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DESIGN OF A NUCLEAR-POWERED ROVER FOR LUNAR OR MARTIAN EXPLORATION

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To perform more advanced studies on the surface of the moon or Mars, a rover must provide long-term power (^{3}10 kW_e). However, a majority of rovers in the past have been designed for much lower power levels (i.e., on the order of watts) or for shorter operating periods using stored power. Thus, more advanced systems are required to generate additional power. One possible design for a more highly powered rover involves using a nuclear reactor to supply energy to the rover and material from the surface of the moon or Mars to shield the electronics from high neutron fluxes and gamma doses. Typically, one of the main disadvantages of using a nuclear-powered rover is that the required shielding would be heavy and expensive to include as part of the payload on a mission. Obtaining most of the required shielding material from the surface of the moon or Mars would reduce the cost of the mission and still provide the necessary power. This paper describes the basic design of a rover that uses the Heatpipe Power System (HPS) as an energy source, including the shielding and reactor control issues associated with the design. It also discusses briefly the amount of power that can produced by other power methods (solar/photovoltaic cells, radioisotope power supplies, dynamic radioisotope power systems, and the production of methane or acetylene fuel from the surface of Mars) as a comparison to the HPS.

1. INTRODUCTION

As the number of explorations that take place in space increases, the purpose and extent of these missions will also increase. In particular, missions to explore the surface of Mars or the moon also will expand and increase in complexity. To perform such missions, a larger, more efficient power source will be required. Currently, there are several options available for supplying power to a rover system, including radioisotope power supplies (RPSs), Dynamic Radioisotope Power Systems (DIPSs), photovoltaic/solar cells, wind power, laser techniques, conversion of carbon dioxide (or CO_2) in the atmosphere to methane and/or acetylene fuel, and nuclear power. Nuclear power has the advantage in that a small amount of fuel can provide large amounts of energy if it is properly designed to ensure that the system remains safe. Unfortunately, one of the disadvantages of a nuclear-powered system is that it can produce large amounts of radiation and must be shielded appropriately. Transporting shielding from Earth on a space mission can become expensive; thus, it is more economical to obtain the material from the surface itself. There are several options for using surface material; the ones studied here include using lunar regolith (on the moon) and either Mars soil or carbon dioxide converted to dry ice on Mars. This paper presents some background information regarding the various power methods for rovers and then describes proposed shielding options and operational safety issues associated with a nuclear-powered rover.

2. BACKGROUND/VARIOUS POWER SOURCES FOR ROVERS

Although a wide variety of power sources can be used for a rover system, most of the sources provide fairly low amounts of thermal power. Radioisotope power sources are radioisotope power systems that comprise a nuclear heat source and appropriate power conversion equipment.[1] The most common radioisotope used for this is ^{238}Pu. Approximately 0.56 W of power is produced from every gram of ^{238}Pu [see Eq. (1)], but every gram of a ^{238}Pu heat source is also fairly expensive to fabricate. Thus, the costs involved in the fuel requirements for a large-scale mission would not make the RPS option economical. An RPS also would require a power storage unit to satisfy peak power demands (an RPS simply provides a constant heat source that cannot be increased or decreased to suit power needs). Such storage requirements would require a fuel cell mass of up to 2000 kg for a 10-kW$_e$ system,[2] thus reducing the overall power density of this source. The efficiency of an RPS, using a silicon-germanium unicouple as a thermoelectric converter, is ~6%.

$$\text{Power } (W_t) = m * sa * E * 1.6*10^{-13} \text{ J/MeV} \quad (1)$$
$$= 0.56 \text{ W/g} * m$$

where

m = mass (g)

sa = specific activity (Bq/g = disintegrations/s-g) = 6.36e+11 for ^{238}Pu, and

E = energy per disintegration (MeV) = 5.45 for ^{238}Pu.

Another power source related to this is a DIPS. This technique combines an RPS with a highly efficient dynamic thermal-to-electric conversion device to achieve higher electric-power conversion efficiencies than other types of conversion systems (i.e., it has an 18% efficiency compared to other systems with 5 to 10%) and can be used to increase the power from an RPS by up to three times. The conversion device uses an organic working fluid in a Rankine cycle. Although this can help reduce the mass of the RPS required for a given power level, it has the limitation that it is best suited for power demands between 1 and 5 kW$_e$.[1]

Another possible source of power involves producing methane and/or acetylene fuel from atmospheric carbon dioxide on Mars.[3] By supplying (i.e., transporting) liquid hydrogen from Earth to a processing module on the surface of Mars, carbon dioxide from the atmosphere (where it is 95% abundant) can be converted into methane (or CH_4) with the aide of a nickel/graphite catalyst. The methane then could be converted to acetylene fuel (or C_2H_2). The equations below describe the conversion reactions.

$4H_2 + CO_2 \;\; 2H_2O + CH_4$ (2)

$6CH_4 + O_2 \;\; 2C_2H_2 + 2CO + 10H_2$ (3)

One of the disadvantages of this option is that energy is still needed to convert the carbon dioxide into fuel; this would require a separate power source to be transported from Earth. Even more energy is needed to convert methane to acetylene fuel; however, using acetylene fuel would decrease the payload mass of liquid hydrogen (or H_2) by a factor of four because it produces liquid hydrogen that can be reused in the production of methane. In addition, methane produces water (or H_2O), which also can be converted back to liquid hydrogen for further use; however, this requires additional processing (e.g., electrolysis). To produce 100 kW of power, methane with a energy density of 49.3 MJ/kg needs a flow rate of 2.04 g/s produced from 1.02 g/s of liquid hydrogen. Acetylene, with a energy density of 30.81 MJ/kg, needs a flow rate of 3.25 g/s produced from 3.0 g/s of liquid hydrogen. The efficiency of using either methane or acetylene fuel is ~40%.[4] Although using chemical fuels such as methane or acetylene makes sense for power generation over short periods of time (i.e., on the order of a day), over a longer duration (i.e., a year), so much material is required that it becomes less economical. For example, the power density decreases from 228 and 143 W/kg for 1 day of operation for methane and acetylene fuel, respectively, to 0.625 and 0.391 W/kg, respectively, for 1 yr. of operation [power densities are obtained by dividing the energy density by the length of operation (in seconds)].

The final option discussed here is photovoltaic cells (i.e., solar power). Three options for using solar power[5] include (1) a deployable high-efficiency flat plate array, (2) an array with a thin layer of photovoltaic material placed onto flexible substrate, and (3) a concentration system. The high-efficiency flat-plate array typically uses either crystalline silicon (or Si) or gallium arsenide (or GaAs) solar cells and is the most widely used with an efficiency of 14.5%. An array with a thin layer of photovoltaic material provides a higher specific power but has a lower efficiency and has never been demonstrated in space. The third option, using a concentration system, focuses sunlight on highly efficient solar cells to yield a conversion efficiency >30%. However, this system is not practical in the Mars environment because it focuses on direct, not diffuse sunlight, of which the majority of the light on Mars is composed. Additionally, the Martian environmental conditions make the use of solar power difficult as compared to other power sources. There are ~10 h of sunlight per day during optimum conditions on Mars (this varies with distance from the equator), resulting in the need for a large power storage area for the 14.5 or more hours of darkness. A storage unit required to provide a power of 10 kW_e would weigh between 1000 and 5000 kg, depending on the type of fuel cell used.[2] The typical power production at the top of Mars' atmosphere is 590 W/m^2 (Ref. 5). Even if power conversion technology is optimized, a relatively large solar array still would be required to generate 10 kW_e of power. Building and transporting a rover with such an array would require many supports, large conversion equipment, and additional insulation to keep parts from freezing overnight. By adding the storage unit and other necessary equipment to the total weight of the system, the power density(s) would decrease by one-half to one-fifth, assuming a 1-ton solar array. In addition, dust storms would decrease the power intensity and the effectiveness of any solar array significantly.

In contrast, the nuclear-powered system presented in this paper produces ~100 kW_t of power and weighs only ~250 kg (excluding the shielding and power conversion system). Depending on whether the reactor were actually placed on the rover itself or used to power the rover remotely, shielding costs and weights could become relatively large. Such shielding options will be discussed further in Section 3.1.

3. NUCLEAR-POWERED OPTIONS

Nuclear power is an inexpensive and efficient method of producing energy for supporting human life and scientific research while on Mars. The reactor needed to produce this mission-critical energy would be relatively small and lightweight, but the shielding necessary to protect the crew of a manned rover mission or the electronics on an unmanned one could be large and heavy. An alternative to bringing a heavy radiation shield from Earth, which would be very expensive and inefficient, is to make a shield from the materials available on Mars.

One method of shielding the crew and habitat from radiation is connecting a stationary reactor to a rover using a long power cable, powering the rover for long excursions, and using the atmosphere and diffusion as the shield. This method is risky because it relies on the durability of the connection between the reactor and the rover, which could present difficulties. In addition, the power cable required for such a job would be heavy and take up valuable payload space. Instead, it was assumed for this analysis that the reactor is located on the rover itself. However, this in itself presents certain difficulties, including the large amount of shielding needed to protect the electronics for an unmanned mission (and/or human operators for a manned mission) and operational safety. These issues for an unmanned mission will be discussed in the following sections.

3.1. Shielding

As mentioned previously, one of the main concerns of using a nuclear-powered system is preventing the radiation from damaging the electronics. Although several different types of nuclear systems can be analyzed, a Heatpipe Power System (HPS) was modeled in this analysis.[6] In the HPS, heat pipes are surrounded by uranium-fueled pins (which avoids the political issues associated with using plutonium) and transfer energy to a conversion system on one end. The particular HPS model used in this analysis produced a power of 100 kW_t and an average flux of $1.4*10^{12}$ neutrons/cm^2-s. To prevent damage to the electronics, the primary objective was to keep the gamma dose rate outside the shielding to $<10^5$ rads/yr. (11.4 rads/h) and the neutron flux to $<10^{13}$ neutrons/cm^2-yr ($3.17*10^5$ neutrons/cm^2-s). These shielding studies included the use of lithium hydride (or LiH), an effective neutron absorber, and tungsten (or W), an effective gamma absorber, as well as lunar/Martian soil or carbon dioxide condensed from dry ice.

3.1.1. Lunar Regolith/Martian Soil

To obtain the desired neutron flux and gamma dose rate, the HPS was modeled using the Monte Carlo N-Particle (MCNP^{TM}) transport code[7]; tally cards were used to perform dose calculations. The electronics were assumed to comprise pure silicon; thus, the gamma dose rate in silicon was desired for radiation calculations. This dose rate was obtained by using energy-dependent dose factors in silicon[8] in MCNP.

The rover modeled in MCNP was broken into four sections: the power conversion system and radiator, reactor, shielding, and electronics (see Figure 1). The reactor section of the rover was in the shape of a cylinder, and the shielding and electronics sections branched off this cylinder in a cone configuration. The cone was surrounded by a thin layer of aluminum, and the various sections were separated by a few centimeters of aluminum to prevent intermixing of the sections. The rover itself originally was contained in an aluminum "box" 5 cm thick. However, because this produced a great deal of scattering, the model was simplified to assume that a thin layer of low-density material holds the reactor in place instead. Calculations also showed that the presence of regolith underneath the rover also contributed to an increased dose rate and neutron flux caused by scattering of the particles. Thus, it was determined that a layer of shielding material must surround the bottom 120° of the reactor to reduce the number of particles that reach the regolith and scatter. Approximately 10 to 15 cm of lithium hydride was required to reduce the neutron flux, and 2 cm of tungsten placed in the middle of the lithium hydride reduced the gamma dose rate to the electronics to acceptable levels. The placement of the two materials relative to each other was extremely important. Although tungsten is a high-density material that can reduce the gamma dose rate, it also has a high probability of inelastic scatter for neutrons and is subject to (n,g) reactions. This means that it captures neutrons and produces gamma rays with energies of ~7 to 8 MeV, which hinders rather than aids gamma shielding. When the tungsten was located in front of the lithium hydride, the neutron flux to the tungsten was relatively high, thus producing a large number of gamma rays. By placing the tungsten behind the lithium hydride, fewer gamma rays were produced because a lower neutron flux entered the tungsten. In addition, having the tungsten in front of the lithium hydride helps to reduce the total neutron flux as well. Thus, the "sandwich" configuration shown in Figure 1 was found to be the best in this assessment.

Figure 1 Rover configuration.

The required amount of shielding needed between the reactor and the electronics was determined to be ~85 cm of lithium hydride and 10 cm of tungsten. If material from the surface of the moon or Mars is used as shielding, the amount of lithium hydride and/or tungsten can be decreased and less material must be shipped as part of the payload on a mission. Approximately seven times as much regolith or Martian soil is needed as lithium hydride to decrease neutron fluxes, and approximately 20 times as much regolith or Martian soil is needed in place of tungsten to reduce the gamma dose rate. However, some amount of lithium hydride and/or tungsten still is needed to keep the size of the rover reasonable. Also, by increasing the thickness of material in the shield at the bottom of the reactor or by having the shield encompass 240° of the reactor core instead of 120°, dose rates and/or additional shielding requirements can be reduced. However, more design is necessary before detailed volume and mass requirements for the system can be made.

3.1.2. Carbon Dioxide-Dry-Ice Radiation Shield for a Nuclear Reactor on Mars

The atmosphere on Mars, although short on the oxygen needed to support human life, has an abundant supply of carbon dioxide. When in gas form, carbon dioxide is a poor radiation shield; however, in a solid, denser form, it can serve as an effective shield. In this scenario, the carbon dioxide would be obtained from the atmosphere of the planet and condensed into dry ice using a cooling fin. A shield's effectiveness is directly dependent on how much matter is contained in the shield between the source of the radiation and that which is being shielded. Thus, the effectiveness is dependent on the density and thickness of the shield (which is also why tungsten, which is a dense material, was used to reduce the gamma dose rate in the previous section). By using thermal conductivity equations,[9,10] the thickness of dry ice that can be created as a function of time can be obtained and is plotted in Figure 2.

Figure 2 Thickness of dry ice as a function of time.

This figure was created under the assumption that the coolant will remain at a constant temperature. The coolant must be moving fast enough to remove all heat gained through the condensation of carbon dioxide; if it moves too slowly, it could heat the portions of the dry ice that are in contact with the cooling surface. The speed at which the dry ice can grow is limited by its thermal conductivity. The dry ice grows more slowly as it gets further from the cooling surface because the heat gained by the condensing carbon dioxide must travel a progressively greater distance to the cooling surface.

By combining the dry ice with lithium hydride and tungsten shielding, 50 to 100 cm of dry ice would be required to obtain the desired gamma dose rates and neutron fluxes. Figure 2 shows that 50 cm of carbon dioxide can be formed within 50 days; additional material can be formed relatively quickly thereafter.

In addition, the heat flux, which is gained by condensing the carbon dioxide, must be radiated into the atmosphere to maintain an effective coolant loop, which adds more power requirements to the system. The heat flux is plotted as a function of time in Figure 3. This analysis does not account for the heating rate of neutrons and gamma rays absorbed in the shield but rather is solely representative of the system itself.

Such heat could be removed from the system with a reasonable energy investment but would still require a small amount of power from the reactor itself.

3.2. Operations Safety

A nuclear reactor normally is kept at safe operating conditions through the use of control rods or drums. These devices contain a strong neutron absorber that captures neutrons and prevents them from fissioning. At a constant operating power, a reactor is said to be critical, which means either that its effective multiplication factor (k_{eff}) is equal to one or that one neutron effectively is produced per each neutron destroyed. Power production ultimately results from fission reactions within the reactor, which create neutrons as well as a large amount of energy. At the beginning of operation, a large number of fissile atoms (those capable of fission with any neutron) exist per absorbing atom, and a relatively large amount of absorbing material is needed to keep the reactor critical. As the reactor runs, more absorbing fission products are produced and the effective multiplication factor of the reactor decreases; thus, less absorbing material is needed to keep the reactor critical. Control rods or drums can be adjusted to provide more absorbing material when the reactor is first started and less as the reactor runs and the amount of fissile material in the system decreases. The HPS model follows this pattern, and control drums regulate the amount of absorbing material that is present at various steps.

Figure 3 Heat flux as a function of time.

When a rover explores the surface of Mars, it will encounter rough terrain, many rocks, and other obstacles. One of the problems of having a nuclear reactor on a rover is that the control drums could get bumped and/or dislocated during reactor operation, thus causing the reactor to go either slightly above or below critical. Thus, the reactor must be designed to adjust back to a critical condition automatically. Fortunately, the amount of burnup in the HPS model is small, which means that the quantity of fissile material decreases slowly over time (once operation begins) and relatively few control drum adjustments are necessary. One option to avoid problems with unplanned control drum movement caused by this low burnup is to design sturdy control drums that can be locked into one position at the beginning of each excursion and then remain there throughout the excursion. Another option is to rely on the fact that the reactor is designed to have a negative temperature coefficient, which means that if the reactor goes supercritical (i.e., $k_{eff} > 1$), the temperature of the system will increase, materials will expand, and the value of k_{eff} will decrease as a result. In contrast, if the reactor goes subcritical (i.e., $k_{eff} < 1$), the temperature will decrease and materials will shrink, which will cause the k_{eff} to increase slightly. In either case, the reactor is designed so that it can remain at a critical condition and still allow steady-state operation to continue.

4. CONCLUSIONS

There are many methods by which a rover can be powered for excavations on the moon and/or Mars. Nuclear power is one of the most economical and efficient methods; however, certain considerations, such as shielding necessary for the electronics and safe operating conditions, must be taken into account in its design. Although a relatively small amount of shielding is needed to produce acceptable gamma dose rates and neutron fluxes for a nuclear reactor in a vacuum situation, much more is needed in a realistic situation for a rover on the moon or Mars because of scattering of particles off various surfaces. Lunar regolith, Martian soil, and/or carbon dioxide can be used to help reduce the large costs involved with the shielding (both in payload mass and obtaining the material), and the reactor can be designed so that the rugged terrain will not affect the safe operation of the system. A better option to reduce the necessary shielding may be to power the rover from a stationary nuclear reactor using either rechargeable fuel cells on the rover, a long cable connected to the rover, or a laser to beam power to the rover from a location in orbit. All options must be studied further before an absolute decision can be made.

5. REFERENCES

1.

Joseph A. Angelo, Jr., Ph.D., and David Buden, *Space Nuclear Power* (Orbit Book Company, Inc., Malabar, Florida, 1985), pp. 126-157.

2.

P. M. O'Donnell *et al.*, "Energy Storage Considerations for a Robotic Mars Surface Sampler," in *Proceedings of the 23rd Intersociety Energy Conversion Engineering Conference* (The American Society of Mechanical Engineers, New York),Vol. 2, pp. 385-389.

3.

Geoffrey A. Landis and Diane L. Linne, "Acetylene Fuel from Atmospheric CO_2 on Mars," *Journal of Spacecraft and Rockets* 29:2, 294-295 (1991).

4.

"Gas Industry Online: Gas Technology Spring '98," http://www. infoinc.com/ newgio/gio/gt/field.html.

5.

Geoffrey A. Landis and Joseph Appelbaum, "Photovoltaic Power Options for Mars," *Space Power* 10:2 225-237 (1991).

6.

Michael G. Houts and David I. Poston, "Heatpipe Power System and Heatpipe Bimodal System Development Status," in *Proceedings of the Space Technology and Applications International Forum* (Woodbury Publishing, New York, 1998), pp. 1189-1195.

7.

Judith F. Breismeister et al., "MCNP^{TM}—A General Monte Carlo N-Particle Transport Code, Version 4B," Los Alamos National Laboratory report LA-12625-M, pp. 3-65, H-6 (March 1997).

8.

Norman J. Rudie, *Principles and Techniques of Radiation Hardening* (Western Periodicals Co., North Hollywood, California, 1980), Vol. 1, p. 5-11.

9.

Warren M. Rohsenow *et al.*, *Handbook of Heat Transfer Fundamentals* (McGraw-Hill, New York, 1985), pp. 3-88, 3-99.

10.

Dwight E. Gray, *American Institute of Physics Handbook*, 3rd ed. (McGraw-Hill, New York, 1972), p. 4-226.