CHAPTER II

"The universe needs to be protected from the Conquistadores who are coming"
Willa Elam, Cassini protestor (Platt 1997).

A Brief Overview Of The Cassini Mission And The Technology

The Cassini mission was designed to explore Saturn, its rings and moons. The Cassini mission is a collaborative research program involving scientists from the United States, France, Italy, Germany, and several other nations. Launched on October 15, 1997, Cassini will spend six years traveling to Saturn. It will generate the velocity required for the 890 million mile trip by traveling Sunward to Venus, using Venus' gravitational pull to gather additional speed, circle back to Earth, and use the Earth to gather even more speed to be slingshot to Saturn (Figure 1). The Cassini spacecraft carries the Huygens probe which will land on Titan—the first probe to set down on a moon outside Earth-orbit—for geological analyses of Titan's ice crust. Cassini will map Saturn, Titan, and Saturn's ring system. It is the last of the U.S. great solar system exploration missions. These missions were comprised of very big spacecraft with very big price tags. Cassini is the size of a small school bus, and cost a total of $3.3 billion. Because of its size and the power required by its scientific payload, the Cassini mission is powered by a SNP technology, a radioisotope thermoelectric generator (RTG). The Cassini RTGs (there are three) are fueled by a total of 72 pounds of Plutonium-238 (NASA 1997) (Figure 2).

Nuclear Power as the Enabling Technology for Space Exploration

Many technologies are critical to the space program. Reliable, cost-effective launch systems, large data-bandwidth capabilities, and light weight materials are three ‘technologies’ that were invented for the U.S. space program. However, the nuclear power supplies, called here *space nuclear power* (SNP) to differentiate them from terrestrial applications of nuclear energy, are considered *the enabling technologies* for deep space exploration (AIAA 1995). To put it simply, there are no other technologies available now, or in the next ten to fifteen years, that can provide adequate electrical power to spacecraft and experiments, for exploration outside of Earth orbit. For example, in a recent gathering protesting the Cassini flyby, a former NASA astronaut reminded the protestors (Franklin Chang Diaz, July 23, 1999, as quoted on *Space.com* at www.space.com in an article by G.T. Whitesides):

> “Nuclear energy in space has been subject to a lot of irrational fear… Folks have to make it clear in their minds what the choices really are… in space, power is life. We must have a power rich environment.”

There are solar cell and chemical battery technologies that are capable of delivering respectable amounts of power in Earth orbit, and for short periods of time. For example, the International Space Station is powered by solar arrays and the space shuttle is powered by chemical batteries. However, solar arrays are large, hard to move, delicate, and have to be pointed at the Sun in order to function. Solar arrays are also limited by their distance from the Sun: their efficiency declines exponentially with increasing distance from the Sun (Bennett, Hemler and Schock, 1996; NASA 1997). Chemical batteries are heavy and are drastically limited in amount of power and lifetime. For space exploration beyond Earth orbit, which necessarily implies missions that are years in duration, solar arrays and batteries become a technological second choice (NASA 1997). In these applications solar power is not viable, as the technology becomes too fragile for the distances involved, and with significantly diminished capability caused by greater distance from the Sun. See Figure 3 for a comparison of power availability of competing technologies.

NASA maintains that the safety record and design of the RTG are above reproach:

> "The United States has an outstanding record of safety in using RTGs on 23 missions over the past three decades… More than 30 years have been invested in the engineering, safety analyses, and testing of RTGs. Safety features are incorporated into the RTG's design, and extensive testing has demonstrated that they can withstand physical conditions more severe than those expected from most accidents" (NASA 1997, P. 1).

Space nuclear power is commonly used for passive electrical power supply on missions outside of Earth orbit, usually as RTGs. The RTG has no moving parts and uses neither fission nor fusion to produce energy. Instead, it provides power through a natural radioactive decay that produces heat which is changed into electricity by solid-state thermoelectric converters. [1] Plutonium-238 is used for space exploration because it is non-fissile (cannot produce a nuclear chain reaction leading to an explosion), has an 87.8 year half-life and a comparatively low level of radiation emissions (NRC 1996, NASA 1997). RTG's are used infrequently on Earth because there exist other, more cost-effective, power sources that match the RTG for power and robustness. For example, while use of RTGs is banned in the United States, the U.S. Antarctic research station at McMurdo base is powered by an RTG that uses Strontium-90 for the fuel supply (Teledyne Brown, 1997). These long-lived technologies provide higher power levels for research payloads, maintain a high tolerance for hostile environments, and

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[1] Fission requires the addition of an extra neutron (from an exterior source) to split the atom. Radioactive decay does not cause atoms to split but is a natural process whereby alpha particles are given off and the mass of the nucleus is

demonstrate very high levels of reliability (Bennett 1996). The Pioneer 10 spacecraft, launched March 2, 1972, is powered by an RTG, and is still sending signals from well outside the Solar System.

A related nuclear technology for space exploration, that was for many years a Department of Defense (DOD) secret, is the space nuclear reactor. Unlike RTGs, reactors sustain a nuclear chain reaction and can also be used for propulsion power. Seemingly in an eternal conflict between technological desirability and programmatic squeamishness, the U.S. has funded research in this area totaling $10 billion (in 1992 dollars) for over 40 years. Referred to as ‘a capability in search of a mission’, only one reactor was flown by the United States, one time, in 1965, and that reactor no longer exists (Federation of American Scientists 1997).

> “History has shown that it takes longer to develop a nuclear reactor system than to develop a space mission. Hence today’s civil and military space project managers cannot include any nuclear reactor space power system—or any other system—in their mission planning until that system has been developed and tested. This dilemma is sometimes referred to as the ‘chicken and egg syndrome.’ The persistence of the aerospace nuclear propulsion community…. Derives from this chicken and egg dilemma. Long and hard experience has revealed the transient and ephemeral character of mission requirements, in contrast to the protracted realities of developing workable aerospace nuclear propulsion systems. This has engendered a belief within the aerospace nuclear propulsion engineering community that if only reactors could be developed, users would emerge to claim them” (Federation of American Scientists 1997).

In the late 1960s public opinion regarding nuclear power increased the programmatic risk to the government funded research programs, and NASA and the DOE found wisdom in developing alternatives to early mission designs that relied on cheap nuclear power for propulsion. While the space propulsion community was atttracted to the concept of space nuclear reactors, “nuclear energy has proven resistant to propulsion applications” (Federation of American Scientists 1997).

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reduced. (Personal Communication from E. Douple, Ph.D., Director, NRC Board on Radiation Effects Research, May 1, 1999)

In the 1980s, re-energized and financed by the Reagan Administration's Strategic Defense Initiative, space nuclear reactors became the hoped-for, *rapidly achievable* technology which could deliver the amounts of power needed to form the protective anti-nuclear missile blanket around the United States as envisioned by the 'Star Wars' program (Morone and Woodhouse 1986, NRC 1996). However the programs were derailed and most research and development (R&D) was halted in the early 1990s, when the Soviet Union fell and the Cold War effectively ended. The United States purchased what it considered to be a mature Soviet space nuclear reactor in 1992, the TOPAZ, but the reactor did not test to expected power levels, and Congress halted the program in 1996 (NRC, 1996; Reichhardt, 1996). The space propulsion community predicted that the cancellation of the TOPAZ program would cause the total loss of space nuclear reactor technology in the United States (AIAA 1996; NRC 1996, Reichhardt 1996).

The United States government was interested in nuclear power for space even before NASA was created in 1958. The first RTG was launched soon after, in 1961. This spacecraft burned up, by intention, high in the upper atmosphere and the data generated was used to redesign the RTG (Bennet 1996, NASA 1997). As a mature technology, the RTG is the natural choice of power supply for mission designers who are faced with shrinking budgets and therefore no ability to test new technologies. For example, although the Cassini mission flew the largest, most powerful, RTG ever launched, its technology is essentially the same as that completed in the mid-1970s and flown on a total of 23 missions.

There have been no accidents or failures of RTGs in the U.S. space program (NRC 1996a). While three RTG-powered spacecraft have been involved in accidents, none of these accidents was caused by the RTG, and in every case the power supply behaved as it was designed to do (Bennett 1996, NASA 1997). See Appendix B for the SNP Launch History in the United States. In the early 1970s, new developments in solar power technologies made photovoltaic arrays the optimal power-supply choice within Earth orbit. Thus, most RTG-powered missions have traveled outside Earth orbit. Over time, further development of RTG technology improved generator performance and efficiency as measured by an increase in Watts generated per kilogram launched, but the fundamental design has remained essentially unchanged (Federation of American Scientists 1997).

Alternative Technologies to Space Nuclear Power

New advances in solar arrays and photovoltaic cells will reduce the requirements for RTGs on the surface of Mars for applications requiring small amounts of power. For example, the Mars Pathfinder was powered by high-efficiency gallium-arsenide solar cells. However, the size of a solar power array needed to provide power for the Cassini mission to Saturn would have been too large to launch (NASA 1996a). By comparison, the solar arrays on the International Space Station, in Earth orbit, will be as long, and almost as wide, as a football field. Although the Cassini mission will require less peak power than the International Space Station, the low concentration of solar power past Mars' orbit would require solar arrays up to three football fields in length (NASA 1997).

NASA's Marshall and Lewis Space Flight Centers have the mandate to advance propulsion technologies to the test phase. However, these programs, during the 1990s at least, are funded minimally. NASA is slowly pursuing electric ion propulsion, nuclear fusion, and antimatter propulsion options, in addition to its minimal maintenance of its nuclear propulsion programs. Any of these alternative technologies would require billions of dollars in advanced technology development (ATD) funds to develop, and they are still in many ways unproven alternatives. NASA has chosen to concentrate its limited ATD funds on the development of life-support technologies to support human occupation of Mars. While NASA predicts that advances in research on photovoltaic power, wind turbine power, and geothermal power from the environmental and DOE research programs will reduce reliance on nuclear reactors for the power supply on the surface of Mars, it nonetheless has included a reactor into its mission designs, along with RTGs (NASA 1996a).

NASA considered alternative powerplants for the Cassini mission, specifically: RTGs powered by other isotopes; smaller RTGs with less plutonium; a nuclear reactor; or other non-nuclear power systems including power beaming from Earth (NASA 1997, pages 2-51–2-58).

- *Other radioisotopes*. RTGs can use any radioisotope, not only plutonium-238, with a half-life long enough to provide sufficient power throughout the mission and with a high enough specific activity to provide the required power with a suitably small generator. NASA identified strontium-90 and curium-244 as alternatives, but neither has a "significant environmental advantage over plutonium dioxide" (NASA 1995, page 2-51.) Unlike plutonium-238, strontium-90 emits gamma radiation and curium-244 emits both gamma and neutron radiation, requiring extensive shielding during production, handling, and safety testing to protect workers. The additional risk was not considered feasible.

- *Power systems requiring less plutonium dioxide*. In brief, to wring more power from less plutonium, a new and more efficient thermal electric conversion system would be required. While the thermoelectric converter for the Cassini mission has an efficiency of 6.8 percent, clearly there is room for improvement. New designs for a dynamic thermoelectric converter have not been tested for performance, degradation, and spacecraft integration and were not deemed flight ready within the time constraints of the Cassini mission. NASA chose not to delay the mission to wait upon potential advances in energy conversion systems.
- *Nuclear reactors*. A nuclear reactor presents the possible environmental advantage of launching a smaller amount of nuclear material. However, “a nuclear reactor of a size and operating lifetime suitable for Cassini does not exist nor is it being developed in the United States” (NASA 1997, page 2-52).
- *Non-nuclear power systems.* NASA considered solar energy, chemical batteries, and microwave or laser power beaming. Solar power is impractical, as discussed above. The mass of chemical batteries large enough to provide the power needed for the Cassini mission would be too large for any existing launch vehicle. Laser power beaming systems do not currently exist, and the environmental effects and possible hazards are not understood. Power beaming is a hypothetical system where microwave or laser power is generated and transmitted from Earth to a spacecraft, the energy collected onboard, and converted to electricity.

Proposed Human Missions to Mars: a Further Requirement for Nuclear Power

Most of NASA's conceptual mission designs for human exploration of Mars require SNP in the form of RTGs or reactors. Human missions require more energy than do robotic missions, for everything from creating an environment to keep humans safe to preserving food and to protecting humans from space radiation. Power requirements for space missions are often defined in terms of the peak power demand. For example, Cassini's peak power demand is 100 kWe (kilowatts electric) to power the scientific instruments and navigation instruments when they are actually in use. The peak power demand for a human mission to Mars is predicted to be 1000 kWe, or 1 megawatt, for a crewed research base on Mars (as opposed to a robotic research base), and in the range of tens of megawatts for high-power electric propulsion for crewed vehicles to Mars (Bennett 1996; NASA 1997). At this time, any project requiring power levels higher than 1000kWe would require a space nuclear reactor, a technology that does not actually exist. One leading mission design for a human mission to Mars requires 16 launches, first of material then people, to Mars for the first cycle of exploration. Of the 16 launches, 12 would carry some form of SNP technology (Zubrin 1996).

As NASA begins to seek the funding for human missions to Mars, there are several factors that are different from other missions.

1. The Mars Reference Mission calls for a series of scientific exploration missions in which rotating teams of scientists will travel to Mars, work for a time, and then return home. Eventually, the infrastructure will be in place to support very long-term tours of duty. These research bases, like

their analog in Antarctica, are to be powered by nuclear reactors. The day to day lives of the citizen scientists will be totally dependent, to an extent unknown on Earth, on the smooth and efficient functioning of a nuclear technology.

2. The crew return vehicle will be fueled by a process that is dependent upon a nuclear reactor. The hydrogen based chemical rockets that will propel the returning crew will produce their fuel on Mars through an autonomous manufacturing process called *in situ* (on-site) resource utilization.
3. The Mars reference mission incorporates the idea that the material and supplies needed to support humans will travel to Mars before humans ever leave Earth so as to provide additional safety factors. These 'shipments' will reach Mars and all devices will be proved functioning, before humans crews leave Earth, so as to provide humans with a technological safety net. Thus, the nuclear technologies will be designed to operate autonomously - a capability that does not currently exist.
4. The use of nuclear power supplies on Mars is predicated on Mars 'having no environment and thus no environmental impact' (Zubrin 1998).

Other mission scenarios range from simple "flags and footprints" missions to grand plans that colonize and later terraform Mars. These alternative mission designs differ in cost, longevity and goals. However, they all feature nuclear power technologies.

This chapter began with a discussion of the Cassini mission's enabling technology, and ended with a discussion of nuclear technologies for human missions to Mars. Human missions to Mars represent the next major programmatic drive for the U.S. space program, and the next major design demand for space nuclear power. The Cassini mission represented an unacceptable risk to the protestors, a manageable risk to NASA mission designers, and, I believe, a significant programmatic risk to a human Mars exploration mission. The next chapter will describe the risk from NASA's viewpoint.