Martin B. Kalinowski (Ed.)

Energy supply for deep space missions
Risks of nuclear power in space and prospects for solar alternatives
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Risks of nuclear power in space and prospects for solar alternatives

Editor: Martin B. Kalinowski
Technical Editing: Kathrin Prettl

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Contact:

Interdisziplinäre Arbeitsgruppe Naturwissenschaft Technik und Sicherheit (IANUS)

Dr. Martin B. Kalinowski
IANUS
Hochschulstr. 10
64289 Darmstadt
Germany

fon: +49 6151 163016, fax: +49 6151 166039
kalinowski@hrzpub.tu-darmstadt.de
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In October 1997 a Titan IV rocket was successfully launched which carried the Cassini/Huygens spacecraft that was developed in cooperation by NASA and ESA on its flight to the planet Saturn. On board are 32.8 kg plutonium-238 which is used for a nuclear energy source developed for deep space missions. Most of this highly radioactive material is used for thermoelectric power generators and a few grams are used for radionuclide heating units.

A few concerned scientists and many dedicated citizens protested against the launch of Cassini because it poses a great risk to human health and the ecosphere of our planet. They called for cancellation or at least for a postponement of the start. In fact, an alternative launching date was available about two and a half years later at which the flight path of Cassini would not come back to earth for a so-called fly-by manoeuvre which is used to accelerate the space probe in the gravity field of our planet. Thus the most risky scenario at which Cassini would reenter the earth’s atmosphere and disperse its plutonium fright in tiny aerosol particles could have been avoided. If all the plutonium would be released, most of the world’s population would be affected and in the order of a few thousand people would suffer and die from early cancer. The very small probability of such an accident (less than one in a million) was used as an excuse not to design the radionuclide battery with a proper shielding that could withstand the extreme high reentry speed. Such a shielding would have „wasted“ too much of the precious weight that is available for the payload. In its Final Environmental Impact Statement for the Cassini Mission dated June 1995 NASA first admits that „the 2001 mission alternative would achieve most of the planned science objectives“ but then argues against this alternative saying that due to the resulting delay „the international partnerships formed to develop the Cassini spacecraft, Huygens Probe, and other space-related projects could be disrupted“ (page x). Moreover, NASA downplays the number of 2300 estimated cancer fatalities by stating that they „would represent an additional 0.0005 percent above the normally observed 1 billion cancer fatalities“ (page viii). Nobody would notice a difference.

This cynical approach does not strengthen the public trust in the responsibility of scientists and engineers. A few concerned people realised that the severe risks posed by nuclear energy in space are not only downplayed and ignored but also that it is very hard to raise any significant public awareness. Therefore, IANUS studied this topic and invited a number of experts to contribute papers to this edited report. The starting point for this project was a symposium on „Peace in Outer Space? The Ambivalence of Space Technology“ that took place on March 20 and 21, 1997 at Darmstadt University of Technology. It was organised by IANUS in cooperation with the following non-governmental peace organisations:
- International Network of Engineers and Scientists Against Proliferation (INESAP)
- Global Network Against Weapons and Nuclear Power in Space
- Friedens- und Begegnungsstätte Mutlangen
- Naturwissenschaftler Initiative Verantwortung für Zukunfts- und Friedensfähigkeit.
This selection of papers is written by ten authors from Germany, Russia and the USA. Two papers go back to the space symposium of 1997 (Grossman and Strobl). Most of the others are original papers which were written for this project and first published in this volume. A number of those concerned persons who played a crucial role in bringing the issue of nuclear power in space into the public are authors in this report. The selection of papers is not limited to pointing fingers at the risks of nuclear power in space. It opens the view to new technical developments which will free the way for breaking the current monopoly of nuclear power for deep space missions. The first applications of solar power as an alternative are on their way.

Fortunately the launch of Cassini/Huygens in October 1997 was successful. However, on August 12, 1998 another rocket of the Titan IV type exploded shortly after its start and the payload was dispersed in the atmosphere. What if this had happened with Cassini. This accident ridiculed the overoptimistically low overall probability of the a start phase accident which NASA estimated as one to 500 (FEIS, page 4-75). This low probability estimate was not even backed by empirical data. One out of 11 launches of the Titan IV rocket failed in August 1993 due to a malfunction in one of the solid rocket motors (FEIS, page 4-41). A dozen out of 82 utilisations of the upper stage of the launch vehicle called Centaur failed. The low estimate for the start phase accident probability was explained with increased technical insight and the elimination of the problem that caused the accident in August 1993. This approach is not naive technical optimism, it is dishonesty.

The United Nations have adopted Principles Relevant to the Use of Nuclear Power Sources in Outer Space. These principles are completely reprinted in this report. Accordingly any nation which plans to use nuclear energy in space is responsible for understanding and minimising the risks.

The biophysical and radiological foundations to understand the risks generated by atmospheric releases of plutonium are laid down in the paper by Roland Wolff. Special emphasis is put on the consequences of past accidents and contaminations. Michio Kaku presents a profound critique of the Final Environmental Impact Statement for the Cassini Mission that was released in June 1995 by NASA. He demonstrates a number of particular methods which are used by NASA to downplay the risks.
Scientific investigations were very helpful to understand the real dimensions of risks involved in the use of nuclear energy in space. Even simple calculations were instrumental for shifting the risk perception from a unconscious and numbed state to a mode of scare and bewilderment. A striking example for this is the back-on-the-envelope calculation demonstrated by Martin Kalinowski in which he shows that the total activity of plutonium on board of Cassini is about 1.5 to 2 times as high as the activity of all plutonium that has ever been emitted into the atmosphere by human activities. I.e. the release of all plutonium on board of Cassini can virtually increase the activity of all artificially released plutonium by a factor of 2.5 to 3.\(^1\) This is difficult to believe if one takes into account that about 5 to 6 tonnes of plutonium have been released to the atmosphere by nuclear weapons testings. The reason is that due to its short half-life of 88 years plutonium-238 has a very high specific activity (i.e. decays per second and per gram of the material) which is exactly why it is so attractive for space applications. This very active isotope is scarcely included in weapons or reactor plutonium in which Pu-239 is the major component (cf. Pu-239 has a half-life of 24,000 years).

Karl Grossman summarises the risk of the Cassini Mission and paints a clear picture of the political interests and dependencies that are connected to the downplaying and neglecting of the risks. In his analysis he draws on a number of original documents including the one of Michio Kaku that is published here. Ross McCluney provides a similar description of the political background of downplaying nuclear risks and at the same time blocking the development of solar alternatives.

Gerhard Strobl describes in his contribution the development of new solar cells which have achieved in laboratory experiments an efficiency of up to 27%. The development of these solar cells has been initiated in 1991 specifically for the conditions of deep space missions (low intensity and low temperature). They will first be applied for the ROSETTA mission of ESA to the comet Wirtanen that starts in the year 2003.

From the paper of Uwe Bonnes it becomes clear that the use of radionuclide generators does in future not need to be the only answer to the limitations of solar energy supply in deep space missions. Just like on earth, energy efficiency and energy conservation are the necessary and possible supplements to the solar energy path. The energy demand of scientific payloads can be significantly reduced by means of modern electronic components and technologies which are partly already available on the market for the construction of consumer electronic products. In the case of a Mössbauer spectrometer that is discussed by Uwe Bonnes it is demonstrated that the power demand of previous laboratory devices of more than 10 Watt was reduced by a factor of more than 4 to 2.5 Watt by means of miniaturising and optimising the electronics.

The Mössbauer spectrometer which was developed for a Mars mission by the working group of Prof. Egbert Kankeleit at the Institute for Nuclear Physics at Darmstadt University of Technology can serve as an example how scientists are confronted with the possibility to be drawn into a space mission that inflicts risks to the whole world by the use of plutonium for power generation. In this particular case, it is likely that a radionuclide thermoelectric power genera-

\(^1\) The activity (i.e. the number of radioactive decays per time unit) of the isotope Pu-238 which has been introduced artificially into the environment worldwide is about 1 Peta Bequerel (i.e. \(10^{15}\) decays per second). This could theoretically be increased by one order of magnitude, if all plutonium in the RTGs of Cassini would be dispersed. The factor of 2.5 to 3 applies, if one takes all other plutonium isotopes into account as well. It should be noted that NASA's calculation in the FEIS of 1995 expected a release of one third of the plutonium in Cassini in the case of re-entry from fly-by. Another safety study of April 1997 assumed a release of only about 6 percent of the plutonium inventory.
tor is dispensable. However, the application of radionuclide heating units is definitely decided. It is curious to note that NASA does provide the sub-contractor with all technical details and boundary conditions for the available power supply but leaves out the information by what technical means the electric power will be provided. This is again an indication for the poor information policy of NASA.

Conclusion

From the collection of papers presented in this volume it becomes clear that the risks of nuclear energy in space are not only significant in comparison to other known sources of radioactive contamination. These particular risks are downplayed and neglected in an irresponsible way. The startling result of this study is that by means of the newly propagated NASA strategy of „faster, better, cheaper“ it could be possible that future space missions could be designed completely without nuclear power and could rely solely on solar power.
Nuclear Powered Space Missions - Past and Future

by Regina Hagen

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1 Introduction

"On January 16, 1959, a dramatic photograph appeared in a Washington, D.C., newspaper. The headline proclaimed »President Shows Atom Generator«. The photograph pictured President Eisenhower and a group of U.S. Atomic Energy Commission (AEC) officials in the Oval Office at the White House. They were gathered around the president’s desk, staring at a strange grapefruit-shaped object. Dubbed the world’s first atomic battery, it was actually one of the earliest models of a radioisotope thermoelectric generator (RTG), a nuclear generator specifically developed by the AEC to provide electric power during space missions." [USDOE/d, page 4]¹

This text from the DoE brochure „Nuclear Power in Space“ describes the early steps of what continues until today: the use of nuclear power to produce electrical energy for spacecraft instruments and experiments. Since the 1980s, when concerned U.S. citizens, scientists, and journalists protested against the NASA (National Aeronautics and Space Administration) Galileo and Ulysses missions, public interest in nuclear powered space missions has increased. Just one year ago, citizens’ groups in the U.S. and in Europe attempted to prevent the launch of the joint NASA/ESA (European Space Agency) mission Cassini with its payload of 72 pounds of plutonium dioxide. (Cassini was launched in October 1997.) Most articles and reports about Cassini mentioned 63 previous nuclear powered space missions, nine of which resulted in problems and/or accidents. It proved difficult, however, to find details beyond the two or three most spectacular accidents.

Therefore, this paper attempts to give basic information about the nuclear technology used for space missions, followed by a comprehensive chronology of all nuclear powered space missions launched by the U.S. and by the USSR/Russia.² An overview of future NASA plans (which involve eight nuclear powered deep space missions, four of which can be done solar according to several NASA documents), a conclusion, a list of acronyms, and a literature list complete the text.

Currently, the chronology in this paper lists 71 nuclear powered space missions, ten of which encountered problems or accidents, respectively. A few more space missions leave open questions. Fully aware that some information might be missing, mis-interpreted, or even wrong, it is hoped that this paper helps to come to a better understanding of past and future nuclear powered space missions. Rather than talk about speculative data, it might then be possible to discuss facts. Corrections and comments on the information presented below are expected and welcomed by the author.

Apart from several hardcopy documents, Internet search provided vast amounts of information. Huge numbers of documents from U.S. government organizations, mostly NASA and the U.S. Department of Energy, were found on various homepages. Consequently, it was decided to base this paper mainly on official information from government agencies and the space industry rather than to rely on books, magazines, and newspapers.³ Not surprisingly, the data basis is much smaller when it comes to the Soviet/Russian missions - which is reflected by the lack of details about many Soviet space missions in Chapter 3, Past Missions – a Chronology.

¹ See Chapter 7, Literature List for references. Page numbers are given for formatted and page-oriented documents. DoE develops and produces all RTGs used by DoD and NASA.
² So far, no nuclear powered space missions seem to have been launched by other countries. However, the European Space Agency as well as individual universities and research institutes from other countries used U.S. and Russian space missions to send their own experiments/instruments/probes into space.
³ Invaluable information about the use of nuclear power in space by NASA as well as by the U.S. military can be found in many articles as well as in a book and a video by journalistic professor Karl Grossman. For the purpose of this article, however, it seemed to make sense to not quote him but official sources. Some of Karl Grossman’s publications are listed at the end of Chapter 7, Literature List.
For the purpose of this paper, it was decided to quote (sometimes in length) the original statements from the official organizations instead of summarizing their contents in the author's own words. This leaves room for the reader's interpretation of the data given (although, admittedly the choice of quotes is a matter of interpretation by itself.)

2 Technology

2.1 The U.S. - RTG, Nuclear Reactor, And RHU

2.1.1 Radioisotope Thermoelectric Generators (RTGs)

All but one of the nuclear powered space missions launched by the U.S. used RTGs. In a document about the Ulysses mission, ESA/ESTEC (European Space Agency/European Space Research and Technology Center) explains the RTG technology as follows:

„What Are RTGs?

RTGs are lightweight, compact spacecraft power systems that are highly reliable. RTGs are not nuclear reactors and have no moving parts. They use neither fission nor fusion processes to produce energy. Instead, they provide power through the natural radioactive decay of plutonium (mostly Pu-238, a non-weaponsgrade isotope). The heat generated by this natural process is changed into electricity by solid-state thermoelectric converters. RTGs enable spacecraft to operate at significant distances from the Sun or in other areas where solar power systems would not be feasible. In this context, they remain unmatched for power output, reliability and durability.

Safety Design

More than 30 years have been invested in the engineering, safety analysis 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.

First, the fuel is in the heat-resistant, ceramic form of plutonium dioxide, which reduces its chance of vaporizing in fire or reentry environments. This ceramic-form fuel is also highly insoluble, has a low chemical reactivity, and primarily fractures into large, non-respirable particles and chunks. These characteristics help to mitigate the potential health effects from accidents involving the release of this fuel.

Second, the fuel is divided among 18 small, independent modular units, each with its own heat shield and impact shell. This design reduces the chances of fuel release in an accident because all modules would not be equally impacted in an accident.

Third, multiple layers of protective materials, including iridium capsules and high-strength graphite blocks, are used to protect the fuel and prevent its accidental release. Iridium is a metal that has a very high melting point and is strong, corrosion resistant and chemically compatible with plutonium dioxide. These characteristics make iridium useful for protecting and containing each fuel pellet. Graphite is used because it is lightweight and highly heat-resistant.” [ESTEC/b]4

On its web page "Cassini RTG Information", NASA’s Jet Propulsion Laboratory gives additional technical information:

„Each RTG NASA uses on recent planetary spacecraft contains approximately 10.9 kg (24 lb.) of plutonium dioxide fuel. On Galileo's two RTGs, that amounted to a total of about 48 lb. On Cassini, which has three RTGs, it's about 72 lb. ..."
RTGs have been used on 23 U.S. space missions including Voyager, Pioneer, Viking, Apollo, and more recently the Galileo and Ulysses missions. As in the past, Cassini’s RTGs are to be provided by the U.S. Department of Energy (DoE). Heat source technology pursued by DoE has resulted in several models of an RTG power system, evolving from the Systems for Nuclear Auxiliary Power (SNAP)-RTG to the Multi-Hundred Watt (MHW)-RTG, to the currently used General Purpose Heat Source (GPHS)-RTG used on Galileo, Ulysses and Cassini spacecraft. The GPHS technology is the culmination of almost 25 years of design evolution.

A GPHS-RTG assembly weighs 56 kg (123.5 lb), is approximately 113 cm (44.5 in) long and 43 cm (16.8 in) in diameter and contains 10.9 kg (24 lb) of plutonium dioxide fuel. At launch, the three RTGs will provide a total of 888 watts of electrical power from 13,182 watts of heat. By the end of the mission the power output will be 628 watts.” [JPL/c]

A specific aspect of RTG usage is pointed out by Canadian journalist Michael Bein: "Although the American planners have obviously been concerned enough about safety to draft general criteria and institute a three-step, multi-agency review process that must be completed before each launch, there are a number of weaknesses in the U.S. regulatory system vis a vis NPS [Nuclear Powered Satellites]. First of all, there is no licensing by an independent authority like the Nuclear Regulatory Commission, the watchdog of America’s commercial nuclear power industry. All the nuclear missions flown to date have been classed as research devices and have therefore been exempted from licensing under a provision of the Atomic Energy Act. DoE, meanwhile, reserves the right to approve deviations from the published safety criteria. And, perhaps most importantly, there is no provision for public participation in the safety review process.” [BEIN]

2.1.2 Nuclear Reactors

Although the U.S. has also worked on nuclear reactors for space missions, they launched but one spacecraft equipped with a reactor: the SNAPSHOT mission of 1965 (see Section 3, Past Missions – a Chronology for details.) The funding to build or test space nuclear reactor systems was stopped in 1972. After the end of the Cold War, U.S. nuclear laboratories purchased Russian Topaz II reactors and tested them thoroughly (British, French, and Russian scientists were part of the research team.) However, plans for a test space mission were not pursued for various reasons.

2.1.3 Radioisotope Heater Units (RHUs)

Many of NASA’s scientific space missions are not (only) equipped with RTGs but also with nuclear heaters, the RHUs. „The Cassini spacecraft and the Huygens Probe will use approximately 117 lightweight radioisotope heater units (RHUs) to regulate temperatures on the spacecraft and on the probe. Each RHU provides about one watt of heat, derived from the radioactive decay of 2.7 gm (0.1 oz) of non-weapons grade radioisotope, plutonium 238-dioxide, contained in a platinum-30 rhodium alloy clad. The exterior dimensions of an RHU are 2.6 cm (1 in) by 3.2 cm (1.3 in) long, weighing about 40 gm (0.09 lb).” [USDOE/a]

RHUs are used to keep instruments warm during cold Moon and Mars nights as well as during deep space missions. RHUs were for example used for the Apollo 11-17 missions, for Galileo, as well as for Cassini. This article focuses on RTGs and reactors, therefore the use of RHUs is not listed in the chronology of past missions.

5 Various DoE and NASA documents give different numbers of previous nuclear powered space missions, namely between 21 and 25. Chapter 3, Past Missions – a Chronology lists 30 corresponding missions.
2.2 The USSR/Russia - RORSAT, Topaz, And RTG

2.2.1 RORSAT Nuclear Reactors

Generally, little information was found about the RORSAT missions. A few pages in the book „Der rote Orbit“ (The Red Orbit) by journalist Harro Zimmer (published in 1996) deal with Soviet nuclear powered space missions. Some additional information was found at the Federation of American Scientists’ Internet homepage [FAS].

Harro Zimmer describes the RORSAT missions as follows [ZIMMER, pages 110- 112]6:

„Additional details became known about a ‘dirty’ side of Moscow’s military spaceflight program. From December 1967 to March 1988, the USSR orbited 33 radar satellites with nuclear reactors. They functioned at orbits of appr. 255 km altitude with an average lifetime of two to three months. Usually, the RORSATs - the acronym for RADAR OCEAN RECONNAISSANCE SATELLITE - were launched to coincide with major naval maneuvers of NATO and US Navy.

The characteristic feature were their large radar antennae the signals of which were sent to the surface of the ocean in order to locate the ships. Ideal objects were aircraft carriers with their large and flat surfaces which made particularly good reflectors. When planning these satellites, the Soviets had to compromise between various requirements. On the one hand, the orbit of a reconnaissance satellite must be low enough to receive the weakly reflected signal. On the other hand, the orbit must be high enough to cover a maximum area. Considerable electronic deficiencies enforced simple but power-consuming solutions, as a result of which only a small nuclear reactor could be used.

A RORSAT consists of three major components: the payload and propulsion section, the nuclear reactor, and the disposal stage, which is used to maneuver the reactor to an orbit of 900 to 1,000 km of altitude at the end of the mission. The satellite is 1.3 m in diameter and 10 m in length. A RORSAT weighs 3,800 kg, of which 1,250 kg are made up by the reactor and the disposal stage. These two components are 5.3 m long. The reactor core consists of 37 cylindrical fuel elements with 31.1 kg of highly enriched (90%) uranium-2357 embedded in a beryllium casing.

The cooling liquid for the reactor is liquid sodium-potassium. The thermo-ionic converter uses the dissipated heat to create electrical energy with an efficiency as low as 2 to 4%.

For the radar equipment, a RORSAT requires appr. 2 kilowatt electrical power. The technical structure of the system was extremely simple. Shielding was omitted unless absolutely required. Therefore, these satellites were a flying source of radiation which severely impacted the operation e.g. of science satellites equipped with gamma ray detectors.

As mentioned before, the active RORSAT lifetime was fairly short. The ‘record’ was 134 days. How should the radioactive payload - which was not limited to the reactor alone - be dealt with? From the relatively low orbit, the satellites would have entered the denser spheres of Earth’s atmosphere after one year at the latest, and they would have burned up only partially. The purpose of the disposal stage was to avoid this happening by injecting the reactor into a higher orbit between 900 and 1,000 km of altitude.

The lifetime of a fairly massive object at this altitude should be appr. 600 years, while uranium-235 and uranium-238 have a half-life of more than one billion years."

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6 Translation of the quotation by the author of this article.
7 The amount and enrichment of the U-238 in the Soviet RORSAT nuclear reactors stated by Harro Zimmer is confirmed by the Bellona Report, see [NILSEN].
After describing the two major accidents (Kosmos 954 and Kosmos 1402, see Chapter 3, Past Missions – a Chronology), Harry Zimmer continues with the following conclusion [ZIMMER, page 113]:

"The heritage of this program: at appr. 900 to 1,000 km of altitude about 940 kg highly enriched uranium as well as more than 15 metric tons of radioactive material orbit with an inclination of 65°. In addition, recent radar observation indicates that several ten thousand 'drops' 0.6 to 2 cm in diameter circle on this orbit. The drops consist of liquid sodium-potassium, the reactor coolant."

2.2.2 TOPAZ

About the Topaz program, Harro Zimmer writes as follows: "These [RORSAT] missions were not discontinued because the risks of using nuclear power in the orbit might be too high as compared to the advantages. Rather, ocean surveillance should have been continued by means of satellites at a higher altitude, equipped with larger and more powerful reactors. As soon as February 1, 1987, Kosmos 1818 was launched into an orbit at 800 km altitude. On board the large satellite was a reactor of the Type Topaz, weighing appr. 1,000 kg, which produced electrical power of about 5 to 6 kilowatt with an improved efficiency between 5 and 10% for six months. ... On July 10, 1987, Kosmos 1867 followed, equipped identically. This reactor operated about one year. At their altitude, these satellites might be safely stored at least for the next three hundred years."

The Russian Institute of Physics & Power Engineering describes the development process and results as follows: "In 1958 comprehensive research was started to develop a reactor-converter with the advanced thermionic principle of direct energy conversion. As compared to thermoelectric conversion, thermionic conversion makes it possible to increase efficiency, to prolong the life-time, and to improve the overall dimensions of the power system and the spacecraft as a whole.

The investigations performed at the IPPE in the field of small-sized reactors and shadow radiation shielding, the solution of the problems concerning collector and emitter materials selection and elaboration, investigations of the processes of electron emission and diffusion in cesium plasma, heat and mass exchange and liquid metal coolant technology (Na, K-alloy) provided creation of the first in the world intermediate neutrons thermionic reactor-converter which was called ‘TOPAZ’.

Between 1970-1984 seven power systems with reactors of this type were tested on the ground at the special IPPE test site. ‘TOPAZ’-units were tested twice in space as an electric power source for the ‘COSMOS’ satellites. Thermionic fuel elements (TFE’s) for ‘TOPAZ’ reactors were designed, fabricated, and in-pile tested in the IPPE.”

Whereas funding for space nuclear reactors was stopped in 1972 in the U.S. [USAF], research continued in the USSR and led to the development of a follow-up version of Topaz I.

"TOPAZ-2 small-sized nuclear power system with a thermionic converter represents a power source developed around a nuclear reactor and a thermionic heat-to-electricity converter. Advantages: high power and reliability; long lifetime; small overall dimensions; complete radiation safety; the possibility to fully discharge the fuel and to store/ship it separately from the system; the possibility of final fuel loading directly during the system pre-flight preparation.

Application: space power systems. ... Characteristics of the reactor core: height, mm 375; diameter, mm 260; uranium charge, kg up to 27; guaranteed lifetime, yr over 3." [KURCHATOV]
In the mid-90s, a "program managed by the Ballistic Missile Defense Organization" resulted in the purchase of six Topaz II reactors from Russia by the U.S. A joint team of U.S., British, French, and Russian engineers tested the space reactors "to evaluate the Russian technology and to find peaceful civilian applications". [USAF] None of the Topaz II reactors have actually been used for space missions, however.

2.2.3 Radioisotope Thermoelectric Generators (RTGs)
Extremely little information could be found about the use of RTGs in the Soviet and Russian space program. Information that RTGs are used at all was made public by the media in their reports about the accident of the Russian Mars-96 probe in November 1996. This mission got out of control soon after launch and decayed over South America (see Chapter 3, Past Missions – a Chronology for further details.)

2.2.4 Radioisotope Heater Units (RHUs)
RHUs are also used in the Soviet/Russian space program. For example, the Moon missions Luna 17 (1970) and Luna 21 (1973) used polonium-210 isotopic heat sources to keep the Lunokhod rovers warm during the lunar nights. No further details are known.

2.3 Other Nations - "RTG Technology Is Not Available"

Up to date, no other nations launched nuclear powered space missions and little information is available about corresponding research programs. The American Institute of Aeronautics and Astronautics (AIAA) sums the status up as follows:

"During the 1960s and early 1970s several other nations, including France, Germany, and the United Kingdom (U.K.) examined space nuclear reactor power systems. In the 1980s some studies were done by Japan and the U.K. The French government assembled a design team that worked on a reactor concept employing a Brayton cycle to convert reactor heat into electrical power. The French, Japanese, and Chinese now have small programs to explore the use of space nuclear technologies. Currently the U.S. is not producing plutonium-238 for space use, so DoE has been buying some plutonium-238 from Russia to supplement the existing inventory." [AIAA]

The non-availability of RTG technology has quite an impact on space mission planning outside the U.S. and Russia. The most striking examples are ESA's Rosetta mission to comet Wirtanen and ESA plans for the EuroMoon 2000 mission.

Wirtanen is a comet at approximately the same distance from the Sun as planet Jupiter. This means that the brightness of the Sun at Jupiter reaches about 5% of the brightness at Earth. According to NASA, current solar energy technology is not yet advanced enough to provide enough power for the spacecraft instruments at that distance. ESA, on the other side, had to look for an alternative for their Rosetta mission.

"ESA's next cometary mission takes its name from the Rosetta Stone. Just as the Rosetta Stone deciphered the hieroglyphics of ancient Egypt, so the Rosetta spacecraft will help to decode the messages of atoms and molecules that help us to make sense of our cosmic origins."
The Rosetta spacecraft will rendezvous with comet 46 P/Wirtanen as it makes one of its periodic visits to the Sun. The spacecraft will map the comet’s surface in fine detail and land a package of instruments (the Rosetta Lander) on it. Waltzing around the comet for many months, Rosetta will be able to watch its surface erupting in the warmth of the Sun. On-board instruments will analyse the effusions of dust and gas.

Scheduled for launch by Ariane-5 in January 2003, Rosetta will take eight years to reach its target. On the way it will inspect two asteroids (planned targets currently Mimistrobell and Rodari) at close quarters." [ESTEC/c]

In a Press Release from 1994, ESA explains why RTG technology could not be used:

„New solar cells with record efficiency

Under contract with ESA, European industry has recently developed high efficiency solar cells for use in future demanding deep-space missions such as the recently approved ROSETTA mission. The new solar cells reach a 25% efficiency under deep space conditions. ...

Until now, deep space probes had to use thermonuclear power generators, like the so called RTGs (Radioisotope Thermoelectric Generators). As RTG’s technology is not available in Europe, ESA therefore attempted to develop a power source based on very high-efficiency solar cells. ...

ESA expects that the new high performance Silicon solar cells could profitably be used in deep space missions for Europe and that this technology could also be of interest for near-Earth orbit space applications as well as for Earth based ones." [ESA/a]\[10\]

Similarly, ESA had to be inventive for EuroMoon 2000 to be launched in autumn 2000.

„What is EuroMoon 2000? 

The EuroMoon 2000 mission consists of a Lander and an Orbiter with a total mass in lunar transfer orbit of at least 2900 kg. The composite spacecraft would be placed into a circular polar orbit of 200 km altitude with a dedicated Ariane-4 launch. After about one month of observations, mainly for establishing preliminary gravitational data, the composite's altitude would be lowered to 100 km, where the Orbiter (weighing about 300 kg) would be separated from the Lander.

The Orbiter’s task would be to make a detailed topographic map using a stereoscopic camera and to establish the lunar gravitational potential more accurately with the help of a small subsatellite, in order to assist the subsequent landing operation. The Orbiter's payload (approx. 50 kg) would also address a large proportion of the MORO mission's objectives, including geochemical science.

The Lander would set down (to within ±100 m) on the highest point of the rim of the South Pole crater, in order to take advantage of the permanent sunlight there. The landed mass of 1000 kg would include more than 250 kg of payload, the primary objective of which would be to study the soil composition, heat flow and possibly seismic activity in the neighbourhood of the intended landing site, which lies inside the largest lunar crater, the Aitken Basin.

In addition to the ESA element, more than half of the Lander's payload capacity would be allocated to three or four 'Millennium Challenge' experiments. These would be the winners of a contest involving Universities and European Industry. Their 'challenge' would be to devise various robotic devices to investigate the inside of the South Pole crater (20 km in diameter and approximately 3000 m deep, with temperatures on the order of 200 deg C), hopefully reaching the South Pole itself." [ESTEC/a]

\[10\] For further information about solar cells development for deep space missions, see Gerhard Strobl’s article in this volume.
This design has two advantages: ESA’s lander can use solar panels as it will not descend into the deep crater where no sunlight is available but remain on the rim of the South Pole crater. “This location enjoys almost continuous sunlight thus missions can rely on solar power instead of bulky batteries or costly and potentially hazardous nuclear power generation.” [ESA/b] And ESA leaves it to the participating universities and industry enterprises to find a solution for robotic devices’ power supply - knowing they can not use nuclear power.

In addition to having found alternatives to nuclear power for board instruments, ESA was also successful in solving another problem. As described above, Radioisotope Heater Units (RHUs) are used to keep the sensitive instruments warm during the cold space nights. ESA managed to develop “a thermal control system securing operation without the use of radioactive heaters” [JPL/q] for the Rosetta Lander. “The design of the thermal control subsystem is challenging, because the lander has to operate on a comet nucleus with unknown rotation period, in distances between 3 and 1 AU from the sun with temperatures of the environment in the range between 120 K and 350 K. Special effort has to be taken for thermal insulation and heat storage to keep the temperature inside the lander in a range between -55°C and +70°C throughout the mission.” [JPL/q]

3 Past Missions – a Chronology

The following pages list those missions launched by the U.S. and the USSR/Russia which use(d) nuclear power to provide electrical energy for the on-board instruments.

For each mission, some basic data are given:
- Mission name mostly from the TRW Space Log 1996 [TRW]; other information sources
- Launch date mostly from the TRW Space Log 1996 [TRW]; other information sources
- Country mostly from the TRW Space Log 1996 [TRW]; other information sources
- Mission Type various information sources
- Launch Site TRW Space Log 1996 [TRW], other information sources
- Power Source DoE, NASA, and other information sources
- Number NASA’s Cassini FElS [NASA/c] and other information sources
- Source Term NASA’s Cassini FElS [NASA/c] and other information sources for the US RTGs; Harro Zimmer, "Der rote Orbit” [ZIMMER] for the Soviet RORSAT nuclear reactors
- Status DoE information [USDOE/d], TRW Space Log 1996 [TRW]; NASA’s Cassini FEIS, others.

The Estimated Life Duration given for the Soviet RORSAT missions is stated in the Missions database of the Institut für Luft- und Raumfahrt, Technische Universität Berlin (Institute of Aeronautics and Astronautics at the Technical University of Berlin). [ILR]

This is followed by additional information about the mission, the power source, the current mission status, and specific mission-related events where appropriate. Accidents and problems are marked by bold print. In order to avoid redundant information, details are not repeated for similar missions (e.g. many of the Kosmos missions.)

Where contradictory information was found in official sources, this is specifically pointed out.
In 1961, the first RTG used in a space mission was launched aboard a U.S. Navy transit navigation satellite. The electrical power output of this RTG, which was called Space Nuclear Auxiliary Power (SNAP-3), was a mere 2.7 watts. But the important story was that it continued to perform for 15 years after launch.

Since that initial SNAP-3 mission, RTGs have been an indispensable part of America’s space program. They have been involved in more than 25 missions, orbiting Earth and traveling to planets and their moons both nearby and in deep space. (Astronauts on five Apollo missions left RTG units on the lunar surface to power the Apollo Lunar Surface Experiment Packages.)

The RTG used for the Transit 4A and the Transit 4B missions worked on polonium-210, which has a half-life of 138.4 days. Therefore, it seems rather unlikely that it actually operated for 15 years. This would mean that at the end of its lifetime, 2% of the original heat dissipation would have been sufficient to provide the power for the satellite. See also Transit 4B mission.

The stage used to launch this satellite exploded after the launch. It broke up into 298 pieces, of which approx. 200 were still tracked in orbit according to a 1995 report of NASA’s Johnson Space Center [KESSLER].

Contradictory information exists about the operating time of this SNAP. The DoE states „RTG operated for 9 years. Satellite operated periodically after 1962· high altitude test. Last reported signal in 1971.” [USDOE/d, pages 15/16] The TRW Space Log 1996 states “In orbit; transmitted until 7/62, SNAP-3 operated 8 months.” [TRW, page 71]

This was the first U.S. satellite which used an RTG based on plutonium-238.11

On the use of plutonium RTGs, the DoE says the following: „Although other radioactive fuels have been considered for RTGs, plutonium-238 (Pu-238) has been used most widely. Pu-238 is a radioactive isotope - a form of plutonium that gives off energy as rays and particles. It continues to be the radioactive fuel of choice today and in planned future missions. ... Longer

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11 Plutonium-238 is not identical to the weapons-grade plutonium-239 used for nuclear weapons. For details about the effects and toxicity of Pu-238 see the articles of Karl Grossman, Michio Kaku, and Roland Wolff in this Working Paper.
space missions require a radioisotope with a longer half-life. Pu-238, with its half-life of 87.7 years, fills the need. For example, after five years, approximately 96 percent of the original heat output of Pu-238 is still available. ... Because the nuclear fuel in RTGs is radioactive, safety is a critical issue. ... Only lightweight shielding is necessary because alpha particles cannot penetrate a sheet of paper." [USDOE/d, pages 18-19]

**Accident?:** Contradictory information exists about the status of this satellite. DoE states: „RTG operated as planned. Non-RTG electrical problems on satellite caused satellite to fall after 9 months." [USDOE/d, pages 15/16] No further information about this incident could be found. The TRW Space Log 1996 [TRW, page 80] as well as the NASA Cassini FEIS [NASA/c] state that the satellite is currently in orbit.

**Name:** Transit 5-BN-2
**Launch Date:** Dec. 5, 1963
**Country:** U.S.
**Mission Type:** Navigational (US Air Force & Navy)
**Launch Site:** Vandenberg AFB, California
**Power Source:** SNAP-9A
**Number:** 1
**Source Term:** 17,000 Curies
**Status:** in orbit

„RTG operated for over 6 years. **Satellite lost ability to navigate** after 1.5 years." [USDOE/d, pages 15/16, emphasis added]

**Name:** Transit 5-BN-3
**Launch Date:** April 21, 1964
**Country:** U.S.
**Mission Type:** Navigational (US Air Force & Navy)
**Launch Site:** Vandenberg AFB, California
**Power Source:** SNAP-9A
**Number:** 1
**Source Term:** 17,000 Curies

**Status:** burned up during re-entry

**Accident:** „Mission was aborted because of launch vehicle failure. RTG burned up on re-entry as designed." [USDOE/d, pages 15/16] This is the short version of the events on April 21, 1964.

A more detailed account is given by another DoE document: „In 1964, a U.S. Navy Transit navigation satellite failed to reach orbit and disintegrated in the atmosphere. The satellite received its electrical power from a 4.5 pound, grapefruit-sized radiothermal generator that produced energy from the heat of its decaying radioisotopes. The device, known as a SNAP or System for Nuclear Auxiliary Power, disintegrated, scattering plutonium particles in the atmosphere over the southern hemisphere." [USDOE/b] According to a U.S. General Accounting Office report, the Transit 5-BN-3 RTG contained 2.2 pounds of plutonium fuel. [USGOA], page 18

In the Cassini FEIS, NASA describes the results of this accident: „Since 1964, essentially all of the SNAP-9A release has been deposited on the Earth's surface. About 25 percent ... of that release was deposited in the northern latitudes, with the remaining 75 percent settling in the southern hemisphere. ...The Pu-238 in the atmosphere from weapons tests (about 3.3 x 10^{14} Bq [9,000 Ci]) was increased by the 1964 reentry and burnup of a Systems for Nuclear Auxiliary Power (SNAP)-9A RTG, which released 6.3 x 10^{14} Bq (17,000 Ci). ... The release into the atmosphere was consistent with the RTG design philosophy of the time. (Subsequent RTGs, including the RTGs on the Cassini spacecraft, have been designed to contain the Pu-238 fuel to the maximum extent possible, recognizing that there are mass and configuration requirements relative to the spacecraft and its mission that must be considered with the design and configuration of the power source and its related safety requirements.) ... Since 1964,
essentially all of the SNAP-9A release has been deposited on the Earth's surface." [NASA/c, page 3-44]

The following table from NASA’s Cassini FEIS [NASA/c, page 3-44] lists the effect of this SNAP-9A burn-up on the worldwide plutonium-238 distribution.

### Table 1: Plutonium-238 Distribution from SNAP-9A Burn-Up

<table>
<thead>
<tr>
<th>Sources</th>
<th>Amount [Bequerels (Curies)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric Testing 1945-74</td>
<td>$3.3 \times 10^{14}$ (9,000)</td>
</tr>
<tr>
<td>Deposited near testing sites and worldwide</td>
<td></td>
</tr>
<tr>
<td>Space Nuclear - SNAP-9A, 1964</td>
<td>$6.3 \times 10^{14}$ (17,000)</td>
</tr>
<tr>
<td>Overseas Nuclear Reprocessing Plants, 1967-1987</td>
<td>$1.1 \times 10^{14}$ (3,000) (estimated)</td>
</tr>
<tr>
<td>Chernobyl Nuclear Power Station, 1986</td>
<td>$3.0 \times 10^{13}$ (810)</td>
</tr>
<tr>
<td>Total</td>
<td>$1.1 \times 10^{15}$ (29,810)</td>
</tr>
</tbody>
</table>

**Name:** SNAPSHOT  
Power Source: SNAP-10A (reactor)  
Launch Date: April 3, 1965  
Number: 1  
Country: U.S.  
Source Term: $?^{12}$  
Mission Type: Experimental (US Air Force & Army)  
Launch Site: Vandenberg AFB, California  
Status: in orbit

The satellite successfully achieved orbit. According to NASA’s Cassini FEIS, the reactor was shut down after 43 days in orbit.

Journalist Michael Bein commented this test flight of a space mission powered by a nuclear reactor as follows: "The only U.S. satellite thus far to carry a nuclear fission reactor failed in 1965 after 43 days aloft and was subsequently boosted into a 4000-year orbit in order that its radioactivity might have time to decay to safer levels before it descends to earth. Injection into higher orbit is the method of reactor ‘disposal’ preferred by both the American and Soviet programs." [BEIN]

Some additional information is given in the TRW Space Log 1996: "SNAP-10A operated at more than 500 W for 43 days. Since 1979, many objects separating. The only U.S. space reactor flown, a test flight in 1964, used uranium-235 as the fuel." [TRW, page 90, emphasis added]

Technical information about the SNAP-10A, the amount of U-238 used, or the effect of the continuing disintegration of the satellite mentioned in the TRW Space Log 1996 was not given in the sources available at the time of writing.

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12 NASA’s Cassini FEIS states the source term of all other missions it lists, but not for this reactor.  
13 For more details about the injection of reactors into higher orbit see the information given for Kosmos 198.
Kosmos 84 is generally regarded as the first mission of the USSR which used nuclear power to provide energy for the on-board instruments. Like the U.S., the USSR used polonium-210 to power their first RTGs. "Due to the short half life (138 days), this RTG model had a lifetime of only 3000 hours." [NILSEN] The USSR used RTGs only for the first two nuclear powered missions. All other Kosmos missions which relied on nuclear power used nuclear reactors instead.

<table>
<thead>
<tr>
<th>Name:</th>
<th>Kosmos 84</th>
<th>Power Source:</th>
<th>Polonium-RTG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date:</td>
<td>Sept. 3, 1965</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td>Source Term:</td>
<td>?</td>
</tr>
<tr>
<td>Mission Type:</td>
<td>Military communication</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
</tbody>
</table>

Kosmos 90

<table>
<thead>
<tr>
<th>Name:</th>
<th>Kosmos 90</th>
<th>Power Source:</th>
<th>Polonium-RTG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date:</td>
<td>Sept. 18, 1965</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td>Source Term:</td>
<td>?</td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
</tbody>
</table>

Kosmos 198

<table>
<thead>
<tr>
<th>Name:</th>
<th>Kosmos 198</th>
<th>Power Source:</th>
<th>reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date:</td>
<td>Dec. 27, 1967</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
</tbody>
</table>

| Estimated Life Duration: | 500a yrs |

This was the first of the 33 so-called RORSAT missions usually listed as nuclear powered space missions launched by the USSR. RORSAT is the acronym for ‘Radar Ocean Reconnaissance Satellite’. According to the Federation of American Scientists (FAS), Kosmos 198 was a „1-day flight test of spacecraft support systems” [FAS]. For more details about the RORSAT reactors, see Section 2.2, The USSR/Russia - RORSAT, Topaz, And RTG.

Kosmos 209

<table>
<thead>
<tr>
<th>Name:</th>
<th>Kosmos 209</th>
<th>Power Source:</th>
<th>reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date:</td>
<td>March 22, 1968</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
</tbody>
</table>

| Estimated Life Duration: | 500a yrs |

See Kosmos 198. According to the Federation of American Scientists, this was the second 1-day flight test of spacecraft support systems [FAS].

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14 The Kosmos missions are sometimes spelled Cosmos.
15 Tyuratam is a launch site in Kazakhstan. The Bellona Report [NILSEN] mentions that the Kosmos missions were launched from Plesetsk. The TRW Space Log 1996 [TRW], however, names Tyuratam for all Soviet nuclear powered space missions.
16 HEU-235 = highly enriched uranium-235
Name: Nimbus-B-1  Power Source: SNAP 19B2
Launch Date: May 18, 1968  Number: 2
Country: U.S.  Source Term: 34,400 Curies
Mission Type: Meteorological (NASA & US Air Force)
Launch Site: Vandenberg AFB, California  Status: failed to orbit; RTG recovered

According to information from the DoE, this was the first RTG usage on a non-military, i.e. on a NASA mission. [USDOE/a]

**Accident:** „Mission was aborted because of range safety destruct. RTG heat sources recovered and recycled.” [USDOE/d, pages 15/16] A ‘range safety destruct’ is a deliberate destruction of a mission by the Range Safety Officer of the mission launch pad when a launch vehicle gets out of control.

A report of the U.S. General Accounting Office describes the event as follows: „In 1968, a NIMBUS-B-1 weather satellite was destroyed after its launch vehicle malfunctioned. The plutonium fuel cells from the spacecraft's two RTGs were recovered intact from the bottom of the Santa Barbara Channel near the California coast.” [USGOA, page 18] The plutonium from the RTGs was recycled and re-used for another RTG.

Name: Nimbus III  Power Source: SNAP 19B2
Launch Date: April 14, 1969  Number: 2
Country: U.S.  Source Term: 37,000 Curies
Mission Type: Meteorological (NASA)
Launch Site: Vandenberg AFB, California  Status: in orbit

„RTGs operated for over 2.5 years.” [USDOE/d, page 15/16] A fact sheet published by the Florida State University, Department of Meteorology states: ”The craft was powered by 10,500 solar cells and two SNAP-19 nuclear powered generators.” [FSU/b]

Name: Kosmos 305  Power Source: reactor
Launch Date: Oct. 22, 1969  Number: 2
Country: USSR  Source Term: 2 x 31.1 kg highly enr. U-235
Mission Type: RORSAT
Launch Site: Tyuratam  Status: decayed

See Kosmos 198.

**Accident:** The TRW Space Log 1996 states, „Decayed Oct. 24, 1969; possible lunar mission test; two modules.” [TRW] Proposition One suggests that „radiation was detected as craft burns up in atmosphere.” [PROP1]

This mission is frequently listed in newspaper articles about accidents which occurred with nuclear powered spacecrafts. However, no details are given. This mission is not contained in the otherwise comprehensive Berlin database [ILR].

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17 In his book „The Wrong Stuff” (Common Courage Press, 1997), Karl Grossman mentions Kosmos 305 as one possible lunar mission which fell back to earth in 1969. As a second one he lists Kosmos 300, launched on Sept. 23, 1996. As this information was not confirmed by the information sources used for this article, Kosmos 300 is not listed here. It should be pointed out, however, that the TRW Space Log 1996 explicitly mentions two modules for Kosmos 305. Therefore, it may be concluded that this mission carried two reactors.
Nuclear powered space missions

**Name:** Apollo 12  
**Launch Date:** Nov. 14, 1969  
**Country:** U.S.  
**Mission Type:** Lunar surface (NASA)  
**Launch Site:** Cape Canaveral, Florida  
**Status:** on Moon

"RTG operated for about 8 years until station was shut down." [USDOE/d, page 15/16]

It is a little known fact that the seismic stations left on the Moon in the course of the Apollo 12 and Apollo 14 to Apollo 17 missions contain one RTG each. The plutonium heat source was loaded into the SNAP RTGs by the astronauts on the moon. [USDOE/d, page 5]

**Name:** Nimbus IV  
**Launch Date:** April 8, 1970  
**Country:** U.S.  
**Mission Type:** Meteorological (NASA)  
**Launch Site:** Vandenberg AFB, California  
**Status:** in orbit

Other than the Nimbus III mission, Nimbus IV to Nimbus VII are not contained in any of the official NASA and DoE mission lists. However, fact sheets about these missions were published by the Florida State University, Department of Meteorology. For all four missions, this organization states: "The craft was powered by 10,500 solar cells and two SNAP-19 nuclear powered generators." [FSU/b to FSU/f] The launch and mission data is confirmed by the TRW Space Log 1996 [TRW] which does not mention the RTGs (neither does it for any of the Apollo missions). Therefore, information about the four additional Nimbus missions was included in this list.

"Stage exploded Oct. 17; 300 pieces." [TRW, emphasis added]

**Name:** Apollo 13  
**Launch Date:** April 11, 1970  
**Country:** U.S.  
**Mission Type:** Lunar surface (NASA)  
**Launch Site:** Cape Canaveral, Florida  
**Status:** returned to Earth  
**RTG recovered**

**Accident:** "The Apollo 13 mission was aborted and the spacecraft returned to Earth. The RTG was attached to the lunar module, which broke up on reentry. The RTG heat source reentered the Earth atmosphere intact, with no release of plutonium, and currently is located deep in the Tonga trench in the Pacific Ocean. Extensive testing of RTGs in sea water has been conducted, and there will be no release of plutonium over time from this unit." [USDOE/a]

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18 One DoE list [USDOE/d, pages 15/16] also mentions Apollo 11 which was launched on July 16, 1969. It states 'ALRH' as the power source. The text continues to say that Apollo 11 was equipped with RHUs (Radioisotope Heater Units) for the seismic experimental package. Therefore it may be assumed that no RTG was on board for this mission.
19 Apollo 13 did not reach the moon; see below.
<table>
<thead>
<tr>
<th>Name:</th>
<th>Status:</th>
<th>Estimated Life Duration:</th>
<th>Power Source:</th>
<th>Number:</th>
<th>Source Term:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kosmos 367</td>
<td>in orbit</td>
<td>600a yrs</td>
<td>reactor</td>
<td>1</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Launch Date:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct. 3, 1970</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td>Country:</td>
<td></td>
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<td></td>
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<td>USSR</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mission Type:</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>RORSAT</td>
<td></td>
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<td></td>
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<tr>
<td>Launch Site:</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tyuratam</td>
<td></td>
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</tr>
<tr>
<td>See Kosmos 198.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Name:</th>
<th>Power Source:</th>
<th>Number:</th>
<th>Source Term:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 14</td>
<td>SNAP-27</td>
<td>1</td>
<td>44,500 Curies</td>
</tr>
<tr>
<td>Launch Date:</td>
<td>Jan. 31, 1971</td>
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</tr>
<tr>
<td>Country:</td>
<td>U.S.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission Type:</td>
<td>Lunar surface (NASA)</td>
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<td></td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Cape Canaveral, Florida</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Status:</td>
<td>on moon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>See Apollo 12. “RTG operated for over 6.5 years until station was shut down.” [USDOE/d, page 15/16]</td>
<td></td>
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<table>
<thead>
<tr>
<th>Name:</th>
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<th>Source Term:</th>
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<tbody>
<tr>
<td>Kosmos 402</td>
<td>reactor</td>
<td>1</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Launch Date:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>April 1, 1971</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission Type:</td>
<td>RORSAT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Status:</td>
<td>in orbit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated Life Duration: 600a yrs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>See Kosmos 198.</td>
<td></td>
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<th>Name:</th>
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<tbody>
<tr>
<td>Apollo 15</td>
<td>SNAP-27</td>
<td>1</td>
<td>44,500 Curies</td>
</tr>
<tr>
<td>Launch Date:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>July 26, 1971</td>
<td></td>
<td></td>
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<td>Country:</td>
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<td></td>
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<td>Mission Type:</td>
<td>Lunar surface (NASA)</td>
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<td>Launch Site:</td>
<td>Cape Canaveral, Florida</td>
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<td></td>
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<tr>
<td>Status:</td>
<td>on Moon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>See Apollo 12. “RTG operated for over 6 years until station was shut down.” [USDOE/d, page 15/16]</td>
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<th>Name:</th>
<th>Power Source:</th>
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<th>Source Term:</th>
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<tr>
<td>Kosmos 469</td>
<td>reactor</td>
<td>1</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Launch Date:</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Dec. 25, 1971</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Country:</td>
<td>USSR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission Type:</td>
<td>RORSAT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Status:</td>
<td>in orbit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated Life Duration: 600a yrs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>See Kosmos 198.</td>
<td></td>
<td></td>
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</tr>
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</table>
Nuclear powered space missions

Name: Pioneer 10
Launch Date: March 2, 1972
Country: U.S.
Mission Type: Planetary/solar system escape (NASA)
Launch Site: Cape Canaveral, Florida

Power Source: SNAP-19
Number: 4
Source Term: 80,000 Curies

Status: departed solar system

"RTGs still operating. Spacecraft successfully operated to Jupiter and is now beyond orbit of Pluto." [USDOE/d, page 15/16]

Other information sources [NSSDC/c and TRW] give March 3, 1972, as the launch date.

Name: Apollo 16
Launch Date: April 16, 1972
Country: U.S.
Mission Type: Lunar surface (NASA)
Launch Site: Cape Canaveral, Florida

Power Source: SNAP-27
Number: 1
Source Term: 44,500 Curies

Status: on Moon

See Apollo 12. "RTG operated for about 5.5 years until station was shut down." [USDOE/d, page 15/16]

Name: Kosmos 516
Launch Date: Aug. 21, 1972
Country: USSR
Mission Type: RORSAT
Launch Site: Tyuratam

Power Source: reactor
Number: 1
Source Term: 31.1 kg HEU-235

Status: in orbit
Estimated Life Duration: 600a yrs

See Kosmos 198.

Name: "Transit" (Triad-01-1X)
Launch Date: Sept. 2, 1972
Country: U.S.
Mission Type: Navigational (US Air Force)
Launch Site: Vandenberg AFB, California

Power Source: Transit-RTG
Number: 1
Source Term: 24,000 Curies

Status: in orbit

"RTG still operating." [USDOE]

Name: Apollo 17
Launch Date: Dec. 7, 1972
Country: U.S.
Mission Type: Lunar surface (NASA)
Launch Site: Cape Canaveral, Florida

Power Source: SNAP-27
Number: 1
Source Term: 44,500 Curies

Status: on Moon

See Apollo 12. "RTG operated for almost 5 years until station was shut down." [USDOE/d, page 15/16]

/d, pages 15/16]
Name: Nimbus V  
Launch Date: Dec. 11, 1972  
Country: U.S.  
Mission Type: Meteorological (NASA)  
Launch Site: Vandenberg AFB, California  
Status: in orbit

See Nimbus IV. The satellite was deactivated on March 29, 1983 [FSU/d].

Name: Pioneer 11  
Launch Date: April 5, 1973 (?)  
Country: U.S.  
Mission Type: Planetary/trans-solar trajectory (NASA)  
Launch Site: Cape Canaveral, Florida  
Status: departed solar system

There is contradictory information about the RTG operation: „RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.” [USDOE/d, pages 15/16] But: „The Mission of Pioneer 11 has ended. Its RTG power source is exhausted.” [NASA/h] The latter is confirmed by another source: „Instrument power sharing began in February 1985 due to declining RTG power output. Science operations and daily telemetry ceased on September 30, 1995, when the RTG power level was insufficient to operate any experiments.” [NSSDC/d] DoE states: „The spacecraft contained two [sic?] nuclear electric-power generators, which generated 144 W at Jupiter, but decreased to 100 W at Saturn.” [USDOE/a]

As for Pioneer 10, contradictory information is given about the launch date. Other information sources (NSSDC/d and TRW, page 151] give April 6, 1973, as the launch date.

Name: Kosmos  
Launch Date: April 25, 1973  
Country: USSR  
Mission Type: RORSAT  
Launch Site: Tyuratam  
Status: failed to orbit

See Kosmos 198.

Accident: The TRW Space Log 1996 lists this mission as „Failed to orbit. Rorsat.” [TRW, page 152] Proposition One adds „Location: Pacific Ocean, north of Japan. Radiation released from the reactor was detected.” [PROP1] No further details about this accident could be found

Name: Kosmos 626  
Launch Date: Dec. 27, 1973  
Country: USSR  
Mission Type: RORSAT  
Launch Site: Tyuratam  
Status: in orbit  
Estimated Life Duration: 600a yrs

See Kosmos 198.
<table>
<thead>
<tr>
<th>Name: Kosmos 651</th>
<th>Power Source: reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date: May 15, 1974</td>
<td>Number: 1</td>
</tr>
<tr>
<td>Country: USSR</td>
<td>Source Term: 31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type: RORSAT</td>
<td>Status: in orbit</td>
</tr>
<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
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</table>

See Kosmos 198.

<table>
<thead>
<tr>
<th>Name: Kosmos 654</th>
<th>Power Source: reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date: May 17, 1974</td>
<td>Number: 1</td>
</tr>
<tr>
<td>Country: USSR</td>
<td>Source Term: 31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type: RORSAT</td>
<td>Status: in orbit</td>
</tr>
<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
</tr>
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</table>

See Kosmos 198.

<table>
<thead>
<tr>
<th>Name: Kosmos 723</th>
<th>Power Source: reactor</th>
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</thead>
<tbody>
<tr>
<td>Launch Date: April 2, 1975</td>
<td>Number: 1</td>
</tr>
<tr>
<td>Country: USSR</td>
<td>Source Term: 31.1 kg HEU-235</td>
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<tr>
<td>Mission Type: RORSAT</td>
<td>Status: in orbit</td>
</tr>
<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
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</table>

See Kosmos 198.

<table>
<thead>
<tr>
<th>Name: Kosmos 724</th>
<th>Power Source: reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date: April 7, 1975</td>
<td>Number: 1</td>
</tr>
<tr>
<td>Country: USSR</td>
<td>Source Term: 31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type: RORSAT</td>
<td>Status: in orbit</td>
</tr>
<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
</tr>
</tbody>
</table>

See Kosmos 198.

<table>
<thead>
<tr>
<th>Name: Nimbus VI</th>
<th>Power Source: SNAP-19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date: June 12, 1975</td>
<td>Number: 2</td>
</tr>
<tr>
<td>Country: U.S.</td>
<td>Source Term: 37,000 Curies</td>
</tr>
<tr>
<td>Mission Type: Meteorological (NASA)</td>
<td>Status: in orbit; broke up</td>
</tr>
<tr>
<td>Launch Site: Vandenberg AFB, California</td>
<td></td>
</tr>
</tbody>
</table>

See Nimbus IV.

**Accident?:** Broke up into 236 parts; currently tracked are 190; date of event: May 01, 1991. This is NASA information [JSC/a]. No further information is given, therefore it is not clear whether it is the satellite which broke up and what happened to the RTGs.
**Name**: Viking 1  
**Launch Date**: Aug. 20, 1975  
**Country**: U.S.  
**Mission Type**: Mars surface (NASA)  
**Launch Site**: Cape Canaveral, Florida  
**Power Source**: SNAP-19  
**Number**: 2  
**Source Term**: 40,980 Curies  
**Status**: on Mars  

"RTGs operated for over 6 years until lander was shut down." [USDOE/d, page 15/16] The RTGs are contained in the Viking Lander, not in the orbiter. Another NASA document adds the following information: "Power was provided by two radioisotope thermal generator (RTG) units affixed to opposite sides of the lander base, each containing plutonium 238, providing 70 W continuous power." [NSSDC/e]

**Name**: Viking 2  
**Launch Date**: Sept. 9, 1975  
**Country**: U.S.  
**Mission Type**: Mars surface (NASA)  
**Launch Site**: Cape Canaveral, Florida  
**Power Source**: SNAP-19  
**Number**: 2  
**Source Term**: 40,980 Curies  
**Status**: on Mars  

See Viking 1. "RTGs operated for over 4 years until relay link was lost." [USDOE/d, page 15/16] According to the TRW Space Log 1996, the lander operated less: "Lander died April 12, 1978." [TRW, page 167]

**Name**: Kosmos 785  
**Launch Date**: Dec. 12, 1975  
**Country**: USSR  
**Mission Type**: RORSAT  
**Launch Site**: Tyuratam  
**Power Source**: reactor  
**Number**: 1  
**Source Term**: 31.1 kg HEU-235  
**Status**: in orbit  
**Estimated Life Duration**: 600a yrs  

See Kosmos 198.

**Name**: LES 8  
**Launch Date**: March 14, 1976  
**Country**: U.S.  
**Mission Type**: Communications (US Air Force)  
**Launch Site**: Cape Canaveral, Florida  
**Power Source**: MHW-RTG  
**Number**: 2  
**Source Term**: 159,000 Curies  
**Status**: in orbit  

"RTGs still operating." [USDOE/d, page 15/16]

**Name**: LES 9  
**Launch Date**: March 14, 1976  
**Country**: U.S.  
**Mission Type**: Communications (US Air Force)  
**Launch Site**: Cape Canaveral, Florida  
**Power Source**: MHW-RTG  
**Number**: 2  
**Source Term**: 159,000 Curies  
**Status**: in orbit  

"RTGs still operating." [USDOE/d, page 15/16]
Name: Kosmos 860
Launch Date: Oct. 17, 1976
Country: USSR
Mission Type: RORSAT
Launch Site: Tyuratam
Power Source: reactor
Number: 1
Source Term: 31.1 kg HEU-235
Status: in orbit
Estimated Life Duration: 600a yrs

See Kosmos 198.

Name: Kosmos 861
Launch Date: Oct. 21, 1976
Country: USSR
Mission Type: RORSAT
Launch Site: Tyuratam
Power Source: reactor
Number: 1
Source Term: 31.1 kg HEU-235
Status: in orbit
Estimated Life Duration: 600a yrs

See Kosmos 198.

Name: Voyager 2
Launch Date: Aug. 20, 1977
Country: U.S.
Mission Type: Planetary/trans-solar trajectory (NASA)
Launch Site: Cape Canaveral, Florida
Status: departed solar system
"RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, Uranus, Neptune, and beyond." [USDOE/d, pages 15/16]

Power Source: MHW-RTG
Number: 3
Source Term: 240,000 Curies

Name: Voyager 1
Launch Date: Sept. 5, 1977
Country: U.S.
Mission Type: Planetary/trans-solar trajectory (NASA)
Launch Site: Cape Canaveral, Florida
Status: departed solar system
"RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond." [USDOE/d, pages 15/16] Another DoE document points to the fact that "...the Voyager spacecraft ...[has been] providing data over the last 20 years. The Voyager spacecraft are expected to provide data for another 25 years." A NASA Voyager Project Information specifies: "Power System: Radioisotope Thermal Generators (RTGs) of 420 W. ... Data collection continues as the recently renamed Voyager Interstellar Mission searches for the edge of the solar wind's influence (the heliopause) and exits the solar system." [NASA/k]
**Name:** Kosmos 952  
**Launch Date:** Sept. 16, 1977  
**Country:** USSR  
**Mission Type:** RORSAT  
**Launch Site:** Tyuratam

**Power Source:** reactor  
**Number:** 1  
**Source Term:** 31.1 kg HEU-235  
**Status:** in orbit  
**Estimated Life Duration:** 600a yrs

See Kosmos 198.

**Name:** Kosmos 954  
**Launch Date:** Sept. 18, 1977  
**Country:** USSR  
**Mission Type:** RORSAT  
**Launch Site:** Tyuratam

**Power Source:** reactor  
**Number:** 1  
**Source Term:** 31.1 kg HEU-235  
**Status:** decayed

See Kosmos 198.

**Accident:** The re-entry of Kosmos 954 is one of the best covered and most serious accidents of a nuclear powered space mission. DoE states: „Decayed Jan. 24, 1978; spread radioactive debris over western Canada at re-entry.” [USDOE/d, pages 15/16] RADNET details the amount of radioactive material which was spread: „Reentry inventories: 3TBq strontium-90; 131-I: 0.2 Bq; 137-Cs: 3TBq (81 Curies.)” [CENTER, quoting Health Physics, No. 47, pages 225-233]

In an article almost ten years after the accident, journalist Michael Bein describes the Canadian efforts to recover part of the radioactive material: „Operation Morning Light continued into October and eventually resulted, according to Canada’s Atomic Energy Control Board (AECB), in the estimated recovery of 0.1 percent of Cosmos 954’s nuclear core. Tens of millions of pepper-flake sized radioactive particles, comprising a fifth to a quarter of the core, remained scattered over a 124,000 square kilometer ‘footprint’, stretching southward from Great Slave Lake into northern Saskatchewan and Alberta. The clean-up of these populated and frequented areas and the recovery of a number of large satellite fragments from the more remote bush cost Canada nearly $14,000,000, of which only $3,000,000 was later recovered from the USSR.” [BEIN]

He continues: „Within a week after the Cosmos crash, U.S. President Carter called for »an agreement with the Soviets to prohibit earth-orbiting satellites with atomic radiation material in them.«” [BEIN] Although this request was not enforced afterwards, the incident resulted in broad discussions of the issue. „At the end of the year, in November 1978, the General Assembly of the United Nations authorized its Committee on the Peaceful Uses of Outer Space (UNCOPUOS) to establish a technical working group. The assembly also passed a resolution requesting that a country whose NPS [Nuclear Powered Satellite] is about to fall notify others of the impending danger.” [BEIN]

Many years later, in 1992, discussions in the UNCOPUOS resulted in the „Principles Relevant to the Use of Nuclear Power Sources in Outer Space” (resolution 47/68). This document “recognizes that nuclear power sources are essential for some missions, but that such systems should be designed so as to minimize public exposure to radiation in the case of accident.” [UN]

In the U.S., the accident provoked discussions not only on a political but also on a technical level: „Regarding the best form of dispersal upon re-entry, a 1979 DoE-commissioned safety
study found that "break-up of the reactor into non-respirable particles ... is preferable to uncontrolled intact re-entry or to high altitude vaporization." In other words, break-up into pepper-flake sized particles like those produced by Cosmos 954 is the best (as well as the most likely) form of reentry." [BEIN]

In the USSR, the opposite conclusion was drawn from the Cosmos 954 accident. It led to a re-design of the future nuclear powered Kosmos missions as described by the Federation of American Scientists: "Following the reentry of Kosmos 954 over Canada in 1978, the RORSAT reactor underwent several modifications, including the ability to eject the fuel assembly at the end of life, hopefully in the disposal orbit but prior to reentry in the event of accident, e.g. Kosmos 1402 in 1983. Between 1980 and 1988, at least 14 RORSATs did perform fuel assembly ejection in the higher altitude storage orbits. However, not until 1994 did terrestrial-based space surveillance sensors detect what may be large numbers of very small particles of NaK reactor coolant released when the fuel assembly was ejected." [FAS] (For more details see Kosmos 1176.)

**Name:** Nimbus VII  
**Launch Date:** Oct. 24, 1978  
**Country:** U.S.  
**Mission Type:** Meteorological /environmental research (NASA)  
**Launch Site:** Vandenberg AFB, California  
**Status:** in orbit

**Name:** Kosmos 1176  
**Launch Date:** April 29, 1980  
**Country:** USSR  
**Mission Type:** RORSAT  
**Launch Site:** Tyuratam  
**Status:** in orbit  
**Estimated Life Duration:** 600a yrs

This is the first mission where in addition to lifting the reactor to the higher storage orbit, 'core separation' was introduced, i.e. in a case of a re-entry the 'naked' core would completely burn up in the atmosphere rather than come back to Earth (see description of the FAS quoted for Kosmos 954 above.) This method was demonstrated a few years later, when Kosmos 1402 entered the Earth atmosphere and burned up.

Core separation had an unexpected side aspect which was described by NASA. In its April-June, 1997 edition of the *Orbital Debris Quarterly News*, NASA gives details about "a large number of small-debris objects injected into orbit with very low velocities relative to one another. ... Times of increased flux at 600 km altitudes were found to be associated with overhead passing of COSMOS 1900, A Radar Ocean Reconnaissance Satellite (RORSAT) orbiting around 720 km - providing a clue about, but not explaining the higher-altitude debris. Specially-configured measurements using the Haystack radar determined the orbital inclination of the debris source between 850 km and 1000 km to be between 63 and 67 degrees, matching that of the remaining orbiting RORSATs. The RORSAT design was examined to determine a possible cause of this debris and was found to contain a significant amount of coolant consisting of the liquid-metal alloy Sodium-Potassium (NaK). The leakage of this coolant from COSMOS 1900 and a number of other RORSATs, producing a large number of orbiting liquid metal spheres, was consistent with all observations." [KESSLER]
<table>
<thead>
<tr>
<th>Name: Kosmos 1249</th>
<th>Power Source:</th>
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</tr>
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<tr>
<td>Launch Date: March 5, 1981</td>
<td>Number:</td>
<td>1</td>
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<tr>
<td>Country: USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type: RORSAT</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
<td></td>
</tr>
</tbody>
</table>

See Kosmos 1172.

<table>
<thead>
<tr>
<th>Name: Kosmos 1266</th>
<th>Power Source:</th>
<th>reactor</th>
</tr>
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<tbody>
<tr>
<td>Launch Date: April 21, 1981</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country: USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type: RORSAT</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
<td></td>
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</table>

See Kosmos 1172.

<table>
<thead>
<tr>
<th>Name: Kosmos 1299</th>
<th>Power Source:</th>
<th>reactor</th>
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<tr>
<td>Launch Date: August 24, 1981</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country: USSR</td>
<td>Source Term:</td>
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<td>Mission Type: RORSAT</td>
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<td>in orbit</td>
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<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
<td></td>
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See Kosmos 1172. „Raised Sept. 6, 1981.” [TRW, page 208]

<table>
<thead>
<tr>
<th>Name: Kosmos 1365</th>
<th>Power Source:</th>
<th>reactor</th>
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</thead>
<tbody>
<tr>
<td>Launch Date: May 14, 1982</td>
<td>Number:</td>
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</tr>
<tr>
<td>Country: USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type: RORSAT</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
<td></td>
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See Kosmos 1172. „Raised Sept. 27, 1982.” [TRW, page 214]

<table>
<thead>
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<th>Name: Kosmos 1372</th>
<th>Power Source:</th>
<th>reactor</th>
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<td>Launch Date: June 1, 1982</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country: USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type: RORSAT</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
<tr>
<td>Launch Site: Tyuratam</td>
<td>Estimated Life Duration: 600a yrs</td>
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See Kosmos 1172. „Raised Aug. 11, 1982.” [TRW, page 215]
<table>
<thead>
<tr>
<th>Name:</th>
<th>Kosmos 1402</th>
<th>Power Source:</th>
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<tr>
<td>Launch Date:</td>
<td>August 30, 1982</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type:</td>
<td>RORSAT</td>
<td>Status:</td>
<td>decayed</td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

See Kosmos 1172.

**Accident:** The mission Kosmos 1402 is another one of the often mentioned accidents which occurred with nuclear powered space missions. It "decayed January 23, 1983; reactor core separated; completely burned-up." [ILR] Proposition One adds the following information: "Location: South Atlantic; 68 lbs uranium-238; it is unknown whether any debris reached the ground." [PROP1] According to Harro Zimmer, the reactor casing burned up on January 24, 1983 above the Indian Atlantic, the reactor core burned up on February 7, 1983, above the South Atlantic [ZIMMER, page 113].

<table>
<thead>
<tr>
<th>Name:</th>
<th>Kosmos 1412</th>
<th>Power Source:</th>
<th>reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date:</td>
<td>Oct. 2, 1982</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type:</td>
<td>RORSAT</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td>Estimated Life Duration: 600a years</td>
<td></td>
</tr>
</tbody>
</table>

See Kosmos 1172.

<table>
<thead>
<tr>
<th>Name:</th>
<th>Kosmos 1461</th>
<th>Power Source:</th>
<th>reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date:</td>
<td>May 7, 1983</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type:</td>
<td>RORSAT</td>
<td>Status:</td>
<td>in orbit; exploded?</td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

See Kosmos 1172.

**Accident:** The TRW Space Log 1996 mentions the following status: "In orbit: Rorsat. Exploded March 11, 1985." [TRW] A NASA report also mentions "Catalogued upon breakup: 158 parts; Currently tracked in orbit: 3 parts." [JSC/a] No information is given about the nuclear reactor. Therefore, it might be assumed that the spacecraft exploded after the reactor had been injected into the higher orbit. This mission is not listed in the Berlin database [ILR].

<table>
<thead>
<tr>
<th>Name:</th>
<th>Kosmos 1579</th>
<th>Power Source:</th>
<th>reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date:</td>
<td>June 29, 1984</td>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Country:</td>
<td>USSR</td>
<td>Source Term:</td>
<td>31.1 kg HEU-235</td>
</tr>
<tr>
<td>Mission Type:</td>
<td>RORSAT</td>
<td>Status:</td>
<td>in orbit</td>
</tr>
<tr>
<td>Launch Site:</td>
<td>Tyuratam</td>
<td>Estimated Life Duration: 600a years</td>
<td></td>
</tr>
</tbody>
</table>

Name: Kosmos 1607
Launch Date: Oct. 31, 1984
Country: USSR
Mission Type: RORSAT
Launch Site: Tyuratam

Power Source: reactor
Number: 1
Source Term: 31.1 kg HEU-235
Status: in orbit
Estimated Life Duration: 600a years

See Kosmos 1172.

Name: Kosmos 1670
Launch Date: August 1, 1985
Country: USSR
Mission Type: RORSAT
Launch Site: Tyuratam

Power Source: reactor
Number: 1
Source Term: 31.1 kg HEU-235
Status: in orbit
Estimated Life Duration: 600a years

See Kosmos 1172.

Name: Kosmos 1677
Launch Date: August 23, 1985
Country: USSR
Mission Type: RORSAT
Launch Site: Tyuratam

Power Source: reactor
Number: 1
Source Term: 31.1 kg HEU-235
Status: in orbit
Estimated Life Duration: 600a years

See Kosmos 1172.

Name: Kosmos 1736
Launch Date: March 21, 1986
Country: USSR
Mission Type: RORSAT
Launch Site: Tyuratam

Power Source: reactor
Number: 1
Source Term: 31.1 kg HEU-235
Status: in orbit
Estimated life duration: 600 years

See Kosmos 1172.

Name: Kosmos 1771
Launch Date: August 20, 1986
Country: USSR
Mission Type: RORSAT
Launch Site: Tyuratam

Power Source: reactor
Number: 1
Source Term: 31.1 kg HEU-235
Status: in orbit
Estimated Life Duration: 600a years

See Kosmos 1172.
<table>
<thead>
<tr>
<th>Name</th>
<th>Power Source</th>
<th>Number</th>
<th>Source Term</th>
<th>Status</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kosmos 1818</td>
<td>Topaz I reactor</td>
<td>1</td>
<td>31.1 kg HEU-235</td>
<td>in orbit?</td>
<td>This was the first development test of a Topaz I reactor in space. For more details about the Topaz reactors, see Section 2.2. <em>The USSR/Russia - RORSAT, Topaz, And RTG.</em></td>
</tr>
<tr>
<td>Kosmos 1860</td>
<td>reactor</td>
<td>1</td>
<td>31.1 kg HEU-235</td>
<td>reactor in orbit</td>
<td>See Kosmos 1172. &quot;Craft split up July 20; RTG boosted to high orbit on July 28, 1987.&quot; [ILR, emphasis added]</td>
</tr>
<tr>
<td>Kosmos 1867</td>
<td>Topaz I reactor</td>
<td>1</td>
<td>31.1 kg HEU-235</td>
<td>in orbit?</td>
<td>See Kosmos 1818. This was the second development test of a Topaz I reactor in space.</td>
</tr>
<tr>
<td>Kosmos 1900</td>
<td>reactor</td>
<td>1</td>
<td>31.1 kg HEU-235</td>
<td>in storage orbit, but too low Estimated Life Duration: ?</td>
<td>Accident: The reactor was injected into a storage orbit but reached only an altitude of 720 km. This means the reactor will take considerably less than 600 years to decay.</td>
</tr>
</tbody>
</table>

20 Although the TRW Space Log 1996 [TRW] often gives information about the mission status, this is not the case for the two Topaz test missions Kosmos 1818 and Kosmos 1867.
Name: Kosmos 1932  
Launch Date: March 14, 1988  
Country: USSR  
Mission Type: RORSAT  
Launch Site: Tyuratam  
Power Source: reactor  
Number: 1  
Source Term: 31.1 kg HEU-235  
Status: in orbit  
Estimated Life Duration: 600a years

See Kosmos 1172. This was the last of the Soviet RORSAT missions. The missions were not continued by Russia. See also text for Kosmos 1818.

Name: Galileo  
Launch Date: Oct. 18, 1989  
Country: U.S.  
Mission Type: Planetary  
Launch Site: Cape Canaveral, Florida  
Power Source: GPHS-RTG  
Number: 2  
Source Term: 264,000 Curies  
Status: on interplanetary trajectory

"[Galileo] will involve the first-time use of the shuttle to transport a RTG power source to low Earth orbit." [NASA/b] This sentence is from the Draft Environmental Impact Statement for Project Galileo from 1985. Galileo actually became the first RTG powered mission to be launched by a shuttle. Before, however, the shuttle Challenger exploded during its January 28, 1986 launch. Seven astronauts died. The shuttle failure was eventually traced back to an O-ring seal. [TRW]

Therefore, two RTG missions, Galileo and Ulysses (see below) were delayed by several years. Finally, Galileo with its 49 pounds of plutonium was "lifted into space in October 1989 aboard the space shuttle Atlantis. Its mission involves a scheduled eight-year, deep-space voyage to the solar system's largest planet, Jupiter, and its four major moons. ... Galileo used a technique called gravity-assist to make the journey to Jupiter, which is nearly 500 million miles from Earth. ... The craft flew by Venus first, then made two passes by Earth. ...

The effectiveness of Galileo's instruments depends not only on RTG power, but also on heat from radioisotope heater units (RHU). Because the journey is far from the sun, these compact, light, and long-lasting RTGs and RHU units are the only effective power and heat sources for the Galileo mission. 22

Two RTGs provide electrical power to drive the Galileo spacecraft and its instruments. Each RTG produces about 285 watts of electricity at the beginning of the mission. One hundred and twenty small RHUs protect the craft's sensitive instruments from damage in the cold vacuum of outer space, which can reach -400 degrees Fahrenheit. ... Each heater unit produces about 1 watt of heat - about as much as a miniature Christmas tree bulb. But, it is enough to protect the instruments from the cold. ... None [of the Pioneer, Voyager, Ulysses, and Galileo] missions could have been accomplished without RTGs, which have played a key role in helping the U.S. establish its position as the world leader in outer planetary and space science exploration." [USDOE/d, page 14]

"If you think about it, we run our entire spacecraft on less than half the power of an average hair dryer!" [NASA/d] Without knowing this argument, the protest movement against the Cassini mission of 1997 used the same comparison to oppose the RTG usage: it was thought that 72.3 pounds of plutonium is too much to produce no more than 750 watts - less than an

---

21 The Berlin database [ILR] does not include this information. However, there is no reason to believe life duration should be any different from the other Kosmos missions.

22 Radioactive Heater Units (RHUs) were used on all Apollo and interplanetary missions. One recent example of RHU usage is the otherwise solar powered mission Sojourner/Pathfinder which landed on Mars on July 4, 1997.
ordinary hair dryer would consume. The argument is valid for Galileo too: "Galileo carried 49 pounds of Pu-238 on board to meet its electricity needs." [ANDERSON]

<table>
<thead>
<tr>
<th>Name: Ulysses</th>
<th>Power Source: GPHS-RTG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date: Oct. 6, 1990</td>
<td>Number: 1</td>
</tr>
<tr>
<td>Country: U.S. and ESA</td>
<td>Source Term: 132,500 Curies</td>
</tr>
<tr>
<td>Mission Type: Planetary/Solar</td>
<td>Status: on interplanetary trajectory</td>
</tr>
</tbody>
</table>

"The Ulysses mission is a joint enterprise of the European Space Agency and NASA, with the Jet Propulsion Laboratory in California providing major support. The craft was launched in October 1990 aboard the space shuttle Discovery. Its mission is to study the sun, the magnetic fields and streams of particles the sun generates, and the interstellar space below and above it. ... A single RTG provides all the power for instruments and other equipment aboard Ulysses. It is the only available power source capable of meeting the mission’s power requirements. Furthermore, the RTG will provide power for many years, enabling mission scientists and program managers to extend the life of the spacecraft by several years and reap more scientific benefits." [USDOE/d, pages 12 - 14]

<table>
<thead>
<tr>
<th>Name: Mars-96</th>
<th>Power Source: Pu generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date: Nov. 16, 1996</td>
<td>Number: 4</td>
</tr>
<tr>
<td>Country: Russia</td>
<td>Source Term: 200 g Pu-238</td>
</tr>
<tr>
<td>Mission Type: Mars</td>
<td>Status: decayed</td>
</tr>
</tbody>
</table>

This is the most recent and also a broadly covered accident of a nuclear powered space mission. Mars-96 was meant to send two penetrators and two launchers to Mars. The spacecraft, however, went out of control and re-entered the Earth atmosphere on November 17, 1996. The US Space Command, which followed the route of the craft, claims that it fell intact into the sea off the coast of Chile. Eye-witnesses, however, report they saw the craft falling down in the Chile/Bolivia border area - disintegrating and burning. So far, no proof for either version has been presented.

"No news stories have appeared that RADNET is aware of since this date. Presumably, if the plutonium had been recovered intact, some type of public relations effort would result to emphasize the safety of the upcoming Cassini mission. In lieu of a public relations news byte on this topic, one may assume the plutonium vaporized upon re-entry." [CENTER, written before the Cassini launch]

<table>
<thead>
<tr>
<th>Name: Cassini</th>
<th>Power Source: GPHS-RTG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date: Oct. 15, 1997</td>
<td>Number: 3</td>
</tr>
<tr>
<td>Country: U.S. and ESA</td>
<td>Source Term: 398,760 Curies</td>
</tr>
<tr>
<td>Mission Type: Planetary</td>
<td>Status: on interplanetary trajectory</td>
</tr>
</tbody>
</table>

This is a joint mission by NASA and the European Space Agency (ESA). After a Venus Venus Earth Jupiter gravity assist (VVEJGA), Cassini will be flung to Saturn, its moons, and its rings. The Earth flyby is scheduled for August 1999. The European probe Huygens shall be released over the Saturn moon Titan and collect information about Titan’s atmosphere and surface while
parachuting down. Cassini carries three RTGs with a total of 72 pounds of plutonium to produce 750 W of electrical energy for the on-board instruments.\textsuperscript{23}

4 NASA Plans

Russian information policy with respect to space missions differs considerably from U.S. policy. Therefore, this Chapter deals exclusively with NASA plans to launch nuclear powered space missions. It should, however, be pointed out that the Russian government and space organization also continue to push development of nuclear power systems for space missions. In February 1998, an ITAR-TASS press release announced that the „Russian government approved the concept of space nuclear power development in Russia“.\textsuperscript{24} According to this press information, the Russian government considers nuclear power in space as a key aspect for space and military technology.

4.1 „Upcoming Plutonium Launches“ (pre-1997)

During the Cassini protest campaign, one of the web pages from the Florida Coalition for Peace and Justice provoked particular discussions. It is titled „Upcoming Plutonium Launches“ and lists twelve planned NASA missions with a total of 132.5 kg plutonium [FCPJ]. NASA as well as DoE kept repeating that the list was wrong and that they did not know how the Florida Coalition came to post this information. However, the data given by the Florida Coalition are a perfect match of a spreadsheet with no indication as to its origin or creation date which is titled „Plutonium-238 Requirements (kg)“ [USDOE/c].\textsuperscript{25} The spreadsheet lists twelve mission names with additional information about the launch year, the number and watts of RTGs, the plutonium requirements for the years 1992 to 2001, and the total plutonium-238 requirements in kg. The following table repeats the information from the spreadsheet with the exception of the individual plutonium amounts for the years 1992-2001.

<table>
<thead>
<tr>
<th>Table 2: Plutonium-238 Requirements (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Year of Launch</strong></td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td><strong>Outer Solar System</strong></td>
</tr>
<tr>
<td>Cassini</td>
</tr>
<tr>
<td>Comet Nucleus Mission</td>
</tr>
<tr>
<td>Pluto Flyby</td>
</tr>
<tr>
<td>Mars</td>
</tr>
</tbody>
</table>

\textsuperscript{23} For further details about Cassini, see the articles by Karl Grossman and Michio Kaku in this Working Paper.

\textsuperscript{24} Private communication with a Russian space engineer; he quoted an ITAR-TASS press release of February 10, 1998.

\textsuperscript{25} Although no origin is stated on the hardcopy available to the author of this article, it is safe to assume that the spreadsheet was created by DoE and lists the plutonium-238 inventory required to build the RTGs for the planned NASA missions. As the lists refers to requirements from 1992-2001, the spreadsheet has probably been created in 1992. Earlier compilation of the list is unlikely, as according to [JPL/CIT] a Pluto Flyby mission was first considered in 1992.
4.2 „Potential Future Nasa Space Missions With RTGs” (1997)

Although NASA insisted on the invalidity of the „Upcoming Plutonium Launches” list, the organization was rather reluctant to provide up-to-date information about nuclear power usage for their planned deep space missions. In August 1997, a few weeks before the Cassini start, NASA headquarters issued a Fact Sheet with the title „Information on potential future NASA space science missions which may be powered with Radioisotope Power Sources (RTGs or RHUs)”. As the Fact Sheet lists the conditions for RTG and RHU use as well as potential missions, it is quoted in full length here:

„Information on potential future NASA space science missions which may be powered with Radioisotope Power Sources (RTGs or RHUs).

Radioisotope Power Sources (RPSs) and/or RHUs are generally considered for potential use on missions constrained by one or more of the following conditions:

• the mission occurs too far from the sun to make feasible use of solar power,
• the mission occurs in a space radiation environment too harsh to allow sustained use of solar cells,
• the mission occurs near a planet's poles where solar illumination is insufficient for solar arrays,
• the mission occurs on a dust- or cloud-enshrouded world, or in a subsurface application, where the use of solar power is impractical or impossible,
• the mission must operate in night environments with time frames beyond practical battery capacity, and/or
• the mission occurs where the solar intensity is so high as to be damaging (i.e., very near sun environment).

Examples of potential space science missions that are under study [and] fall into one or more of these categories include:

• Europa (Jupiter's Moon) Ocean Explorer (Orbiter) - this mission would occur far from the
Sun (5 times the Earth-Sun distance), in an intense radiation environment, and with the possibility of lengthy eclipses.

- **Europa Lander** - this mission would not only occur far from the Sun in an intense radiation environment, with frequent day-night cycles and Jupiter solar eclipses, but might also involve submersible exploration of a Europa ocean.

- **Pluto Express (Flyby)** - this mission would occur very far from the Sun (30 times the Earth-Sun distance).

- **Titan (Saturn's Moon) Biologic Explorer** - this mission would involve the use of an aerobot within Titan's atmosphere and a data relay orbiter; both would be far from the Sun (9 times the Earth-Sun distance), and the aerobot would be operating in Titan's cloud enshrouded atmosphere.

- **Interstellar Probe** - this mission would occur at 150 to 200 times the Earth-Sun distance.

- **Mars landers, rovers, or penetrators** involving extended operations (2 to 19 years) in very dusty conditions, at extremely low temperatures, or in subsurface applications (generally, RHUs are required).

- **Venus lander** - would involve operation beneath dense clouds; carbon dioxide and sulfuric acid atmosphere.

The amount of plutonium-238 dioxide potentially required for each of these missions generally ranges between roughly 3 grams (one RHU) to 2 kg (for a 150 watt-electric class RPS).

Such missions are currently being studied, but are not yet approved. Other missions that potentially could require RPSs or RHUs are in the conceptual phase - the foregoing being examples that establish power requirements for technology planning purposes. August 1997“ [NASA/e]


In response to a Freedom of Information Act inquiry of journalistic professor Karl Grossman, NASA’s JPL finally issued another Fact Sheet in April 1998: „NASA FACTS: Future Spacecraft: Solar Arrays, Batteries, and Radioisotope Power and Heating Systems.” When he returned from the international annual meeting of the Global Network Against Weapons and Nuclear Power in Space which took place in the first week of April 1998 in Colorado Springs/Colorado, he found the long-asked-for information in his mail. At the same time, NASA made the fact sheet available in the Internet [JPL/f]. Shortly afterwards, the same text was re-posted on the Internet by NASA under a different web address. The title has been changed to „NASA Facts: Future Missions”, the layout has been improved, and all pictures have been included [JPL/e]. As this Fact Sheet states the current NASA policy with respect to nuclear powered space missions and future plans, it is re-printed in full length in this Working Paper.

In summary, the 1998 Fact Sheets says that no nuclear powered missions are planned for the next five years (RHU usage is mentioned in the Fact Sheet but not further considered in this section of the article). Three missions are „under advanced study”, i.e., „NASA generally accepts the concept, however, detailed spacecraft and mission design (and sometimes specific funding approval) are needed before development can begin”. Another five missions are „conceptual studies” which „means the mission is an idea that might be proposed by or to NASA but has not been selected for advanced study” [all quotes JPL/e].
In the 1998 Fact Sheet, the conditions given for RTG usage are the same as in the 1997 Fact Sheet. This is not quite the case for the planned missions. As an attempt is made to give more details about the planned missions below, the mission list according to the 1998 Fact Sheet is quoted here:

"Examples of future missions, which may require the use of radioisotope power systems are:

- **Pluto/Kuiper Express** (Adv. Study): Map the surface and characterize the atmosphere of Pluto and its moon Charon.
- **Europa Orbiter** (Adv. Study): Study Europa (a moon of Jupiter) in search of possible liquid water oceans beneath the surface ice.
- **Interstellar Probe** (Conceptual Study): Characterize interstellar dust and gas at 900 million miles from the sun and beyond.
- **Europa Lander** (Conceptual Study): Study the seismology and possibly penetrate the ice crust to reach a liquid water ocean.
- **Io Volcanic Observer** (Conceptual Study): Extensive study of Io’s (a moon of Jupiter) surface and volcanic activity.
- **Titan Organic Explorer** (Conceptual Study): Use landers or aerobots to investigate the surface and chemistry of Titan’s (a moon of Saturn) atmosphere.
- **Neptune Orbiter** (Conceptual Study): Extensive study of Neptune’s system.

4.4 Future RTG Development

In addition to the conditions and future missions, the 1998 NASA Fact Sheet gives some basic information about RTGs and RHUs. In this context, NASA basically repeats the information from the previous Fact Sheet: "NASA is working with the Department of Energy to identify power requirements of future spacecraft, and to design smaller and more efficient power systems. These power systems may only need to carry about 2-3 kg (about 4-7 lb) of nuclear material for power generation." [JPL/b]

The need to develop new RTGs is mentioned by several U.S. government organizations. DoE says: "NASA has identified a number of potential missions that can best or only be undertaken using radioisotope power and/or heat sources. These future missions depend upon two important conditions.

First, there must be a reliable and continuing supply of Pu-238 fuel from the U.S. Department of Energy. U.S. facilities that could supply Pu-238 are being considered, as are foreign sources such as Russia, England, and France.

Second, smaller and more efficient power systems will have to be developed consistent with NASA’s needs." [USDOE/d, pages 26/27]

In another document, DoE becomes more explicit about the infrastructure required to build RTGs – and about the importance of RTG development for ‘national security’: "In all, the Department has provided a total of 41 power sources for 24 missions since 1961. DoE continues to maintain the capability to provide power and heater systems to NASA for further missions.

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26 Identical to the Europa Ocean Explorer mission.
27 Identical to the Titan Biological Explorer mission.
The space and defense radioisotope thermoelectric generator program provides support for radioisotope power source development, demonstration, testing, and delivery. Radioisotope power sources are the enabling technology for space and terrestrial applications requiring proven, reliable and maintenance-free power supplies capable of producing up to several kilowatts of power and operating under severe environmental conditions for many years.

The program will develop new, state-of-the-art power supplies required to support both the National Aeronautics and Space Administration (NASA) space missions as well as the national security applications. The outyear planning for these missions reflects arrangements with the national security users, NASA, and the U.S. Department of Energy (DoE) to ensure the capabilities of the facility infrastructure to produce RTGs. This infrastructure represents the sole national capability to produce radioisotope power systems. Without these systems, critical national security activities and NASA missions to explore deep space and the surfaces of neighboring planets would not occur.”

DoE also describes technological solutions for nuclear spacecraft power supply other than the traditional RTGs: „One option is the dynamic isotope power systems (DIPS), which are much more efficient in converting heat into electricity than the RTGs used on recent missions. ... The range of technologies under investigation is wide. For instance, a process called Alkaline Metal Thermal to Electric Conversion (AMTEC) converts infrared radiation into electricity using liquid metal ions, which are charged atoms. By contrast, the thermo-photovoltaic (TPV) converter changes infrared radiation emitted by a hot surface into electricity. Design goals for AMTEC and TPV technology call for even more efficient conversion of heat into electricity of about 20-30%, or a three-fold increase over RTGs. The higher efficiencies of these new technologies mean that future spacecraft may require less Pu-238 than RTGs typically use. ...

Because of its many advantages, it seems likely that nuclear energy will continue to provide power on space missions into the next century, whether in RTGs, other advanced generators, or nuclear reactors.” [USDOE/a]

In May 1998, the U.S. General Accounting Office (GAO) published a report to U.S. Senator Barbara Boxer, „Space Exploration. Power Sources. for Deep Space Probes”. The report has its focus on the Cassini mission and gives an outlook to future NASA plans. It is one of two official government documents known to the author of this article which deals with financial details of RTG development:

„During the past 30 years, NASA, DoE, and DoD have invested over $180 million in solar array technology, the primary non-nuclear power source. In fiscal year 1998, NASA and DoD will invest $10 million to improve solar array systems, and NASA will invest $10 million to improve nuclear-fueled systems. ... There are no currently practical alternatives to using nuclear fueled power generation systems for most missions beyond the orbit of Mars. ...

NASA is studying eight future deep space missions between 2000 and 2015 that will likely require nuclear-fueled power systems to generate electricity for the spacecraft. None of these missions have been approved or funded, but typically about one-half of such missions are eventually funded and launched.” [USGOA, page 3, emphasis added]

„NASA and DoE are working on new nuclear-fueled generators for use on future space missions.

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29 In a DoE statement from March 1998 [USDOE/e] the figure given for R&D (research and development) alone, i.e. without actually building any RTGs, is $40.5 million. See table below.
NASA and DoE’s Advanced Radioisotope Power Source Program is intended to replace RTGs with an advanced nuclear-fueled generator that will more efficiently convert heat into electricity and require less plutonium dioxide fuel than existing RTGs. **NASA and DoE plan to flight test a key component of the new generator on a space shuttle mission.** The test system will use electrical power to provide heat during the test. If development of this new generator is successful, it will be used on future missions.” [USGOA, page 13, emphasis added]

In a statement explaining the DoE budget 1999, Director Terry R. Lash summarizes the requested budget as follows:

<table>
<thead>
<tr>
<th>Program Element</th>
<th>Request for FY 1999</th>
<th>Budget Authority ($ in Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nuclear Energy R&amp;D</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Radioisotope Power Systems</td>
<td>40.5</td>
<td>116.9</td>
</tr>
<tr>
<td>Test Reactor Area Landlord</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>University Nuclear Science and Reactor Support</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>Nuclear Energy Research Initiative</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>Nuclear Energy Plant Optimization</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>Nuclear Technology R&amp;D</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td><strong>Program Direction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facilities</td>
<td>23.6</td>
<td></td>
</tr>
<tr>
<td><strong>International Nuclear Safety</strong></td>
<td>35.0</td>
<td></td>
</tr>
<tr>
<td><strong>Uranium Programs</strong></td>
<td>66.7</td>
<td></td>
</tr>
<tr>
<td>Isotope Support</td>
<td>22.4</td>
<td></td>
</tr>
</tbody>
</table>

**Total Nuclear Energy, Science and Technology Request** 360.8

*Includes $31.2 million in activities transferred from the Environmental Management budget associated with the Fast Flux Test Facility.* [USDOE/e]

Terry Lash continues to give details about the individual items, among them Radioisotope Power Systems.

**ADVANCED RADIOISOTOPE POWER SYSTEMS**

The Department of Energy and its predecessor agencies have provided radioisotope power systems for use in space and terrestrial applications for over 35 years. These systems are safe, proven, reliable, maintenance free, and capable of producing either heat or electricity for many years under the conditions required for deep space and unattended terrestrial missions. The unique characteristics of these systems make them especially suited to applications where large arrays of solar cells or batteries are not practical, e.g., at large distances from the sun where there is little sunlight or in harsh environments. To date, the Department has provided over 40 radioisotope power systems for use on a total of 25 spacecraft; in addition, two spacecraft were launched with radioisotope heaters on board. In FY 1998, NASA launched the Cassini spacecraft to Saturn. Cassini is entirely electrically powered by three radioisotope thermoelectric generators provided by the Department. Many isotope power systems have also been provided for terrestrial applications. Critical national security activities and NASA missions to explore deep space and the surfaces of planets would not occur without these systems.
In FY 1999, the program will continue developing new power supplies required to support both future NASA space exploration such as a mission to Pluto and national security applications. The national security users will require upgraded versions of existing terrestrial power systems. Future missions by NASA will require both new radioisotope power systems as well as the continued use of radioisotope heater units. The emphasis will be on lighter weight, lower power systems. The R&D will include more efficient energy conversion technology and new materials. There will be an emphasis on developing a relatively standardized family of systems that could meet a range of power requirements based on mission needs at reasonable cost.

The outyear planning for future space missions reflects arrangements with the national security users, NASA, and the Department to ensure maintenance of the facility infrastructure to produce radioisotope power systems. This infrastructure represents the sole national capability to produce radioisotope systems. The Department of Energy recognized the need to keep these facilities operational, and maintenance level operations will continue at each facility with limited amounts of hardware being fabricated. Maintenance of this capability will allow for a quick transition into a production mode without having to requalify facilities and personnel as new missions become finalized. In accordance with arrangements with our customer agencies, NASA, or other users, will provide funds to the Department to pay for mission specific costs including development, hardware fabrication, and other support costs.

A key factor in the ability to provide radioisotope systems for future missions is to have an adequate supply of plutonium-238 (Pu-238) that is used in all of these systems. It is very important to note that Pu-238 is not weapons-grade material and is not useable as the explosive in nuclear weapons. The current inventory of this isotope, with the exception of approximately nine kilograms that were purchased from Russia, was produced in Savannah Rivers K-reactor and processing facilities that have been, or are in the process of being, shut down. In the near term, the inventory will be augmented by purchasing additional Pu-238 from Russia, while development of a domestic production source is investigated further. The Department is discussing with NASA a new funding approach that would have NASA provide the Department with funding prior to making purchases of Pu-238. This new approach could be implemented beginning in FY 1999.

The Advanced Radioisotope Power Systems Program is an important part of the R&D efforts of the Department. In conjunction with the user agencies, the Department will maintain the capability to supply these systems for future missions that are important to the exploration of space and vital to U.S. security interests." [USDOE/e]

With respect to the development of a new RTG type, Pluto Express seems to play a key role: "NASA has asked DoE to sponsor design studies on a lower-power RTG that could be used on the proposed Pluto Express mission, which is under very restrictive mass and cost constraints. In order to reduce both mass and the amount of plutonium-238 a number of advanced thermal-to-electric conversion options are being considered, including small Stirling engines, thermophotovoltaics (essentially solar cells tuned to the infrared radiation of the radioisotope heat source), and alkali metal thermal-to-electric conversion (AMTEC). Maintenance of these technology options is essential to meet the power requirements of the new, smaller, cheaper space missions such as the Pluto Express mission." [AIAA]
4.5 "Advanced Solar Arrays And Solar Reflectors"

NASA information about the future mission Io Volcanic Observer (see Section 4.6.5, Io Volcanic Observer) contains a link to another page titled "Advanced Solar Arrays and Solar Reflectors". This page shows two pictures subtitled "Linear Concentrator Array" and "Inflatable Antenna Experiment". The text of this Internet page describes development work for deep space solar technology (spelling changed by author of this paper):

"Improved solar array technology will enable solar-electric propulsion and inexpensive missions to the Jupiter System.

- 50-100 W required at Jupiter
- Up to 15 kW at 1 AU for SEP
- Efficiency exceeding 100 W/kg
- Radiation and thermal tolerance

Current solar array technology at 40 W/kg is too heavy for many future missions

- New millenium 'Scarlet'
- Inflatable demo completed May 1996

Solar concentrators can focus sunlight on collection surface/converter

Inflatibles or rigid surfaces

Inflatable technology also required to deploy large panels of advances solar arrays." [JPL/a]

4.6 Details About Future Missions

The missions mentioned by the Florida Coalition [FCPJ] and by NASA [NASA/d and JPL/e] amount to a total of 20 launches for which RTG usage has been considered in recent years. The following sections provide some basic information about the objectives of the individual missions. Where available, additional information about the missions' power supply or other features is also given. As will be shown in the quotations below, official NASA documents point to the feasibility of solar power alternatives for several of the RTG missions listed in the 1998 NASA Fact Sheet!

4.6.1 Comet Nucleus

"NASA has selected the 5th and 6th missions to be conducted on behalf of its DISCOVERY program for low-cost interplanetary probes. The US$216-million GENESIS spacecraft will be launched in January 2001 to collect solar wind particles and return them to Earth in August 2003. The US$154-million COMET NUCLEUS TOUR (CONTOUR) mission will be launched in July 2002 to flyby comets P/Encke in November 2003, P/Schwassmann-Wachmann-3 in June 2006 and P/d'Arrest in August 2008." [ORBITAL]

"Science Objectives CONTOUR's goals are to dramatically improve our knowledge of key characteristics of comet nuclei and to assess their diversity. The targets span the range from a very

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31 SEP = Solar Electric Propulsion
evolved comet (Encke) to a future 'new' comet such as Hale-Bopp. CONTOUR builds on the exploratory results from the Halley flybys, and will extend the applicability of data obtained by NASA's Stardust and ESA's Rosetta to broaden our understanding of comets. Key measurements include

- Imaging nuclei at resolutions of 4 m (25 times better than Giotto).
- Spectral mapping of nuclei at resolutions of 100-200 m.
- Detailed compositional data on both gas and dust in the near-nucleus environment at precisions comparable to those of Giotto or better ...

The CONTOUR Comets Encke: A unique object. Comet Encke has been observed at more apparitions than any other comet including Halley. It is one of the most evolved comets that still remains active. In its present orbit, Encke returns to perihelion (dist. ~ 0.34 AU) every 3.3 years. Because Encke has been in this orbit for thousands of years, its continued high level of activity is rather puzzling.

SW3: First discovered in 1930, the activity pattern of SW3 is usually very predictable. However, in late 1995, this comet displayed dramatic variability, and split into at least three pieces. When CONTOUR arrives in 2006, it is likely that relatively unmantled materials will be visible in the cleaved areas, and that evidence of internal structures will remain exposed.

d’Arrest: Since this comet’s discovery in 1851, the repeatability of its visual light curve from apparition to apparition suggests that the rotation state is stable, and that its surface outgassing vents change very little with time ...

CONTOUR Spacecraft
- ... Body-mounted solar array
- ... Designed for 0.75 to 1.5 AU solar distance“ [JHUAPL]

Comet Nucleus is part of NASA’s Discovery program. Discovery missions are not permitted to use RTGs. Therefore, Comet Nucleus will not use RTGs to produce electricity but solar arrays. This mission is no longer listed in the 1998 NASA Fact Sheet.

4.6.2 Europa Lander (Europa Lander Network)

“Europe stands out among outer solar system objects in that it may possess subsurface liquid water in global shells, regional zones, or in isolated pockets. As such the top science objective for such a mission is to detect and characterize these zones.” [NASA/i]

Not much information about this mission is provided in the NASA web. However, the information available clearly points to the feasibility of solar power for the mission.

“Science Objectives:
- Measure ice thickness
- Tomography of layers
- Chemical analysis of surface

32 “Radioisotope Thermal Generators (RTGs) are not permitted on Discovery missions proposed to this AO. Other, smaller radioactive sources (such as radioactive heating units or instrument calibration sources) are permitted.” [NASA/a]
Mission Description:
- Minimum of 3 landers though precursor mission could use just 1 for seismicity measurements
- Semi-hard landing with caging
- Some penetration of ice surface (for rad protection and seismic improvement)
- Precursor mission

Technology:
- "... Efficient, lightweight solar power generation at Jupiter distance..." [JPL/g]

This mission is listed as one of eight nuclear powered space missions in the 1998 NASA Fact Sheet.

4.6.3 Europa Orbiter (Europa Ocean Observer)
Europa Orbiter, which is also named Europa Ocean Explorer, is planned to be launched in 2002 or 2004. This mission is part of NASA’s Outer Planets Program.³³ NASA’s Solar System Exploration Subcommittee identified several criteria which should be addressed before deciding about the Europa Orbiter mission (radar sounder development, radiation tolerance of electronics, propulsion technology, and interpretation of additional Galileo science data, [NASA/i]) – development of non-nuclear power systems for the Europa mission is not one of them.

As for the Europa Lander mission, little information is available about the Europa Orbiter/Europa Ocean Observer mission. But the little information mentions feasibility of solar power for this mission:

Science Objectives:
- Verify presence of liquid layer
- Measure ice thickness and interior properties
- Image surface features

Technology:
- "... Efficient, lightweight solar power generation at Jupiter distance." [JPL/h]

This mission is listed as one of eight nuclear powered space missions in the 1998 NASA Fact Sheet.

4.6.4 Interstellar Probe
"In our present view of the large scale structure of the heliosphere, the solar wind flows radially outward to a ‘termination shock’ surrounded at somewhat greater distance by a contact surface called the heliopause, which is the boundary between solar wind and interstellar plasma. A bubble of solar wind therefore shields the inner heliosphere from the plasma, energetic particles, and fields of the interstellar medium; to observe these directly, one must get outside the heliopause. Although the size of the heliosphere is not certain, several recent estimates place the distance to the termination shock at ~80 to 90 AU³⁴, with the heliopause somewhat further beyond.

The Interstellar Probe Mission would be designed to cross the solar wind termination shock and heliopause and make a significant penetration into nearby interstellar space. The principal scientific objectives of this mission would be to (1) explore the structure of the heliosphere and its interaction

³³ About the Outer Solar System Program, the Solar System Exploration Subcommittee writes: "Technology development progress should govern mission selection, with the goals of conducting the overall program at the lowest possible cost and maximizing science return from the individual missions. A set of decision gates will be laid out to indicate when mission targets must be selected and what criteria will be used. Generally the final selection will be made about 3 years prior to launch." [NASA/i] Although technology development is analyzed by the Subcommittee, non-nuclear power supply is not an issue. Instead, one of the technology criteria are that „all top-priority needs can be met by existing programs” [NASA/i]. Other technology issues are lightweight, low-cost, high-performance chemical propulsion, sensor/detector and instrument development, and avionics development.

³⁴ That equals 80 to 90 times the distance between Sun and Earth.
with the interstellar medium; (2) explore the nature of the interstellar medium, and its implications for the origin and evolution of matter in the galaxy, and (3) investigate fundamental astrophysical processes occurring in the heliosphere and interstellar medium. ...

To accomplish its objectives an Interstellar Probe should acquire data out to a heliocentric distance of \( \sim 200 \) AU [which] requires spacecraft velocities of \( \sim 10 \) AU/year to achieve this within \( \sim 25 \) years or less.” [NASA/g]

„Technology-Requirements: Advanced propulsion and non-solar power source (if not RTGs) ...

Mission Description: ... Potential methods: close Jupiter/Sun flybys; nuclear or RTG electric propulsion.” [NASA/f]

This mission would operate at a distance from the sun where currently only RTGs can provide the required electricity. It is listed as one of eight nuclear powered space missions in the 1998 NASA Fact Sheet.

4.6.5 Io Volcanic Observer

Information provided about the Io Volcanic Observer mission explicitly points at the feasibility of solar power.

„Io’s extraordinary rates of volcanism and heat flow make it a prime target for the study of planetary evolution. Understanding how Io’s volcanism is generated and sustained is key to understanding how planets generate and lose heat. The Earth, while contrasting the styles of volcanism on Io with those of Moon, Mars and Venus, provides a window through which we can view mantle composition and differentiation on these different planets. Galileo’s recent results have shown that high temperature volcanism is abundant on Io, and that the active volcanic centers are more numerous than previously thought. ...

To understand this very active planet [sic! Io is a moon of Jupiter], a mission is needed which can unequivocally determine the total heat flow and the mechanism which sustains it, the degree of differentiation of the mantle and the composition of the lavas which rise from it, and the mechanism which feeds clouds surrounding Io. ...

Toirs which orbit Jupiter require a delta V of about 1.2 km/sec, which is achievable within Discovery resources. A flyby requires significantly less delta V, permitting a larger spacecraft (or larger solar panels). Solar Electric Propulsion (SEP) is practical and is a good match with the large solar arrays needed at 5.2 AU. Inflatable and concentrator arrays both appear useable at Jupiter, though the radiation effects can be serious for missions of long duration.” [JPL/o]

This evaluation is repeated in another NASA document: „Tech[ology]: ... Efficient, radiation-tolerant solar arrays.” [JPL/i] (See also Section 4.5 „Advanced Solar Arrays And Solar Reflectors”.)

This mission is listed as one of eight nuclear powered space missions in the 1998 NASA Fact Sheet.

4.6.6 Mars Missions (5 Launches)


Mars landers, rovers, or penetrators are listed as RTG missions in the 1997 but not in the 1998 NASA Fact Sheet. Quite on the contrary: a picture subtitle in the 1998 Fact Sheet explicitly explains: „The Mars Surveyor Program would embark on a mission to bring back soil samples from

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35 „Nuclear or RTG electric propulsion” is very imprecise. Nuclear propulsion has been under consideration for many years, is not identical with the RTG technology used to provide electrical energy for instruments, however.
Nuclear powered space missions

Mars. These samples would help us understand whether life ever existed on Mars. The Lander and Rover can use solar arrays and batteries for power, but may need RHUs to keep electrical components warm enough to survive the cold Martian nights." [JPL/e]

In all, NASA plans a total of ten Mars launches within the next years:

- Mars Surveyor '98 consisting of Mars Climate Orbiter (planned launch Dec. 10, 1998) and Mars Polar Lander (planned launch Jan. 3, 1999)
- Mars Surveyor 2001 consisting of the 2001 Orbiter (planned launch Jan. 27, 2001), the 2001 Rover (planned launch on April 3, 2001) and 2001 Lander (planned launch April 3, 2001)
- Mars Surveyor 2003 with an Orbiter, a Lander, and a Rover (planned launch May/June 2003)
- Mars Surveyor 2005 with an Orbiter and a Lander for sample acquisition and return of the samples to Earth (planned launch July/August 2005).36

4.6.7 Moon Missions (4 Launches)


One Moon mission, the Lunar Prospector, was launched by NASA on Jan. 6, 1998. The NASA web pages contain no information which points to any future planned Moon missions.

4.6.8 Neptune Orbiter

"The results from the highly successful Voyager Neptune encounter pose many profound questions that only follow-on missions will be able to answer. Recent investigations of other star systems have resulted in fundamental questions that may be approached through probing our solar system’s gas giants as astrophysical analogs and solar system laboratories. The Neptune Orbiter mission is a high priority part ... for the future NASA Solar System Exploration program. The potential science returned from a Neptune Orbiter mission is in the break through category and enabled by advanced technologies.” [JPL/p]

"Science Objectives
- Atmospheric structure and circulation at Neptune and Triton
- Ring particle physical properties, dynamics, and distribution
- Magnetosphere structure and dynamics
- Map the gravity field (Neptune)
- Composition, structure, and activity of Triton surface

Mission Description
- Delta-class launch vehicle
- Flight time: 6-7 years using advanced SEP
- Autonomous operation and navigation
- Aerocapture for orbit insertion
- Daily flybys of Triton possible“ [JPL/b]

In addition to investigating Neptune, the mission is also planned to explore Triton, Neptune’s largest moon. Although NASA plans to use high-power solar electric propulsion for this mission, the use of solar panels is not feasible at Neptune. Neptune is too far away from the Sun, consequently there is not sufficient light available.

This mission is listed as one of eight nuclear powered space missions in the 1998 NASA Fact Sheet.

36 For detailed information about the Mars missions, see http://mars.jpl.nasa.gov/
4.6.9 Pluto/Kuiper-Express (2 Launches)

"Pluto is the largest of a class of primordial bodies at the edge of our Solar System which have comet-like properties and remain relatively unmodified by warming from the Sun. Pluto is thought to be compositionally similar to Triton, the largest moon of Neptune, which was reconnoitered by Voyager 2. These two bodies may also be similar to Charon at 10 to 20 AU and the recently discovered Kuiper belt objects out at 40 AU and beyond. All of these objects probably hold important clues to the origin of comets and the evolution of the solar system. Pluto has a large moon, Charon, which has properties very different from Pluto, and this bizarre double body system may have resulted from a catastrophic planetary collision.

At the present time, Pluto has just passed perihelion at 30 AU and is now moving farther away from the Sun on its way out to 50 AU. Stellar occultation observations have shown that Pluto currently has a temporary atmosphere now that it has been warmed by the Sun during this very brief 'summer' in its 248 year orbit. It is anticipated that these gases will freeze out onto the planet's surface sometime over the next 2-3 decades. It is highly desirable to observe this atmosphere with UV and radio occultation experiments before it disappears, and to observe surface features and chemical makeup that may be obscured if and when the atmosphere collapses." [JPL/CIT]

"Planned launch date: 2001
Launch vehicle: Delta or Russian Proton
Planned on-orbit mass: <100 kg
Power System: Radioisotope Thermal Generators (RTGs) of 65 W

Originally designated the Pluto Fast Flyby (PFF), the Pluto Express mission is planned to be a two spacecraft mission designed to make studies of the planet Pluto and its satellite Charon. Its major science objectives are to: (1) characterize the global geology and geomorphology of Pluto and Charon; (2) map the composition of Pluto’s surface; and (3) determine the composition and structure of Pluto's atmosphere. Intended to reach Pluto as quickly as possible (before the tenuous Plutonian atmosphere can refreeze onto the surface as the planet recedes from the Sun), the two Pluto Express spacecraft will arrive one year apart after 6-9 years of travel, depending on the ultimate mass of the spacecraft. Studies of the double-planet system will begin 12-18 months prior to closest approach. The overall structure of the spacecraft is an aluminum hexagonal bus with no deployable structures. Power will be provided by radioisotope thermal generators (RTGs) similar in design to those used on earlier missions (e.g. Galileo). A potential cooperative effort with Russia may lead to the inclusion of Zone probes, to study the Plutonian atmosphere." [UNKNOWN]

The information about two launches for the Pluto-Kuiper Express mission is repeated in an official document: "The current plan is to have two launches to Pluto, each carrying one flight system and possibly attached probes." [JPL/CIT]

"In order to reduce the launch costs the Pluto Express spacecraft will loop around Venus three times, building momentum with each passing before getting a final tug at Jupiter to fling them on through the outer Solar System.

This trajectory path is one of several options being considered providing an opportunity to arrive at the distant double-planet system in 2013." [JPL/k]

The optimum trajectory is a major issue for NASA. The direct trajectory to Pluto would be preferred

37 That equals 10-20 times the distance between Sun and Earth.
38 This document also gives information about NASA’s effort to use state-of-the-art and miniaturized technology to keep the mission small (and therefore cheaper as a smaller launch vehicle can be used.) The article explains that many of the „enabling technologies result from breakthroughs by the Ballistic Missile Defense Organization (BMDO).” [JPL/CIT]
39 Cassini uses a Venus-Venus-Earth-Jupiter Gravity Assist (VVEJGA) trajectory.
but is considered too expensive as a large rocket with an additional stage would be required for the launch. "Today's funding environment" does not allow for this option. Therefore, a flyby trajectory must be chosen.

"In order to allow for lower cost missions on Delta or Molniya class launchers without the expense of an upper stage, there are other mission design options. Earth/Jupiter gravity assist trajectories can achieve flight times of around ten years, but require the spacecraft to be capable of surviving significantly higher radiation levels\textsuperscript{40}, and require a much larger onboard propulsion system. Another drawback with these trajectories is the amount of effort needed to ensure that the probability of an Earth impact during the Earth flyby is acceptably low. A straight Jupiter Gravity Assist (JGA) trajectory is available for Delta and Molniya class launchers in 2003 and 2004. ... There is an attractive option for a Venus/Venus/Jupiter Gravity Assist (VVVJGA) trajectory which avoids an Earth flyby and can be launched on a Delta or Molniya class vehicle without an upper stage, with a flight time of about 11.8 years, launching in March 2001. There is a backup Venus/Venus/Jupiter Gravity Assist (VVJGA) trajectory available in July 2002." [JPL/CIT]

Pluto is the last planet in our solar system. Its distance from the sun is so large that virtually no light is available which could be used to produce solar electricity. This mission is listed as one of eight nuclear powered space missions in the 1998 NASA Fact Sheet.

4.6.10 Solar Probe
As for several of the other missions, NASA documents show the feasibility of solar power for the Solar Probe mission:

"The solar corona is one of the last unexplored regions of the solar system and one of the most important to understand in terms of Sun-Earth connection. SOHO and Ulysses results have focused understanding of regions to the point when the in situ measurements are necessary for further progress.

This report describes a robust, scientifically important space mission to explore the source of the solar wind from inside the solar corona at 2 to 110 solar radii from the Sun.

Our primary science objective is to understand the processes that heat the solar corona and produce the solar wind. ...

The mission and spacecraft designs are partly derived from concepts developed for earlier missions but with important differences which result in cost saving and enhanced science return:

A science payload mass of under 16 kilograms, requiring less than 16 watts and a data return of up to 100 kilobits per second meets the focused science objectives." [JPL/l]

"The present design uses non-nuclear power systems, ..." [JPL/n] "As shown above [in a picture], low illumination solar panels will provide power for the spacecraft from 5 AU to 0.7 AU, where the panels will be discarded. In the baseline mission, high temperature arrays will be used from 0.7 to 0.2 AU, where this second set will be jettisoned. Power will be supplied by batteries from 0.2 AU to perihelion plus 14 hours. In a mission option, high temperature arrays which are currently under technological development will be used from 0.7 to 0.1 AU and will then be tucked into the spacecraft umbra inside 0.1 AU. They will be redeployed at 0.1 AU on the outbound leg and the mission will continue until perihelion plus 17 days." [JPL/m]

This mission is listed as one of eight nuclear powered space missions in the 1998 NASA Fact Sheet.

\textsuperscript{40} High natural background radiation is a mission problem in the Jupiter environment.
4.6.11 Titan Organic Explorer
(= Titan Biologic Explorer)

"Titan has an atmosphere with a higher surface pressure than Earth's that is filled with organic compounds produced by the action of sunlight. A Titan organic explorer would determine the composition of organic compounds in Titan's atmosphere and on its surface, and whether these organics display pre-biological characteristics." [OSS]

Although this mission is mentioned in several NASA documents, no further details are provided. Titan is a moon of planet Jupiter. The ESA probe Huygens of the joint ESA/NASA mission Cassini/Huygens (see Section 3, Past Missions – a Chronology for more details) is planned to descend to Titan and explore the moon's atmosphere.

Although not explicitly mentioned, it seems that Titan's atmosphere is so dense that not enough sunlight might pass through to power solar panels. This mission is listed as one of eight nuclear powered space missions in the 1998 NASA Fact Sheet.

4.6.12 Venus Lander

The full mission name is Venus Geophysical Network Pathfinder (VGNP) and includes a Venus surface lander. In addition to some mission details, Malin Space Science Systems, Inc. (MSSS) specifies the power supply of the mission as follows: "On top of the lander, beneath the boom, is the cylindrical housing of the radioisotope thermoelectric generator, which generates 6500 thermal watts to supply 260 electrical watts needed to power a three-stage refrigeration system. The system is capable of cooling the electronics, housed in a dewar, to about 80 deg. C. The VGNP is designed to survive in the 460 deg C, 93 bar ambient Venusian environment for at least one Earth year."

[MALIN/b]

According to MSSS, Venus Lander is planned to be launched in early June 1999 and due to arrive at Venus appr. 120 days later.

The MSSS document informs about the VGNP power generation in some detail:

"Although the science instruments and their support electronics require only a small amount of power (~12 W, only 5. W within the refrigerated dewar), the refrigeration subsystem itself will require a significant amount of uninterruptable electric power for the duration of the mission. Several options were examined in terms of meeting the following criteria:

1. The power system must operate in the ambient Venusian atmosphere for a period of at least one year.
2. The power system must utilize technology of a developed and proven nature. Modifications were allowed within the overall paradigm.
3. The power system must meet cost and schedule constraints consistent with a Discovery-class mission.

There are few power sources available at the surface of Venus. Batteries would not meet the mission duration requirements, and would have difficulty in the ambient environment. Sunlight reaching the Venusian surface is roughly 2% at its cloud tops, mostly long wavelength and very diffuse – that, along with the high operating temperature, precludes the use of solar cells. Although wind energy may be a potential source of power, it is probably unreliable for continuous operations on the timescale of a year. Brayton, high condenser temperature Rankine, and Sterling technologies are not reasonable power systems for reasons noted earlier. After careful consideration, Radioisotope Thermal Generators (RTGs) utilizing silicon-germanium thermo-electric elements were chosen as the most appropriate technology for this mission. Based primarily on a design utilized by Cassini..."
and planned for MESUR, General Electric/AstroSpace Space Power division have outlined a system which could operate on the Venussian surface." [MALIN/a]

It should be pointed out that MSSS mentions the involvement of General Electric (GE) in RTG development and production. After some explanations about required RTG modifications for the Venussian environment, the MSSS document continues to talk about financial matters:

"Future availability of RTGs is presently a topic of considerable discussion within the Federal government. The Department of Energy's (DoE) Special Projects office provides RTGs to NASA more or less at cost. NASA has not, in the past, been required to pay a fee towards maintaining DoE's ability to provide these devices. However, with the decrease in demand for weapons-grade Pu and other issues leading to the shutdown of DoE facilities, there is concern that RTGs may not be available in the future. This proposal assumes that NASA must maintain access to radioisotope power generation, both for large unmanned missions and for initial power systems for large space endeavors. Discussions with GE and DoE indicate their willingness and ability to meet the VGNP requirements, and the cost estimate given assumes a worst case wherein VGNP would be responsible for the entire production cost." [MALIN/a]

Venus Lander is part of the Discovery program, therefore RTG usage is not permitted. Consequently, this mission is no longer listed in the 1998 NASA Fact Sheet.

4.7 Future Missions Summary

Of the 20 missions which have been mentioned as nuclear powered missions during recent years, the 1998 Fact Sheet lists still eight (Pluto/Kuiper Express is listed as one mission although it will involve two launches.)

Of the eight missions listed, four are technically feasible only when RTGs are used (based on today's technology and under the assumption that Titan Organic Explorer can not be powered by solar arrays.)

For four of the eight missions listed in the latest Fact Sheet, however, other NASA information clearly shows that the missions can be done with solar power - and that corresponding planning is under way!

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41 These are the Mars missions; see above.
42 The MSSS document was written in 1996.
5 Conclusion

Currently, hundreds of kilograms plutonium and almost a metric ton of uranium circle the Earth on board of U.S. and Soviet spacecrafts - many of them on orbits which are all but safe. It is hoped, that the list in Chapter 3, Past Missions = a Chronology creates an awareness of just how huge these amounts are and how many accidents occurred. On an average, there is one accident for each seven space missions - this is also true for nuclear powered space missions.

Another obviously ignored problem might yet seem ahead. In the Orbital Debris Quarterly News, Volume 2, Issue 4 (1997), NASA’s Johnson Space Center pointed to a ‘mystery’: the slow disintegration of spacecrafts many years after launch. The author of this article can not evaluate the implications this might have for the nuclear powered U.S. satellites orbiting Earth. It should, however, not be excluded that disintegration could happen for such satellites also – with a sharp increase in the likelihood of RTGs decaying into the Earth atmosphere almost any time.

As degradation seems to be a serious and ‘mysterious’ spacecraft behavior, the beginning of the article is quoted here:

„Naval Space Operations Center Finds New Evidence of Debris Separations from Three Spacecraft by Nicholas Johnson

During July and August personnel of the Naval Space Operations Center, which serves as the alternate Space Control Center for the US Space Surveillance Network, detected five new debris from three spacecraft, each more than 15 years old. The causes of these ‘anomalous events’, which involve very low separation velocities, remain a mystery, although material degradation or small particle impacts are probable agents.

At least six polar-orbiting Transit satellites have generated debris more than 20 years after launch. Sometime between 20 and 23 July, a single object was released from Transit 17 (1967-92A, Satellite Number 2965), marking at least the fourth such event for this spacecraft since 1981. The last previous debris release was in December 1996 (see Orbital Debris Quarterly News, January 1997). The five debris previously cataloged with this source all exhibited high area-to-mass ratios and have decayed from orbit.

Another newly discovered debris has been traced to Transit 10 (1965-109A, Satellite Number 1864) which was also involved in a late 1996 release. The debris was found in early August, but orbital analysis could not determine when it had been created. The two debris pieces remain in orbits very similar to that of the parent.

In late August the NOAA 7 spacecraft (1981-59A, Satellite Number 12553) spawned at least three new debris, one of which was cataloged as Satellite Number 24935. The debris appear to have been released, perhaps at the same time, during 23-24 August. The spacecraft had previously released two debris on 26 July 1993, three years after spacecraft deactivation, but both decayed the following year.

The mechanism behind the generation of anomalous event debris large enough to be tracked by ground-based sensors remains poorly understood. Some space objects, e.g., U.S. Transit spacecraft and Soviet Vostok upper stages, seem predisposed to such incidents and, therefore, are probably related to the design or materials selection of the vehicles. Transit spacecraft are likely to exhibit multiple events, whereas the Vostok upper stages appear limited to a single event. However, only a small percentage of vehicles in these families are involved in anomalous events.“ [JSC/b]
For information about nuclear powered Transit missions, see Chapter 3, Past Missions – a Chronology.

In addition to the past accidents and the recently observed ‘anomalous events’, the burden left to future generations has so far been completely neglected. Orbits of 900 km altitude for the Soviet RORSAT satellites are safe a few hundred years – but eventually they will fall back to Earth. Responsibility demands to think about methods to prevent re-entry and burn-up of these generators and reactors today, rather than leave the problem to our descendants. And of course, alternatives to nuclear powered space missions should be found. The innovative approach of the European Space Agency described in Section 2.3, Other Nations - „RTG Technology Is Not Available” gives an example for future-oriented solutions. In addition, NASA documents clearly show that for four of the eight suggested nuclear powered space missions the solar alternative is feasible.

6 Acronyms

The following acronyms were used in this article:

ACE Atomic Energy Commission (U.S.)
AECB Atomic Energy Control Board (Canada)
AFB Air Force Base
AMTEC Alkaline Metal Thermal to Electric Conversion
AO Announcement of Opportunity
AU Astronomical Unit (1 AU = distance between Sun and Earth)
Bq Becquerel
C Celsius
Ci Curie
DIPS Dynamic Isotope Power Systems
DoD Department of Defense (U.S.)
DoE Department of Energy (U.S.)
ESA European Space Agency
ESTEC European Space Research and Technology Centre
FEIS Final Environmental Impact Statement
GAO General Accounting Office (U.S.)
GE General Electric
GPHS General Purpose Heat Source
HEU Highly Enriched Uranium
JGA Jupiter Gravity Assist
JSC Johnson Space Center (part of NASA)
K Kelvin
lbs pound; 1 lbs = 453,59 g
MSSS Malin Space Science Systems, Inc.
NASA National Aeronautics and Space Administration (U.S.)
NPS Nuclear Powered Satellite
PFF Pluto Fast Flyby
Pu-238 plutonium-238
Radar Radio detecting and ranging
RHU Radioisotope Heater Unit
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<tr>
<td>RORSAT</td>
<td>Radar Ocean Reconnaissance Satellite</td>
</tr>
<tr>
<td>RPS</td>
<td>Radioisotope Power Source</td>
</tr>
<tr>
<td>RTG</td>
<td>Radioisotope Thermoelectric Generator</td>
</tr>
<tr>
<td>SEP</td>
<td>Solar Electric Propulsion</td>
</tr>
<tr>
<td>SNAP</td>
<td>Space Nuclear Auxiliary Power</td>
</tr>
<tr>
<td>TFE</td>
<td>Thermionic Fuel Element</td>
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<td>TPV</td>
<td>Thermo-Photovoltaic</td>
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<td>uranium-235</td>
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<td>UNCOPUOS</td>
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<td>USSR</td>
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<td>VGNP</td>
<td>Venus Geophysical Network Pathfinder</td>
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<td>WE</td>
<td>Watts electric</td>
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Future Missions

NASA currently has over 30 spacecraft in Earth orbit and in deep space on missions of scientific exploration. Most of these missions rely primarily on solar power, generated using large wing-like solar arrays, along with battery back up, for electrical power to operate the on-board scientific equipment, cameras, radio communication systems and computers. Missions which operate in regions of space where solar arrays cannot provide adequate power rely on radioisotope power systems (e.g., Radioisotope Thermoelectric Generators [RTGs]), which generate electrical power from the heat of decaying plutonium in specially designed rugged containers.

Over the next 5 years NASA has in the planning stages (i.e., the mission is being funded and is under development) about 20 space science missions. None of those missions require the use of radioisotope power sources and 2 may require small Radioisotope Heater Units (RHUs) like the ones used for the Mars Pathfinder rover. Additionally, about 30 other potential missions are under study and may be selected for development. There are two categories of study: "Advanced Study" means NASA generally accepts the concept, however, detailed spacecraft and mission design (and sometimes specific funding approval) are needed before development can begin. Currently there are 3 missions under advanced study that may require radioisotope power systems and RHUs, and 2 missions that may need RHUs for heating purposes. "Conceptual Study" means the mission is an idea that might be proposed by or to NASA but has not been selected for advanced study. Currently there are 5 conceptual missions that may require radioisotope power systems and RHUs, and 1 that may require RHUs for heating purposes. Any mission implementation is dependent on a decision to proceed after the required environmental review process is completed.
Below are some examples of missions that will be able to use arrays of solar cells and batteries to enable the missions.

- **Deep Space-1** (Planned to launch in July 1998): Validate advanced spacecraft and instrument technologies (including ion propulsion and high efficiency solar arrays).
- **Stardust** (Planned to launch in February 1999): Collect interstellar dust and cometary material by flying by a comet and returning the sample to Earth.
- **Space InfraRed Telescope Facility** (Planned): Collect information about the early universe using infrared imaging & spectroscopy.
- **Mars 2001 Orbiter** (Planned): Globally map elemental composition of the surface.
- **Mars 2003 Orbiter** (Adv. Study): Establish a sustained communications and navigation capability at Mars.

Sometimes it is not possible to use arrays of solar cells for space missions. This is especially true when a mission is constrained by one or more of the factors below:

- too far from the sun to make use of solar power
- in a space radiation environment too harsh to allow sustained use of solar cells (e.g., very near the Sun)
- landing near a planet's poles where solar illumination is insufficient
- in night environments with time frames beyond practical battery capacity
- on a dust- or cloud-enshrouded world, or in a subsurface application, where the use of solar power is impractical or impossible
When arrays of solar cells and batteries are not feasible, other power designs are needed. Similar to past missions to the outer solar system, some future explorations may require radioisotope power systems to generate electricity for the scientific instruments and for the spacecraft or lander. For example, the recent Cassini mission to Saturn needed three RTGs to power the scientific instruments and the Saturn Orbiter itself. Examples of future missions, which may require the use of radioisotope power systems are:

- **Pluto/Kuiper Express** (Adv. Study): Map the surface and characterize the atmospheres of Pluto and its moon Charon.
- **Europa Orbiter** (Adv. Study): Study Europa (a moon of Jupiter) in search of possible liquid water oceans beneath the surface ice.
- **Interstellar Probe** (Conceptual Study): Characterize interstellar dust and gas at 900 million miles from the sun and beyond.
- **Europa Lander** (Conceptual Study): Study the seismology and possibly penetrate the ice crust to reach a liquid water ocean.
- **Io Volcanic Observer** (Conceptual Study): Extensive study of Io's (a moon of Jupiter) surface and volcanic activity.
- **Titan Organic Explorer** (Conceptual Study): Use landers or aerobots to investigate the surface and chemistry of Titan's (a moon of Saturn) atmosphere.
- **Neptune Orbiter** (Conceptual Study): Extensive study of Neptune's system.

The RTG design used on the Cassini mission generates electrical power by converting the heat from the natural decay of plutonium.
through the use of solid-state thermoelectric converters. It is about 113 cm (about 44 in) long and about 43 cm (about 17 in) in diameter, and contains about 10.8 kg (about 24 lb) of plutonium dioxide. RTGs have been designed to contain their plutonium dioxide in the event of launch or reentry from Earth orbit accident. NASA is working with the Department of Energy to identify power requirements of future spacecraft, and to design smaller and more efficient power systems. These power systems may only need to carry about 2-3 kg (about 4-7 lb) of nuclear material for power generation.

Some future missions may require the use of RHUs in order to keep a spacecraft, lander, or rover electrical components warm enough to function. For example, the 1997 Mars Pathfinder rover, Sojourner, used three RHUs to keep its electronics from freezing during the cold Martian nights. RHUs provide about one watt of heat, derived from the radioactive decay of plutonium. They are cylindrical in shape, about 2.5 cm (about 1 in) in diameter and about 3.2 cm (about 1.3 in) long, and contain about 2.7 g (about 0.1 oz) of plutonium dioxide. RHUs have been designed, built, and tested to contain their plutonium dioxide even if they were to be exposed to an accident during launch or reentry from Earth orbit. Missions that may require the use of RHUs include:

- **Mars 2001 Lander/Rover** (Planned): Explore a site for biologic or prebiologic processes and store samples for possible return to Earth by Mars Sample Return mission.
- **Mars 2003 Lander/Rover** (Planned): Akin to Mars 2001 Lander/Rover, but would explore a different site.
- **Mars Sample Return** (Adv. Study): Mission to Mars that could return to Earth samples of Martian surface material and atmosphere for analysis.
- **Deep Space-4** (Adv. Study): Demonstrate advanced spacecraft technologies by landing a probe (Champollion) on a comet nucleus and possibly returning a sample to Earth.
- **Jupiter Deep Probe** (Conceptual Study): Study Jupiter's composition and atmospheric structure at multiple locations.

For more information about NASA's space science enterprise, visit the NASA home page at: ________________________

Office of Space Science Public Affairs Office: 202/358-1547
Nuclear thermoelectric power units in Russia, US and European Space Agency research programs

A.A. Pustovalov

Abstract

This paper discusses the role and the significance of the radionuclide thermoelectric generators (RTG) in space research as reliable long-life service autonomous sources for power and heat supply. There are concerns connected with the RTG design and provisions for radiation safety in standard and emergency situations. The main characteristics of basic RTGs which were used in USA and Russia space programs are presented. The prospects of the use of RTGs in future US, Russian and ESA space programs are shown.

Introduction

One of the main problems that developers of any space program have to face and that is often restricting the variety of options for solving problems is a problem of a reliable power supply of the SC support and scientific equipment. Solar panels, chemical current sources, fuel elements and, at last, radionuclide thermoelectric generators should help, each in its field, to solve the standing problem. The RTG use as autonomous power supply sources for spacecrafts on-board equipment of the SC became expedient and, in some cases the only choice for solving space programs due to their unique technical and operational characteristics, namely:

- full autonomy and high reliability during the service life; independence of the action of the solar radiation;
- high specific power capacity (up to 10 kW/kg); high life service (up to 20 years);
- possibility of the use of the spent heat generated for equipment heating;
- possibility of the work with the buffer accumulating systems;
- high quality of the used power.

Up to now, RTGs have been used for a number of space programs on researching the Moon, Mars and other planets of the Solar system [1]. In addition to their incontestable advantages, RTGs have the essential drawback of the potential danger of radioactive pollution of the environment in case of the failure of the capsule which contains the radionuclide (radionuclide source of the heat - RSH). Especially this problem appears during the launch the space craft with RTG aboard because extremely hard emergency situations are possible with the rocket carrier during the launch and in the phase of the spacecraft ejection into the orbit or on the calculated trajectory. In these cases RTGs can be effected by extreme influences caused by: the explosion of the rocket carrier and, as a consequence the generation of the explosive wave and the formation of fragments of different masses with various rates of scattering; the fire and the burning of the rocket fuel components with the temperature in the epicentre up to 3800 C; the descent in the dense layers of the atmosphere by gentle or steep ballistic trajectories, accompanied by the aerodynamic heating, thermal shock, mechanical overloads; the crash on the Earth surface with an end velocity of up to 80 m/sec; the fall on the ocean bottom and the effect of the hydrostatic pressure of up to 1000 atm. etc.
The problem of ensuring the RTG radiation safety under the given conditions is solved due to the preservation of the integrity of the capsule with the radionuclides and the use of the radioactive matter in the form of a chemical composition with a high melting temperature which is not soluble in water, alkaline solutions and acids, and which cannot be diffused in air.

Up to now, the sole radionuclide, meeting all above-mentioned requirements and having the acceptable radiation and physical characteristics, is plutonium-238. Plutonium-238 in RTGs is used as pellets of plutonium dioxide, caked at the temperature of 1200 °C, which are placed in a sealed multishell containment, additionally surrounded with the thermal protective body made of carbon-carbon materials. Such a construction is called a radionuclide heating units - RHU. The development, design and creation of RHUs should be done in full correspondence with the principles referring the use of nuclear power sources in space, approved by the United Nations General Assembly in resolution 47/68 of December 14, 1992 [2]. According to this document RTGs can be used in space only if the physical form of the radioactive matter used in them and the system of the protective shells guarantees that no radioactive matter is emitted into the environment during the standard use and during the emergency effects connected with the unstandard situations which can appear during the spacecraft launch and ejection into the orbit or on the calculated trajectory.

1. Status of RTG development for space in the USA

In the USA the developments of RTGs for space were performed by the SNAP program (Systems for Nuclear Auxiliary Power) [31]. The first RTG (SNAP-3B) on polonium-210 with the electric power of 2.7 W was launched into the near-Earth orbit in 1961 as part of the onboard equipment of the navigation satellite “Transit-4A”. Up to now, the USA undertook 25 launches of spacecrafts with RTGs aboard. All together 40 RTGs a total of about 105 kg of plutonium were launched in space. RTGs were used as part of navigation satellites (“Transit” series), communication satellites (LES series), meteorological satellites (“Nimbus” series), spacecraft for searching the Moon (“Apollo” series), Mars (Viking-1, and 2), deep space (“Pioneer-10, 11”, “Voyager-1, 2”, “Gallileo”, “Uliss” [1]).

![Fig. 1. RTG powered space missions](image-url)
The logical result of the completion of works on the SNAP program was the creation of fully unified RTG by the middle of the 80s, the so called module isotopic thermal generator (MITG), afterwards named as General Purpose Heat Source (GPHS-RTG, 9), (Fig.2), [4].

**Fig. 2. General Purpose Heat Source RTG (GPHS RTG)**

The typical peculiarity of the design of this RTG was, together with the achievement of optimum electrical characteristics, the possibility to vary the level of its electric power from tens of Watts up to hundreds of Watts due to the use of the standard radionuclide heat units (GPHS) and sections of thermal and electric panels in the design. The fact should be noted that in this case was achieved a high level of the radiation safety.

**Fig. 3. Diagram of General Purpose Heat Source Module**
Table 1 gives the main characteristics of GPHS-RTG.

Table 1. Main Characteristics of GPHS-RTG

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</tr>
<tr>
<td>output voltage, V</td>
<td>30</td>
</tr>
<tr>
<td>fuel</td>
<td>PuO2</td>
</tr>
<tr>
<td>fuel mass, kg</td>
<td>10.9</td>
</tr>
<tr>
<td>heat power, W</td>
<td>4284</td>
</tr>
<tr>
<td>number of single modules of GPHS.</td>
<td>18</td>
</tr>
<tr>
<td>thermoelectric materials</td>
<td>Si-Ge</td>
</tr>
<tr>
<td>operating temperature, C</td>
<td>1060</td>
</tr>
<tr>
<td>efficiency, %</td>
<td>6.4</td>
</tr>
<tr>
<td>dimensions, m</td>
<td></td>
</tr>
<tr>
<td>- diameter</td>
<td>0.42</td>
</tr>
<tr>
<td>- height</td>
<td>1.13</td>
</tr>
<tr>
<td>weight, kg</td>
<td>56.2</td>
</tr>
<tr>
<td>service life, years</td>
<td>16</td>
</tr>
</tbody>
</table>

GPHS-RTG was recommended as a main source of power supply for all following programs in deep space researches.

GPHS-RTG was firstly mounted on the "Galileo" spacecraft which was launched in space in October, 1989. The purpose of the expedition was the research of Jupiter from the fly-by orbit and by the probe landed on its surface. The "Galileo" spacecraft reached Jupiter in August 1994 and from its board was photographed the reverse side (invisible from the Earth) of the planet shortly after its collision with the Shoemaker-Levy comet. At present, the researches on the "Galileo" program are being continued. GPHS-RTG was used on the "Ulysses" spacecraft, launched in October 1990, as a main source of the power supply. The task of the "Ulysses" spacecraft is the research of the nearest vicinities of the Sun (corona, solar wing, magnetic field, solar radiation etc.).

In October 1997 the USA launched the "Cassini" project to research Saturn. The spacecraft includes 3 GPHS-RTG and 157 tiny radionuclide heat units for the control of the temperature in compartments with scientific equipment (Fig.4).
2. Status of RTG development for space in Russia

In the USSR the practical use of RTGs in space started 1965 when for supplying the onboard equipment of the Earth artificial satellites “Cosmos-84” and “Cosmos-90” RTGs with polonium-210 were used with a thermal conditional name “Orion-1” and “Orion-2”. In 1969 and 1971 for heating the compartment with “Lunokhod-1” and “Lunokhod-2” equipment there were used radionuclide heat units on polonium-210 with the power of 800 W (Fig 5).

Fig. 5. Radioisotope Heat Source for Space Mission.
As is known not RTG were then used in space in the USSR but the nuclear power plants (NPP) with thermoelectric conversion (NPP) which were used in the satellites of the “Cosmos” series intended for the sea radiation probing and for the radar investigation of the ocean. These missions are known al RORSAT (Radar Ocean Reconnaissance Satellite).

The output electrical power of the NPP “Bouk”, 2.5-3 KW, was generated due to the thermoelectric conversion of the heat released in the nuclear reactor with a heat power of 100 kW. More than 30 plants “Bouk” were launched within the period from 1967-1988.

In 1987 two NPP “Topaz” with the electrical power of 6 kW from thermoelectric conversion of the heat energy passed successful flight tests on “Cosmos-1818” and “Cosmos-1867” satellites. The nuclear power plants of the “Bouk” and “Topaz” type were intended only for the use in the near-Earth space as their life time was limited to 1-2 years.

The problem of the space RTG development for the fulfillment of the Russian space programs became again actual with the beginning of the realisation of the international project Mars-96 on the complex research of Mars (Fig. 6) which as is known has been ended with the unsuccessful launch of the “Mars-96” spacecraft.

By this project small autonomous stations (SAS) and penetrators (PN) intended for the long work under Martian conditions should have been shot on the Mars surface from the orbit. (Fig. 7,8)
Fig. 7.

Fig. 8 Penetrator "Mars 96"
To provide the operation of the scientific equipment, processing and transmission of the obtained information the mission included RTGs in the SAS and in the PN with the electrical power of 200 and 400 mW, respectively, as well as radionuclide heating units with a heat power of 8.5 W intended for the station equipment heating (RHU “Angel”) (Fig. 9).

![Radioisotope Thermoelectric Generator for Space Mission](image-url)

**Fig. 9. Radioisotope Thermoelectric Generator for Space Mission- RTG “Angel”**.

The radionuclide heating units “Angel” were used both autonomously and as part of the RTGs. The plutonium-238 dioxide in form of pellets was the radionuclide fuel for them. The radiation safety was provided by the physical form of the used radionuclide, by the design of the heating unit and with the use of anticorrosive, heat-resistant materials and coatings, including heatprotective materials on the basis of composition graphite materials.

Tables 2 and 3 give the main parameters of RHU “Angel” as well as the RTGT based on “Angel”.

By the results of the ground tests the RHU “Angel” was certified by the center of the certification of the rocket and space technics of the Russian Space Agency for the safety of its use in space [5].
Table 2. Main Characteristics of the RHU “Angel” for the “Mars-96” SC

<table>
<thead>
<tr>
<th>Name of the parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat power, W</td>
<td>85</td>
</tr>
<tr>
<td>Fuel</td>
<td>plutonium-238 dioxide</td>
</tr>
<tr>
<td>Mass of Pu-238, g</td>
<td>15</td>
</tr>
<tr>
<td>Sizes, mm</td>
<td></td>
</tr>
<tr>
<td>- diameter</td>
<td>40</td>
</tr>
<tr>
<td>- height</td>
<td>60</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>0.2</td>
</tr>
<tr>
<td>Design materials</td>
<td>multishell</td>
</tr>
<tr>
<td>1st shell - anticorrosive</td>
<td>platinum-rhodium alloy</td>
</tr>
<tr>
<td>2nd shell - power</td>
<td>tantalum-tungsten alloy</td>
</tr>
<tr>
<td>3rd shell - heatprotective</td>
<td>carbon-carbonic composition materials</td>
</tr>
<tr>
<td>Service life, years</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3. Main Characteristics of the RTG “Angel” for the “Mars-96” SC

<table>
<thead>
<tr>
<th>Name of the parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical power, W</td>
<td>0.22</td>
</tr>
<tr>
<td>Voltage, V</td>
<td>15</td>
</tr>
<tr>
<td>Fuel</td>
<td>Pu-238 dioxide</td>
</tr>
<tr>
<td>Heat power, W</td>
<td>8.5</td>
</tr>
<tr>
<td>Thermoelectric battery</td>
<td>telluride’s bismuth</td>
</tr>
<tr>
<td>Temperature of “hot seams”, C</td>
<td>160</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>2.6</td>
</tr>
<tr>
<td>Sizes, mm</td>
<td></td>
</tr>
<tr>
<td>- diameter</td>
<td>85</td>
</tr>
<tr>
<td>- height</td>
<td>125</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>0.5</td>
</tr>
<tr>
<td>Service life, years</td>
<td>10</td>
</tr>
</tbody>
</table>

Despite a small number of plutonium-238 (in comparison with the American projects) used in RTG “Angel” for the “Mars-96” project, and a milliwatt level of their output power, the completion of the developments of such RTG has important significance for the Russian space programs on deep space researches.

First, this is because Russia has fully completed the development of RTG on plutonium-238 for space research purposes and manufacture of flight samples satisfying both national and international requirements on radiation safety.

Second, the radionuclide heat units, as potentially dangerous for the spacecraft environment, were officially certified by the state bodies for the safety of their use in space.

Third, the analysis of the existing approaches in Russia and USA on the provision of the space RTG radiation safety and the certification for the safety of their use in the spacecraft showed the proximity in the problem solutions both in the certification of such products and in the scope of RTG tests during the standard usage and emergency situations.
Fourth, the RTG development for the “Mars-96” project opens the prospects of the RTG use in other national and international space programs, which are planned for the future.

3. The use of RTGs in the European Space Agency (ESA) space programs

Up to now there exists a number of projects developed by ESA which plan to use radionuclide power or heat sources. One of the most far progressed is the “Rosetta” project. This projected spacecraft is planned to be launched in January, 2003, for the rendezvous with the comet 46P/Wirtanen in 2011 at a distance of 5.2 astronomical units from the sun. “Rosetta” contains a small lander. “RoLand” is a small (45 kg) compact research station of the cubic form (the cube side length is 90 cm) will be landed on the comet surface for investigating the physical and chemical composition of the comet soil, its elementary composition etc. (Fig.10).

The consortium formed of leading institutes of Europe includes the scientific organisations of Germany, Finland, Italy, Hungary, Great Britain and Austria, which have not the technological capacity to manufacture RTGs. It was therefore decided to develop new high-efficiency solar cell for this deep space mission.

Fig. 10 Roland-Cometary Lander for the Rosetta Mission
“RoLand” includes not only the solar power generator but also RHU on plutonium-238 of the RHU “Angel” type. By the opinion of the project experts, the RHU use is the most desirable, sensible and reliable means for achieving the main goal of the mission”.

4. The perspective of RTG use in space programs of the XXI century

In the next years a number of international projects with the use of RTGs of American and Russian manufacture are planned to be developed and realised.

In 2001 it is planned to continue the complex researches of Mars in correspondence with the Russian-American project “Mars Together”. For this project the orbiter and the scientific complex are being developed by the American side, and the rover, shot on the Mars surface, and a part of scientific equipment - by the Russian experts.

The spacecraft will be launched by the Russian rocket “Molniya” from the Russian launching site “Plesetzk”. For the rover operation the radionuclide heating units “Angel” are under consideration and RTGs with preliminary electric power of 3-5 W are offered from the Russian manufacturer.

The future step of the Russian-American space co-operation in deep space exploration will use RTGs in the “Solar Probe” project for the direct investigations of the Sun coronas, solar wind and other important parameters of the near-sun space.

Two spacecrafts of American and Russian manufacturers are planned to be launched by one rocket from the “Plesetzk” launching site. Aboard the American spacecraft RTGs of the GPHS-RTG type will be used, on the Russian spacecraft RTGs will be used with a total electric power of 40-50 W as well as a thermoelectric generator with output electric power in the order of 500 W which generates the electric power due to the thermoelectric conversion of solar radiation.

Further in 2003 it is planned to start the Russian-American project on the research of the most removed planet from the Earth, Pluto and its satellite Harron (“Pluto Express” project) [6]. There will be two RTGs on the spacecraft which is developed in the USA:

- one is of the American manufactured GPHS-RTG type with the electrical power of 90 W (of others, more effective radionuclide power sources providing the operation of the scientific equipment);
- the other RTG is of the Russian manufactured ”Angel” type with an electrical power of 0.5-1.0 W. It is mounted on the probe (Drop Zond) which is separated from the SC while approaching the planet. The Drop Zond is used for more detailed research of the space near planets.

It is proposed to use “Molniya” as a rocket carrier that has the highest reliability at minimum cost. The “Molniya” will be launched from the Plesetzk launching site with the ejection of the SC into the orbit with an inclination of about 70 degrees to lay the flight route along the arctic sea-coast to decrease the consequences in case of hardly probable, but possible failures of the rocket and in case of a collapse of this spacecraft with RTGs.

It should be mentioned that the exploration of deep space and planets at considerable distance from the sun (such as Pluto) is possible only with the use of radionuclide power sources
because solar panels do not operate efficiently at such low levels of the solar radiation and because the power capacity of chemical sources is not sufficient to provide power for long-term space programs.

Taking into account the high cost of radionuclide power sources, the realisation of such projects becomes possible only with sufficient participation in international co-operation including the technically developed countries and only when each of the participating sides takes the obligation not only in the development of some aspects of scientific programs, but makes its contribution to the solution of problems connected with the financing of the project on the whole.

Up to now there are some projects developed by the European Space Agency (ESA) with RHU use, such as the “Rosetta” project and also the project on the creation of constantly acting moon stations. The realisation of these projects is planned in the first decade of the next century.

The concept of power plants for the moon base is being developed also in Russia and Japan. In this concept it is assumed to obtain the electrical power by a direct conversion of the solar energy in a module consisting of the thermoelectric and thermoemission units.

There are some hints on works carried out in France on the RTG development for the ESA space program. But the absence of concrete information on this question does not make it possible to draw conclusions about the achieved level of developments.

As a conclusion, the development and the creation of RTGs for space programs played a positive role and promoted the further profound research of space and planets of the solar system.

At the same time, a number of alternative power sources is under development, such as AMTEC (Alkali metal thermal for electric conversion), thermophotovoltaic power sources, installations with a Stirling engine, having an efficiency of 2-3 times higher than the efficiency reached in RTGs [8, 9]. However, the practical use of such power sources in the nearest future remains rather problematic because of their insufficiently high reliability and short service life.

In conclusion, it can be surely assumed that in the XXI century RTGs will be used as before in large-scale projects on the space and in the solar system planets exploration which will become possible only in case of close co-operation of technically developed countries.
Acknowledgement

I am grateful to my NPP colleagues at Biapos who helped me to make this paper. I acknowledge that members of the Space Research Institute of the Russian Academy of Sciences for discussions of this paper.

References

[6] See contribution of G. Strobl in this volume
United Nations’ Principles Relevant to the Use of Nuclear Power Sources in Outer Space

The General Assembly,

Having considered the report of the Committee on the Peaceful Uses of Outer Space on the work of its thirty-fifth session and the text of the Principles Relevant to the Use of Nuclear Power Sources in Outer Space as approved by the Committee and annexed to its report,

Recognizing that for some missions in outer space nuclear power sources are particularly suited or even essential owing to their compactness, long life and other attributes,

Recognizing also that the use of nuclear power sources in outer space should focus on those applications which take advantage of the particular properties of nuclear power sources,

Recognizing further that the use of nuclear power sources in outer space should be based on a thorough safety assessment, including probabilistic risk analysis, with particular emphasis on reducing the risk of accidental exposure of the public to harmful radiation or radioactive material,

Recognizing the need, in this respect, for a set of principles containing goals and guidelines to ensure the safe use of nuclear power sources in outer space,

Affirming that this set of Principles applies to nuclear power sources in outer space devoted to the generation of electric power on board space objects for non-propulsive purposes, which have characteristics generally comparable to those of systems used and missions performed at the time of the adoption of the Principles,

Recognizing that this set of Principles will require future revision in view of emerging nuclear-power applications and of evolving international recommendations on radiological protection,

Adopts the Principles Relevant to the Use of Nuclear Power Sources in Outer Space as set forth below.
Principle 1. Applicability of international law

Activities involving the use of nuclear power sources in outer space shall be carried out in accordance with international law, including in particular the Charter of the United Nations and the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.

Principle 2. Use of terms

1. For the purpose of these Principles, the terms "launching State" and "State launching" mean the State which exercises jurisdiction and control over a space object with nuclear power sources on board at a given point in time relevant to the principle concerned.

2. For the purpose of principle 9, the definition of the term "launching State" as contained in that principle is applicable.

3. For the purposes of principle 3, the terms "foreseeable" and "all possible" describe a class of events or circumstances whose overall probability of occurrence is such that it is considered to encompass only credible possibilities for purposes of safety analysis. The term "general concept of defence-in-depth" when applied to nuclear power sources in outer space refers to the use of design features and mission operations in place of or in addition to active systems, to prevent or mitigate the consequences of system malfunctions. Redundant safety systems are not necessarily required for each individual component to achieve this purpose. Given the special requirements of space use and of varied missions, no particular set of systems or features can be specified as essential to achieve this objective. For the purposes of paragraph 2 (d) of principle 3, the term "made critical" does not include actions such as zero-power testing which are fundamental to ensuring system safety.

Principle 3. Guidelines and criteria for safe use

In order to minimize the quantity of radioactive material in space and the risks involved, the use of nuclear power sources in outer space shall be restricted to those space missions which cannot be operated by non-nuclear energy sources in a reasonable way.
1. General goals for radiation protection and nuclear safety

(a) States launching space objects with nuclear power sources on board shall endeavour to protect individuals, populations and the biosphere against radiological hazards. The design and use of space objects with nuclear power sources on board shall ensure, with a high degree of confidence, that the hazards, in foreseeable operational or accidental circumstances, are kept below acceptable levels as defined in paragraphs 1 (b) and (c).

Such design and use shall also ensure with high reliability that radioactive material does not cause a significant contamination of outer space.

(b) During the normal operation of space objects with nuclear power sources on board, including re-entry from the sufficiently high orbit as defined in paragraph 2 (b), the appropriate radiation protection objective for the public recommended by the International Commission on Radiological Protection shall be observed. During such normal operation there shall be no significant radiation exposure.

(c) To limit exposure in accidents, the design and construction of the nuclear power source systems shall take into account relevant and generally accepted international radiological protection guidelines.

Except in cases of low-probability accidents with potentially serious radiological consequences, the design for the nuclear power source systems shall, with a high degree of confidence, restrict radiation exposure to a limited geographical region and to individuals to the principal limit of 1 mSv in a year. It is permissible to use a subsidiary dose limit of 5 mSv in a year for some years, provided that the average annual effective dose equivalent over a lifetime does not exceed the principal limit of 1 mSv in a year.

The probability of accidents with potentially serious radiological consequences referred to above shall be kept extremely small by virtue of the design of the system.

Future modifications of the guidelines referred to in this paragraph shall be applied as soon as practicable.

(d) Systems important for safety shall be designed, constructed and operated in accordance with the general concept of defence-in-depth. Pursuant to this concept, foreseeable safety-related failures or malfunctions must be capable of being corrected or counteracted by an action or a procedure, possibly automatic.

The reliability of systems important for safety shall be ensured, inter alia, by redundancy, physical separation, functional isolation and adequate independence of their components.

Other measures shall also be taken to raise the level of safety.
2. Nuclear reactors

(a) Nuclear reactors may be operated:

(i) On interplanetary missions;

(ii) In sufficiently high orbits as defined in paragraph 2 (b);

(iii) In low-Earth orbits if they are stored in sufficiently high orbits after the operational part of their mission.

(b) The sufficiently high orbit is one in which the orbital lifetime is long enough to allow for a sufficient decay of the fission products to approximately the activity of the actinides. The sufficiently high orbit must be such that the risks to existing and future outer space missions and of collision with other space objects are kept to a minimum. The necessity for the parts of a destroyed reactor also to attain the required decay time before re-entering the Earth's atmosphere shall be considered in determining the sufficiently high orbit altitude.

(c) Nuclear reactors shall use only highly enriched uranium 235 as fuel. The design shall take into account the radioactive decay of the fission and activation products.

(d) Nuclear reactors shall not be made critical before they have reached their operating orbit or interplanetary trajectory.

(e) The design and construction of the nuclear reactor shall ensure that it cannot become critical before reaching the operating orbit during all possible events, including rocket explosion, re-entry, impact on ground or water, submersion in water or water intruding into the core.

(f) In order to reduce significantly the possibility of failures in satellites with nuclear reactors on board during operations in an orbit with a lifetime less than in the sufficiently high orbit (including operations for transfer into the sufficiently high orbit), there shall be a highly reliable operational system to ensure an effective and controlled disposal of the reactor.

3. Radioisotope generators

(a) Radioisotope generators may be used for interplanetary missions and other missions leaving the gravity field of the Earth. They may also be used in Earth orbit if, after conclusion of the operational part of their mission, they are stored in a high orbit. In any case ultimate disposal is necessary.

(b) Radioisotope generators shall be protected by a containment system that is designed and constructed to withstand the heat and aerodynamic forces of re-entry in the upper atmosphere under foreseeable orbital conditions, including
highly elliptical or hyperbolic orbits where relevant. Upon impact, the containment system and the physical form of the isotope shall ensure that no radioactive material is scattered into the environment so that the impact area can be completely cleared of radioactivity by a recovery operation.

**Principle 4. Safety assessment**

1. A launching State as defined in principle 2, paragraph 1, at the time of launch shall, prior to the launch, through cooperative arrangements, where relevant, with those which have designed, constructed, or manufactured the nuclear power sources, or will operate the space object, or from whose territory or facility such an object will be launched, ensure that a thorough and comprehensive safety assessment is conducted. This assessment shall cover as well all relevant phases of the mission and shall deal with all systems involved, including the means of launching, the space platform, the nuclear power source and its equipment and the means of control and communication between ground and space.

2. This assessment shall respect the guidelines and criteria for safe use contained in principle 3.

3. Pursuant to article XI of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, the results of this safety assessment, together with, to the extent feasible, an indication of the approximate intended time-frame of the launch, shall be made publicly available prior to each launch, and the Secretary-General of the United Nations shall be informed on how States may obtain such results of the safety assessment as soon as possible prior to each launch.

**Principle 5. Notification of re-entry**

1. Any State launching a space object with nuclear power sources on board shall in a timely fashion inform States concerned in the event this space object is malfunctioning with a risk of re-entry of radioactive materials to the Earth. The information shall be in accordance with the following format:

   (a) System parameters:
      (i) Name of launching State or States, including the address of the authority which may be contacted for additional information or assistance in case of accident;
      (ii) International designation;
      (iii) Date and territory or location of launch;
      (iv) Information required for best prediction of orbit lifetime, trajectory and impact region;
      (v) General function of spacecraft;

   (b) Information on the radiological risk of nuclear power source(s):
      (i) Type of nuclear power source: radioisotopic/reactor;
(ii) The probable physical form, amount and general radiological characteristics of the fuel and contaminated and/or activated components likely to reach the ground. The term "fuel" refers to the nuclear material used as the source of heat or power.

This information shall also be transmitted to the Secretary-General of the United Nations.

2. The information, in accordance with the format above, shall be provided by the launching State as soon as the malfunction has become known. It shall be updated as frequently as practicable and the frequency of dissemination of the updated information shall increase as the anticipated time of re-entry into the dense layers of the Earth's atmosphere approaches so that the international community will be informed of the situation and will have sufficient time to plan for any national response activities deemed necessary.

3. The updated information shall also be transmitted to the Secretary-General of the United Nations with the same frequency.

Principle 6. Consultations

States providing information in accordance with principle 5 shall, as far as reasonably practicable, respond promptly to requests for further information or consultations sought by other States.

Principle 7. Assistance to States

1. Upon the notification of an expected re-entry into the Earth's atmosphere of a space object containing a nuclear power source on board and its components, all States possessing space monitoring and tracking facilities, in the spirit of international cooperation, shall communicate the relevant information that they may have available on the malfunctioning space object with a nuclear power source on board to the Secretary-General of the United Nations and the State concerned as promptly as possible to allow States that might be affected to assess the situation and take any precautionary measures deemed necessary.

2. After re-entry into the Earth's atmosphere of a space object containing a nuclear power source on board and its components:

(a) The launching State shall promptly offer and, if requested by the affected State, provide promptly the necessary assistance to eliminate actual and possible harmful effects, including assistance to identify the location of the area of impact of the nuclear power source on the Earth's surface, to detect the re-entered material and to carry out retrieval or clean-up operations;

(b) All States, other than the launching State, with relevant technical capabilities and international organizations with such technical capabilities shall, to the extent possible, provide necessary assistance upon request by an affected State.
In providing the assistance in accordance with subparagraphs (a) and (b) above, the special needs of developing countries shall be taken into account.

Principle 8. Responsibility

In accordance with article VI of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, States shall bear international responsibility for national activities involving the use of nuclear power sources in outer space, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that such national activities are carried out in conformity with that Treaty and the recommendations contained in these Principles. When activities in outer space involving the use of nuclear power sources are carried on by an international organization, responsibility for compliance with the aforesaid Treaty and the recommendations contained in these Principles shall be borne both by the international organization and by the States participating in it.

Principle 9. Liability and compensation

1. In accordance with article VII of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, and the provisions of the Convention on International Liability for Damage Caused by Space Objects, each State which launches or procures the launching of a space object and each State from whose territory or facility a space object is launched shall be internationally liable for damage caused by such space objects or their component parts. This fully applies to the case of such a space object carrying a nuclear power source on board. Whenever two or more States jointly launch such a space object, they shall be jointly and severally liable for any damage caused, in accordance with article V of the above-mentioned Convention.

2. The compensation that such States shall be liable to pay under the aforesaid Convention for damage shall be determined in accordance with international law and the principles of justice and equity, in order to provide such reparation in respect of the damage as will restore the person, natural or juridical, State or international organization on whose behalf a claim is presented to the condition which would have existed if the damage had not occurred.

3. For the purposes of this principle, compensation shall include reimbursement of the duly substantiated expenses for search, recovery and clean-up operations, including expenses for assistance received from third parties.
**Principle 10. Settlement of disputes**

Any dispute resulting from the application of these Principles shall be resolved through negotiations or other established procedures for the peaceful settlement of disputes, in accordance with the Charter of the United Nations.

**Principle 11. Review and revision**

These Principles shall be reopened for revision by the Committee on the Peaceful Uses of Outer Space no later than two years after their adoption.

*These principles were adopted in 1992 as resolution 47/68 by the UN General Assembly after discussion in the Committee on the Peaceful Uses of Outer Space and its legal subcommittee.*

Source: http://www3.un.or.at/OOSAltreat/nps/
1. An overview of the element plutonium

Seaborg and McMillan were the first to synthesise plutonium in the cyclotron at Berkeley, USA in 1940. Following this, several kilograms of plutonium were manufactured in the reactors and chemical separation plants at Hanford, USA as part of the Manhattan Project. The first atomic bomb, detonated at Alamogordo in the desert of New Mexico on 16th July 1945, was a plutonium bomb, as was "Fat Man", which was dropped on Nagasaki on 9th August 1945. Since then, several hundred tonnes of plutonium have been manufactured for military purposes.

The abbreviation for plutonium is Pu and its atomic number is 94. It is therefore placed after uranium in the periodic system and so belongs to the transuranic elements. It has a density of 19.81 g/cm³. Its melting point is 640 °C, and it has a boiling point of 3235°C.

All plutonium isotopes are radioactive and no stable forms occur. Pu-233, Pu-235, Pu-237 and Pu-241 emit radiation and all other isotopes undergo decay. The following table gives an overview of the physical properties of the most important plutonium isotopes:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Physical half-life</th>
<th>Decay type</th>
<th>Specific activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu-238</td>
<td>87.74 a</td>
<td>(5.5 MeV)</td>
<td>646 GBq/g</td>
</tr>
<tr>
<td>Pu-239</td>
<td>24 131 a</td>
<td>(5.2 MeV)</td>
<td>2.3 GBq/g</td>
</tr>
<tr>
<td>Pu-240</td>
<td>6 650 a</td>
<td>(5.2 MeV)</td>
<td>8.5 GBq/g</td>
</tr>
<tr>
<td>Pu-241</td>
<td>14.4 a</td>
<td>(max. 21 keV)</td>
<td>4.1 TBq/g</td>
</tr>
<tr>
<td>Pu-242</td>
<td>376 300 a</td>
<td>(4.9 MeV)</td>
<td>1.5 GBq/g</td>
</tr>
<tr>
<td>Pu-244</td>
<td>8.26*10⁷ a</td>
<td>(4.6 MeV)</td>
<td>N.C.</td>
</tr>
</tbody>
</table>

([Schwa85], [Koel89], [Stoll81])

The specific activity gives the number of nuclear decay events per gram. A long physical half-life leads to a low specific activity. The effective ranges of radiation in tissue are in the micrometer range. Locally this leads to a high energy dose, and explains the high radiotoxicity of plutonium.

In addition to its use as a weapons-grade material, it can be used as a nuclear fuel in breeder reactors. Among others, France backed this technology, but has since given it up. The breeder concept has never been put into practice in Germany. Mixed oxide fuel elements, also known as MOX fuel elements, contain uranium and plutonium as nuclear fuel and can also be used in light-water reactors. A big disadvantage is the low thermal conductivity of the oxide, for
which reason thin fuel rods have to be manufactured. In Germany two boiling water reactors have been licensed to use MOX fuel elements, and were actually loaded in 1997. Of the 13 pressurised water reactors, five use MOX fuel elements. [KeI93, Str98]

Another application is to use the radiation from Pu-238 as a power supply in radiothermal generators (RTGs) inside spacecraft. Here the radiation is braked and the resulting heat converted into electrical energy. In October 1997, the space-probe CASSINI set out on its Saturn mission and led to much controversy and discussion about the use of plutonium as a power supply for space-probes.

2. Plutonium in the environment

2.1 Occurrence in nature

In nature plutonium occurs in trace amounts, particularly in uranium ores. It is continuously replicated from U-238 by neutron capture. The concentration is very low and is usually given as one plutonium atom to \(10^{12}\) uranium atoms. Even with an estimated occurrence of several million tonnes of uranium, this amounts to no more than a few grams of plutonium. [GRS79] Other estimates calculate a few kilograms of Pu-239 in the upper layers of the earth's crust [GSF89]. Pu-244 stems from element synthesis during the birth of the solar system. [Schwa85] Keller cites 20-70 kg of naturally occurring plutonium (Pu-239 and Pu-244). [KeI93]

Some 1-2 billion years ago, several tonnes of plutonium were created in natural nuclear reactors at the site of what is now a uranium mine at Oklu, Gabon. At that time the deposit was below sea-level. Water was therefore present as a moderator; there was enough fissile U-235 available to operate reactors. The "operating time" is estimated at several 100,000 years. Shifts in the composition of certain isotopes in the uranium mine can be explained by nuclear fission in particular. The plutonium has completely decayed since then [Schwa85, KeI93, GSF79, KfK89].

2.2 Generation and release from nuclear installations

2.2.1 Nuclear power stations

The quantity of plutonium created in a nuclear reactor depends on the burn-up, the fuel element type and the energy of the neutrons used for nuclear fission. Depending on the reactor type, plutonium is produced at an overall rate of 0.2-0.6 kg/MWe per year. In light-water reactors the rate is 0.26 kg/MWe a year. In breeder reactors the amount of Pu-239 which is generated exceeds the amount which decays due to fission. This results in a Pu-239 gain. The quantity of this net gain depends on the design of the reactor core [GRS79].

2.2.2 Reprocessing plants

In reprocessing plants the fissile isotopes are first recovered from the mixture in the fuel elements, after which the uranium and plutonium are separated out from the reclaimed material. The uranium and plutonium are then re-used in new fuel elements such as MOX fuel elements.
2.2.3 Releases from nuclear installations

Information about releases from nuclear installations is sparse. For the most part nothing is known about the smaller emissions. According to Keller, some 5-60 g of plutonium have been released during the operation of nuclear installations, mainly from military installations [KeI93]. Following a fire on 11th May 1969 in the Rocky Flats Laboratories, the highest quantity of plutonium to date was released, amounting to some 5-60 g. Most of this precipitated out within the grounds of the research site. Even so, soil samples taken within a 40 km radius exhibited an increased concentration of plutonium [KfK89].

On the occasion of the Hanau nuclear controversy in 1988, a check was made to see if there may have been an uncontrolled discharge of waste substances, including plutonium, into rivers and streams. Sediment analysis is especially well suited for this purpose on account of its high enrichment factor for plutonium. In North Rhine-Westphalia, radionuclide analyses of this kind had been ongoing since 1975 and the samples had been stored. Re-analysis by the Landesamt für Wasser und Abfall (State Authority for Water and Waste Disposal), Düsseldorf, of sediments taken from the river Rur at a point to the south of Jülich in 1988 and 1989 showed a Pu-238 component that could not be explained by nuclear weapons tests. Further tests confirmed the indication of a plutonium leakage from the nuclear research installation at Jülich. Until then it had been believed that plutonium in emissions occurred in trace amounts only; similarly, the German Radiological Protection Commission was unaware of any plutonium leakage. It was suspected that the leakage came from the experimental reactor (AVR), but no explanation could be given. An assessment according to Klös showed no significant contribution to background radiation. Plutonium was also found in samples of sediment from the Thorium High Temperature Reactor, Hamm, which was operating at that time [Klös90].

As a result of the accident at Block 4 of the Chernobyl nuclear power station in 1986, some 6*10^{13} Bq Pu of the calculated 2*10^{15} Bq plutonium inventory was released and deposited mainly on the accident site [Keller93].

2.3 Fallout from atmospheric nuclear testing

The main contribution to the fallout from atmospheric nuclear weapon tests came from the series of tests carried out in the USA and USSR in the years 1954-58 and 1960-62, ending with the Test Ban Treaty of 1963. Since 1964 isolated atmospheric nuclear weapon tests have been carried out by France and China, but their contribution to fallout from nuclear weapons is not measurably significant. The following charts show the composition of the plutonium isotopes in nuclear weapons fallout as a percentage by weight and activity in samples taken in the early 1970s.
Of the total fallout from atmospheric nuclear weapon tests which was deposited on the earth's surface, Pu-239 constitutes the main component at 84 % by weight, whereas Pu-238 contributes only a few hundredths of a percent. In contrast, the alpha-activity of the fallout plutonium shows that the greatest contribution comes from Pu-239 (some 60 %) followed by Pu-240 (approx. 40 %), whereas Pu-238 makes up only 3-5 %. Due to the different physical half-lives of the plutonium isotopes, the beta-activity of the Pu-241 in the release is over an order of magnitude higher than the alpha-radiating plutonium isotopes. [GSF89]

In total, nuclear weapon tests released world-wide approximately 3 t Pu-239 into the atmosphere up to 1962. The activity amounted to \(1.3 \times 10^{16}\) Bq for Pu-239 and Pu-240. The quantity of plutonium deposited in the Federal Republic of Germany is estimated at 5-10 kg. [GSF89, Keller93]

The illustration shows a typical fallout particle.

### 2.4 Accidental release

#### 2.4.1 Accidents during space flight

In 1964 a US satellite burned up at an altitude of 50 km over the Pacific. On board was a type SNAP9-A radio-isotope battery containing 1 kg of Pu-238. It was a further two years before an increase in the Pu-238 deposited on the earth's surface was observed. The ratio of Pu-238 to (Pu-239+Pu-240) was 1:1. A return to the earlier ratio had been achieved by about the mid 1970s. The chart shows plutonium deposition in total and separately for the northern and southern hemispheres. More than half the Pu-238 deposited on the earth was released by the SNAP-9A accident. [GSF89,
Roland Wolff: Atmospheric release of plutonium

Kel93]

Other malfunctions prior to 1989 involving Pu-238 isotope batteries used as heat sources in spacecraft have been known, but did not result in releases. For instance in 1968 a NASA weather satellite was deliberately destroyed after a faulty launch. Two containers with a total of $1.3 \times 10^{15}$ Bq Pu-238 were recovered undamaged from the Pacific. Around $1.6 \times 10^{15}$ Bq Pu-238 have been lying on the floor of the Pacific since a technical problem with Apollo 13 in April 1970. [GSF89]

2.4.1 Accidents involving military aircraft

On 17th January 1966 a B52 bomber crashed with four atomic bombs on board after colliding with another aircraft over the Palomares Peninsula in southern Spain (Province of Almeria). One bomb parachuted undamaged to earth and another sank in the sea. The conventional explosive for the ignition mechanism detonated in two of the bombs. About $4 \times 10^{11}$ Bq of plutonium were released (some 0.2 kg) and scattered over an area of 250 hectares. The top 10 cm of the most highly contaminated ground was removed and sent to the USA. In all, 1700 t of soil were packed in 5500 barrels holding 200 litres each. Cereals in fields exhibiting contamination levels $>120$ kBq/m² were destroyed. Ground contaminated in the range 12-120 kBq/m² was drenched with water and ploughed to a depth of around 30 cm, thereby reducing the concentration of plutonium.

On 21st January 1968, a B52 bomber caught fire about 160 km away from the US Air Force base at Thule, Greenland. After attempting without success to put out the fire, the flight commander, Captain John Haug, decided to abandon the aircraft. It crashed in the Bylot Sound, 11 km to the west of Thule. Aviation fuel caught fire during the crash and ignited the chemical explosive triggers in the four atomic bombs stored on board. Several kilograms of plutonium were released, and formed a fused mixture with the ice and snow. The greater part was spread over an area of $130 \times 700$ m². The top layer of contaminated snow was taken to the USA.

Danish scientists have been regularly checking the surrounding area for plutonium ever since. In the first summer after the crash, part of the contaminated ice thawed and drifted northwards. As far as 15 km away, double the usual concentration of plutonium was noted in mussels and other creatures. The estimated plutonium inventory of 1 TBq in the marine sand has remained obstinately high (last measured 1984). The water close to the sea bed exhibited a background level four times higher than the surface water at the crash site. Accumulation in the food chain could not be established; higher animals (such as fish and birds) showed lower values than the plankton and marine sediment. [GSF89, Wel97]

In both cases, contaminated earth etc. was taken to Savannah River, USA.
3. Atmospheric spread

The chemical and physical behaviour of plutonium in the air is not the same as on the ground. In air it oxidises rapidly into plutonium dioxide and is held as aerosols. In certain circumstances it is transported over wide areas; heavy aerosols sink rapidly to earth under their own weight. [GSF89]

The behaviour of these aerosols has been known since the era of atmospheric nuclear weapon tests. Long-distance transport occurs only in the case of fine-grained dust particles. The distances they are transported depend on the altitude at which the Pu was released and particularly on weather conditions.

In high altitude explosions the fireball does not come into direct contact with the earth's surface. The initially gaseous fission products rise with the fireball to a great altitude in the troposphere or the stratosphere. When the fireball has cooled, the radioactive materials condense and coalesce into small particles which due to their small size settle very slowly earthwards (a matter of several months). They are carried around the globe on the stratospheric winds and precipitate as predominantly global or delayed fallout. In due course, long-lived nuclides are distributed uniformly over the northern or southern hemisphere. No interchange takes place. A maximum in the deposited activity per area can be observed between the 40th and 50th degree of latitude.

In the case of an explosion near the earth's surface, the fireball comes into contact with the ground. Earth and debris are swallowed up by the fireball along with fission products. When the fireball has cooled, radioactivity condenses onto particles of soil and other terrestrial materials. These are quite large and fall back to earth under their own weight relatively close to the point of the explosion (around 100-150 km radius). This is known as local or early fallout.

In releases due to an event such as a reactor fire, strong thermal up currents carry the particles to high altitudes. In the case of the Chernobyl reactor incident, particles were transported to an altitude of around 1700 metres. In the upper atmosphere the extent of the spread is determined by the prevailing winds. [GSF89, Ambio83]

4. Transport to the earth's surface and behaviour on the ground

The aerosols are held on condensation nuclei and are relatively easily washed out with them ("wash-out"). Special cases are "rain-out" and "snow-out".

The concentration of plutonium and other long-lived fission products in airborne fallout from nuclear weapons and precipitation is governed by seasonal variations. Maxima are regularly observed in the summer months and minima in the winter. From this it is assumed that a reservoir of radioactive particles is forming in the stratosphere. During the spring months there is an intense interchange between the stratosphere and troposphere. As a result, particles are gradually transported down to the earth during the months that follow. Due to their electrostatic charge and low weight, PuO₂ particles precipitate very slowly. The particles are precipitated onto plants, with a small proportion being taken up by the leaves directly. Through the weathering effects of rain or wind and through decomposition of the
parts of the plant above ground, plutonium reaches the soil.

Plutonium in the soil can reach plants directly through the roots and even get into the food chain. It invades ground water via percolation from the fallout. Plutonium in the upper layers of the soil is returned to the air when dust is raised (resuspension). It can then recontaminate plants. It can even conceivably be transported long distances on the wind. It then becomes possible for it to be taken up into the human body by inhalation. [GSF89]

5. Plutonium in the human body

5.1 Incorporation of plutonium

Radionuclides can find their way into the human body in various ways:
1. Through the alimentary tract: by ingestion,
2. Through the respiratory tracts: by inhalation,
3. Through wounds, leading to direct uptake into the circulatory system.

They are then transported to the organs in the bodily fluids, in particular the blood. Due to their biochemical properties, radionuclides generally become concentrated in certain organs. Their retention time is determined not only by their physical half-life but also by their biological half-life, which is governed by metabolic processes.

In the case of plutonium ingestion, over 99 % is eliminated again via the gastro-intestinal tract. In radiological protection, accepted transgression factors from the intestines into the blood stream range from 0.001 % to 0.1 % depending on the plutonium compound concerned. The principal incorporation path is thus the inhalation of small particles. Of all incorporated plutonium, 30 % is deposited in the liver and 50 % in the skeleton. [GSF89] The biological half-life is given as 40 years for the liver and 100 years for the skeleton. A small proportion is transported to the gonads and the remainder is eliminated. [Tur95]

As a rule, the experimental basis for these findings is experiments on animals. No reliable studies have been carried out on humans. There is some data for a few incidents involving persons exposed to radiation at work and for population groups exposed to nuclear weapons fallout. Some authors make reference to injection experiments on humans from the years 1945-1946. [GSF89] Particulars of government-backed radiation experiments on humans in the USA during the period 1945-1975 have been known since 1993, and the related documents have been released. According to these, injection experiments involving plutonium were carried out at the University of Rochester, the University of California and Manhattan District Hospital, Oak Ridge, during the years 1943-1947. [McCal94] The criticism was levelled that the studies were carried out on chronically sick and predominantly elderly people, so that conclusions about a healthy "normal population" are therefore of doubtful value. [IPPNW94] The biological half-life has been estimated at 118 years with a variation range of 84-175 years. It is therefore certain that plutonium stays in the human body for a very long time, predominantly in the lungs. [Lang80]

In order to model the biokinetics of radionuclides in the human body, we can think of the
latter as consisting of various compartments. Individual organs or parts of the body may in turn be made up of compartments. The activity in a compartment is then determined by deposition behaviour (uptake and elimination) and radioactive decay. The equivalent dose can then be calculated when the level of activity in the body is known. Metabolic models have been developed for this purpose on the basis of the recommendations of the International Commission on Radiological Protection (ICRP), including:
- The ICRP model of the respiratory and alimentary tracts,
- Model parameters for Pu metabolism (ICRP publications).
They have also become established in legally prescribed calculation bases in the field of radiological protection.

5.2 Plutonium in the respiratory tract

5.2.1 The biokinetics of uptake by inhalation

The size of the particle determines the site of deposition in the respiratory tract. According to the calculation models, some 30 % of fine-grained aerosols are stored in the nasopharyngeal passage, some 8 % in the tracheobronchial passage and a further 25 % in the pulmonary passage. Coarse-grained aerosols precipitate practically all the activity in the nasopharyngeal passage. [GSF89] The following table gives an overview of deposition sites:

<table>
<thead>
<tr>
<th>Aerosol size</th>
<th>Deposition site</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 10 ( \mu )m</td>
<td>Nose, nasopharyngeal passage</td>
</tr>
<tr>
<td>2-10 ( \mu )m</td>
<td>Intrathoracic respiratory tracts</td>
</tr>
<tr>
<td>0.2-5 ( \mu )m</td>
<td>Bronchia (4th generation)</td>
</tr>
<tr>
<td>&lt; 2 ( \mu )m</td>
<td>Lungs</td>
</tr>
<tr>
<td>&lt; 0.5 ( \mu )m</td>
<td>Alveoli</td>
</tr>
</tbody>
</table>

(acc. [Cryst91], [Diot93])

Cleaning mechanisms in the nasopharyngeal passage use mucus and cilia to expel aerosols from the nasal passages towards the exterior. Similar mechanisms are at work in the superior lobes of the lungs to expel aerosols back towards the pharynx. The foreign bodies are then coughed up or find their way into the alimentary tract and in the case of plutonium are largely eliminated.

Insoluble plutonium oxide is stored long-term in the lungs; just a fraction of it finds its way very gradually into the blood.
5.2.2 Fractionation effect

A special characteristic of the same chemical compound is observed in the case of Pu-238 dioxide and Pu-239 dioxide: the former is eliminated more rapidly from the lungs into the blood. [Park79, GSF89, Tur95]. The chart according to data from Diel et al. [Diel83] illustrates this observation.

It has been shown experimentally that Pu-238 dioxide particles and Pu-239 dioxide particles differ in their size distribution. Stradling et al. [Stra78] found that in a suspension of Pu-238 dioxide with a particle size <5 μm the proportion of particles 0.001 μm in size increases in 32 weeks. Other authors were unable to observe this effect for Pu-238 dioxide. It was possible to confirm the fragmentation in vivo [Diel83]. Fleischer and Raabe [Flei77] found that there was fragmentation of PuO₂ particles in water. They trace this back to a recoil effect during alpha decay.

The smaller particles are more soluble. Macrophages transport substances in the alveoli away to the lymphatic system by phagocytosis. As a result they can be conveyed to other organs via the circulation of the blood.

The recoil effect is a well-known problem in radiological protection. Particles are continuously ejected from the surface of plutonium compounds or mixtures and distributed in the vicinity as aerosols. Recoil particles tend to invade the objects they encounter, thereby complicating the decontamination process. [GRS79]

5.3 Mathematical models

5.3.1 Reference man

A reference man was defined in the "Report of the Task Group on Reference Man", ICRP Publication 23 (1975). This publishes anatomical reference values, chemical composition and physiological reference data based at the time on data from the literature or experiments carried out by the members of the ICRP Task Group. It turns out to be a man, 20-30 years old, weighing 70 kg and 170 cm in height, living in a climate where the average temperature is 10-20 °C. It applies to a Caucasian, West European or North American. Comparatively few individuals in a population resemble the reference man; even so, the concept represents an important basis for internal dosimetry. It can be adapted to individual cases on the basis of the algorithm, and underlying assumptions can be made. Since then, reference data for an adult woman, a child and an infant have been made available. [Tur95]
The ICRP model of the respiratory tract with three main compartments was first developed in respect of inhalation:

- Nasophaeyngeal passage (*nasal passage (NP)*)
- Tracheo-bronchial passage (*trachea and bronchial tree (TB)*)
- Pulmonary passage (*pulmonary parenchyma (P)*, *pulmonary lymphatic system (L)*)

Depending on their size distribution, the inhaled aerosols are deposited in these different regions. The old ICRP model of the respiratory tract [ICRP30] divides radionuclides into three retention classes according to their elimination behaviour, depending how long they remain in the respiratory tract. This takes account of different half-lives in the three compartments.

Under this scheme, plutonium compounds are assigned to retention class W (weeks). To this group belong radionuclides with a biological half-life of between 10 and 100 days. In contrast, plutonium dioxide is assigned to class Y (years). This corresponds to a half-life of over 100 days. Turner points out the difference in biokinetic behaviour of the dioxides of Pu-238 and Pu-239. [Tur95] Obviously this does not form part of the models.

The new ICRP lung model [ICRP66] divides the radionuclides into absorption classes. In the absence of empirical data, they are assigned to the corresponding retention classes. Class W corresponds to absorption type M (moderate) and class Y corresponds to type S (slow). The new model differs from the old in the way it defines the compartments and takes account among other things of the differences in sensitivity to radiation in the case of the tissue in the respiratory tract. Particulars can be found in the literature. [Raabe94]

5.3.4 Model of the alimentary tract

The ICRP model of the alimentary tract includes four compartments:

1. Stomach (ST)
2. Small intestine (SI)
3. Upper large intestine (ULI)
4. Lower large intestine (LLI).

Average retention times for food are between 1 hour in the stomach and one day in the lower large intestine. Particulars can be found in the literature on this subject as well. [Tur95]

6. Dose calculation and risk evaluation

6.1 Principles of internal dosimetry - the equivalent dose concept

Activity in the respiratory and alimentary tracts, as well as in individual organs, is estimated from the given activity with the aid of the described compartment models for metabolic processes. The energy deposition due to nuclear decay events is described as a physical quantity on the basis of the energy dose. In the end this energy deposition becomes carcinogenic at the cell level. Conversion to the equivalent dose uses a quality factor or evaluation factor. The International Commission on Radiation Protection (ICRP) has defined risk factors based on studies of survivors of the atomic bombs dropped on Hiroshima and Nagasaki. According to this model, a factor can be used to convert the equivalent dose into a risk of dying from the effects of a certain type of tumour.
The purpose of the equivalent dose concept is to enable a comparison of different types of radiation in relation to their damaging effects. As a reference quantity, ionising radiation is loosely classed alongside beta, gamma and X-rays. They are assigned evaluation factor 1, that is, these types of radiation are considered by definition to have the same biological effects. However, when the quality factors were defined it was known from radiobiological experiments that the relative biological effects differ by a factor of as much as five, depending on the type of radiation, biological effect and energy. At that time the International Commission on Radiation Protection considered the observable differences to be slight. According to international recommendations, sources of alpha radiation are accorded an evaluation factor of 20. [Krie92, Tur95, Wol97]

6.2 Internal dosimetry of alpha radiation sources

In the dosimetry of incorporated radionuclides, we encounter the problem that we cannot measure the energy dose and have to rely on the calculation models described. The effective ranges of alpha radiation in tissue are in the micrometer range. We therefore assume uniform irradiation of a cell in which a nuclide has been deposited, and uniform irradiation of organs. It is known that some radiopharmaceutical substances are unevenly accumulated in organs, and non-uniform deposition has even been demonstrated at cell level. There is a lack of experience in this area with regard to the majority of chemical compounds and nuclides. The dosimetry model ignores such enrichment effects and can lead to an underestimate of the cell dose in the event of uneven nuclide distribution. Yet the average organ dose may agree with the value derived for uniform distribution. These are the limits of the model at cell level.

6.3 Risk evaluation

There is another aspect which affects the evaluation of risk due to radiation exposure. The atomic bomb survivors are so far the most important reference group. On the other hand, the irradiation conditions of this group differ from the usual radiological protection conditions, especially where there is internal background radiation. This concerns the type of radiation and the size of the energy dose, as well as conditions such as acute or chronic exposure or uniform irradiation by external or internal background radiation. Transferring a risk factor derived in this way to anyone other than the Japanese population is questionable, since their lifestyle and environmental influences are different. Some authors take this into account by means of correction factors based on national mortality statistics. It is also known that there are significant individual differences in risk on account of genetic predisposition to certain diseases such as breast cancer.

As in many other countries, the recommendations of the ICRP dating from 1977 (ICRP26) have been incorporated into German legislation. The new recommendations contained in ICRP60 dating from 1990, with new risk coefficients, have not yet been taken into account by our national legislation. On the other hand it must be stated that there is no legal obligation to translate the recommendations of the ICRP into national law.

Turner writes about the ICRP risk coefficients: "However, it should be understood that they (remark: probability coefficients) entail recognised uncertainties and are subject to continuing
Other radiological protection committees have recommended coefficients that exhibit considerable variations. It is therefore not surprising that calculated estimates of damage give differing results.

7. CASSINI Mission - NASA study on environmental impact

In October 1997 the CASSINI space probe started on its way to Saturn carrying 32.8 kg of plutonium on board for its power supply. NASA has published its studies on environmental impact. In April 1997 the "Supplemental Environmental Impact Statement for the Cassini Mission" [NASA97] was published, as was the expert report of the Halliburton NUS Corp. [HNUS97], to which NASA makes reference. The results were heatedly discussed, and details are given below, in particular on evaluation with regard to radiological protection. I restrict myself to accidents accompanied by a release of plutonium dioxide. I should also like to refer to Professor Kakuf's critique, which can be found elsewhere in this volume.

7.1 On the methodology of the NASA study

NASA postulated accident scenarios during different phases of the CASSINI Mission, such that the plutonium dioxide barriers would be damaged resulting in a release. The safety analysis of the radiothermal generators (RTGs) was based on Monte-Carlo programs. These programs use a combination of known natural laws and input data to simulate random processes, and must reflect reality as closely as possible. The probability distributions for a plutonium dioxide release were defined on the basis of data from NASA. The probabilities for the occurrence of accidents involving a release were derived using error-tree analysis. An error-tree analysis takes as its starting point a trigger event that leads to the failure of a certain component (single-event failure). The art is to think of all the possible events in the ideal case that in the end lead to the failure of a component. On this depends the estimated probability of an occurrence. This model ignores human error and manufacturing errors.

The models take account of the following influences with regard to atmospheric spread and deposition on the earth's surface:
- Quantity and location of the plutonium dioxide release,
- Particle size distribution,
- Factors affecting the transport and deposition in the environment.
Calculations of atmospheric spread are simulations using empirical data and simplified models. Decisive factors for the concentration of activity in the atmosphere are the type of source (size, particle size etc.) and in particular the state of the atmosphere (wind direction and speed, turbulence, temperature stratification etc.). All the influencing factors are taken into account in different ways in the various models. For instance, current models of atmospheric spread predict a cigar-shaped dose distribution for the fallout from a nuclear weapon explosion or nuclear power station emissions. But this gives a picture which is only temporary in space and time. A change in the weather changes the dose distribution, for instance a change in wind direction or the onset of rainfall. Lastly it leads to hot spots, as was observed after nuclear weapon tests and after the reactor accident at Chernobyl. The chart shows the influence of ground contours [Rot91]. Simulations of atmospheric spread can therefore only ever show tendencies. Usable estimates for the effects of harmful substances can only be derived for continuous long-term emissions. [Vog92]

The radiological consequences of a plutonium release are judged on the basis of the ICRP models. We have already gone into detail on their limitations. The reliability of the assessment of radiological consequences is determined by the accuracy of the plutonium release rate. Kaku raises the particular criticism that the release rate is underestimated because surface contamination is underestimated and the assumed population density is too low. The NASA study assumes, for instance, that in the event of an accident on launch the fallout would fall over an area of 0.18 km² and at the same time ignores the above described influences of wind and ground structure. It was assumed that an accident during the swing-by manoeuvre would lead to a contaminated area of 2,000 km², which in the supplementary environmental study was reduced to 7.0 km². The post-launch accident scenarios ignore the possibility that the fallout could precipitate over the five surrounding districts, where over one million people live. When estimating harm from the swing-by manoeuvre, the collective dose is averaged over the world's population, even though the population density of the earth varies enormously. [Kaku, in this volume]

7.2 Scenarios and outcomes

7.2.1 Consequences of an accident during the launch phase

An accident during launch accompanied by a plutonium release would be an event with
regional effects. One possible cause could be an explosion aboard the Titan launch vehicle. Like a low altitude nuclear weapon explosion, this not only raises dust and debris but also forms aerosols. Depending on heat generation and pressure waves from the explosion, material is transported to a high altitude with subsequent regional fallout. The effects are of course highly dependent on meteorological behaviour.

The average probability for an accident to occur before launch or during the early launch phase is given by NASA as \(6.2 \times 10^{-3}\). This corresponds to a frequency of 1:161.3. Regarding pre-launch releases, NASA states a maximum collective dose of 1.4 Person Sv and a maximum individual dose of \(2.4 \times 10^{-1}\) Sv. The corresponding values for the early launch phase are 4 Person Sv and 6.1 Sv. [HNUS97]

7.2.2 Consequences of an accident in the atmosphere

Post-launch or during the swing-by manoeuvre in 1999, accidents involving a release into the atmosphere are conceivable. In this case the situation is like a high altitude nuclear weapon explosion, with distribution of aerosols in the atmosphere combined with transport over long distances. The atmosphere's inventory of Pu-238 would be enlarged. On a global scale, long-term deposition over the earth's surface is entirely imaginable. For some individuals incorporation of plutonium is possible but statistically difficult to ascertain.

NASA is here considering a situation involving accidents along the normal flightpath due to malfunction of the Centaur stage, after separation from the payload but before entering the planned orbit. It is assumed there would be re-entry during which the space vehicle breaks up in the atmosphere. The RTG components are released and can reach the earth's surface. The Atlantic Ocean, southern Africa or Madagascar are named as possible impact sites. The average probability of an occurrence is \(1.4 \times 10^{-3}\). The same consequences are calculated following intentional destruction after a malfunction along the planned flightpath. The average probability of an occurrence is \(1.2 \times 10^{-2}\). This accident represents the dominant scenario in the "post-launch accidents" group. Other scenarios with lower probabilities of occurrence are described in the Halliburton report. For the later launch phase 0.88 Sv is stated as the maximum collective dose and 0.014 Sv as the maximum individual dose.

NASA data is used to give the risk of a re-entry during the swing-by manoeuvre due to a failure of the control or propulsion systems. In this case the average probability of an occurrence is given as \(8 \times 10^{-7}\). The maximum collective dose is given as \(2.2 \times 10^{3}\) Sv and a value for the maximum individual dose is not available. [HNUS97]

7.3 Comparison of the radiological consequences

In the course of time the International Commission on Radiation Protection (ICRP) has redefined the risk factors for contracting fatal cancers. They are contrasted in the following table and the consequences of a plutonium release are determined on the basis of the equivalent doses in the Halliburton report.
The risk factors are given in accordance with Rotblatt [Rot96] and Turner [Tur95]. Comparison with the results of the Halliburton expert report makes it obvious that risk coefficients in accordance with ICRP60 from 1991 were used. The calculated damage estimates agree; slight inconsistencies can be traced back to different sources.

8. Summary and conclusions

In nature plutonium occurs in trace amounts only. In prehistoric times it was created in nuclear reactors in the uranium mine at Oklu in Africa, but none exists there now due to radioactive decay. Since its discovery it began to be manufactured for military use. Man subsequently built up an artificial plutonium inventory and there were also releases into the environment. Man, along with other living creatures, takes it in mainly by inhalation. Opinions about the dose are only possible within limits given the currently available models and the inadequate database. The limitations of the models for dosimetry, metabolism and behaviour in the environment have been explained. It is certain that plutonium remains in the lungs for a long time. The carcinogenic risk is therefore unambiguous, though difficult to express in figures without some degree of uncertainty.

The use of this radiotoxic element should therefore be avoided as far as possible. For space missions in the vicinity of the sun, solar energy should be used and further developed. Zimmerli considers the "Ethical problems of the civil use of nuclear energy" and writes: "Accepting responsibility means ... before taking action, declaring oneself prepared to stand up personally for the possible consequences of those actions, even if necessary with one's own good reputation, one's own wealth, one's own freedom or even possibly with one's own life. In the strict sense, then, in accordance with this definition it is only possible to answer individually for actions

- whose foreseeable consequences do not exceed the life expectancy of the person or persons starting them off;
- whose foreseeable consequences do not reach an order of magnitude or intensity that makes it meaningless to say that someone stands up for them;
- whose foreseeable consequences cannot be reversed in the sense that they render the rights
Due to their ambivalent character, there is no unambiguous distinction between the civil and military uses of nuclear technology. This is true of many technologies. However, the risks should always be envisaged, and in the process we should do more than merely calculate probabilities of an occurrence.

9. Literature


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M. B. Kalinowski (Ed.): Energy for space missions


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10. Software (CD-ROM)


A scientific critique of the accident risks from the Cassini space mission

Michio Kaku

Abstract:

If we carefully re-examine, line-by-line, the physics analysis behind NASA's Final Environmental Impact Statement, we find that this FElS has consistently underestimated the possible risks of an accident with the Cassini space mission. Originally, NASA estimated the number of cancer fatalities from a maximum credible accident over a 50 year period to be 2,300. We detail how this figure of 2,300 deaths could easily be off by a factor of 100, i.e. true casualty figures for a maximum accident might number over 200,000. Furthermore, property damage and lawsuits could be in the tens of billions. In addition, the FElS has overestimated the difficulty of using alternate sources of energy, such as solar and fuel cells. In line with the new NASA philosophy of faster, cheaper, better, the Cassini mission should be downsized and made into smaller, more frequent solar-powered missions to Saturn with less power requirements.

I. Introduction

The Cassini mission contains about 400,000 curies of plutonium-238, making it the largest space mission ever undertaken involving plutonium power packs (RTGs). The plutonium, about 72 pounds in weight, is distributed in 3 RTGs, with 18 modules each. If that quantity of plutonium is somehow dispersed into a populated environment, there is no question that such an accident could cause significant health effects resulting in thousands of casualties. All scientific experts are agreed on this point.

What divides the experts is:
(a) how much plutonium can be realistically released in a maximum credible accident and
(b) the likelihood of such an event. may happen that the Cassini mission may be a resounding, flawless success. However, it's only a matter of time before some disaster strikes. Instead of relying on misleading computer programs which tell you what you want to hear, one should carefully examine the actual track record of accidents in the space program, with numerous booster rocket failures and space probes which malfunction.

Unfortunately, the true risks from such an accident and the consequences have been downplayed. In a democracy, the American people can make rational decisions only on the basis of scientific truth, not simplistic, misleading press releases. It is inevitable that there will be spectacular accidents with the space program, some involving casualties, and the American people have a democratic right to know what the true risks are. Thus, it is a matter of scientific interest to go over line-by-line the calculation of the FEIS.
NASA calculates in its FEIS that up to 2,300 people might come down with fatal cancer over a 50 year period from the dispersal of plutonium-238 over a populated area. More recently, it has lowered this figure to 120. However, the calculation of these figures depends on three important steps, each of which has been underestimated by NASA:

- the calculation of the "source term," i.e. the amount of plutonium-238 which actually escapes and is dispersed into the environment
- the calculation of the land contamination area over which the plutonium-238 is spread
- the calculation of the population density and how many may come down with cancer.

In each category, we will show that:

a) the FEIS consistently underestimates the possible risks, avoiding the maximum credible scenarios
b) since NASA has never conducted a full-scale test of a realistic accident scenario, the FEIS simply makes up numbers to compensate for its ignorance. However, the FEIS consistently fabricates these numbers in a certain way: to arrive at the lowest casualty figures.
c) the FEIS disguises this fact by giving the results to three significant figures, which makes the figures seem authoritative and accurate, when in fact they are largely created by fiction.

Of course, it is justified to make estimates. But it is then standard procedure within the scientific community to give error bars or estimates of uncertainty. However, one immediately spots a glaring error: no uncertainties are ever given in the FEIS, which is a serious flaw. No uncertainties are given because their numbers are simple educated guesses, not real experimental numbers at all.

II. Calculation of casualties from a maximum accident

A. Launch Phase

We will investigate all three steps for two crucial phases, the early launch phase and the fly-by phase.

a) Source Term

The most important component of the calculation is the determination of the "source term." The FEIS admits that plutonium will escape from the RTGs during an accident both in the launch phase as well as the fly-by. However, the FEIS typically concedes that only a tiny fraction of a percent of the plutonium inventory will escape. This severely underestimates the true impact of a maximum credible accident and results in artificially low casualty figures. This is the main weakness of the FEIS.

The FEIS admits that plutonium in the RTGs will be subject to three extreme conditions during a launch phase accident: high temperatures, shrapnel, and explosive over-pressure. However, the essential problem is that NASA engineers have failed to perform a full-scale, realistic test of an explosion involving the RTGs.
In other areas of engineering, we have a good understanding of what happens when many different types of catastrophes happen, e.g. plane crashes and train wrecks, because we have a large body of experimental data. However, we have no experimental data by which to estimate the true dispersion of plutonium during a launch phase explosion because no realistic tests have ever been conducted.

NASA, however, has conducted some partial tests, which already reveal the vulnerability of the RTGs to extreme environments. The FEIS in fact, concedes that plutonium will escape the RTGs during a launch phase explosion, but its analysis is purely hypothetical and results in only a rough estimate.

In particular, we find:

i) High temperatures. The iridium casing surrounding the RTGs begins to oxidise and degrade at 1,000 degrees C, and begins to melt at 2,425 degrees C. Graphite eutectic melting points are even lower: 2,269 C. Experiments with the fuel cladding show that they may resist temperatures of about 2,360 C found in propellant fires, which is just 65 degrees below the melting point of the iridium casing, but are expected to fail beyond that.

Several conclusions can be drawn:

• The laws of thermodynamics show that there is a statistical distribution of molecules at kinetic energies beyond the average one, given by the Maxwell-Boltzmann distribution, indicating that structurally the iridium casing will begin to soften and weaken even as it approaches its melting point. In other words, the structural integrity of the iridium casing will degrade as it approaches its melting point and make it possible for shrapnel and explosive over-pressure to burst open the casing. Thus, the combination of temperature, shrapnel, and over-pressure may be sufficient to burst most of the containers wide open.

• Temperatures even beyond 3000 degrees C can typically be found locally in chemical explosions and reactions (e.g. an acetylene torch typically burns at 3,315 C). This is well beyond the melting point of the iridium casing. As a rough estimate, we know from the Stefan-Boltzmann and Wien's law that the colour of a flame is roughly correlated with temperature, and the colour red typically found in combustive reactions (at wavelengths of 7,000 angstroms) will be correlated with temperatures of about 4,000 C. Thus, we can expect some melting of the iridium casing due to local heating within the fireball, although the average temperature may be lower than the melting point.

ii) Shrapnel. Tests have shown that aluminium bullets fired at the RTGs at velocities of 1,820 ft/sec and titanium bullets fired at 1,387 ft/sec have caused a breach of containment. Edgeon fragments at velocities as low as 312 ft/s can rupture the leading fuel clads. So even at room temperature, we can expect high-velocity fragments to pierce the RTGs. But at high temperatures near the melting point of iridium, where the RTG casings are weakened by high temperatures and pressures, we can expect shrapnel to do even more damage to the RTG casings, bursting many of them open.

iii) Over-pressure. Chemical explosions can cause local over-pressures of several thousand pounds per square inch. The RTGs have been tested to 2,210 lb/ft² without fuel release. However, under the weakened conditions created by high temperature, shrapnel, etc., it is not known how much can actually escape.
The point is that a full-scale test involving the simultaneous conditions of high temperature, shrapnel, and over-pressure has never been done. It is likely that the combination of all three will cause severe rupturing of the RTGs.

In spite of all these factors and uncertainties, the FEIS on p. 4-48 confidently concludes that a maximum of 28.7 curies, or less than 0.01% of the plutonium, will escape during a launch phase accident.

Several points can be made:
- This estimate is sheer speculation. The number is made up. Since no one has ever done a full-scale test of the RTGs in the explosive environment of a booster rocket failure, it pure guesswork as to how much plutonium will escape.
- However, the estimates are given as a statement of fact, with no error bars or indications of reliability. We have no indication of the confidence level of this number. This is a severe statistical mistake.
- The figure of 28.7 curies of plutonium is given to three significant figures, which is rather surprising, revealing a lack of grasp of statistical analysis on the part of the engineers. According to the laws of statistics, the propagation of errors determines that a calculation is no more reliable than its largest source of error. The largest source of error in this calculation is the fact that the engineers have made up many of the numbers out of thin air. Thus, calculating the plutonium release to three significant figures reveals a remarkable lack of understanding of even elementary statistics.
- Given the fact that the simultaneous effect of high temperature, shrapnel, and over-pressure has never been fully tested, and given the fact that in combination they will probably cause a large failure of the iridium casing, a figure of 30% to 40% release is probably more realistic.

b) Area of Impact.

In typical radiological computer programs conducted by the military and the commercial nuclear industry, the area of impact of the accident is largely a function of wind conditions. Computer calculations involve solving a simple second-order partial differential equation (the standard Helmholtz equation with mass, the source term is the driving term within this second order differential equation, sometimes called the diffusion equation).

In addition, actual experiments have shown that micron-sized particles of U-238 can be dispersed by the wind over 25 miles. In nuclear power plant accidents, radiation has been dispersed several thousand miles from the original accident. (For example, in the Windscale disaster in England in 1957, which was completely hushed up by British authorities, the radioactive cloud emerging from the carbon-moderate reactor was tracked going over London, sailing over the British channel, and finally dispersing over Cairo, Egypt. More recently, the radiation from Chernobyl was widely tracked over Europe and even the U.S.)

However, what is rather remarkable is that the FEIS totally ignores wind conditions and merely postulates that the plutonium will be dispersed, in one scenario, within an area of 7.18 x 10^-2 square miles. This is a roughly a square area 1,000 feet on each side. Again, the fact that this is presented without any error bars, and to three significant figures, shows the ignorance of the engineers who calculated this number.
But what is revealing is that the FEIS assumes that almost all the plutonium will be confined to the launch facility. According to the FEIS, no plutonium is expected to leave the launch pad area. In other words, NASA engineers have discovered a new law of physics: the winds stop blowing during a rocket launch.

But anyone who lived through the Challenger explosion, the Delta rocket explosion, etc., will realise that debris has been pulverised and spread over a significant area. Eye-witness accounts of the recent Delta rocket explosion indicated debris scattered over several miles.

In fact, experiments conducted on metal oxides have shown that a significant percent of the inventory can be pulverised into a fine dust of micron-sized particles, which can then be blown miles from the original site by the winds. These micron-sized particles are especially dangerous because they stay lodged deeply in the lungs for decades, where ciliary action is useless in expelling these particulates. Thus, these particles can emit radiation at close range to nearby lung tissue for decades to come, causing cancer.

c) Population density.

Yet another reason for attaining low estimates of risk is the FEIS's assumption that the population density is rather low. In this calculation, one problem is determining the number of person-rems which will initiate a cancer. One can reasonably assume that 5,000 person-rems will induce a single cancer. (Although some critics have placed the true figure as low as 300 person-rems/cancer.)

However, what is in dispute is the fact that the FEIS assumes a rather average density of people per square mile. This is therefore not a maximum credible accident, which would assume that the winds blow the plutonium into a major city.

For example, the FEIS assumes that, for a Phase 5 accident over Africa, the expected health risk would be $1.5 \times 10^{-4}$ over a population of only 1,000 people. This is low even for Africa. Not to mention that the rocket may misfire during the launch phase and tumble in a partial orbit, thereby landing almost anywhere on the earth, rather than in Africa.

A Phase 1 accident would release plutonium in an area populated by only 100,000 people. But if the winds blow, then the area affected within 5 counties of the launch site could total over a million people.

B. Fly-by Phase

The source of greatest concern, from the point of view of plutonium release, is the fly-by. The Cassini probe will be whipping around the earth at around 40,000 miles per hour, significantly faster than the escape velocity of the earth (25,000 miles per hour) and faster than many meteorites. If there is even the tiniest miscalculation of the trajectory, the Cassini may burn up in the atmosphere and spray a significant portion of land area with plutonium. There is ample experimental evidence that space probes, without heat shields, will vaporise upon re-entry. However, the FEIS again takes a low estimate of plutonium release.
a) Source term.

The FEIS admits that about 32% to 34% of the plutonium is expected to be released high in the atmosphere. However, the FEIS then dismisses this factor by diluting it over the population of the entire earth. This neglects the fact that the mixing of plutonium in the atmosphere takes a considerable amount of time, and in the meantime it may concentrate or hover over certain regions of the earth. This effect is ignored by the FEIS.

The FEIS then calculates how much plutonium may actually land on the earth, and again underestimates the real risks.

The FEIS first divides the source term into three parts: a rock impact, soil impact, and water impact, and then calculates the percent distribution of each on the planet earth. For example, the FEIS estimates that 4% will hit rock, 21% will hit soil, and 75% will hit water.

This is a rather odd way of calculating maximum risks, because it confuses probability of an accident with the consequences of that accident. The calculation of how much surface area of the earth is divided into rock, soil, and water belongs in a calculation of the probability of mishap, not in the calculation of maximum risk.

The calculation of maximum credible risk necessarily assumes maximum risk by definition, i.e. that all the plutonium will hit rock, since that is the maximum credible scenario. Rather than 4% of the plutonium hitting rock, one should assume that all of it does.

Second, the FEIS calculates the percent of plutonium that can be released on impact with rock, soil, and water. Again, these numbers are simply pulled out of hat, with no justification. For example, in one scenario, it assumes that all of the plutonium will be dispersed if it hits rock, 25% of the plutonium hitting soil will escape, and none hitting water will escape. However, no justification is given for these estimates, because there are none.

The important point is that no one has ever done an experiment calculating the effect of entering the atmosphere with RTGs at 40,000 miles per hour. Until this experiment is done (using a replacement for plutonium), all these numbers are purely speculative.

b) Area of impact

The estimated land contamination for this plutonium accident is on the order of 2,000 sq. km. That is roughly equivalent to a square about 27 miles on a side.

More recently, on April 1997, the Supplemental Environmental Impact Statement has revised the early estimate of cancer fatalities from 2,300 to 120 (p. 2-19). This may seem strange, until one realises that their assumptions have become even more conservative. Instead of assuming that land contamination can be 2,000 sq. km, the new estimate puts it at a surprisingly small area of 7.9 sq. km. This is a square about 1.7 miles on each side. In other words, the new EIS assumes that the Cassini probe, coming down in flames from outer space at 40,000 miles per hour, will hit a bull's eye and then remain there, without any winds whatsoever.

This is a remarkable reduction by a factor of 250, which once again is pulled out of a hat, without any justification. Not surprisingly, the casualty figures have also dropped significantly, from 2,300 to 120, a factor of 20.
c) Population density

Again, the FEIS assumes average figures for population density, and totally neglects the fact that there are large population concentrations on the earth where tens of millions live. Within a 50 mile radius of Manhattan, for example, there are about 20 million people, or about 8% of the entire population of the U.S. Similarly, there are other concentrations of people on the earth with even larger densities, such as around Tokyo, Mexico City, and Shanghai.

III. Calculation of Risk

The analysis used by the EIS to calculate the probability of a maximum accident with the Cassini mission uses methods pioneered by the nuclear power industry (e.g. single event failures, event tree analysis, Monte Carlo calculations, etc.)

Although these methods are standard for the field, these methods have largely been discredited by the actual operating record of nuclear power accidents. Three Mile Island, for example, was a Class IX accident which was largely unforeseen by MIT's WASH-1400, the standard reference within the industry, which largely ignored small pipe breaks.

The methodology is flawed for several reasons

i) Human error and design flaws

Most of the major accidents that have taken place in the past are beyond the simple-minded event-tree analysis. However, this does not foresee the fact that someone might drive this car over a cliff.

The actual track record of accidents shows that computer calculations are often misleading and give a false sense of confidence:

- Three Mile Island was caused by human error (misreading the PORV valve light on the control panel) and design flaws (lack of a water gauge meter in the containment vessel and poor design of the PORV warning light). It was not foreseen by WASH-1400, which concentrated on large pipe breaks.
- The Chernobyl disaster was caused by human error, when the engineers and managers manually disengaged the control rods. There were also design flaws, since the carbon-moderated reactor was prone to a positive reactivity power surge. During the accident, when a transient sent power levels rising, the lack of a SCRAM system caused neutron levels to rise exponentially, causing a steam/hydrogen gas explosion which blew the top of the reactor.
- The Hubble Space Telescope was launched into space with incorrectly ground mirrors. This mishap was also caused by human error. Part of the fault, among others, lies in a worker who inserted a ruler in backwards in Danbury, Connecticut, where the mirror was being machined, thereby making possible an incorrect shape for the mirror. Remarkably, the flaw was later detected, but ignored by engineers. It was not noticed until the mirror was launched into space, causing a billion dollar public relations disaster.
- Star Wars. In a well-known mishap, the Space Shuttle was conducting a test of the Star Wars laser system, with a laser beam sent from Hawaii. Because of human error...
(converting miles to meters incorrectly), the Shuttle was oriented in space away from Hawaii, not towards it, and missed the signal completely.

The real danger is that the engineers begin to believe their own computer calculations, which are only a guide, not a law of nature. Then they become overconfident and fail to foresee the inevitable.

ii) GIGO. There is an expression, "garbage in, garbage out." Even if you use the world's largest supercomputer, if your assumptions are faulty, then your conclusions will also be faulty. For example, one can use a supercomputer to calculate the precise number of angels that can dance on the head of a pin. But giving you this number to three significant figures is meaningless, since the original assumption was in question.

iii) Similarly, the basic assumption of the FEIS is that one can model accidents on the basis of single event failures, when multiple failures, common mode failures, human error, and design flaws have contributed to most accidents. Unfortunately, it is beyond the power of computers to realistically model these more complex types of accidents.

iv) Weakest link: the Titan IV
A chain is no stronger than its weakest link. The weakest link is the Titan IV booster rocket, which has a failure rate of about one in 20. And booster rockets in general have a failure rate of 1 in 70 or so. Furthermore, there have been 3 failures among the 23 missions involving plutonium power packs, one of which released a significant amount of radiation. In fact, everyone on the earth has a piece of the SNAP 9A satellite in their body. The SNAP 9A satellite also significantly increased the amount of plutonium-238 on the planet earth.

v) Where does one-in-a-million figure come from?
The FEIS typically has accident probabilities in the range of one-in-a-million. By analysing the calculation, one can see where this figure comes from. One can see that most of the one-in-a-million comes from the impact of a micrometeorite on the Cassini probe. In the FEIS, very little of the probability comes from errors in transmission, errors from ground control, etc. This patently violates the actual experience with space probes.

Meteorite damage is of a real concern, but human and technical flaws are much more likely to cause failure. For example, it has been recently estimated that the International Space Station Alpha may suffer a 50% probability of a catastrophic meteor impact during its 15 year life span. This is certainly a significant danger. But actual operating experience has shown that in almost all space missions, the real danger comes from human and technical flaws, i.e. sending the wrong instructions to space probes, failure of transmitters and solar panels to unfurl correctly, etc. These are almost impossible to model by computer.

vi) Furthermore, a one-in-a-million figure assumes that one million Cassini space probes have been fired into space, and only one Cassini space probe malfunctioned. This is clearly untrue. In other words, the table of probability given by NASA is just a wish list. The one-in-a-million figure is wishful thinking masquerading as reputable science.
IV. Calculation of alternatives

The FEIS undertakes a half-hearted effort to calculate alternatives to using plutonium. Since only 800 watts of power need to be replaced, or the output of roughly eight light bulbs, the alternatives must be taken seriously.

There is no question that, in deep space, there is not much sunlight. At the distance of Saturn, there is only 1% of the solar flux found on the planet earth (in watts/sq. meter). The debate revolves around whether solar/fuel cells can make up the 800 watts necessary to run the mission.

The FEIS on p. 2-56 claims that, if the Cassini is equipped with massive, bulky solar panels, the probe will be 130 pounds too heavy for lift-off. (The Titan IV can lift 13,743 pounds of payload to Saturn). However, the calculation is incomplete, since it does not consider some simple options:

- Downsize the craft. If the probe is 130 pounds overweight, then the obvious solution is to lose 130 pounds of equipment. This means leaving out some experiments. However, the Cassini is the Cadillac of space missions, and a few less redundant experiments will still give us excellent science. This may be the solution.
- Conform to the new NASA philosophy. The new philosophy of NASA is faster, cheaper, better. For example, the Mars Observer was a billion dollar fiasco: bulky, costly, infrequent. The new Mars probes were correctly downsized; the new strategy is to send shots to Saturn should be downsized and made more frequent, not less frequent, and energised by solar cells.

Casino is therefore a left-over from the old NASA philosophy of doing big space shots once every 10 years. Since space probes were so infrequent, this philosophy resulted in space craft that were overloaded with experiments, and hence the Rags seemed a natural solution. But the new philosophy of NASA should generate small, frequent, and cheap probes to Saturn which are well within the capability of solar power.

- Saturn is not going away. All this will cause delays, but Saturn is not going to go away. Other windows of opportunity will open up. Given the fact that one can whip around other planets and change trajectory, windows of opportunities open up all the time.
- Use a combination of solar/fuel cells. The FEIS only considers solar and fuel cells separately, not in conjunction. Fuel cells can be used to store energy when solar cells can no longer receive adequate energy from the sun.

V. Conclusion and recommendations:

We all live in a world of risks. Every day, when we enter cars or aeroplanes, we place our bodies at risk. Therefore, we must be careful in how risks are handled.

But the difference with the Casino mission is that we voluntarily put ourselves at risk when travelling. However, no one asked the American people if they wanted to put themselves in danger. NASA bureaucrats, not the American people, are making this decision.

Second, if we are in a car accident, only a handful at most will die. But no one told the American people that thousands may die if a plutonium accident takes place.
Similarly, the FEIS justifies the figure of 2,300 cancer deaths by stating that that figure is lost in the background cancer levels found world-wide. This is a strange argument. That same argument can be used to justify mass murder. Since thousands die violent deaths in the U.S., it makes no difference if a few hundred more die by a serial killer. They will be lost in the background noise.

Of course, we all want a healthy, vibrant space program to explore the universe. However, it should also be made safe. Since the American taxpayers are paying for it, they have a right to know the true risks, and should be informed of the debate concerning accident risks within the scientific community.

Unfortunately, the American people, being constantly told that the probability of an accident is on the order of one in a million or a one in a billion, will feel betrayed when a catastrophic accident does occur in space. Such a space tragedy could cause a backlash from the American people, who will correctly feel that they were lied to by NASA bureaucrats. This could be the end of the space program, which would be a disaster to science.

Furthermore, there is no mention of property damage in such an accident. The Three Mile Accident, for example, reputedly released just 13 curies of indine (compared to 400,000 curies in the Cassini mission) yet it generated two billion dollars in lawsuits.

Even if no significant amounts of radiation are released in a plutonium accident, property values are expected to plummet. And if significant amounts of plutonium are released, then whole areas must be quarantined, earth dug up and placed in 55 gallon drums, houses hosed down with fire trucks, crops impounded, etc. That was one terrible lesson from Chernobyl. The loss to home owners and the agribusiness in the area around the Cape could amount to tens of billions of dollars.

Therefore, the mission of a critic is to save the space program from NASA bureaucrats.

Unfortunately, NASA commits the worst mistake that a scientist can ever make: believing your own press release. A casual observer, reading the FEIS, may be deceived into thinking that a careful analysis has been done. But when actually reproducing the calculation, the observer will be shocked at how many guesses, hidden assumptions, and minimisation of risks there are in the FEIS.

A true scientist carefully writes down the error bars and the confidence level he or she places in their figures. A careful scientist does not do what NASA has done:
• fail to perform full-scale accident tests
• pull numbers out of hat to compensate for this ignorance
• dress up these fake numbers with complex computer programs that cannot measure the true risks from human error, etc.
• publish the results with an accuracy of 3 significant figures, with no mention of error bars, confidence levels, or a list of assumptions.

This borders on scientific dishonesty.

It is no accident, therefore, that the FEIS comes up with consistently low numbers for a maximum accident.
The simplest way to solve our problem is to use solar cells with fuel cells. This will require downsizing the space craft by at least 130 pounds. But this is also in tune with the new philosophy of faster, better, and cheaper. The Cassini mission, however, is a relic of the old thinking of slower, more expensive, less frequent.

A new program to explore the planets would have these probes downsized and launched much more frequently, using non-nuclear energy sources.

In the interim, this may cost more and cause some delays, but it may also have the lives of thousands, prevent law suits numbering in the tens of billions, and save the space program from NASA bureaucrats.
How the risks of the Cassini mission are played down and neglected*

Karl Grossman

The U.S. government is pushing ahead with the use of nuclear power in space - despite the tremendous danger, huge expense and a clear energy alternative: solar power.

In October, NASA plans to launch the Cassini space probe carrying more plutonium - 72.3 pounds - than has ever been used on a space device. The $3.4 billion mission is among a number of space projects using nuclear power planned by the U.S.

Plutonium has long been described as the most toxic substance known. It is to be used on Cassini as a fuel in three radioisotope thermoelectric generators (RTGs) to produce electricity to run the space probe's instruments.

The Cassini probe is to be launched on a Titan IV rocket, despite the poor record of Titan rockets. In 1993 another Titan IV blew up, 101 seconds after launch, from Vanderberg Air Force Base in California, blasting to smithereens an $800 million U.S. spy satellite system it was lofting. "Workhorse, My Foot," was the title of an editorial in the journal Space News, after that mishap. "The Titan frequently is referred to by its misnomer, the workhorse launcher," said the space industry publication. "But it has proven to be more of a temperamental and ornery show horse."

If the Cassini does successfully make it up on the scheduled launch on October 6 1997, an even more potentially lethal scenario lies ahead. In August 1999, NASA intends to have Cassini hurtle back for an Earth "flyby."

Because Cassini does not have the propulsion power to get directly from Earth to Saturn, NASA plans to send the probe to Venus, have it circle Venus twice and then come flying back at 42,300 miles per hour towards Earth to do a "flyby" just 312 miles overhead. The idea: to use the Earth's gravity to increase the velocity of Cassini so it can reach its destination of Saturn.

But if after a billion miles in space, if there is a miscalculation on the 1999 Earth "flyby" and the probe makes what NASA in its Final Environmental Impact Statement for the Cassini Mission calls an "inadvertent reentry" and falls into the 75-mile high Earth atmosphere, disintegrating and releasing plutonium, NASA says "approximately 5 billion of the estimated 7 to 8 billion world population at the time could receive 99 percent or more of the radiation exposure."

* This warning analysis was published before the launch of Cassini took place in October 1997. INESAP Information Bulletin Nr.12, March 1997, p.40-43
NASA in its public relations promotion for Cassini claims the plutonium on Cassini would be contained in a "flyby" accident. PR representatives of NASA stress that the plutonium is in modules that are heavily shielded. But the Environmental Impact Statement says a sizeable amount of the 72.3 pounds of plutonium on Cassini would likely be released in a "flyby" accident and as "vapor or respirable particles." This would maximize the health impacts for plutonium is most dangerous if inhaled as dust.

"For all the reentry cases studied," says the document, "about 32 to 34 percent of the fuel from the three RTGs is expected to be released at high altitude. The fraction of the fuel particles released during reentry estimated to be reduced to vapor or respirable particles less than 10 microns ranges from 66 percent for very shallow reentries (8 degrees) to about 20 percent for steep (90 degree) reentries."

"The way Cassini would burn up," explains Dr. Michio Kaku, professor of nuclear physics at the City University of New York, "is as it flies by Earth if there is a small misfire" of Cassini's "rocket system it will mean that they will penetrate into the Earth's atmosphere and the sheer friction will begin to wipe out the heat shield and it will, like a meteor, flame into the Earth's atmosphere. This thing, coming down into the Earth's atmosphere, will vaporize, release the payload and then particles of plutonium dioxide will begin to rain down." Dr. Kaku says that plutonium particles that are inhaled by people will, because plutonium "is not watersoluble," lodge in peoples' lungs "causing cancer over a number of decades."

Dr. Horst Poehler, a scientist who worked for 22 years for NASA contractors at the Kennedy Space Center, says the plutonium on Cassini will, in fact, not be well-shielded. [The plutonium pellets have an iridium cladding which is just a "fingernail thin", and are encased in a special carbon material which is only a few centimeters thick.] He says a Cassini "flyby" accident releasing plutonium would be "the mother of all accidents." Declares Dr. Poehler: "Remember the old Hollywood movies when a mad scientist would risk the world to carry out his particular project? Well, those mad scientists have moved to NASA."

Underestimated casualties

As for the death toll of a Cassini "flyby" accident, NASA says in its Final Environmental Impact Statement that despite the radiation exposure which, it acknowledges, could impact billions of people, only 2,300 cancer deaths would "occur over a 50-year period to this exposed population."

However, Dr. Ernest Sternglass, professor emeritus of radiological physics at the University of Pittsburgh School of Medicine, after his review of the data contained in NASA's Final Environmental Impact Statement, said that "they underestimate the cancer alone by about 2,000 to 4,000 times. Which means that not counting all the other causes of death - infant mortality, heart disease, immune deficiency diseases and all that - we're talking in the order of ten to twenty million extra deaths." Considering the additional potential causes of death, the total death toll "may be as much as thirty to forty million people."
Dr. John Gofman, professor emeritus of radiological physics at the University of California at Berkeley, says just the amount of plutonium NASA admits could be dispersed in a "flyby" accident "represents an astronomical quantity of a potent alpha-emitting cancer producer. The number of cancer doses is so high as to make calculations extraneous. Scientists and engineers in control of their faculties would surely have eliminated this project from their agenda. Yet it appears that is not the case."

Dr. Helen Caldicott, a founder and president emeritus of Physicians for Social Responsibility, says NASA fails to understand the especially dangerous characteristics of plutonium and the health impacts from "chronic, long-term exposure. This is incredibly deadly stuff." Also, she said, NASA has drastically underestimated the impact by basing it on an "average dose for the overall world population," not providing for those who would receive larger doses of plutonium.

A dispersal of plutonium from Cassini "would be a terrible event," said Dr. Karl Z. Morgan, a noted health physicist, one of the first five health physicists in the world, often described as the "father" of health physics and former director of the Health Physics Division at Oak Ridge National Laboratory. "Each of these plutonium particles would deliver a terrific dose - hundreds or thousands of rems - to the tissue close up against the particle. There would be numerous cancers as a result."

**The solar alternative**

Moreover, plutonium-power is not necessary for the Cassini mission. Solar photovoltaic energy could substitute to generate the mere 745 watts of electricity that the plutonium-powered system is to provide. In 1994 the European Space Agency announced a "technology milestone," a "breakthrough" in "high efficiency" photovoltaic solar cells specifically for use on deep space probes. Declared the ESA announcement: "Under contract with ESA, European industry has recently developed high efficiency solar cells for use in future demanding deep space missions." The new solar cells reach a 25% efficiency "under deep space conditions," stressed ESA. "The 25% mark represents the highest efficiency ever reached worldwide."

"Until now, deep space probes had to use thermonuclear power generators, like the so called RTGs," said the ESA announcement. "As RTG's technology is not available in Europe, ESA therefore attempted to develop a power source based on very high-efficiency solar cells." And, said ESA, this was done by an "industrial team" led by a German company. "ESA expects that the new high performance silicon solar cells could profitably be used in deep space missions."

"If given the money to do the work, within five years the European space agency could have solar cells ready to power a space mission to Saturn," the newspaper Florida Today was told by ESA physicist Carla Signorini in 1995.

And in March 1997, at a symposium at the Technical University of Darmstadt on "The Ambivalence of Space Technology" organized by IANUS and INESAP, Dr. Gerhard Strobl
of the company that developed the high-efficiency solar system for ESA, Angewandte Solarenergie (ASE), indicated that his firm's solar cells could produce adequate power for the Cassini mission although the space probe would have to be redesigned.

In not using solar power for the Cassini mission, "NASA is putting ideology ahead of the laws of physics because the amount of energy that you could generate from solar cells is clearly sufficient to energize Cassini. We are only speaking about a modest amount of electricity. It is well within engineering specifications to use solar cells and, if necessary, fuel cell-batteries to supply the electricity needed. But NASA is ideologically committed to using nuclear." Michiu Kaku acknowledged that "retrofitting Cassini with solar cells would cost more and might delay the mission a bit, yet that is a small price to pay for the lives of people who could be killed if there is a tragedy."

Yet NASA, along with other proponents of a nuclear Cassini mission - the U.S. Department of Energy, the DOE's national nuclear laboratories, Lockheed Martin, the company which in 1993 acquired the GE division which for decades produced RTGs - insist on sticking with atomic power on Cassini.

NASA said in its Final Environmental Impact Statement for the Cassini Mission acknowledges that the European "cells thus far have tested favorably under simulated environments." An analysis by its engineers, says NASA, showed they provide "improved performance." But, NASA says, "greatly increased turn times and greater operational complexity and programmatic risk associated with an all-solar Cassini design makes such a design, from both mission engineering and scientific perspective, infeasible."

"Infeasible?" comments Dr. Kaku. "Using solar on Cassini is only infeasible if safety is not the primary concern."

The military connection

Leading the challenge to the Cassini mission is the Global Network Against Weapons & Nuclear Power in Space based in Gainesville, Florida. Bruce Gagnon, a co-coordinator of the Global Network, says an additional reason "beyond pressure from DOE, the national nuclear laboratories and Lockheed Martin and the nuclear industry" that NASA insists on using nuclear power on Cassini is "the military connection."

The Pentagon, notes Global Network co-coordinator Bill Sulzman, is seeking to use nuclear power for weaponry in space. NASA, seeing its funding shrink with the end of the Apollo moon missions of the 1960s and the early 1970s, began coordinating its operations with the Pentagon to keep its funding up, and continues to "work in step with the military."

The U.S. Air Force in its current planning statements stresses space as a high ground. He points to Colonel Mike Heil of the Air Force's Phillips Laboratory, a research and development facility, declaring in an interview earlier this year that "yesterday's high ground of remote ridge lines and distant hilltops has a modern corollary: space. Our technologies are

* See paper by Gerhard Strobl in this volume.
the ladder that enable military commanders, now and in the future, to reach that ultimate high
ground."

General Joseph W. Ashy, commander-in-chief of the U.S. Space Command, told Aviation
Week & Space Technology recently how the U.S. Air Force intended to "expand into" space.
"We will engage terrestrial targets someday - ships, airplanes, land targets--from space. We
will engage targets in space, from space. It's politically sensitive, but it's going to happen.
Some people don't want to hear this, and it sure isn't in vogue...but - absolutely - we're going
to fight in space. We're going to fight from space and we're going to fight into space."

As for the energy for the weaponry that the U.S. military would like to see used in space -
such as laser weapons, particle beams and hypervelocity guns - an Air Force report issued last
year entitled New World Vistas, said there were "power limitations" for space weapons today.
"A natural technology to enable high power is nuclear power in space," asserted the Air Force
report. "Setting the emotional issues of nuclear power aside, this technology offers a viable
alternative for large amounts of power in space."

The Strategic Defense Initiative or Star Wars as structured during the Reagan administration
was premised on orbiting battle platforms with such nuclear-powered weaponry. The Clinton
administration changed the name of the Strategic Defense Initiative to Ballistic Missile
Defense but retained a multi-billion budget: $4 billion Dollars in the coming fiscal year. It
has continued a commitment to nuclear power in space declaring in a 1993 policy statement
that "space nuclear power and propulsion systems can contribute to scientific, commercial and
national security space missions."

In September 1996, the Clinton administration ordered a development program for nuclear-
propelled rockets for military and civilian uses. The Defense Special Weapons Agency is to
work on "multiple nuclear propulsion concepts," according to a front page article in Space
News.

Other U.S. space nuclear projects

• A scheme to rocket high-level nuclear waste into space was unveiled by scientists from
Brookhaven National Laboratory at the Annual Symposium on Space Nuclear Power and
Propulsion held in Albuquerque, New Mexico in January 1997. Sending high-level nuclear
waste into space was an idea earlier considered by the U.S. government but rejected--up
until now - because of a concern about a rocket carrying such waste blowing up on launch
or undergoing an accident after launch and crashing back down, dousing the Earth with the
atomic waste.

• Sandia National Laboratories is embarked on a program to develop nuclear-powered
satellites to beam down to Earth "high-definition, multichannel television" signals.
"Described as a pathway to making the United States a global telecommunications
superpower, the Sandia proposal would pair controversial space nuclear power with
entertainment and communications on demand," according to The Albuquerque Tribune.
The U.S. Air Force has been studying the use of nuclear reactors to "provide power and propulsion for military satellites," according to Space News. The "bi-modal" nuclear spacecraft would serve both as a "propulsion system and for electric power."

NASA is planning to launch a pair of plutonium-fueled space probes for a mission to Pluto in 1999.

What Space News described as "an aerospace industry alliance has come up with" a scheme to build a "high-powered" nuclear communications satellite. Lockheed Martin mission has been leading a consortium of seven firms, including a Russian company, on this project.

Meanwhile, NASA is looking into nuclear-powered colonies on the moon and on Mars.

Accidents with nuclear power in space

The use of nuclear power in space has been plagued by accidents. In 1964 a SNAP-9A (SNAP for Systems for Nuclear Auxiliary Power) RTG dropped from the sky burning up in the Earth's atmosphere as it fell. The 2.1 pounds of plutonium fuel it had onboard vaporized and "dispersed worldwide," according to a publication called Emergency Preparedness for Nuclear-Powered Satellites issued in 1990 by a grouping of European nuclear agencies. "A worldwide sampling program carried out in 1970 showed SNAP-9A debris to be present at all continents and at all latitudes," it said.

Dr. Gofman, an M.D. and Ph. D. who did early scientific work with plutonium, has long pointed to the SNAP-9A accident as a cause of increased lung cancer on Earth.

There have been three accidents out of the 25 known U.S. space missions involving nuclear power. The Soviet and now Russian failure rate has been the same: about 15 percent. That includes the Soviet Cosmos satellite which in 1978 disintegrated as it crashed to Earth over northwest Canada leaving a swath of nuclear debris over tens of thousands of square miles.

Last year there was the fiery crash of the Russian Mars 96 space probe carrying a half pound of plutonium on Chile and Bolivia. The probe, according to eyewitnesses, broke apart as it fell. John Van der Brink, who had just retired from the European Southern Observatory in Chile, was out in the mountains of northern Chile on the night of November 16 watching meteors when he saw what was clearly "a piece of space debris [with] sparkling bits sort of coming off the back of it" falling to Earth. "This was an extraordinarily spectacular event."

Leo Alvarado, a post-graduate student of geology from the Universidad Catolica del Norte, who had been driving with four other geology students across the Atacama Desert in northern Chile, saw it, too, changing colors as it came down. "We watched it break up into many pieces and burn."

The Chilean government is investigating the health impacts of the probe's fall.
Galileo, Ulysses, Cassini ...: Stop nuclearization of the heavens

Recent U.S. space probe missions involving plutonium-fueled RTGs were Galileo (with 50 pounds of plutonium onboard) launched in 1989, and Ulysses (with 25 pounds) in 1990. Indeed, carrying up Ulysses and its plutonium was to be the next mission of the ill-fated Challenger in 1986. After the Galileo launch, in response to my Freedom of Information Act about the alternatives to using nuclear power on Galileo, I received from NASA's Jet Propulsion Laboratory reports acknowledging that solar power could have substituted for nuclear power on that mission to Jupiter. "Based on the current study, it appears that a Galileo Jupiter orbiting mission could be performed with a concentrated photovoltaic solar array power source without changing the mission sequence or impacting science objectives," one report began.

"Nuclear energy in outer space," says Dr. Kaku, "is the linchpin" of the U.S. space program. "What we are headed for is a nuclear-propelled rocket with nuclear-propelled lasers in outer space. That's what the military and that's what NASA would really like to do. First we have small little reactors called the SNAP reactors. Then we have the RTGs and Galileo and Cassini. And ultimately what they would like to do is have nuclear-powered battle stations in outer space. That's what all of this is leading up to."

Gagnon says: "Our concern is that the United States military and major weapons corporations view space as a new market, ultimately to profit from. They are using taxpayers' dollars to put a new round of the arms race in space. At the same time the nuclear power industry views space as its new market, a place where they can put plutonium and other radioactive sources, whether it's on military missions or civilian inter-planetary missions. What is needed now is for the American public to speak out."
NASA’s choice for nuclear instead of solar power for interplanetary space probes: A look behind the scenes

Ross McCluney, Ph.D.

Questioning nuclear power in space

NASA said solar wouldn’t work on the Galileo mission to Jupiter, launched on 18 October 1989. Two weeks after the Galileo launch, a long-sought Freedom of Information Act request, delayed for over two years, was filled. This forced the release of an internal NASA report from 1981 saying that solar could have substituted for nuclear power for the Galileo probe. This report was finally released only after the launch was a done deal.

Then they said that solar would not work on the Cassini space probe to Saturn, launched in October 1997. Why should we believe them this time? Is this any different from the Galileo case?

To be sure, using solar is more difficult. Saturn is further from the sun. The available sunlight is only about one percent as strong as it is at the Earth’s distance from the sun substantially less than its strength at Jupiter. A much bigger solar collection area is required, about as big as two tennis courts. The big panels might tend to get in the way of the observing instruments. The current flowing through them creates small magnetic fields which might interfere with particle and magnetic sensors on the spacecraft. Keeping the sensors pointed toward the sun while the spacecraft flies in the vicinity of Saturn could be a problem. If they just use the same kind of solar cells employed on near-Earth missions, the sheer mass of them is so much greater that NASA claims the biggest rocket they have can’t lift the Cassini spacecraft, with all its experiments and sub-experiments, and the solar arrays too, and send them to Saturn.

These seem like daunting problems. They say NASA’s Jet Propulsion Laboratory (JPL) has explored all the options and can’t find a way to make solar work.

Are they telling the truth? What’s really going on here? These are difficult questions to answer, because of the secrecy NASA places around its supposedly civilian space probes whenever there’s any significant nuclear material on board. We can make a few educated guesses, however. First of all, let’s sympathize with the scientists responsible for the experiments on Cassini.

We know how important the Cassini mission is to them. They’ve put a lot of their time and professional reputations on the line for this mission, despite the risks that the mission might not be completed. Although we may be sympathetic with these mission scientists, at least we know they are aware of the fact that rockets self-destruct, guidance systems fail, and sometimes interplanetary probes just stop talking to them, as happened recently with the $800M Mars Observer. So our sympathy for them is muted, since they know well the overall risk that they may get no scientific data at all from Cassini, regardless of the probe’s source of power. In a nuclear powered mission, failure means more than just loss of data. Something far more
important can be lost. The Cassini scientists entered the project knowing full well the risks of mission failure.

Now let's look at NASA and the U.S. government interest. The Cassini spacecraft is huge, and NASA proudly boasts about its size. It is very expensive, costing several billions of dollars. (The exact total cost of the mission is in dispute.) Many nations of the world are collaborating on the Cassini mission. The entire astronomical community was waiting a long time with high expectations for this much science on one launch. I'm very excited about it as well. I can't wait to see the close-up results from Saturn, shown to the world on JPL web sites, as they did recently for the marvelous Mars Pathfinder mission. So there is an enormous amount of money, and sweat equity, invested in the Cassini mission. We expect the government and NASA to do just about anything to keep Cassini going.

Returning to the solar issue, NASA says that to fill the 745 Watt power demand near Saturn with solar cells of the current efficiency gives the problems mentioned previously, and these are sufficient to declare that solar can't be used for the current Cassini design.

**Solar alternatives**

Let's look at some alternatives NASA may not have considered, or may just have swept under the rug because they didn't want to stop the mission, delay it, or split it into smaller missions. Here are my main arguments, the things NASA could have done to eliminate the RTG's from this and future probes to the planets.

1. **Better solar cells.** Use new high-efficiency solar cells, described by many authors, which boast efficiencies as great as 20%. One doesn't have to base this figure on the claim of one aggressive solar photovoltaic manufacturer in Europe. This is a factor-of-two increase over the efficiencies of older solar cells, and could reduce the area and mass requirements for solar power for future space probes by that same factor. Many research laboratories are achieving greatly improved solar cell performance, some claiming efficiencies as high as 24%. Of course it may take a year or two to get them in a durable and tested form for use in space, but what's the rush?

2. **Concentrators.** Use new, strong, lightweight solar concentrators, taking advantage of a factor-of-4 advantage (at the theoretically ideal limit) which a new class of optical devices called non-imaging concentrators have to offer over traditional imaging concentrators.

For further information about nonimaging concentrators see High Collection Non-Imaging Optics\(^1\) or the numerous articles on this subject in the Proceedings of SPIE the International Optical Engineering Society and in Applied Optics, a technical journal of the Optical Society of America published since the Welford/Winston book came out. Winston holds the world's record for the concentration of solar radiation on Earth, achieving a concentration ratio of 56,000 to 1 in 1988.\(^2\) Of course it will take a little time and a major increase in the tiny budget NASA is already using to explore the use of solar concentrators in space, but what's the rush?

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\(^1\) W.T. Welford and Roland Winston, Academic Press, 1989

\(^2\) P. Gleckman, Applied Optics, Vol. 27, p.4385
3. **Better electronics.** Use new low-power electronics that need far less power to perform the electronic and computer portions of the mission. For more information, see the July 1997 issue of Military and Aerospace Electronics, an article titled "Low power experiment set for space." If the power requirements are cut in half, for example, so is the size of the solar collection system to meet these requirements. Of course NASA will say that these low-power electronic systems are still in the research stage and some time will be needed to assure their readiness for space, *but what's the rush?*

4. **Multiple missions.** Split future missions into more, smaller, better, faster, cheaper ones. Cassini is a relic of the Cold War, and of the era of large, long-drawn-out, expensive space missions, a direct violation of NASA Administrator Golden's much touted new dictum for "smaller, better, cheaper" missions. Yes it would probably take some time to split large experiments like the Cassini probe into several smaller ones, redesigning the rockets and other hardware that deliver the payloads to their destinations, *but what's the rush?*

5. **Combined strategies.** Put ALL these together for Cassini and other future interplanetary probes.

With these options to choose from, there is no reason to use risky nuclear generators for interplanetary probes. To take that risk in view of the above alternatives is unconscionable, especially in view of the fact that, according to Dr. Michio Kaku, the Cassini probe contains 400,000 curies of plutonium 238, a factor of 30,000 times the 13 curies authorities claimed were released from the Three Mile Island nuclear power plant accident that created billions of dollars in lawsuits.

Lest you think there’s anything particularly new in this claim that solar *can* work for probes to the outer planets, I came across a paper by Paul Stella of NASA’s own JPL, delivered at a meeting on space power systems in 1985, over a decade before the Cassini launch. His opening paragraph anticipated the new NASA dictum for „faster, better, cheaper“ missions:

„Future U.S. interplanetary missions will be less complex and costly than past missions such as Voyager and the soon to be launched Galileo. This will be required in order to achieve a balanced exploration program that can be sustained within the context of a limited budget. Radioisotope Thermoelectric Generators (RTGs) have served as the power source for missions beyond the orbit of Mars. Recent government costing practices have indicated that the cost to the user of these power sources will significantly increase. Solar arrays can provide a low cost alternative for a number of missions.” Stella’s paper was delivered and published long before the decision was made to proceed with the current huge Cassini design.

He described the recommendations of a 1980 high level NASA Solar System Exploration Committee and said, „Of major importance, the program established a critical level of activity consistent with a realistic sustainable budget, ... to provide for stability...the approach specified highly focused, less complex missions that could rely heavily on existing technology and hardware inheritance to reduce costs. Whereas the cost of some early missions ... had exceeded two billion dollars total, the new plan would be based on a total annual funding level of about 300 million Dollars (FY ‘84).“ „ „A critical item in any of these missions is the power source.„ „...
Stella mentioned some probes where RTG’s seemed to be best, and then went on to say: „However, within the past few years the cost of RTGs has come under examination. Historically, the cost of the fuel for an RTG power source has been „subsidized“ by DOE, resulting in a relatively low RTG cost to NASA.“ He mentioned that this was under review and said that if NASA were required to assume these costs, the cost of them per mission would be prohibitive within the context of a constrained budget. „For this reason a number of missions which normally might be RTG powered are potentially open to photovoltaic power.“ He then goes on to discuss a variety of ways that solar cells can be used for outer planet exploration, including the use of concentrators and novel array configurations to reduce view blockage of the sensors on the spacecraft. There was no mention in this report of the safety hazards of massive RTG’s, because I’m sure he was focusing only on the engineering, not on the safety and political aspects which were probably handled elsewhere in NASA at the time.

Of course there are difficulties when you have a big solar collector hanging onto your planetary probe. You have to keep it pointed toward the sun, even when the spacecraft has to twist around to keep the sensors directed toward the target, especially important during approaches, where the spacecraft moves rapidly toward or by the target being observed. However, you also have to point the communications antenna toward the Earth, routinely done at high accuracy now, better than 1/10 of a degree. At Saturn distances, the Earth is quite close to the sun, so the pointing of a solar array and an antenna should not be incompatible.

The main point I have to make here is that I don’t see a lot of innovative options being explored, such as incorporating some solar concentration into the same structure used for the communication antenna, or the use of very lightweight inflatable concentration mirrors, which can be made rigid chemically after inflation, to reduce the consequences of micrometeorite impact. An advantage of concentrating collectors is that light pipes could be used to carry the sunlight to the solar cells, which could be put inside special housings to protect them from damage due to the space environment. Concentrated sunlight would heat up the cells, improving their efficiencies. The metal housings around the cells and their connecting wires could be made to minimize magnetic fields produced by the cells, thereby protecting particle detectors that are sensitive to stray magnetic fields from the spacecraft.

The nuclear powered Cassini spacecraft is a relic of Cold War mentality, when bigger, costlier, more lethal held us captive. Let’s do away with the use of that technology in space now, and free ourselves, while we still have the chance.

Safety Claims

A lot has been said about one chance in a million for this accident and one in several thousand for that one. This does not mean it will take a million or several thousand launches for the accident to happen. It could happen on the first, the tenth or the thousandth.

The problem is with the thinking behind these numbers in the first place. Even if they didn’t „cook the numbers,” as Dr. Kaku has claimed, what’s the practical difference between 1 in 1000 or 1 in 10,000? It doesn’t really matter when the consequences of a worst case scenario are so terribly bad.
If there is even an outside chance during some future launch with nuclear materials on board, of badly contaminating a major portion of Brevard County, where I live, or of putting invisible, relatively undetectable plutonium dust in the lungs of Central Florida citizens, leading to cancer a few years hence, untraceable to the launch accident, then why do it at all? This is the real question you should ask when you hear the big numbers.

"Trust us."

If I, your friend, ask you to stand on the table, facing away from me, and fall backwards into my arms, you may be reluctant. But I’m your friend and I say "trust me." Suppose you go ahead and take the fall, but I don’t catch you. How long do you think it will be before you are willing to trust me again? How many times must this event be repeated, with a safety net, and I do catch you, before you will be willing to try again?

Never accept a person’s request for trust on face value. The best test of the trustworthiness of a person, or a government, is history. Let’s look at the history of the U.S. government in building trust in large scale nuclear projects.

We begin with the Manhattan project. Super secret. Physicists who should have known better exposed themselves and lots of army personnel and private citizens to nuclear radiation, both accidentally and on purpose, to see what the effects would be, never cautioning the innocents of the dangers involved. Some airborne troops were sent to parachute into fallout areas.

Then comes the atmospheric nuclear bomb tests of the 50's. The U.S. National Cancer Institute reported in August 1997 that the fallout from these tests had probably caused 10,000 to 75,000 extra thyroid cancers, over wide areas in the U.S. We learned that the U.S. government was aware of these effects and yet persisted in continuing the tests until the consequences were too obvious and too politically difficult to hide. And then we had a global nuclear test ban treaty.

Next we learned that our same government had been repeatedly informing photographic film manufacturers about fallout from these tests so that they could prevent their newly made film from being fogged up by the radiation. Yet this same government agency not only did not tell the people of the United States about how this fallout could contaminate their bodies, but it reassured the public that there was no health threat from the tests.

We were told in 1987 and 1988 that the Galileo mission to Jupiter could not contain solar cells. Then, after the probe was launched we find out that the government knew all along that they could have converted Galileo to solar power and taken the radioactive substances off of it.

Now they tell us to trust them with Cassini. How many times have we fallen off the table already? They ask us to do it again? They tell us not to worry about an accident with Cassini. The Department of Energy’s Beverly Cook says it is almost impossible to produce significant radioactive contamination, either outside of Kennedy Space Center at launch or around the world on the flyby maneuver.

Suppose, while you are standing on the table waiting to fall back into my arms, you hear me chuckling, or you hear my voice waver when I tell you to trust me. Or suppose you catch a
glimpse of me in a mirror, and you get an inkling that I may be about to pull a fast one on you, do you still trust me?

Now suppose that you read a story by Liz Tucci in Space News quoting NASA’s chief scientist talking about Cassini: “We can’t fail with that mission. It would be very, very damaging for the agency” and going on to say that NASA Administrator Dan Goldin would have cancelled Cassini if he thought he had a choice. He went on to say that “We would not start Cassini today. It is a hard program for [Goldin] morally to deal with, because it has got a number of enormous risk factors.“

What would that do to your trust of NASA and DOE in their claims for safety of the Cassini mission?

The purity of science

We are told that science is the reason we have to go to Saturn and take a bunch of pictures and make some measurements. We are told that it is in the nature of humans to be curious and to seek knowledge, and that the quest for knowledge is of value in and of itself.

Well, perhaps this is true, if the quest is both relatively benign and might produce significantly useful new knowledge. We ask what will this knowledge of Saturn be used for and are told by the Cassini Project Manager, [first name] Spehalski, that it is to help the environment, that better knowledge of Saturn might yield some small increase in knowledge of the Earth’s history and dynamic evolution over geologic time. What irony. That we would risk major radioactive contamination of portions of the planet in order to learn a little about its history! How old is Saturn? At least 4.5 billion years. Will it be there several decades later when we most surely will have developed good solar power alternatives for its exploration? Of course. So don’t give me all this stuff about the purity of science and the grand scientific quest when your science threatens my body.

The military’s role

Here is an excerpt from the March 16, 1997 issue of Space News: “The NASA administrator and the commander of the Air Force Space Command agreed Feb. 28 to coordinate and consolidate Pentagon and space agency efforts …. “ They „agreed to establish a Partnership Council that will meet twice a year to oversee consolidation of long-range planning, joint technology development programs, and consolidation of redundant assets.“ „Anticipated results of joint Air Force and NASA work include ‘streamlining of operations costs, cross utilization of facilities capabilities, consolidation of redundant facilities, sharing of support services [read „contractors”], and leveraging of science and technology investments,’ the agreement states.“

Now let me read to you from two Air Force documents describing plans for the military use and domination of space.

From „Guardians of the High Frontier“ we have this: „The Space Warfare Center at Falcon AFB Colo. (with its motto and arm patch that says ‘Masters of Space’) plays a major role in fully
integrating space systems into the operational Air Force."

"In the next several decades, the spirit of cooperation between Air Force, civil (NASA for example) and commercial space industries will become a way of life in the space lift business."

Speaking of "the-space-based Air Force", it lists several operational goals for the Air Force, among them, "Globally dominant. Tomorrow's Air Force will likely dominate the air and space around the world using earth- and space-borne hypersonic transports to get equipment and people anywhere quickly. Selectively lethal. The Air Force may fight intense, decisive wars with great precision hitting hard while avoiding collateral damage in both 'real' space and in the computer 'cyberspace'."

From the U.S. Space Command's publication, "Vision for 2020," we have this:

"Historically, military forces have evolved to protect national interests and investments – both military and economic. During the rise of sea commerce, nations built navies to protect and enhance their commercial interests. During the westward expansion of the continental United States, military outposts and the cavalry emerged to protect our wagon trains, settlements, and railroads." "The emergence of space power follows [this model]." "During the early portion of the 21st century, space power will also evolve into a separate and equal medium of warfare. Likewise, space forces will emerge to protect military and commercial national interests and investment in the space medium due to their increasing importance."

"The globalization of the world economy will also continue, with a widening between the 'haves' and 'have-nots.' Accelerating rates of technological development will be increasingly driven by the commercial sector—not the military. Increased weapons lethality and precision will lead to new operational doctrine."

"...space superiority is emerging as an essential element of battlefield success and future warfare." "Control of Space is the ability to assure access to space, freedom of operations within the space medium, and an ability to deny others the use of space, if required." "Due to the importance of commerce and its effects on national security, the United States may evolve into the guardian of space commerce – similar to the historical example of navies protecting sea commerce."

"USSPACECOM must assume a dynamic role in planning and executing joint military operations. Included in that planning should be the prospects for space defense and even space warfare. Development of ballistic missile defenses using space systems and planning for precision strike from space offers a counter to the worldwide proliferation of WMD [weapons of mass destruction]."

Finally, it is well known that future military satellites will need huge quantities of electrical power, in short bursts, to power their secret high-power space-based weapons systems, including lasers, particle beams, and other hush-hush hardware. The power source of choice for this is nuclear. It's just the only source they can think about for powering these advanced weapons systems. (Suppose your first shot misses the target. What space battlefield commander wants to wait around for a few minutes while the solar cells re-charge the batteries?)"
Every rocket with nuclear material on board it has to launch through our air space, either at Cape Canaveral or at Vandenberg Air Force Base in California. The latter is needed for polar orbits to give complete coverage of all points on Earth. Failures, and subsequent nuclear contamination, can occur anywhere around the globe. Few people are aware of military plans for nuclear materials in space, not to mention what might already be secretly orbiting the Earth right now.

**Nuclear Trojan Horse**

Although it's difficult to prove the following conjecture, it seems that one of the reasons the government is so intent on launching Cassini, as well as the string of additional nuclear powered space missions to follow, is to get the public accustomed to successful launches with ever-increasing quantities of nuclear material, until, one day, they think they will be able to launch an entire nuclear reactor with little public outcry, except for the few „nuts“ who always protest those things. The general public will have been lulled into complacency by these relatively small nuclear missions, serving as Trojan Horses for the larger missions to come. The problem with this kind of thinking, if indeed anyone in a policy position is thinking this way, is that sooner or later one of those things is going to blow up or vaporize or some other way release nuclear materials in a damaging way, and the whole space venture, not to mention life as we know it, could be severely threatened in consequence.

**Who Calls the Shots?**

NASA says that Cassini and other future planetary explorations with RTGs on board are for scientific purposes, leading us to believe that it must be the scientists who call the shots in the agency, or at least that it is the scientific goals of the missions which are tantamount to the justifications NASA offers to the Congress and the American people in support of its budgets for the missions. We see NASA more and more influenced by its contractors, and a number of large multinational aerospace corporations, or aerospace divisions of even bigger corporations. The power of these corporations to set NASA's agenda is becoming greater and more obvious. The enterprise of space is now so large, and planned to be so large, that the scientists used to justify the missions are starting to become little more than pawns in the bigger game of corporate greed for the highly profitable military/nuclear/industrial complex.

Just listen to this quote from Florida Today, July 1997. „There is no question—there are profits to be mined from high-tech platforms parked outside the Earth’s atmosphere.“ Speaking of the new International Space Station, the article says „Many think the $40 billion space station will be the centerpiece of whatever steps are to be taken. Once assembly is complete and government science missions exhausted, advocates would like to see private tenants move in. In fact, the Commercial Space Act would make it law that the station’s priority is the ‘economic development of Earth orbital space.’ [Emphasis added.]“
Exhaustion of the government’s science missions? The scientists among us know that science is never „exhausted.“ Could the real purpose of all these so-called scientific missions be any clearer? Who can doubt who really calls the shots at NASA? The agency is in danger of becoming little more than a conduit for an incredible new government welfare program for large multinational corporations.

Conclusion

The increasing nuclearization of space is both a real threat and unnecessary. Nuclear power is not needed for interplanetary science probes—solar power can and should be used instead. Likewise, the purported gains from mining the planets, the moon, and the asteroids simply aren’t great enough to justify any use of nuclear power to make them possible. The military use of space, incorporating nuclear materials, is a very bad idea, and could be a destabilizing political factor, pushing other countries into space nuclear projects as a costly defensive measure, in attempts to keep the U.S. from making real on its threat to dominate space. As U.S. economic might declines, relative to large emerging nations, and it loses other areas of dominance, there is a real possibility that U.S. government leaders will seek through space-based military might what they fear they cannot achieve by peaceful means.

Every reporter covering space news, and every citizen, should look for seemingly benign civilian (and secret military) missions to space containing any amount of nuclear material. Vigilance will be required as we see an increasing number of press releases and news stories about missions to the Moon, to Mars, and to the asteroids. Where will these missions obtain the energy needed to power them? If it is nuclear, these missions should be canceled or redesigned, insuring that near-Earth space becomes a nuclear-free zone. If it is solar, then we can join in the excitement of discovery and the joy of exploring new frontiers.
1 Introduction

The majority of the space missions implemented up to now or presently under development have called for the utilisation of solar cells suitable for satisfactory operation under the environmental conditions typical of geosynchronous and low Earth orbits. Scientific missions devoted to deep space and planetary explorations have mostly relied on radioisotope thermoelectric generators (RTGs) to provide spacecraft with the required amount of electrical energy. In principle, the photovoltaic technology could be viable also for this type of applications characterised in some cases by extremely low illumination intensities.

The interest in the exploitation of photovoltaics for deep space missions has recently increased. Reasons are the future ESA deep space and planetary programs, the announced resurgence of USA planetary exploration programmes as well as the disadvantages in terms of cost, safety, technology transfer and social acceptance associated with RTG systems.

To meet the ESA needs, the R & D program „Solar Cells for Low Intensity/Low Temperature“ (LIL T) has been initiated in 1991. At the beginning of the development program an insolation equivalent to 0.11 solar constant of AMO (air mass zero – solar insolation intensity outside the Earth atmosphere) and a temperature of -100°C have been selected as „average deep space“ operation conditions for the operation of these solar cells with no specific mission in mind.

On the basis of the promising achievements of the LIL T cells R & D programme, the use of photovoltaic generators has been selected as one of the baseline design elements for ROSETTA, the ESA mission for cometary material investigation scheduled for launch in 2003. With the aim of this short term application, the LIL T cell development objectives have been revised according to the ROSETTA requirements: low intensity insolation equivalent to 0.03 solar constant of AMO, corresponding to 5.25 AU (astronomical units), and low temperature down to -130°C.
2 Deep space missions

In figure 1 the solar intensity versus distance from the sun can be seen. Due to the inverse quadratic dependence of intensity and distance the available energy input for the solar cells rapidly decreases with distance from the sun.

![Diagram of solar intensity versus distance from the sun]

Fig. 1. Solar intensity versus distance from sun

In Figure 2 the corresponding temperature behaviour is displayed.

![Diagram of solar cell temperature versus distance from the sun]

Fig. 2. Solar cell temperature versus distance from sun
In November 1993 the ROSETTA mission was approved by the Science Program Committee as the new cornerstone of ESA’s long term science program Horizon 2000.

ROSETTA is defined as a mission to rendezvous with the comet Wirtanen and its flight trajectory is shown in Figure 3. The in-situ investigation of the comet nucleus being the prime objective of the mission, the ROSETTA spacecraft will carry several instruments as well as a surface science package, which will be deployed on the comet surface. The deployment will take place at a sun distance of 3.25 astronomical units (AU), before the onset of gas and dust ejection off the comet’s surface. Scientific measurements will continue during the comet’s approach to perihelion, enabling to observe the evolution of comet processes as a function of heliocentric distance.

![Fig.3. Ecliptic projection of a Rosetta baseline comet rendezvous mission with major events](image)

ROSETTA will be launched by an ARIANE 5 in January 2003 within a ten day launch window imposed by the needed planet constellation to allow the spacecraft to make use of one Mars and two Earth swing-by manoeuvres. This launch strategy is necessary to gain the needed velocity to travel towards the incoming comet, which ROSETTA will meet after eight years of interplanetary travel.

During its mission the spacecraft will encounter a very large variation of sun distance, ranging from 0.9 AU at Mars swing-by to 5.25 AU during comet approach. The solar irradiation input will consequently vary from roughly 1700W/m² at closest sun distance to about 50W/m² at maximum sun distance. This creates a challenging requirement for the solar cells that have to generate the needed 650 Watt of electrical power at maximum sun distance under low sun intensities and at temperatures down to approximately -130°C.
3 LILT silicon solar cells

In the early ’70s silicon solar cell operation has already been studied for deep space missions such as Jupiter fly-by. At that time it has been realised that uncontrollable adverse effects of LILT degradation occurred with standard silicon solar cells. These effects are responsible for diode loss currents and cause severe power losses with preference at low temperature. These losses are occurring on a statistical basis with large variations and could not be assessed from room temperature measurements. Thus silicon solar cells could not be used for LILT missions so far.

In Figure 4 the illuminated current voltage characteristics of a standard silicon solar cell under LILT conditions is displayed. The power output is tremendously reduced by the „flat spot“ and „edge channelling“ effect, low shunt resistance or Schottky barrier [1-4]. These effects are responsible for a fill factor and thus power reduction of the standard silicon solar cell under LILT condition. These effects are occurring on a statistical basis with varying magnitude and cannot be assessed from room temperature measurements.

In the newly developed 10 LiT HI-ETA®3 silicon solar cell all of the degradation effect at low temperature and low intensity are avoided. The 10 Li THI-ETA®3 silicon solar cell is representing the most sophisticated cell of ASE’s trademarked HI-ETA® cell family at the moment. The nomenclature in front of the word HI-ETA® is concerned with base material and front side characteristics and the nomenclature after it with rear side characteristics: 10 stands for 10 Ωcm, Czochralski grown base material, L for special LILT features, iT for textured front surface by means of inverted pyramids and 3 for local back surface field. Special LILT features are a front contact grid optimised for low intensity operation, and measures in order to avoid the reduction in fill factor under LILT conditions, such as heavy n++ -diffusion under the front contact grid or a p+ guard ring channelstopper around the edges of the solar cell [5-6]. A cross section of this 10 LiT HI-ETA®3 silicon solar cell is displayed in Figure 5.
Some characteristic features of the 10 LiT HI-ETA®3 silicon solar technology are:

- high resistivity $10\Omega\text{cm}$, boron doped, Czochralski grown silicon base material with its high charge carrier mobility at low temperature and its space radiation hardness,

- shallow, radiation resistant emitter, $p^+-$back surface field and passivating front and rear side oxides,

- non-reflective front surface by inverted pyramids and multilayer antireflection coating of $\text{TiO}_x/\text{Al}_2\text{O}_3$,

- fine gridline pattern defined by photolithography, aluminium rear side reflector and space proven contact system with an alloy of titan, palladium and silver.

The grid spacing and grid finger width of the 10 LiT HI-ETA®3 silicon solar cell have been adapted to 0.11 solar constant (sc)insolation intensity and the cell area is 3.78 cm x 6.19 cm with three equidistant welding pads sizing 6 mm x 1mm each.

Although the structure of the 10 LiT HI-ETA®3 silicon solar cell is rather complex, it can be realised by means of the standard processes of the trademarked HI-ETA® cell technology (e.g. photolithography).
The illuminated current-voltage (I-V) characteristics of 10 LiT HI-ETA®3 silicon solar cells as measured under an insolation intensity of 0.11 SC and 0.037 SC in the temperature range of -150°C to +25°C are displayed in Figure 6 and Table 1.

![Illuminated current-voltage (I-V) characteristics of 10 LiT HI-ETA®3 silicon solar cells](image)

**Fig.6.** Illuminated current-voltage (I-V) characteristics of 10 LiT HI-ETA®3 silicon solar cells

The measurements have been performed in a vacuum chamber with quartz window, where the samples could be cooled by liquid nitrogen and the insolation intensity of the solar simulator could be adjusted by a grey filter and the lamp current.

<table>
<thead>
<tr>
<th>Insolation [SC]</th>
<th>T [°C]</th>
<th>V_{oc} [mV]</th>
<th>I_{sc} [mA/cm²]</th>
<th>FF</th>
<th>Eff. η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>25</td>
<td>563</td>
<td>5.42</td>
<td>0.782</td>
<td>15.9</td>
</tr>
<tr>
<td>0.11</td>
<td>-100</td>
<td>832</td>
<td>5.06</td>
<td>0.889</td>
<td>25.1</td>
</tr>
<tr>
<td>0.11</td>
<td>-150</td>
<td>934</td>
<td>4.70</td>
<td>0.921</td>
<td>27.1</td>
</tr>
<tr>
<td>0.037</td>
<td>-150</td>
<td>920</td>
<td>1.27</td>
<td>0.915</td>
<td>26.3</td>
</tr>
</tbody>
</table>

Table 1: Illuminated I-V characteristics of bare 10 Li HI-ETA® 3 silicon solar cells (3.78 cm x 6.19 cm) as measured under an insolation intensity of 0.11 SC and 0.037 SC in the temperature range of -150°C to +25°C.

As can be realised from Table 1 and Figure 6 even for an insolation intensity of only 0.037 SC with its very low generated photocurrent, the fill factors FF are close to their theoretical limit and thus all kind of LILT degradation effects are suppressed proving the elimination of the „flat spot“ or „edge channelling“ effects for 10 LiT HI-ETA®3 silicon solar cells.
4 Production experience with 10 LiT HI-ETA®3 silicon solar cells

In the framework of the ROSETTA program 1000 10 LiT HI-ETA®3 silicon solar cells have been produced by ASE under ESA contract for qualification purpose. 700 of these cells should meet the electrical requirements and 300 had to be delivered as mechanicals, only.

In Table 2 the average electrical performance of the 700 cells is displayed as measured at 1SC, 25°C and 0.03 SC, 25°C.

<table>
<thead>
<tr>
<th>V&lt;sub&gt;oc&lt;/sub&gt; [mV]</th>
<th>I&lt;sub&gt;oc&lt;/sub&gt; [mA/cm²]</th>
<th>V&lt;sub&gt;mp&lt;/sub&gt; [mV]</th>
<th>FF</th>
<th>Eff. η</th>
</tr>
</thead>
<tbody>
<tr>
<td>645</td>
<td>47.61</td>
<td>499</td>
<td>0.7909</td>
<td>16.1</td>
</tr>
<tr>
<td>534</td>
<td>1.42</td>
<td>443</td>
<td>0.776</td>
<td>14.6</td>
</tr>
</tbody>
</table>

Table 2: Average electrical performance of 700 10 LiT HI-ETA®3 cells for ROSETTA qualification.

In Table 2 the high average fill factor of 0.776 at the conditions of 0.03 SC and 25°C is most remarkable. The fill factor at 1 SC, 25°C is quite low due to the resistive losses in the front contact grid which is optimised for low intensity operation.

Since low intensity, low temperature measurements are expensive and time consuming they were realised with a reduced number of 16 cells, which have been selected randomly. The average results of these measurements are displayed in Table 3.

<table>
<thead>
<tr>
<th>V&lt;sub&gt;oc&lt;/sub&gt; [mV]</th>
<th>I&lt;sub&gt;oc&lt;/sub&gt; [mA/cm²]</th>
<th>V&lt;sub&gt;mp&lt;/sub&gt; [mV]</th>
<th>FF</th>
<th>Eff. η</th>
</tr>
</thead>
<tbody>
<tr>
<td>927</td>
<td>43.72</td>
<td>829</td>
<td>0.879</td>
<td>26.3</td>
</tr>
<tr>
<td>873</td>
<td>1.28</td>
<td>808</td>
<td>0.898</td>
<td>24.7</td>
</tr>
</tbody>
</table>

Table 3: Average electrical performance of 16 10 Li HI-ETA3 cells at LILT conditions.

The high fill factor at the extreme LILT conditions of 0.03 SC and -130°C is most remarkable. The fill factor is close to its theoretical limit and there obviously is no effect of LILT degradation.
In Figure 7 the statistical distribution of short-circuit current, fill factor and efficiency for 700 10 LiT HI-ETA®3 solar cells are displayed as measured at 0.03 solar constant (AMO) at 25°C.

Most remarkable are the high fill factor and the narrow fill factor distribution at 0.03 SC and 25°C. This indicates low diode loss currents and subsequently good LILT performance of these cells [5,6].

5 Conclusion

Prior to this work it was not possible to use silicon solar cells for deep space mission due to LILT degradation effects. With the development of the 10 LiT HI-ETA®3 cell, these problems have been overcome and this cell type will be used to power the ROSETTA spacecraft which is travelling as far as 5.25 AU from the Sun.

For qualification within the ROSETTA program 1000 10 LiT HI-ETA®3 silicon solar cells have been fabricated with excellent performance especially at low intensity, low temperature conditions. By this work it has been shown that this cell type is ready for large volume production and can be provided to the international community.
6 Acknowledgements

The author wishes to express his thanks to Dr. Bogus, C. Signorini and H. Fiebrich of ESA/ESTEC for discussions, support and funding of this work, to H. Bebermeier and A. Ahrens from DASA for deep space mission analysis and low temperature measurements, respectively. Also the contributions of Dr. Kern, F. Schomann, Dr. Rasch, Dr. Roy, W. Schmidt, K.-H. Tentscher and P. Uebele from ASE are greatly appreciated.

References


Reducing the energy requirements of the payload on space missions.  
Technical developments and their limitations in an example

Uwe Bonnes

1. Introduction

The inhabitants of Central Europe have at their disposal a high quality and ever-ready energy supply in the form of mains electricity. It is only in the unlikely instance of a power outage that a normal citizen is really aware just how much he depends on this arrangement and how much energy he needs even for the simplest of tasks. As a rule, a short term power failure merely represents a slight inconvenience for these people and is not the cause of further damage or injury. Organisations such as computer centres, where a power failure can result in the loss of sensitive data, or hospitals, where lifesaving equipment must be guaranteed a constant power supply, have emergency generating equipment on standby in case the public power supply should fail. In case the outage takes longer they can moreover be replaced externally.

On the other hand, space missions, irrespective of whether they are close to the earth or interplanetary, have to be fully self-sufficient in energy right from the moment of take-off. The only possible external energy source for supplying the payload is solar radiation. All internal sources of energy contribute to the weight of the mission and either increase the amount of fuel required for lift-off or reduce the weight allowance of the payload itself. Batteries can be used for short term jobs. Fuel cells and thermonuclear generators are other commonplace providers of energy. Fuel cells depend on the supply of hydrogen and oxygen which has to be carried, however the water resulting from these elements can be used to supply any people or other living creatures that might be on the mission. In thermonuclear generators, a radioactive substance decays which heats up in comparison with the outside world. This temperature difference is converted into electric power using many semi-conductors switched in series. However, as these semi-conductors demonstrate high thermal conduction properties, the operating efficiency is low and requires a large inventory of radioactive substances. Other papers in this collection report on the problems of thermonuclear generators. Radioisotope heating units (RHUs) are often used for permanently heating sensitive areas, where the heat released by the radioactive breakdown process is used directly.

Given that rocket propulsion is a very inefficient way of accelerating an object, the weight of the payload and the weight of the energy supply it necessitates are important cost factors for the entire mission. Furthermore not only the weight but also the energy demand of the equipment of space probes needs to be minimized. To discuss the reduction of energy requirements in this paper a Mössbauer spectrometer developed for a mission to Mars serves as example. In this article some aspects of using a miniaturised Mössbauer spectrometer (MIMOS) will be taken into consideration which have contributed to a reduction in the energy consumption of this instrument. The instrument was developed at the Institute for Nuclear Physics at Darmstadt University of Technology by a team led by Prof. Egbert Kankeleit [1]. It is to fly to Mars with other payload as part of the Athena Project of NASA in the Mars Surveyor Programme 2003 of the NASA and, by means of a Rover, take measurements of the geology of Mars. The Rover power supply will be used to take a first look at the various aspects of energy supply on space missions in general and use the Rover’s power supply as an example.
2. Requirements and problems of energy supply on a space mission, using the Mars Rover 2001 as an example

Mars [2] is about twice as far from the sun as earth and therefore gets only a quarter of the solar power arriving on its surface compared with a location on earth. Due to its rotation there is a day/night cycle of 24.6 hours. This corresponds to approximately one earth day and is called a "sol". One orbit around the sun (Mars year) lasts about 683 days. Because of the inclination and elliptical shape of the orbit, there is a strong seasonal variation in the amount of energy available on a daily basis. After dust storms, you can count on dust deposits which will, for instance, obscure solar cells and, when added to the seasonal change, result in a continuous reduction in the daily energy available.

In order to be able to drive around autonomously with the Rover [3] apart from solar cells, rechargeable batteries are also necessary for supplying power, to make sure that control functions of general importance are maintained and that measurements can still be taken at night. It is not possible to produce a cell to last a season with the energy density of today's rechargeable batteries. With a weakening power supply, the functions of the Rover, such as mobility, measuring and communication must be limited even further in favour of keeping basic system functions going. Therefore, provided no other disastrous error arises beforehand, the design of the solar supply and
battery system determines when the Rover can no longer be used viably because of a fading power supply caused by dust obscuring the solar cells and general system ageing.

Despite the use of highly efficient gallium arsenide solar cells, only about 160 watt-hours of available power can be expected per sol from the 0.36 m² area available on the Rover for solar cells. Depending on the latitude of the area, there is also strong seasonal variations discussed above. These are, for example at a latitude of 15 degrees north plus/minus 5% and plus/minus 30% at 15 degrees south. Therefore, on average 6.5 watts is available as power, less than that consumed by a rear light on a car. The battery itself has a usable energy content of about 130 Watt hours.

For a typical projected day on Mars (sol), on which most of the measurements are made, a total energy consumption of 150 watt-hours is projected. Table 1 shows how this amount of energy is distributed to the various sub-systems:

| System services (computer, input and output, storage of measured values) | 38% |
| Taking and storing samples | 15% |
| Losses during battery charging/discharging | 15% |
| Communication | 11% |
| Supply to instruments | 10% |
| Motion and navigation(motors, sensors, navigation cameras) | 6% |
| Heating | 3% |

Table 1: Percentage distribution of energy consumption

The most important job here is communication with earth through a relay. Without this, no useful data could be transmitted back to earth and there would be no point to the mission. In each sol there are two time-slots each of about 6 minutes, in which the Orbiter going around Mars comes up over the horizon of the Rover and therefore within range of its aerial. To this end, a transmitter power of 55 watts is necessary in order to guarantee adequate certainty of successful transmission, so that the measurement and telemetry data stored in the semi-conductors storage can be sent back to earth using the Orbiter as a relay. This is the minimum power that is necessary to continue the mission.

The high percentage of total consumption of system services falls into proportion if one converts this value into an average power of just 2.5 watts. The CPU of a normal personal computer alone needs in excess of 10 watts, yet the system services of the Rovers are far greater in number. Therefore, an important means of reducing power consumption lies in matching the processor clock speed to the particular computer performance required for each task.

With ambient temperatures on the surface of Mars in a range from -125 °C to 0 °C, it is necessary to protect as many electronic parts as possible - and especially the battery - from low temperatures. To achieve this, they are built into a thermally insulated container ("warmbox"). The internal heat sources created by the function units are not sufficient to guarantee an acceptable temperature range of -40 °C to + 40 °C. To significantly improve the form of heat insulation would throw up many other technical problems. There would be a danger of overheating, especially during the times in which the electronic equipment located in the warmbox had to provide peak power, such as during communication with the relay satellite. It is therefore planned to preheat the warmbox with up to 5 watts thermal power from radioisotope heating units. At the same time, excess energy from the solar cells will be used to provide supplementary heating for the warmbox if the batteries are fully charged.
If partially shaded, arrays of solar cells will produce drastically lower amounts of power. When operating the Rover with the planned camera mast and a mobile instrument arm, some attention must always be devoted to potential shading. This is to be kept to a minimum in order not to exceed the safety margins described above. Apart from a reduction in power consumption, the optimisation of energy collection therefore represents a second important point for improving the balance of energy. This affects both the electrical energy for immediate use or storage in the rechargeable batteries, and the thermal energy in the warmbox.

3. Operation and design of a Mössbauer spectrometer

Using Mössbauer spectroscopy, it is possible to determine the oxidation state and the magnetic properties of iron in its compounds. It is hoped to use this to find signs of the possible previous existence of water on Mars. Having water available in its liquid form is a prerequisite for the development of life. It is one of the main aims of the current Mars missions to gather signs for or against life on Mars in the past.

For the Mössbauer spectroscopy [4] of iron compounds, a radioactive cobalt-57 source is used. As a result of decay, this is converted into iron-57. During this conversion into its normal state, the excited iron-57 radiates a cascade of gamma quanta at discrete energies with very high spectral purity \(10^{13}\). Quanta with 14.4 and 6.4 keV energy can then excite the iron-57 atoms of the test material once again. If the excited atom in the test now turns into the normal state, a quantum with the same energy as the excited one is radiated, but this time evenly distributed throughout space. In this way, the passing beam is weakened, or in other words part of the beam is diverted. However, thanks to the different crystal gratings into which the iron-57 of the test object is integrated, a typical detuning occurs in the frequency of the gamma quanta, during which this reciprocal effect takes place. At \(5 \times 10^{-11}\) this frequency detuning is minimal. It can be reached by a movement of the source of about 15 mm/s as a result of Doppler shift by motion in the source. If you distribute the number of backscattered quanta over the source speed, spectra typical of the material result.
Therefore, for a Mössbauer spectrometer you need the following basic set-up:

- A drive puts the radioactive source into motion. It has a similar design to a loudspeaker. To achieve a high level of linearity, the deviation of the motion signal from the reference signal is also minimised in a control loop.

- Detectors capture the backscattered quanta and convert them into charge pulses. As a quantum with 14.4 keV releases approximately 4000 electron hole/pairs in a silicon semi-conductor detector, this demands extremely low-noise, but at the same time sensitive amplifiers.

- A discriminator determines the energy of the quantum received and rejects the high number of quanta received in the form of background radiation. This arises because of various effects through the other lines of gamma radiation from the source. Only quanta with the above-mentioned energy of 14.4 or 6.4 keV are subject to the reciprocal effect described above and are the useful signal.

- A control computer then totals the detected quanta synchronously with the speed of the drive in individual channels.

- A separate power supply unit is usually also necessary for adaptation to the available voltage source.

Only backscatter geometry is suitable for measurement on unprepared test samples. The source lights up like a reading lamp on the object under investigation and the detectors are located close to the source, pointing at the object. With this arrangement and sources of sufficient strength, after about 10 hours is collected a spectrum of sufficient quality useful to make statements about the object being measured.

Previous laboratory equipment consisted of a voluminous electronic set-up, consuming much more than 10 watts of power. Current drives all weigh more than 1 kg. Given the physical size and power consumption, this means that use in space experiments such as Mars Rover 2003 are out of the question. Described below are a few measures which make it possible with MIMOS II to
prepare a device weighing about 700 g and using 2.5 watts. These measures mostly concern the use of modern electronic components, materials and techniques.

4. Technical measures

4.1 Drive
The use of modern highly coercive magnetic materials means that considerably smaller designs are now possible. At the same time, as a result of this, the resonant frequency of the drive is shifted close to the working frequency, so that with sufficiently accurate control electronics because of the resonant characteristics, only a small amount of power is necessary to maintain the correct drive oscillation.

4.2 Detectors
For MIMOS, silicon photodiodes are used as opposed to the previous frequent use of proportional counters. This facilitates significantly more compact detector designs, not to mention longer service lives and greater mechanical stability. However, current leakage at the photodiodes used rises exponentially with temperature and causes the measured spectrum to deteriorate. With the prevailing temperatures on Mars, this does not pose a problem, but in other environments the diodes would have to be cooled and this would have a negative effect on the balance of energy.

4.3 Amplifiers
Mobile telephones and laptops, like the electronic equipment used on space missions, should only use a minimum amount of energy. As these consumer applications represent a considerably larger market sector than space missions, they are an evident incentive for the industry to develop energy-efficient, integrated modules for very exacting requirements. One result of this development has been modules which will operate on considerably reduced voltages. At the same time, the current requirements of these modules are also dropping constantly so that an overproportional reduction in energy requirements is being achieved. It was only by using these modern components that it became possible to develop an amplifier which still had the required characteristics at a power consumption level of just 150 milliwatts and which has been successfully tested in the laboratory for the conditions expected on the mission.

4.4 Discriminators
Under normal circumstances, the energy signal from the detectors necessary for the Mössbauer analysis is converted through a so-called "AD converter" into a digital signal. This is communicated to the control computer which again compares the digital value with threshold values and establishes whether the result is valid, rejecting any invalid ones. As this means a lot of activity in the system and requires an accordingly powerful computer, this goes hand in hand with a corresponding power requirement. However, it does make it possible to quickly record the energy distribution of the quanta arriving at the detector (energy spectrum). Energy spectra make it possible to make a statement on the function of the device and the quality of the measurement conditions. For MIMOS II, on the other hand, an arrangement was chosen in which the analogue amplifier signal is already compared with preset thresholds and only valid results lying within these thresholds are passed on. In spite of this, it is still possible to gather an energy spectrum by shifting the thresholds gradually. More time is needed for this process, as quanta can no longer be recorded in parallel in the different energy windows, but a distinct time slot is to be provided for each window. A spectrum adequate for quality control purposes can, however, be achieved in a time shorter than that required for a meaningful Mössbauer spectrum and justifies that design.

4.5 Control computer and system services
Just like amplifiers, control computers and system services such as instrument parameter memories, communication circuits and fault protection equipment benefit from the development described in 4.3. The number of functional elements is, however, many times greater than for the other modules, although these functional elements are available as a smaller number of highly integrated modules. Therefore, the general trend in the semi-conductor industry for smaller feature sizes is taking particular effect here, which increases functionality yet still reduces energy consumption and the number of modules. This has the side effect that the total chip area exposed to cosmic and solar radiation falls. Space missions are far more exposed to these types of radiation than circuits on earth. These forms of radiation can lead to such effects as parameter shifts, the production of unanticipated values or the causing of temporary short circuits in the component which could destroy it if countermeasures were not taken. When selecting components, one must take these effects into account and in the case of important parts this can result in being restricted to a greatly reduced selection of suitably radiation-resistant components, along with higher energy requirements and much higher prices. Another measure that can be taken is to switch off all modules when not actually in use. For the processor of the control computer, this can for instance take place using what is known as “Sleep mode”, as long as the module selected supports this mode, during which it waits for an external or internal signal and only uses minimum energy.

4.6. Power supply
Voltage regulators are necessary to match the variable voltage coming from the solar cells/batteries to that required by the instrument. Linear regulators can be ruled out here for reasons of efficiency. Modern switching regulators have experienced enormous improvements recently for the reasons mentioned above. Thanks to considerably increased switching frequencies it has been possible to lower both the space and weight requirements. In the wide input voltage range for which MIMOS is designed, the circuit we have selected can achieve an operating efficiency of over 80%, with about 10% based on unavoidable physical effects.

With the measures shown, up to now aspects of the availability of the necessary components with explicitly documented suitability for use in space have been discussed sparse. If this demand is enforced, it requires that the selection of components be restricted to types that are available as designs which comply with MIL Standards. The classification of a new module necessitates considerable expenditure of both time and money, as well as possible modifications to the manufacturing process. This is only profitable for the manufacturer under appropriate circumstances. With defence and space exploration budgets falling, the probability of getting the necessary modern components to MIL Standards is falling at the same time. On the cost side, the insistence on the demand for virtually exclusive use of equipment types as per MIL Standard was a major factor in the enormous costs of missions in the past. In the same way, the opportunities for a significant reduction in energy requirements through the use of modern components cannot be used.

With NASA’s new motto of "Faster, Better, Cheaper" [4] in the wake of the budget cuts, these restrictions can, however, no longer be maintained strictly. It is increasingly the case that components of the best industry quality class are acceptable, especially if previous experience of even selected tests are available. Also a risk assessment should be undertaken relevant to the particular application of every module and every important component.

5. Conclusions

Modern techniques, materials and electronic components nowadays allow functions to be carried out with significantly reduced energy requirements when compared with the recent past. In most instances, this should make it possible to supply space missions with solar energy, avoiding the use
of thermonuclear generators. When it comes to providing heating for sensitive parts in equipment in extreme temperature conditions, radiothermic generators remain the central choice and can facilitate enormous savings in other areas.

An estimation has to be made for the individual functions of components, as to whether modern parts with low energy requirements and other attractive properties, but higher or unknown sensitivity to radiation can be used, or whether one is limited to the significantly smaller selection of components specially approved for use in space. In this risk assessment, the dangers of the effects of radiation on the component, on the individual experiment and on the entire mission must be taken into consideration. Safety measures in the event of a fault are something else which can be looked at, too. For instance, a temporary short circuit caused by cosmic radiation can be detected because of a sharp increase in supply current. By switching off the power supply at the right time, the short circuit will disappear and the module can then be switched on again with no further damage.

References


Authors

Uwe Bonnes reached his Diploma degree in Electronics 1987 at the Friedrich Alexander University Erlangen, Germany. He then worked at the Lehrstuhl für Technische Elektronik in Erlangen in the area of Semiconductor technology, Electronic circuits and Sensors. Since 1995 he is head of the Electronic Laboratory at the Institut für Kernphysik at the Darmstadt University of Technology. He is in charge of the development of most parts of the Mimos electronics.


Regina Hagen holds a university degree as translator. After many years in the computer industry, she works now as a freelance technical translator and as quality assurance engineer. She has been active in the peace movement for more than 15 years and is a member of the grassroot group Darmstaedter Friedensforum. This group focuses on two topics: protest against nuclear weapons and promotion of peaceful and sustainable use of space. In April 1998, she was elected into the Board of Directors of the Global Network Against Weapons and Nuclear Power in Space. This network is involved in a variety of actions, from circulating petitions to political activities. It tried to block the Cassini launch by a series of demonstrations at Cape Canaveral in the months before the planned launching date.

Michio Kaku is the Henry Semat professor of theoretical physics at the Graduate Center of the City University of New York. He is one of the world's leading authorities on Einstein's Unified Field Theory. He is the co-founder of string field theory. He received his B.A. in physics from Harvard in 1968 and his Ph.D. at the Radiation Laboratory at the University of California at Berkeley in 1972. He was a research associate at Princeton University in 1973, and has been a professor at CUNY for the past 25 years. He has been a visiting professor at Cal Tech, the Institute for Advanced Study at Princeton, and New York University. He has published 9 books and 70 articles in the scientific literature (including Nuclear Physics, Physical Review, Physics Letters, Physical Review Letters). He is a Fellow of the American Physical Society, and honor held by the top 10% of physicists in the U.S.

Martin B. Kalinowski was born 1961 in Hamburg, Germany. In 1988 he received his Diplom in physics at Technical University Aachen. Since 1989 he works with IANUS at Darmstadt University of Technology on technical aspects of nuclear nonproliferation. He specialized in international tritium control carrying out an interdisciplinary programm together with the political scientist Lars Colschen. In February 1997 Kalinowski passed his PhD examination in nuclear physics. Since then he worked on remote monitoring of clandestine nuclear activities, especially through measurements and modelling of atmospheric Krypton-85. In 1994 and 1995 Martin Kalinowski worked with the International Network of Engineers and Scientists Against Proliferation (INESAP) as scientific coordinator. Since 1996 he is member of the Coordinating Committee of INESAP. He managed INESAP conferences in Gothenborg, Shanghai and Geneva and edited the proceedings. In October 1998 he joins the Provisional Technical Secretariat of the Comprehensive Test Ban Treaty Organisation.
Ross McCluney, Ph.D. is working as principal research scientist with the Florida Solar Energy Center. He is an optical physicist and author of a textbook on radiant energy transfer (Introduction to Radiometry and Photometry, Artech House, Boston, 1994). Ross McCluney was a research scientist at NASA's Goddard Space Flight Center from 1973 to 1976. He has been studying the use of solar energy as an alternative to nuclear energy power for interplanetary space probes such as the Cassini mission launched from Cape Canaveral in October of 1997.

Alexei Antonovich Pustovalov is project engineer at the scientific and industrial enterprise “BIAPOS” in Moscow. He is cooperating with the Space Research Institute of the Russian Academy of Sciences. BIAPOS took part in the development of the Russian radionuclide thermoelectric generator and the heating unit “Angel” which was used in the failed mission “Mars-96”. Alexei Pustovalov continues to work on nuclear energy projects which in his view are of particular importance for the Russian programs on deep space research.

Gerhard Strobl has engineering degrees from the University of Arizona/USA and Universität Stuttgart/Germany. His Ph. D. degree in solid state physics he earned from the Université de Nice – Sophia Antipolis /France. He is with Angewandte Solarenergie – ASE GmbH since 1983. At ASE he is responsible for the development of high efficiency silicon solar cells. G. Strobl belongs to the Product Center Space Solar Cells Heilbronn of ASE. This center has previously been known as the AEG Space Solar operation, also as AEG – Telefunken and as the Space Solar Cell Operation of Deutsche Aerospace (DASA). At this time it is part of ASE GmbH which, in turn is wholly owned by RWE AG, a major German Utility, through a subsidiary. ASE is operating internationally in the development, production and marketing of components, systems and plants for the decentralized supply of power employing photovoltaic technology. More than 25 years of experience is combined in terrestrial and orbital photovoltaic technology with a wide spectrum of modern solar cells and systems technology.

Roland Wolff was born 1961 in Klagebach, Germany. He studied physics in Dortmund and specialised on nuclear and elementary particle physics and received his first degree in 1989. His Diplom thesis in physics deals with limitations of measurements in gamma spectroscopy with regard to radiation protection. Since 1989 he is working in applied nuclear medicine at Tübingen and Lüdenscheid. In 1997 he qualified as medical physicist through a course at the Free University Berlin that he attended from 1994 to 1996. His special interests are radiation physics and biology, nuclear technology, radiation effects and risk assessment, radiation protection and disarmament of nuclear weapons. He is editor of the German monthly journal Strahlentelex which concentrates on critical and neglected issues on radiation protection.
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