg Crate" PYRAMID OPTIC Solar Concentrator provides extremely rigid solar panel structure of very light weight)

Front and rear high emissive thermal radiation to cold space results in solar cell temperatures equivalent to or less than flat plate cell temperatures

WIDE ACCEPTANCE ANGLE minimizes solar tracking requirements (See Angular Response Plot)

Covered by U.S. Patent 6,034,319 (Technical paper available)

Electro-statically clean design minimizes electrostatic voltages on cells

Company

1. Spectrolab.com
2. Optical Energy Technologies, Inc.

4.1.4 Secondary power Sources

The secondary power sources that we have used are rechargeable Lithium-Thionyl Chloride (Li-SOCl2) or Lithium – ion batteries.

4.1.4.1 Battery Technical Information - Rover

Cells

Chemistry - Lithium-Thionyl Chloride (Li-SOCl2) or Lithium - ion

Size - D-Size

Weight - 118 grams

Capacity – 8 to 12 amp-hrs

Batteries

Number - 3

Cells Per Battery - 3 cells in series

Size - 40 mm dia, 186 mm length

Weight - 1.24 kg

Operating Voltage - 8 - 11 volts

Cell Contractor - SAFT America Cockeysville, MD

Number of hours that the Rover could work on the rechargeable batteries = 11.5 hours approximately.

Number of hours that the rover could work on the rechargeable batteries = Number of ampere hours * Voltage/Power

= 8*3*3*8/50 = 11.5 hours

4.1.4.2 Power Electronics Technical Information

Distribution Architecture - Single string w/graceful degradation

User Voltages

Main bus - 8 to 18 volts

Secondary - +/-12v, 9v, +/-7.5v, 5v, +/-5v, 3.3v

Power Electronics Suppliers - Pico Electronics, Power Trends, Nation Semiconductor, Motorola, Emtech

Trivia!

Lithium Ion batteries are also a viable option for the Rover

Source: www.saftbatteries.com

Some Features:

- Smaller and lighter than conventional technology (30 to 50% weight reduction compared to $Ni\text{-}H_2$)
- High specific energy: 125 to 165 Wh/kg
- Low thermal power and high energy efficiency leads to smaller solar panels and battery radiators
- Easier launch pad operations
- No memory effect
- An energy gauge given by the voltage
- Modular flexibility in designing batteries

Data Sheet

http://www.saftbatteries.com/130-Catalogue/PDF/space_li-ion.pdf

Trivia!

4.2 Lunar Night?

The lunar nights extend for 354 hours which is approximately 2 weeks. There is no sunlight and hence solar power is not a viable option to power up the rover and the Lander during this time.

What are the other options!
We intend to use rechargeable batteries both on the rover and the Lander.
As we mentioned earlier the rover has 3 rechargeable batteries.

The rover batteries have an estimated decay time of around 11.5 hours (when the rover is in motion). We intend to survey the surface of the moon for 2 hours every lunar night. The hours could increase depending upon need and hence the battery power required would be around 30 hours. The rover could recharge its batteries at the Lander every time its battery power discharges, i.e. it will recharge 3 times during a lunar night. This would help saving huge cost and weight requirements as the number of rovers deployed by our mission increases.

The rovers would be powered down when they are not surveying or may be just communicating with the Lander which requires very less power.

If the Lander was equipped with 50 batteries with 3 cells each.

Then Number of hours that the Lander could work on the rechargeable batteries and supply power to the rover 3 times a Lunar night is = (Number of ampere hours * Voltage/Power)- 34.5 hours

= (8*3*50*8/100) = 60 hours approximately

Hence with 50 Batteries at the Lander it could operate on the rechargeable batteries 60 hours approximately

Budget Estimate – ($2000/battery)*53 = $106,000

4.3 Two options that we could consider during Lunar Nights in the future when the power requirements of the rover and the Lander increase are

4.3.1 AMTEC Cells

The **Alkali Metal Thermoelectric Converter** (AMTEC) is a thermally regenerative electrochemical device for the direct conversion of heat to electrical energy. It is characterized by high potential efficiencies and no moving parts, which make it a candidate for space power applications.

This device accepts a heat input at 900K-1300K and produces direct current with predicted device efficiencies of 15-40%. In this device sodium is driven around a closed thermodynamic cycle between two heat reservoirs at different temperatures. The unique feature of the AMTEC cycle is the isothermal expansion of sodium vapor through a solid electrolyte which causes sodium atoms to separate into sodium ions and electrons. The AMTEC thus converts the work of isothermal expansion of sodium vapor directly into electric power.

The converter is based on the electrolyte used in the sodium-sulfur battery, sodium beta-alumina. The device is a sodium concentration cell which uses a ceramic, polycrystalline beta-alumina solid electrolyte (BASE), as a separator between a high pressure region containing sodium vapor at 900 - 1300K and a low pressure region containing a condenser for liquid sodium at 400 - 700K. For the single cell, the open voltage of 1.37 V and the maximum power of 7.89 W and maximum power density of 0.40 W/cm2 at temperature of 1077 K have been obtained.

Efficiency of AMTEC cells has reached 16% in the laboratory. High voltage multi-tube modules are predicted (using state-of-the-art computer simulations) to be 20% to 25% efficient, and power densities up to 0.2 kWe/liter appear to be achievable in the near future. Calculations show that replacing sodium with a potassium working fluid increases the peak efficiency from 28% to 31% at 1100 K with I mm thick BASE tube. Further development will raise the power densities substantially, and raise the efficiency into the 35% to 40% range.

AMTEC requires energy input at modest temperatures, and not at a specific wavelength, it is easily adapted to any heat source, including radioisotope, concentrated solar, external combustion, or nuclear reactor. A solar thermal power conversion system based on an AMTEC has advantages over other technologies (including photovoltaic systems) in terms of the total power that can be achieved with such a system and the simplicity of the system (which includes the collector, energy storage (thermal storage with phase change material) and power conversion in a compact unit). The overall system could achieve as high as 14 We/kg with present collector technology and future AMTEC conversion efficiencies. The energy storage system outperforms batteries, and the temperature at which the system operates allows long life and reduced radiator size (heat reject temperature of 600 K). Deep-space applications would use Radioisotope thermoelectric generators, Hybrid systems are in design.

While space power systems are of intrinsic interest, terrestrial applications will offer large scale applications for AMTEC systems. Projected efficiency is 25%. Cathodic protection of pipelines, remote telemetry from oil well sites are other areas where this type of electrical generation might be used. The potential to scavenge waste heat may allow for integration of this technology into general residential and commercial cogeneration schemes although costs per kilowatt-hour would have to drop substantially from current projections.

4.3.2 RTG

A **radioisotope thermoelectric generator** (**RTG**) is a simple electrical generator which obtains its power from radioactive decay. In such a device, the heat released by the decay of a suitable radioactive material is converted into electricity by the Seebeck effect using an array of thermocouples. RTGs can be considered as a type of battery and have been used as power sources in satellites, space probes and unmanned remote facilities. RTGs are usually the most desirable power source for unmanned situations needing a few hundred watts or less of power for durations too long for fuel cells, batteries and generators to provide economically, and in places where solar cells are not viable.

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