Making Space Nuclear Power A Reality

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Our current space exploration missions are power limited. Space nuclear reactors could provide the power for both onboard electrical power and propulsion to enable a new generation of space science and exploration. Implementing a mission using a space nuclear reactor presents many technical challenges. However, nuclear technologies are safely and reliably used throughout U.S. industries and the Government. Well-defined processes and regulations currently exist for the use of nuclear technologies in space or any other application. These processes and regulations assure safe, reliable use of nuclear technology in a manner that protects the public and the environment. The question is not one of choosing between safety and space science, but of investing in a technology that includes rigorous processes and procedures to assure safety.

Nomenclature

RTG = radioisotope thermoelectric generators

I. Introduction

Humans have always had a fascination with space. Understanding and investigating the heavens has occupied scientists, engineers, explorers, and the general public for most of human history. The exploration of the stars and space has especially fascinated children. Most parents spend many hours staring at the sky with their children and trying to answer impossible questions like "how many stars are there?" and "do people live on other planets?" As the children get older, they ask things like "how do we know the temperature of the sun?" and "where do the moons of the planets come from?" Our fascination with space has driven many young people towards math, physics, chemistry, and engineering. Not all of those children have ended up working in space science. Many have made outstanding contributions in other technologies. However, that first interest in science often came from the driving desire to understand our place in the universe.

We are at an exciting time in space exploration. Up until now, our exploration has consisted of obtaining important information using very restricted resources. Even within our solar system, the other planets are very far away. We have visited most of them and landed on a few. Our knowledge comes from short duration studies, quick fly-bys, and limited looks. To more fully understand our solar system, and to prepare for human visits to other bodies in our solar system, will require significant leaps in technical capabilities. The most important of the enabling capabilities is to increase power generation, which can provide greater maneuverability (propulsion) and increased electrical power for instruments.

To put this in perspective, the Cassini spacecraft, which is powered by three radioisotope thermoelectric generators (RTGs), has the most electrical power onboard any past or current deep space vehicle. Cassini currently produces onboard power of 900 watts electric. Think about your hair dryer or the number of 60 watt light bulbs in your bedroom and bathroom. On any given morning, you probably exceed the demand for 900 watt just in your bathroom. Despite the power limitations of past and current spacecraft, however, NASA continues to provide outstanding science return on many, many mission through the inventiveness of the science instrument designers, who maximize the very limited available electrical power.

Our ability to move into a new age of discovery and exploration—an age that will include the use of high-power instruments and human exploratory missions—is limited by our current power generation techniques. Moving forward into that next age of space exploration demands that we develop next generation power sources, ones that could to increase available onboard electrical power and support electrical propulsion.

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It is time, therefore, for us to decide whether we want to take the next step. Nuclear reactor technology is a viable option for providing adequate power for both propulsion and onboard electrical power. The additional power will provide the maneuverability that is needed at the planets and moons once we get there and the ability to power the important instruments and send back the data at a reasonable rate.

II. Nuclear Technologies

To understand the process for utilizing nuclear reactors in a space application, it is important to understand the maturity of nuclear technologies in general, the processes and practices that are used in developing and implementing nuclear technology for any applications, and the challenges of using those technologies to new applications.

The use of nuclear technology is not new to this country. It is an advanced technology, with many applications that are widely accepted and utilized by the public in general. In December 1951, an experimental reactor produced the first electric power from the atom, lighting four light bulbs. Nuclear energy has been used since 1953 to power U.S. navy vessels and since 1955 to provide electricity for home use. The government organizations and private companies that design, build, and operate these systems have a long history of success.

A. Commercial Nuclear Power Production

Currently, there are 103 commercial nuclear power plants producing electricity in the United States, located at 64 sites in 31 states. They are, on average, 24 years old, and are licensed to operate for 40 years with an option to renew for an additional 20 years. License renewal is expected for virtually all U.S. nuclear power plants. Today, nuclear power plants—the second largest source of electricity in the United States—supply about 20 percent of the nation's electricity each year.

Nuclear power is also extensively used worldwide. Currently 30 countries worldwide are operating 439 nuclear plants for electricity generation. Twenty-six new nuclear plants were under construction in 11 countries. Nuclear power plants provided approximately 16 percent of the world's energy production in 2003. In total, 16 countries relied on nuclear energy to supply at least one-quarter of their total electricity.

Nuclear power plants provide low-cost, predictable power. The average electricity production cost in 2003 for nuclear energy was 1.72 cents per kilowatt-hour. By comparison, the cost for coal-fired plants 1.80 cents, for oil 5.53 cents, and for natural gas 5.77 cents. The energy in a single uranium fuel pellet—the size of the tip of your little finger—is the equivalent of 17,000 cubic feet of natural gas, 1,780 pounds of coal, or 149 gallons of oil.

Of all energy sources, nuclear energy has, perhaps, the lowest impact on the environment, including water, land, habitat, species, and air resources. Nuclear power plants produce no air pollutants, such as sulfur and particulates, or greenhouse gases. Also, Nuclear power plants utilize a small land area compared to what would be required for similar energy output from other sources, such as windmills or solar panels. The use of nuclear energy in place of other energy sources helps to keep the air clean, preserve the Earth's climate, avoid ground-level ozone formation and prevent acid rain.

Throughout the nuclear fuel cycle, the small volume of waste by-products actually created is carefully contained, packaged, and safely stored. As a result, the nuclear energy industry is the only industry established since the industrial revolution that has managed and accounted for all of its waste, preventing adverse impacts to the environment. Water discharged from a nuclear power plant contains no harmful pollutants and meets regulatory standards for temperature designed to protect aquatic life.

1. Public Safety

For years, America's commercial nuclear energy industry has ranked among the safest places to work in the United States. U.S. Bureau of Labor statistics show that it is safer to work at a nuclear power plant than in the manufacturing sector and even in the real estate and finance industries.

Even if you lived right next door to a nuclear power plant, you would still receive less radiation each year than you would receive in just one round-trip flight from New York to Los Angeles. You would have to live near a nuclear power plant for over 2,000 years to get the same amount of radiation exposure that you get from a single diagnostic medical x-ray.

B. Medical Diagnosis and Treatment

The largest man-made source of radiation is medical diagnosis and treatment, including x-rays, nuclear medicine, and cancer treatment. More than 28,000 American doctors practice medical specialties that use radiation. The use of radiation for medical diagnosis and treatment is so widespread that virtually every U.S. hospital has some form of nuclear medicine unit. One radioactive isotope, molybdenum-99, is used about 40,000 times each day in the

United States to diagnose cancer and other illnesses. All ten of the Nobel Prizes granted in physiology and medicine from 1975 to 1989 were based on research using radioactive materials.

C. Food Processing and Preservation

Irradiation kills bacteria, parasites, and insects in food—including listeria, salmonella, and potentially deadly E. coli—and retards non-microbial spoilage of certain foods, increasing their shelf life. In the United States alone, according to the national Centers for Disease Control and Prevention, more than 6.5 million serious cases of food-related illness occur each year, causing more than 10,000 deaths. The United States is among more than 35 countries that permit irradiation of certain foods. Since the 1960s, NASA has included irradiated food on its space flights.

In 1963, the U.S. Food and Drug Administration approved the irradiation of wheat, flour and potatoes; in 1983, spices and seasonings; in 1985, pork; in 1986, fruits and vegetables; in 1990, poultry; and in 1997, red meat.

D. Industrial Applications

Radiation is used to sterilize everything from baby powder, bandages, contact lens solution to many cosmetics, including false eyelashes and mascara.

Small amounts of a radioactive substance are commonly used as tracers in process materials. They make it possible to track leakage from piping systems, monitor the rate of engine wear and corrosion of processing equipment, observe the velocity of materials through pipes, and gauge system-filtration efficiency. Many industries use nuclear technologies to inspect materials for flaws and conformance to requirements.

As you can see the use of nuclear technologies is not new or infrequent. There are a wide range of applications that are accepted and utilized by the public and industry in general. It is highly regulated, and although the regulation of the various applications of nuclear technology resides with multiple Federal and State organizations, the regulations are very consistent. Only a very limited set of Government organizations are allowed to utilize nuclear technologies. This is based on the expertise and processes that are used by those organizations to assure the safe and reliable utilization of the technologies. The use of nuclear technologies in the U.S. has been safe, reliable and cost effective for over 50 years.

III. Space Nuclear Power

Nuclear power has been used for deep space vehicle for over 40 years. RTGs have been used for spacecraft electrical power since 1961. All RTGs have operated as designed, both in normal operations and accident conditions. RTGs were designed carefully with consideration for the accident environments that might be experienced during every phase of the launch. The design requirement is to protect public and worker health and safety during all phases of operations during launch and accident conditions.

IV. Nuclear System Design

There are many challenges to using a basic technology in a new way. There are regulatory challenges and engineering challenges.

A. Regulatory Challenges

The regulatory framework for utilizing nuclear technologies is in place, including the use of nuclear power technology (both RTGs and reactors) for space applications. This regulatory framework ensures that: 1) approved, rigorous processes and procedures are used to design, build, and operate new nuclear technologies, 2) the technology is verified and validated by appropriate independent organizations, and 3) appropriate approval for final utilization of the technology is obtained. No new regulatory processes need to be developed.

B. Engineering Challenges

The engineering challenges for developing and using space nuclear reactors have been discussed and evaluated for many years. Much of the work that has been done in the past is still relevant, and many new aspects must be considered because of new supporting technologies, such as advance materials developments and operational experience. The fundamental engineering process that should be used is not new; the process starts with clearly defining requirements.

What performance is needed?

In designing any system for a space application, the same considerations apply: mass, volume, performance. With a space nuclear reactor, the challenge is to reliably provide the needed power output within a reasonable mass allowance.

Performance will also consider safety. That is, the space nuclear reactor must provide safe and reliably power under both normal operation and accident conditions. This is not a new concept for the nuclear industry. Accident conditions are always considered in the design of nuclear power systems and other nuclear technology applications. The challenge is in fully understanding all relevant accident conditions and then designing a viable system that can be safely utilized given those conditions. Potential accident environments are included in the designs for any nuclear system.

The field of accident evaluation continues to mature. We see it in every aspect of our lives and with every technology with which we interface. There are generally understood standards for accident evaluation and for the depth at which an accident environment must be fully considered in the system design.

In automobiles, for example, we now have mandatory seatbelts; that is, regulations require that this safety feature be included in the hardware and used by the operator and passengers. Additionally, many car manufacturers include front and side airbags in their design. However, with a very rare exception, automobiles are not designed to be amphibious. It is possible that an accident might result in an automobile ending up in water;, it is not reasonable, however, to require all automobiles be designed for this accident condition. It is a possible event, but not probable.

Building codes now have provisions that require structures to withstand earthquakes. The requirement is very location specific, depending on the "design basis" earthquake for that region of the country. Buildings are not designed to withstand earthquakes that will not happen in that part of the country. We do not require all buildings in mid west to be designed to withstand the next ice age. Is it possible we will have one: yes. Is it reasonable to design for one: no.

The concept of probability, therefore, is critical to the design of a technology. Just because you can think of it, or cannot prove it is physically impossible, does not mean it should be considered in every design. If the likelihood of some accident conditions is remote, that condition would not be reasonably considered a design requirement.

However, with regard to the design of nuclear systems, accident scenarios that are beyond credible are often discussed in the safety analysis and the potential consequences are identified. In addition, the actions that would need to be taken if the scenario occurred are also often discussed. This has often led to confusion. A discussion of a low-probability accident sequence and the possible outcomes in a nuclear safety analysis does not mean that it is likely that condition will happen or that it should be part of the design requirements. This is no different that other, large scale, technology applications. Severe consequences could occur if an airplane impacted any chemical or power-producing plant. And yet, they are not designed to withstand a direct impact of a large airplane. The purpose of discussing low-probability, high-consequence events is to identify compensatory measures that can be taken to prevent the event or to lower the consequences of the event.

When it is determined that a specific accident sequence should be considered in the system design, it might not be possible to fully prevent that condition through engineering systems alone. Therefore, other measures are taken. Secondary safety features, such as redundancy and detection systems, are considered. Often the precursor events are evaluated and actions are taken to reduce the likelihood or eliminate altogether the event.

Training of operators and others who might interface with the system is required to help minimize human error. The field of man-machine interface has been the subject of great study in the last 20 years. In fact, the Three Mile Island reactor accident contributed greatly to this field. In that accident, the reactor system was designed to correctly respond to the system malfunction that occurred (a stuck open pressure relief valve). However, the reactor operators misread the instrumentation and overrode the automatic systems, resulting in a situation that damaged the reactor core, at great financial loss to the operating utility. Even with this secondary failure, the worker and public health and safety were protected. As a result, all reactor control rooms were significantly modified based on the lessons learned from the TMI accident. The sister plant at that site, Three Mile Island 1, has continued to operate and was the first operating nuclear power plant in the U. S., to be acquired by another company, AmerGen Energy Co., in July 1998. The trend in the commercial nuclear industry at this time is for companies who have good operational record to purchase the plants from those companies who have had difficulties, or who do not operate nuclear facilities as a major part of their business.

The final aspect of designing nuclear systems comes into play with quality assurance. The nuclear industry needed increased reliability for systems, both in normal operation and accident conditions, over what was traditionally expected in other industries. The nuclear industry developed a nuclear quality assurance standard, NQA-1, to be used for parts to be included into the nuclear system, especially those that were related to the safety systems. "Nuclear Grade" has become a term to denote a system or component that has unusually high reliability and performance. Included in NQA-1 and it's successors is a requirement to ensure the pedigree of all components and subsystems in the nuclear system to a high level of fidelity. In the nuclear industry, we know what we want to build, we built what we design, and we operate the system in the manner consistent with the design basis.

V. Space Nuclear Reactors

Space nuclear reactors will be developed using the same rigor and processes that are generally applicable to all nuclear systems. Our challenge is to fully identify the requirements for the space nuclear reactor power plant, including under accident conditions. Standard nuclear engineering practices and principles can then be used to address all of these requirements.

Questions will arise concerning our ability to correctly identify the requirements. The requirements must allow for multiple uses of the space reactor, including use on a variety of launch vehicles and spacecraft. It will be necessary to define an enveloping set of accident conditions that will encompass a variety of potential uses. We must show how we determined the reliability of launch vehicles and the accident environments they might generate.

It is important that the performance requirements are defined as outcomes, so that the reactor designers have the most flexibility in developing a design that will adequately meet the outcomes. Because so much work has been done in the prior 20 years concerning space reactor design, it is the tendency of the space reactor community to define outcomes as specific reactor design features. The most basic requirement is that the reactor must not endanger the public, workers, and the environment. There are many engineering solutions that will accomplish this goal. A design decision for one space reactor application might not be the best solution for another application. It is misleading to identify engineering solutions (i.e., do not go critical before launch) as a firm, fixed requirement when it is only one of many strategies to protect public safety.

Another danger in defining the requirements as specific engineering solutions is that they become viewed by the public and decision makers as the save–all to assuring safety. They become a mantra that is repeated as a shorthand to assure the public that the system is safe. The fallacy of this approach is quickly identified by those who object to the use of the technology. Nuclear reactor powered spacecraft are complicated systems that require an integration of many strategies to ensure safety and reliability. No one engineering or operational approach will fix everything. Focusing on one feature opens the design to legitimate criticism by others who can quickly point to a scenario that will not be prevented by that one feature alone.

VI. Conclusion

The public, in general, does not have a good understanding of the processes and procedures we utilize when designing and operating nuclear systems. They do not understand the regulatory framework that requires those processes to be used. They do not understand that the safety and reliability record of the nuclear industry in the U.S. is achieved through rigor, not luck. The future in which nuclear technologies are safely managed and utilized is now.

I have always worked near and in nuclear facilities and my family has lived in the communities near those facilities. The safe utilization of nuclear technology is something that affects me personally. The misuse of nuclear systems would not be something that just happens to someone else, it would happen to the people most important to me. The benefits of nuclear technology are something I see every day. It is our responsibility to convince the public that rigorous processes are in place and implemented by people with a real and personal concern for the outcome, with rigorous checks and balances, so that we can use the best technologies available to meet our science and exploration goals. We will fulfill this responsibility by have qualified and experienced organizations and personnel responsible for the design and operation of the space nuclear reactors. We are not asking the public and decision makers to chose between safety and space science. Space nuclear reactors used for power and propulsion will be safe and reliable. The decision is whether to invest in the technology, with all the rigor that is required, to meet the science goals for the next phase of space exploration.

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