Running head: CHOOSING NUCLEAR ENERGY

Spacecraft Electrical Power Subsystems:

Choosing Nuclear Energy with a Clear Conscience

James J. Coogan

Embry-Riddle Aeronautical University

May 2006

Abstract

Electrical current to power spacecraft has been successfully generated using the sun, chemical reactions and nuclear power. Engineers and mission planners design electrical power subsystems (EPS) by considering cost, payload weight, spacecraft operation in various regimes and which energy source provides the best possibility for mission success. If such discussion leads to the use of nuclear power, additional consideration is given to international law and public opinion. While every mission has risks, the use of a nuclear power may elevate public fear of routine hazards. Planners thoroughly examine risk probabilities and risk severity, as well as the consequences of an accident. Design and use of nuclear power systems like the radioisotope thermoelectric generator (RTG), greatly enhance space system safety.

Introduction

The wide horizons of Space encourage humanity to reach out as far as technology will allow. In the development of spacecraft, one of the primary design concerns is ensuring that onboard systems continue to operate throughout an entire Space mission. This goal is achieved through the proper choice of energy for the spacecraft's electrical power subsystem (EPS). Mission planners must consider various natural resources for power generation. Currently, the choice of power is limited to the sun, fuel cells, batteries and radioactive isotopes. Engineers must then evaluate factors of such energy creation as it relates to cost, effectiveness of the energy source in the mission environment, weight of payload and danger to the environment and human health. There are often also outside concerns, such as public opinion, that drive the entire process. Public affairs campaigns following the decision must explain the reasons why one source was chosen over another. However, the ultimate hope of all Space mission planners is to ensure a successful mission, both scientifically and politically.

Selection of Electrical Power Subsystems

There are at three energy sources typically used in EPS spacecraft, each has its advantages and disadvantages: solar, chemical and nuclear. While an engineer might wish to utilize the highest quality and reliable system (i.e. expensive), each of these alternatives must be evaluated and rejected before such an optimal system can be chosen. After all of this planning, however, the public may still demand that less desirable means be used to achieve mission goals, hoping to ensure that there is complete safety for humanity and the Earth environment. Defense of the selection, therefore, involves the understanding of the three currently available power sources.

Solar

Solar energy can be used for nearly all spacecraft that orbit the Earth. Electricity can be produced with two methods: directly, by using solar photons to create a flow of electrons; or indirectly, by using sunlight concentration to produce heat, boil a fluid and drive a generator. Photovoltaic cells are one example of the direct conversion method. Sunlight hits a wafer of semiconductor material and the photons in the light release electrons from the semiconductor, which then flow across the material (i.e. electrical current). While the Sun provides nearly limitless power for an orbiting satellite, solar cell efficiency ranges between 15% and 20%. In addition, manufacturing limitations prevent production of large cells, instead requiring connection of multiple small cells. When such solar arrays are mounted on spacecraft and actively track the sun, the EPS system can effectively power spacecraft systems. Advantages of solar energy are: inexpensive materials; low payload weight if arrays are small; and relatively low risk to the environment. Disadvantages of using the sun as a power source are: the solar array will degrade in efficiency as it ages; orbiting satellites cannot generate power (solely with solar power) while in Earth's shadow; and as spacecraft travel farther from the Sun they produce less energy (Sellers, 2000).

Chemical

There are two examples of chemical power systems for spacecraft: fuel cells and batteries. Fuel Cells provide electricity by combining Hydrogen with Oxygen, which together create current and water and can provide large amounts of energy over several weeks. However, there is a limit to the amount of materials that can be stored on the spacecraft, so missions lasting several months cannot make a long-term use of this type of fuel cell. Alternatively, batteries use electrolytes (i.e. fluids with charged ions) and electrodes, which either collect or emit ions.

Together, these components create a current within the battery. However, the electrolyte can eventually be depleted of ions, ending the reaction (i.e. the battery "dies"). Spacecraft batteries are either the primary type (i.e. they discharge only once) or the secondary type (i.e. they can be discharged and recharged many times). One use for secondary batteries is to associate them with solar arrays to allow charging during sunlight hours and depletion during darkness. Advantages of fuel cells and batteries are: life span and storage capacity. Disadvantages of batteries and fuel cells are: batteries can significantly add to the weight of the entire spacecraft and battery energy output can vary with temperature extremes (Sellers, 2000).

Nuclear

There are two types of nuclear power system (NPS) used in spacecraft: nuclear reactor and radioisotope. While the former derives power from the fission of radioactive materials, the latter utilizes the energy produced during the decay of the same materials. The reactor creates power by combining fissile materials, which react to heat water. The resulting steam drives a generator. Radioisotope systems, which include the Radioisotope Thermoelectric Generator (RTG), the Radioisotope Heating Unit (RHU) and other varieties of Radioisotope Fuel Cell, produce electricity by means of a thermocouple consisting of metallic strips of dissimilar metals connected to a heating chamber. Within the chamber, the energy generated by radioactive decay heats one of the metal strips, while the other strip remains at ambient temperature. The resistance created between the two metals allows free flow of electrons, creating a current (Department of Energy [DOE], n.d.). Advantages of nuclear power sources are: their significant power generation, especially in the case of the reactor; and the ability of nuclear power to operate out of effective range of solar power and longer than chemical power. The low weight and small size of the RTG and RHU are also advantageous. Disadvantages of using nuclear energy are: possible environmental contamination; extremely high cost of engineering safe nuclear systems and their associated shielding; and public opposition to deployment of nuclear devices (Sellers, 2000).

While the nuclear reactor may eventually provide the greatest power source for a spacecraft EPS, it has some drawbacks that often have prevented its widespread use in Space. The isotope used by nuclear reactors is Uranium-235. The by-products created by the fission reaction (i.e. beta particles) create the requirement for extensive shielding, which may significantly add to the weight of the payload. Additionally, the concern of the public regarding the possible release of the radioactive materials has thus far overshadowed the potential benefits of such nuclear power systems (Lee, 2003).

Unlike the fission reaction within a nuclear reactor, the radioisotopic fuel cell does not generate harmful radiation. The primary radioactive material used by the RTG and RHU is Plutonium-238, with a half-life of 87.7 years. As it decays, the Plutonium emits radiation in the form of alpha particles. These particles cannot even penetrate a sheet of paper (DOE, n.d.). The latest version of RTG in use is the general-purpose heat source (GPHS), a device designed with multiple levels protection of the nuclear materials. A GPHS is comprised of 18 modules, each including four Plutonium dioxide pellets encased in Iridium. The pellets are further protected within a graphite impact shells and “aeroshells,” designed to withstand the heat of re-entering the atmosphere (DOE, n.d.). The amount of energy derived from a GPHS can be as high as 300 Watts (electrical) and 4,400 Watts (heat). The Voyager missions of the early 1980s continue to provide power, at a reduced capacity, long after their design life span of five years. Despite efficiency as low as 3%, the Voyager thermocouples were still operating at 80% of capacity in 2001 (Wikipedia: Radioisotope Thermoelectric Generator [RTG], n.d.).

Risk Assessment

If a NPS is chosen over the solar and chemical alternative, designers must execute an extensive risk assessment of all issues surrounding the planned mission. As in the terrestrial nuclear industry, the Probabilistic Risk Assessment (PRA) method is used (National Aeronautics and Space Administration [NASA], 2005). The PRA involves the study of all possible accident scenarios. These are then numerically ranked in order of their probability of occurrence and their potential consequence to the public is then considered. The PRA utilizes a variety of risk assessment tools to achieve the ranking, most notably Fault Tree Analysis (FTA). In addition, a Hazard and Operability (HAZOP) study may also be conducted. The combination of these risk assessments can be extremely costly (Bahr, 1997). The results of the risk assessment are combined into a safety analysis report.

For each mission, several regimes are examined to determine the overall risk to the RTG and RHU components of the spacecraft. Each is evaluated individually and then an overall risk for the mission is calculated. As determined by the National Aeronautics and Space Administration (NASA), the basic elements of the nuclear launch safety risk analysis are: accident definition, source term determination, consequence evaluation and risk analysis. For each element, probability determinations are conducted. The final element combines the first three elements so that "the measure of risk is then the probability-weighted sum of consequences" (NASA, 1995, p.4-2). This process is conducted for each accident case throughout the mission profile. In determining the environmental impact of release of Plutonium-dioxide during the Cassini mission, the profile was divided into Pre-Launch phase, Early Launch phase, Late Launch phase, and Venus-Venus-Earth-Jupiter-Gravity Assist (VVEJGA) phase. In addition to simply determining the possibility of risk to the spacecraft and its nuclear components, mission planners also determined the probability of environmental and human exposure to radioactive material (NASA, 1995).

Risk Management

In the United States (US), a launch of a spacecraft containing an NPS must proceed through a Space nuclear safety review. One part of this review is the National Environmental Policy Act process, which considers environmental impact and viable alternatives. Non-governmental agencies are offered an opportunity to provide feedback to Federal planners. The environmental assessment takes nearly two years to complete. The nuclear safety launch approval process begins immediately after, ensuring that other agencies (e.g. Department of Energy [DOE]) are able to evaluate the mission's nuclear safety. The nuclear safety launch approval considers the findings from the safety analysis report and takes another five years to complete. The sponsoring mission agency or contractor must also submit a radiological contingency plan to minimize the potential for release of radioactive material (United Nations [UN], 2002).

Once the approval process is completed, the mission planners must continue to evaluate the risks of the mission. A complete understanding of the probabilities, consequences and exposures of these risks to the general public and the environment will form the foundation for a successful mission, but other issues must be considered. Understanding the history of NPS in Space and the International Law that governs nuclear power above Earth's surface are significant requirements. Additionally, the root causes of public opposition to the use of NPS in Space must be examined, including possible means for alleviating concerns.

History of NPS in Space

The first RTG was launched by the US into Space aboard the Transit-4A spacecraft in 1961 (Wikipedia: RTG, n.d.). Engineers continued to develop radioisotopic fuel cells because they do not require the high amount of control or shielding and because they require only a small amount of radioactive material. Since the early 1970s, the US has launched RTGs aboard 24 missions, involving the use of 44 RTGs. The US has only launched one nuclear reactor, on the SNAP-10A mission. The Soviet Union, however, launched 37 nuclear reactors into Space, principally aboard the RORSAT missions (DOE, 2004). There have also been five known accidents involving spacecraft with RTGs onboard. Two involved the Soviet Cosmos missions, two were launch failures of US satellites, and the last was the re-entry of the Apollo-13 Lunar Module (Wikipedia: RTG, n.d.). The first US loss led to redesign of the RTG to allow for intact re-entry and subsequent failures have shown success in this regard. Currently, one RTG lies at the bottom of the Tonga trench of the Pacific Ocean, with no evident release of radioactive material (DOE, 2004). Failures of Soviet spacecraft using nuclear power, such as Cosmos-954 in 1978, have led to the dispersal of radioactive debris within the borders of unrelated countries and required the international regulation of such devices. Such high-visibility accidents have led to a widespread public fear and skepticism of anything nuclear above the Earth (Lee, 2003).

International Legislation

With the intersection of nuclear technology and space missions, experimentation naturally ensued. However, before the widespread proliferation of nuclear devices was permitted to escalate, the international community developed a "Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Over Water" (1963). Later, a "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the

Moon and other Celestial Bodies" (1967) was developed to govern the use of nuclear power during the race to land on the moon. With the adoption of the "Principles Relevant to the Use of Nuclear Power Sources in Outer Space" in 1992, a standing international code of conduct was created (Lee, 2003). These so-called "NPS Principles" have guided the expansion of nuclear power in Space. Most importantly, consideration for the contamination of the territory of a third party or neutral nation is paramount. Some nations even monitor the space debris of international space programs and hold them accountable to the international community for anything that returns to Earth atmosphere (UN, 2002).

Public Opinion

When evaluating missions using NPS, planners must consider the impact of several issues relating to public opinion. National reputation can be damaged by the failure of an NPS spacecraft. In an extreme scenario, a war could actually ensue from the destruction of a nuclear device in the atmosphere. No less important is the health and safety of international populations, including those of the nation launching the spacecraft. Risk can actually be perceived as greater than it is if the public becomes suspicious of the motives of its own government. Panic can even drive the discussion of anything nuclear in Space. Finally, there may even be a situation in which Federal oversight is not adequate, or when one decision changes the entire PRA. Such scenarios must be discussed and constantly evaluated throughout mission planning and execution (Sarsfield, 1998).

With the proliferation of extensive internet newsgroups, chat-rooms and message boards, the public no longer may accept the findings of a properly conducted risk assessment or national review of safety. An example of such phenomena is the Cassini-Huygens mission of 1997. In one study of the public opinion during the two years before launch (conducted primarily using message board entries), it was determined that the debate over use of nuclear power in Space was prone to "sensationalism, conspiracies, *ad hominem* attacks, [and] exaggeration," all of which reduced the public confidence in any governmental risk assessment (Rodrigue, 2001, p.250). What this study also implies is that there may someday be no way to adequately allay the concerns of the public once the debate progresses beyond the official press release. With every email that is forwarded from one opponent to everyone in his or her address book, risk assessments of NPS in Space cease to be tools for management. For every expert on the side of nuclear power in space, there will soon be several internet "experts." More effective means for clearly stating and justifying risk assessment methods must immediately be found so that future missions will not be cancelled due to a small number of internet users who care passionately about nuclear power (Rodrigue, 2001).

Conclusion

The effective but highly controversial use of nuclear power in Space will remain at the forefront of mission planning in the decades to come. Until a viable energy source for deep-space applications can be found which completely eliminates the need for radioactive materials, the space programs of the international community must struggle to determine how to best balance the cost, safety and reliability of NPS missions. Due to a recent shift in US Space priorities (from unmanned to manned missions) the ambitious Project Prometheus, which involved the launch of a nuclear reactor for the Jupiter Icy Moons Orbiter, was cancelled in 2005 (Wikipedia: Jupiter Icy Moons Orbiter, 2006). Spacecraft like the New Horizon, launched towards Pluto in early 2006, are powered by deep-space battery technology (DOE, 2006). In all missions involving nuclear power in Space, risks (those both real and perceived) must be evaluated and managed throughout design and deployment so that interplanetary exploration may continue.

References

Bahr, N. J. (1997). *System Safety Engineering and Risk Assessment: A Practical Approach*. New York: Taylor & Francis.

Department of Energy. (n.d.). Nuclear Power in Space. [Publication DOE/NE-0071].

Department of Energy. (2004, June 6). Space Nuclear Power Systems: Radioisotope Power Systems. Retrieved May 12, 2006, from Office of Space & Power Systems Web site: http://www.ne.doe.gov/space/space-desc.html.

Department of Energy. (2006, January 19). DOE Technology Helps NASA Seek "New Horizons" (Release 01-19-06). Retrieved May 23, 2006, from Office of Nuclear Energy, Science & Technology Web site: http://www.ne.doe.gov/home/01-19-06.html.

Lee, R. J. (2003). Nuclear and Radioisotopic Power in Space: The Cumulative Content and effect of the United Nations Space Treaties and Declarations (Report IAC-03-IISL.5.01). Report given at the 54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, 29 September – 3 October 2003, Bremen, Germany, and published by the American Institute of Aeronautics and Astronautics.

National Aeronautics and Space Administration. (1995, June). Final Environmental Impact Statement for the Cassini Mission. Washington, DC: Solar System Exploration Division (Office of Space Science).

National Aeronautics and Space Administration. (2005, September 6). Risk Management "Risk as a Resource." Retrieved May 22, 2006, from National Aeronautics and Space Administration Web site: http://www.hq.nasa.gov/office/codeq/risk/risk.htm.

Rodrigue, C. M. (2001). Internet media in technological risk amplification: Plutonium on board the Cassini-Huygens spacecraft. *Risk: Health, Safety & Environment*, 12(3), 221-254.

Sarsfield, L. P. (1998). The Cosmos on a Shoestring: Small Spacecraft for Space and Earth Science (Report MR-864-OSTP). Retrieved May 22, 2006, from RAND Corporation Web site: http://www.rand.org/pubs/monograph_reports/MR864/index.html.

Sellers, J. J. (2000). *Understanding Space* (2nd ed.). New York: McGraw-Hill.

United Nations. (2002, March 12). A review of international documents and national processes potentially relevant to the peaceful uses of nuclear power sources in outer space (Publication A/AC.105/781).

Wikipedia: Jupiter Icy Moons Orbiter. (2006, April 19). Retrieved May 22, 2006, from http://en.wikipedia.org/wiki/Jupiter_Icy_Moons_Orbiter.

Wikipedia: Radioisotope Thermoelectric Generator. (n.d.). Retrieved May 12, 2006, from http://en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator.