Nuclear Space and the Earth Environment: The Benefits, Dangers, and Legality of Nuclear Power and Propulsion in Outer Space

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NUCLEAR SPACE AND THE EARTH ENVIRONMENT: THE BENEFITS, DANGERS, AND LEGALITY OF NUCLEAR POWER AND PROPULSION IN OUTER SPACE

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INTRODUCTION

Launched in October 1997 from the Cape Canaveral Air Station in Florida, the National Aeronautics and Space Administration's ("NASA") Cassini mission to Saturn faced unprecedented protests from environmental and anti-nuclear activists. The sources of the protesters' discontent were the Cassini spacecraft's three radioisotope thermoelectric generators ("RTGs") that provide power to the craft by converting heat from the natural decay of plutonium into electricity. At the start of the mission, Cassini's RTGs contained seventy-two pounds of plutonium-238, more nuclear fuel than had ever been launched into space.

Although RTGs have been employed successfully on NASA missions since the 1960s (including the Apollo missions to the moon, the Viking missions to Mars, and the Pioneer, Ulysses, and Galileo missions to the outer Solar System), a number of environmental groups have condemned their use, citing the dangers posed

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by nuclear material and the likelihood of an accident that would release the material into the Earth’s atmosphere. Critics of the Cassini mission warned of a possible mishap during both the initial launch in October 1997 and the gravitational flyby maneuver in August 1999, which took the craft within 725 miles of Earth. They pointed to the highly toxic nature of radioactive materials and their array of short- and long-term negative biological effects. Some critics warned of a potentially massive health crisis—the Cassini craft could break up during the flyby maneuver and disperse plutonium dust over large populated areas, resulting in environmental damage and a substantial increase in cancer rates.

Officials at NASA and the Department of Energy (“DOE”) rejected the rhetoric of anti-nuclear and environmental activists, highlighting the extensive safety measures undertaken by NASA, the minimal risks posed by the type of nuclear fuel in the RTG, and the extremely small likelihood of a catastrophic event.
project manager Richard J. Spehalski said that the public was "badly misinformed by alarmists." Others stressed the scientific benefits of the Cassini mission, and the inability of solar energy to power such a spacecraft at large distances from the sun.

With the Bush administration's strong support for NASA's Project Prometheus, which targets the development of new Radioisotope Power Systems ("RPS") and nuclear fission-based power systems for spacecrafts, the debate over the desirability of nuclear space has begun anew. According to many scientists and space enthusiasts, nuclear power holds the key to mankind's future in outer space. "[H]umanity is going nowhere, astronautically speaking," says aerospace engineer and Mars Society president Robert Zubrin, "without the power of the atom" to propel

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11 Robert M. Nelson & Dennis L. Matson, Perspective on Space Exploration; Cassini Can Unveil Saturn’s Secrets, L.A. TIMES, Oct. 3, 1997, at B9. The Cassini mission has been called NASA's most ambitious mission in the history of interplanetary space exploration. See, e.g., Ann Schrader, Cassini Begins Voyage; Probe Won’t Reach Saturn for 7 Years, DENVER POST, Oct. 16, 1997, at A2; David L. Chandler, Going for the Rings; Saturn’s Stunning System of Moons and Rings is the Target of $3.3B Mission, BOSTON GLOBE, Oct. 13, 1997, at C1. The last of NASA’s big budget space probes, Cassini entered Saturn’s orbit in July 2004 and has begun its orbital tour of the planet and its moons. NASA Jet Propulsion Lab, supra note 2, at Cassini-Huygens (Home). In December 2004, the orbiter will release the European Space Agency’s Huygens probe on a three-week trajectory to Titan, Saturn’s largest moon and the second largest moon in the Solar System. During its descent by parachute, the probe will sample and analyze Titan’s atmosphere and provide imaging to Earth scientists. Id. If it survives the landing, the Huygens probe will continue transmission from Titan’s surface. Id. Meanwhile, the Cassini craft will continue orbiting Saturn, transmitting information about the planet and its rings, moons, and magnetosphere back to Earth. Id.
12 NASA Space Science, Project Prometheus, at http://spacescience.nasa.gov/missions/prometheus.htm (last visited Sept. 3, 2004) [hereinafter Project Prometheus]. This initiative was “formerly the Nuclear Systems Initiative.” Id.
spacecraft and power their onboard systems and instruments. Environmental and anti-nuclear groups disagree, calling RTGs and other space nuclear power systems a dangerous “nuclear threat to our planet” that is completely unnecessary for successful interplanetary exploration. “It isn’t worth the risk,’ says Karl Grossman, journalist and author of The Wrong Stuff: The Space Program’s Nuclear Threat to Our Planet. ‘The use of nuclear power in space is unnecessary.’

This Note will consider the legal questions of nuclear power and propulsion in space and compare the benefits of the different technologies to the civilian space program with the risks they pose to the terrestrial environment. Ultimately, it concludes that safety measures can drastically reduce the dangers of many nuclear technologies, and that the benefits to science and space exploration often outweigh minimal risks to Earth’s environment.

Part I will discuss the basic science of nuclear power and propulsion in outer space, including the technical workings of RTGs, nuclear reactors, nuclear rockets, and radioisotope heater units (“RHUs”). It will also outline the benefits, both actual and potential, to science and space exploration offered by the inclusion of such technologies on outer space missions. Part II will provide a history of nuclear space missions, with a focus on spacecraft accidents and their environmental ramifications. Part III will

16 Loft, supra note 4.
17 This Note focuses on the civilian space program—specifically, missions involving scientific research and space exploration. Military space programs are not discussed. However, it is worth noting that many of the nuclear technologies advantageous to civilian space efforts could be equally beneficial in the military realm. For example, high levels of power generation, which would be highly desirable for civilian satellites, would also be highly desirable for reconnaissance satellites or a space-based missile defense system. See, e.g., Steven Aftergood, Background on Space Nuclear Power, 1 SCI. & GLOBAL SECURITY 93, 104-06 (1989), available at http://www.princeton.edu/~globsec/publications/pdf/1_1-2Aftergood.pdf.
discuss the dangers to the Earth environment posed by the use of nuclear space technologies, with a focus on efforts to mitigate those dangers through safety measures. Part IV will discuss international law and domestic cases regarding the placement of radioactive materials in outer space and the liability regime for environmental damages if an accident were to occur. Several conclusions will then be offered.

I. NUCLEAR AND RADIOLOGICAL POWER

A. RTGs

RTGs are not nuclear reactors, and do not produce energy through nuclear fission or fusion. Rather, RTGs produce energy by converting heat from the decay of radioisotopic materials into electricity. In a basic RTG, a core of radioactive material is surrounded by a solid state thermocouple, consisting of metal wires connected to the canister of radioisotope (the “hot junction”) and the external generator wall (the “cold junction”). As the radioactive material undergoes its natural decay process, heat is released, and the cold junction captures electrons boiled off by the hot junction. This electron diffusion produces an electric current.

The amount of radioisotopic material in the RTG depends on the duration of the mission and the half-life of the particular radioisotope (the amount of time for one-half of the material to

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21 MMRTG, supra note 20.
22 Id.
decay into another element). Sufficient material must be present to provide adequate thermal energy throughout the operational lifetime of the spacecraft.

A typical RTG generates relatively low levels of electrical power, but provides several key advantages over other power sources in terms of mass, efficiency, longevity, and reliability. Unlike fuel cells or chemical batteries, which can provide only limited power over short durations, a single RTG with a small amount of radioactive material can produce a continuous, unvarying stream of electrical power for over twenty years. Furthermore, RTGs are extremely durable and, because they contain no moving parts, are ideal for use in a setting where mechanical adjustments are not an option.

RTGs offer major advantages over solar power for interplanetary missions. A spacecraft operating at great distances from the sun is faced with a severe reduction in the intensity of solar light. Although a small solar panel could provide adequate power to a craft within Earth's orbit, a solar panel would need to be enormous to provide equivalent power several billion miles from the Sun. Replacing RTGs with massive solar panels would vastly increase the weight and cost of a spacecraft and reduce reliability;

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23 RTG Fact Sheet, supra note 20.
24 Id.
26 MMRTG, supra note 20. For example, the Pioneer 10 satellite and its RTGs continued to operate more than 30 years after its launch in 1972; the satellite's last signal was received on January 22, 2003. Pioneer 10 Spacecraft Goes Silent After 31 Years, WASH. POST, Feb. 26, 2003, at A10.
27 Cassini Spacepower, supra note 19.
28 See, e.g., Furlong & Wahlquist, supra note 25.
30 Id. "[A] 1-meter-square solar array producing 400 watts at a distance of 1 AU [150 million kilometers] would have to be 25 square meters in size out at Jupiter—and almost 2,000 square meters at Pluto to yield the same power." Id. (quoting Geoff Landis of NASA's Glenn Research Center).
solar panels are often complicated to unfurl and must face the sun to provide consistent power production.\textsuperscript{31} Huge solar panels would also increase the difficulty of performing maneuvers in outer space and inhibit the operation of onboard instruments, sensors, and communications equipment, which could be blocked by the large solar panels or face serious levels of electromagnetic interference.\textsuperscript{32} RTGs offer similar advantages to a spacecraft operating on the surface of a planet or moon, where darkness at night, seasonal light variations, harsh weather, and a thick atmosphere can impede or prevent the collection of light by a solar array.\textsuperscript{33} For example, the \textit{Pathfinder} rover, powered by batteries and solar panels, operated only three months after landing on the Martian surface.\textsuperscript{34} If the rover had incorporated an RTG power source, it could have remained functional for several years.\textsuperscript{35}

Ultimately, it is clear that, despite continuing advances in the quality of batteries, fuel cells, and solar arrays, such power sources are insufficient for certain space missions. RTGs offer advantages for deep space and surface missions that other power sources simply cannot provide.

\textbf{B. Space Nuclear Reactors}

A nuclear reactor operates by converting heat generated by the controlled fission of heavy atoms into electricity.\textsuperscript{36} In a traditional uranium reactor, a neutron strikes the nucleus of a uranium-235 atom, which splits into lighter atoms, releasing

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\item\textsuperscript{31} \textit{Cassini Spacepower, supra} note 19.
\item\textsuperscript{32} \textit{Id.}
\item\textsuperscript{34} See Britt, \textit{supra} note 10.
\item\textsuperscript{35} \textit{Id.}
\end{itemize}
\end{footnotesize}
energy and emitting other neutrons.\textsuperscript{37} In an operational ("critical") reactor, a neutron ejected from each fission of a uranium-235 atom causes another fission to occur.\textsuperscript{38} When this process occurs as a continuous, controlled chain reaction, it produces useful amounts of energy.\textsuperscript{39}

Space nuclear reactors operate according to the same process as nuclear reactors in terrestrial nuclear power plants.\textsuperscript{40} To produce usable power, "the heat generated by the controlled fission . . . is transferred by a heat-exchange coolant to either a static (for example, thermoelectric) or dynamic (for example, turbine/alternator) conversion system, which transforms it into electricity."\textsuperscript{41} The system releases waste heat through a radiator.\textsuperscript{42} The amount of fissile material in the reactor depends on the duration and power requirements of the mission.\textsuperscript{43}

Nuclear reactors offer major advantages over solar and chemical power sources in terms of mass, efficiency, durability, and longevity.\textsuperscript{44} Like RTGs, nuclear reactors are capable of producing a reliable stream of electrical power over long periods of time.\textsuperscript{45} Unlike RTGs, however, nuclear reactors are capable of producing extremely high power levels.\textsuperscript{46} "The energy available from a unit mass of fissionable material is approximately [100 million] times larger than that available from the most energetic chemical reactions."\textsuperscript{47} According to one estimate, a five thousand kilogram nuclear reactor operating over a seven-year lifespan is

\textsuperscript{37} Answers to Questions, supra note 36, at 2, 7.

\textsuperscript{38} Id. at 2.

\textsuperscript{39} Id.

\textsuperscript{40} Aftergood, supra note 17, at 94.

\textsuperscript{41} Id.

\textsuperscript{42} Id.

\textsuperscript{43} See id.

\textsuperscript{44} Id.

\textsuperscript{45} See id.

\textsuperscript{46} Aftergood, supra note 17, at 94.

\textsuperscript{47} NASA Jet Propulsion Laboratory, Advanced Propulsion Technology Group, Solid Core Nuclear Rocket, ADVANCED PROPULSION CONCEPTS (1989), available at http://www.islandone.org/APC/Nuclear/01.html (last visited Sept. 10, 2004) [hereinafter ADVANCED PROPULSION CONCEPTS]. Island One created this website, which collects information on basic space nuclear technology.
the equivalent of a 750 square-meter solar array or a six million kilogram chemical power source. These numbers illustrate that nuclear reactors are virtually the only viable power source for space missions requiring high power levels over long time periods.

C. Nuclear Rockets

A number of experimental rocket designs incorporate some form of nuclear power or propulsion. These include nuclear thermal propulsion ("NTP") systems, nuclear electric propulsion ("NEP") systems, hybrid NTP/NEP concepts, and nuclear pulse rockets that are propelled by the force of nuclear explosions. To many observers, the successful development of nuclear propulsion is the key to mankind's exploration of space. Indeed, some scientists believe that manned missions to Mars and the outer Solar System are almost impossible without some sort of nuclear rocket.

Nuclear thermal propulsion systems provide thrust through the heating of liquid hydrogen propellant by nuclear fission. There are several designs for nuclear thermal rockets, including solid, liquid, and gas core nuclear rockets. Solid core nuclear rockets, a relatively mature propulsion technology, operate by pumping the liquid hydrogen propellant through narrow channels in a solid nuclear reactor. As liquid hydrogen moves through the channels, it is heated by the reactor into a high temperature gas, and then ejected from the exhaust nozzle of the rocket at high

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48 Aftergood, supra note 17, at 94.
49 See ADVANCED PROPULSION CONCEPTS, supra note 47.
50 Id.
51 See, e.g., Zubrin, supra note 14.
53 Nuclear Propulsion, Introduction, in ADVANCED PROPULSION CONCEPTS, supra note 47.
54 See ADVANCED PROPULSION CONCEPTS, supra note 47.
55 Solid Core Nuclear Rocket, in ADVANCED PROPULSION CONCEPTS, supra note 47.
speeds. Liquid and gas core nuclear rockets operate according to a similar principle, but, instead of using a solid fuel core to heat the hydrogen propellant, they use a liquid or gaseous nuclear fuel, respectively.

Solid, liquid, and gas core nuclear propulsion systems have never been developed into an operational rocket. However, they offer two potential major advantages over traditional chemical propulsion: a substantially larger specific impulse and a propellant with extremely low molecular weight. First, a large specific impulse translates into faster travel and the possibility of carrying heavier, more complex, and more experiment-laden payloads into space. Second, propellants with low molecular weight increase the propulsive force per unit of propellant flow, allowing for an increased proportion of a mission’s total weight to be composed of payload rather than propellant.

Nuclear electric propulsion systems, already employed on a number of orbital missions, use superconducting magnetic cells to ionize gas and a nuclear reactor to heat the gas to high temperatures. The gas is expelled at very high velocities to provide thrust. Although the total thrust of nuclear electric propulsion is less than that of nuclear thermal propulsion, an electrical engine can provide sufficient thrust over long periods of time to propel an

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56 Id.
57 See Liquid Core Nuclear Rocket, in ADVANCED PROPULSION CONCEPTS, supra note 47, for a discussion of liquid core nuclear rockets. See Gas Core Nuclear Rocket, in ADVANCED PROPULSION CONCEPTS, supra note 47, for a discussion of gas core nuclear rockets.
58 ADVANCED PROPULSION CONCEPTS, supra note 47.
60 Specific impulse is essentially a measure of the engine efficiency of a rocket. It is defined as thrust per unit flow rate of propellant. Spacecraft Propulsion Systems; What They Are and How They Work, ISP and the Rocket Equation, in ADVANCED PROPULSION CONCEPTS, supra note 47.
61 Mars Academy, supra note 59.
62 Id.
63 Introduction to Nuclear Electric Propulsion, in ADVANCED PROPULSION CONCEPTS, supra note 47.
64 Id.
unmanned spacecraft to the outer edges of the Solar System or a manned spacecraft to Mars.\textsuperscript{65}

A different type of nuclear electric propulsion, an electron-bombardment ion engine uses electrical energy, rather than heat energy, to accelerate the exhaust gas to provide thrust.\textsuperscript{66} Energy from the nuclear reactor is converted into electricity and then channeled through an electrostatic grid to accelerate the ionized gas.\textsuperscript{67} Ion engines are considered particularly promising; they combine high levels of conversion of electric power into thrust with much higher exhaust velocities than chemical rockets and an extremely long operational lifetime.\textsuperscript{68}

Perhaps the most futuristic and controversial of the nuclear propulsion concepts is a nuclear pulse rocket propelled by actual nuclear explosions.\textsuperscript{69} The nuclear pulse rocket operates by ejecting specially-constructed low-yield nuclear bombs, which explode some distance behind a large ablative “pusher plate” at the rear of the spacecraft.\textsuperscript{70} The blast from each explosion bounces off the pusher plate, which thrusts the vehicle forward through a system of special hydraulic shock absorbers.\textsuperscript{71} Although such a vehicle has never been tested, it is one of the more intriguing options for advanced space travel.\textsuperscript{72} It offers an even better utilization of the energy yield from the fission reaction than a nuclear thermal rocket.\textsuperscript{73}

Ultimately, nuclear propulsion could revolutionize spaceflight by significantly reducing the difficulty and cost of moving objects...

\textsuperscript{65} Id.
\textsuperscript{66} Electron-Bombardment Ion Engine, in \textit{Advanced Propulsion Concepts}, supra note 47.
\textsuperscript{67} Id.
\textsuperscript{68} Id.
\textsuperscript{69} See Nuclear Pulse Rocket, in \textit{Advanced Propulsion Concepts}, supra note 47 for a detailed description of NASA’s conceptual nuclear pulse rocket project, Orion.
\textsuperscript{71} Id.
\textsuperscript{72} Id.
\textsuperscript{73} Nuclear Pulse Rocket, in \textit{Advanced Propulsion Concepts}, supra note 47.
through space.\textsuperscript{74} It may also hold the key to successful manned space travel.\textsuperscript{75} Manned missions powered by chemical rockets face enormous travel times; a crew may not survive such missions due to exposure to microgravity, solar flares, and space radiation.\textsuperscript{76} Nuclear rockets could eliminate these problems by drastically reducing travel times, enabling manned exploration of the Solar System.\textsuperscript{77}

\textit{D. RHUs}

Radioisotope heater units ("RHUs") operate according to the same principle as RTGs—the production of thermal energy through the decay of radioisotopes—but are extremely tiny and contain no intervening electronic components that convert the heat into electricity.\textsuperscript{78} Instead of serving as a power source, RHUs are designed to produce heat and transfer it directly to sensitive spacecraft instruments and onboard experiments, thus enabling the instruments to operate successfully in a cold environment.\textsuperscript{79}

NASA's current RHUs, like RTGs, use plutonium dioxide as fuel.\textsuperscript{80} Compared to RTGs and space nuclear reactors, however, RHUs face less controversy because they utilize only an extremely small amount of radioisotopic material—an RHU typically contains only a fraction of an ounce of plutonium, whereas RTGs and nuclear reactors can include many pounds of plutonium.\textsuperscript{81}

RHUs generate very low levels of thermal energy. They contain no moving parts, are very compact, and are a reliable and

\begin{thebibliography}{9}
\bibitem{75} Id.
\bibitem{77} Id.
\bibitem{78} Id.
\bibitem{80} See id.
\bibitem{81} Id.
\end{thebibliography}
continuous source of heat. This makes them a valuable option for missions where solar energy cannot provide adequate heating. In addition, they offer significant advantages over electrical thermal technologies, which are often bulky and impractical, use large amounts of a spacecraft's sparse electrical power, and can produce electromagnetic interference that disturbs a spacecraft's sensitive instruments.

II. NUCLEAR SPACE MISSIONS

A. The Use of Radioisotopic Power Sources in Space

The earliest American satellites were powered by a combination of chemical batteries, fuel cells, and solar cells. The first American satellite, *Explorer I* (launched on January 31, 1958, three months after the Soviet *Sputnik I*), was powered by nickel-cadmium batteries. The second American satellite and the first solar powered spacecraft, the *Vanguard I*, used a crude solar array to power a radio transmitter aboard the tiny three-pound craft. Early Soviet satellites included similar technologies; silver-zinc batteries powered *Sputnik I*, and a solar array charged *Sputnik III*.

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82 Id.
83 See id.
84 DOE RPS, supra note 78.
As space missions grew larger and more sophisticated, however, energy needs increased and scientists looked to more robust power sources. Nuclear energy was seen as a promising option. Research into the uses of nuclear power on satellites began in the United States by the mid-1950s.

The earliest RTGs were viewed as an auxiliary power source for satellites. Improvements in RTG technology and performance, however, opened the door for their use as a primary power generation system. The first space flights to incorporate RTGs were the U.S. Navy’s Transit 4A and 4B navigational satellites. Launched in June and November 1961, respectively, the satellites’ polonium-210 based SNAP-3 RTGs ("Systems for Nuclear Auxiliary Power") were flown to prove the operational viability of RTGs in space. Although the power-production was extremely low (three watts), the RTG system proved extremely reliable; according to the Department of Energy, it operated for fifteen years after the launch. On subsequent missions, RTGs were used as the primary power source.

Continuing improvements in technology have resulted in new generations of American RTG models, including the Multi-Hundred Watt ("MHW") RTG flown on the Voyager interplanetary missions in the late 1970s, and the General Purpose Heat Source ("GPHS") RTG first flown on the Galileo mission to Jupiter in the late 1980s. Used on current missions, the GPHS-RTG is a modular system designed to maximize safety in the event of an accident. NASA plans to incorporate GPHS-RTGs aboard the

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89 DOE NPS, supra note 85, at 3.
90 Id.
91 Id.
92 Id.
93 Id.
94 Furlong & Wahlquist, supra note 25, at 26, 28.
95 Id. at 26; DOE NPS, supra note 85, at 20.
96 DOE NPS, supra note 85, at 7.
97 Furlong & Wahlquist, supra note 25, at 26.
98 Id. at 29.
99 DOE NPS, supra note 85, at 22. Each GPHS-RTG includes eighteen general purpose heat source (GPHS) modules, each containing four plutonium-238
New Horizons Pluto mission targeted for launch between 2006 and 2008.100 NASA is developing new RTG systems however, to accommodate a broader range of missions as part of its Project Prometheus research.101 These new RTG systems include a Multi-Mission RTG ("MMRTG") about half the size of the GPHS-RTG and designed for use on both space and planetary missions, and a more complex Stirling Radioisotope Generator ("SRG") with moving parts.102 The MMRTG and SRG are targeted for use on missions after the phase-out of the GPHS-RTG in 2009.103

By the time Cassini launched in 1997, the United States had flown twenty-five separate space missions incorporating an RTG.104 Of the twenty-five missions, only three resulted in failure, and the return of an RTG to the surface of the Earth: Transit 5-BN-3,
Nimbus B-1, and Apollo 13.\textsuperscript{105} "[N]one of the failures were due to problems with the RTGs,"\textsuperscript{106} and no evidence has ever connected the accidents with deaths or cancer cases.\textsuperscript{107}

The Transit 5-BN-3 satellite, launched in April 1964, was aborted due to launch vehicle failure.\textsuperscript{108} The satellite's SNAP-9A RTG, which contained 2.2 lbs of plutonium-238 fuel, entered the upper atmosphere over the Southern Hemisphere.\textsuperscript{109} Subsequent airborne and surface sampling showed that the plutonium, as designed, had completely burned up during re-entry over the West Indian Ocean north of Madagascar.\textsuperscript{110} According to NASA estimates, "[s]ince 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."\textsuperscript{111} The SNAP-9A re-entry is estimated to have nearly doubled the worldwide plutonium-238 distribution.\textsuperscript{112} John Gofman, a professor of molecular and cell biology at University of California at Berkeley who investigated the Transit crash, stated that lung cancer rates


\textsuperscript{106} Id.

\textsuperscript{107} Britt, supra note 10.

\textsuperscript{108} Furlong & Wahlquist, supra note 25, at 27.

\textsuperscript{109} GAO, supra note 105, at 18; \textsc{Joseph A. Angelo Jr. \& David Buden}, \textit{Space Nuclear Power 244} (1985).

\textsuperscript{110} \textsc{Angelo \& Buden}, supra note 109, at 244.

\textsuperscript{111} NASA Solar System Exploration Division, Office of Space Science, \textit{Final Environmental Impact Statement for the Cassini Mission} (June 1995) [hereinafter \textit{Cassini FEIS}].

\textsuperscript{112} Id. According to NASA, nuclear testing from 1945-1974 added 9,000 curies of plutonium-238 to the Earth's atmosphere. Overseas nuclear reprocessing plants and the Chernobyl power station added 3,000 curies and 810 curies, respectively. The SNAP-9A added 17,000 curies. Id. A single curie is the amount of radioactive isotope that decays at the rate of $3.7 \times 10^{10}$ disintegrations per second. \textit{See}, \textit{e.g.}, Dep't of Energy: Office of Environment, Safety and Health, \textit{ACHRE Report, What Is Radioactivity?}, \textit{available at} http://www.eh.doe.gov/ohre/roadmap/achre/intro_9_2.html (last visited Sept. 5, 2004).
increased appreciably as a result of the accident.\textsuperscript{113} In his view, "although it is impossible to estimate the number of lung cancers induced by the accident, there is no question that dispersal of so much Plutonium-238 would add to the number of lung cancers diagnosed over many subsequent decades."\textsuperscript{114} Other scientists, however, argue that a plutonium release comparable to that of the \textit{Transit-5-BN-3} would have no actual health effects whatsoever.\textsuperscript{115} Regardless of the actual environmental impact, NASA's RTG design philosophy changed following the \textit{Transit-5-BN-3} accident.\textsuperscript{116} Subsequent American RTGs were designed to contain their plutonium fuel and survive re-entry intact.\textsuperscript{117}

The second accident involved the \textit{Nimbus B-1} meteorological satellite, launched from Vandenburg Air Force Base in California in May 1968.\textsuperscript{118} The \textit{Nimbus B-1} was terminated in response to a range safety destruct command.\textsuperscript{119} The radioisotope heat source aboard the \textit{Nimbus} was recovered intact five months later from the Santa Barbara Channel near the California coast.\textsuperscript{120} According to NASA, none of the plutonium was released into the environment, and the heat source material was recycled for use in another RTG mission.\textsuperscript{121} The incident confirmed the ability of radioisotope fuel capsules to remain in a marine environment following a mission

\textsuperscript{113} Max Obuszewski, \textit{Real Risks of Cassini}, BALT. SUN, Oct. 15, 1997, at 17A.
\textsuperscript{114} GROSSMAN, \textit{supra} note 15, at 13.
\textsuperscript{115} For a debate about the effects of a plutonium release in the atmosphere (including a more general discussion of the \textit{Cassini} mission), see Online PBS NewsHour Forum, \textit{The Cassini Mission}, at http://www.pbs.org/newshour/forum/october97/cassini.html (last visited Sept. 5, 2004). The participants were John Gofman, "Steven Aftergood, a senior research analyst for the Federation of American Scientists . . . and Dr. Gary Bennett, a retired scientist who has worked with NASA and the Department of Energy." \textit{Id.} at 2.
\textsuperscript{116} Furlong & Wahlquist, \textit{supra} note 25, at 27.
\textsuperscript{117} \textit{Id.}
\textsuperscript{118} \textit{Id.}
\textsuperscript{119} \textit{Id.}
\textsuperscript{120} GAO, \textit{supra} note 105, at 18. The SNAP-19 generator had been designed for intact re-entry and was tested in marine conditions. ANGELO \& BUDEN, \textit{supra} note 109, at 244.
\textsuperscript{121} GAO, \textit{supra} note 105, at 18.
failure without concern for the release of radioisotopic material into the water.\textsuperscript{122}

The third failed mission, the \textit{Apollo 13} mission to the moon, was aborted after the explosion of an oxygen tank led to the loss of electricity, light, and water in the manned \textit{Apollo} command module.\textsuperscript{123} The \textit{Apollo 13}'s lunar module carried a plutonium-fueled SNAP-27 RTG intended to power a lunar seismic station.\textsuperscript{124} During re-entry, the lunar module broke up and the RTG heat source reentered the atmosphere intact.\textsuperscript{125} The material fell into the southern Pacific Ocean, and, according to NASA, is currently located in the Tonga trench, where the ocean is 5 to 6 miles deep.\textsuperscript{126} According to the Department of Energy, "[e]xtensive testing of RTGs in sea water has been conducted, and there will be no release of plutonium over time from this unit."\textsuperscript{127}

The \textit{Transit 5-BN-3}, \textit{Nimbus B-1}, and \textit{Apollo 13} incidents are powerful reminders of the possibility of an accident involving a nuclear spacecraft. Indeed, three crashes in twenty-six total American RTG launches do little to alleviate the concerns of anti-nuclear critics. These accidents demonstrate that if the United States continues to pursue radioisotopic and fission-based power and propulsion for its efforts in space, there is a high probability, if not complete certainty, that a launch failure will occur at some point in the years to come, sending nuclear materials to the surface of the Earth.

Contrary to the claims of some anti-nuclear groups, however, the mere possibility of further accidents should not be determinative of nuclear space policy. As the \textit{Nimbus B-1} and \textit{Apollo 13} incidents indicate, failures involving a spacecraft with nuclear materials need not cause serious harm to the terrestrial environment; indeed, they need not have adverse effects at all, save the actual loss of a spacecraft. An important factor for space

\textsuperscript{122} \textsc{ANGELO} \& \textsc{BUDEN}, \textit{supra} note 109, at 244.
\textsuperscript{124} \textsc{DOE RPS}, \textit{supra} note 78 (Program Description).
\textsuperscript{125} \textit{Id.}
\textsuperscript{126} \textit{Id.;} \textsc{Furlong} \& \textsc{Wahlquist}, \textit{supra} note 25, at 27.
\textsuperscript{127} \textsc{DOE RPS}, \textit{supra} note 78 (Program Description).
The ability of NASA to develop RTGs that can survive re-entry is a powerful indication that the safe use of nuclear materials in space is possible, even if accidents become more likely as an increasing number of missions incorporate such materials.

Outside of the United States, the Soviet Union employed radioisotopic power sources on several satellites and lunar modules. The first two Soviet nuclear-powered satellites, the Cosmos 84 and 90 military communications satellites, both launched in September 1965, incorporated polonium-210 based RTGs. The Soviet Union is believed to have also employed RTGs on two unmanned lunar probes in 1969, the Cosmos 300 and Cosmos 305. Each of the Soviet lunar probes failed to reach the moon; each achieved an Earth orbit but reentered the Earth’s atmosphere. Both accidents resulted in detectable amounts of radioactivity in the upper atmosphere. In a more recent mission that also ended in failure, the Russian Mars-96 satellite reentered the Earth’s atmosphere in November 1996. According to Russia and U.S. Space Command, the satellite, which carried several plutonium-based RTGs, fell intact into the sea off the coast of Chile.

Along with RTGs, tiny radioisotope heater units, or RHUs, have been used on a number of American and Soviet space missions. The United States has employed over 240 RHUs on various satellites and spacecrafts; the Soviet Union employed

128 Aftergood, supra note 17, at 95-97.
129 Id. at 97.
130 Id. at 99.
133 Id. The claims of Russia and U.S. Space Command were disputed in Chile; there were sightings of sky phenomenon and unconfirmed reports of objects on the ground. Id.
RHUs on the *Luna 17* and *Luna 21* missions in the early 1970s.\textsuperscript{135} Together, the *Cassini* spacecraft and *Huygens* probe included 117 separate RHUs.\textsuperscript{136} More recently, eight 2.7 gram RHUs were included in each of the two Mars rovers, *Spirit* and *Opportunity*, which were launched in June 2003 and July 2003, respectively.\textsuperscript{137}

**B. History of Space Nuclear Reactors and Nuclear Rockets**

Compared to its extensive RTG launch record, the United States is inexperienced in the use of space nuclear reactors. To date, the United States has launched only a single reactor into space, the uranium-235 fueled SNAP 10-A, aboard the *Snapshot* satellite in 1965.\textsuperscript{138} The 500-watt reactor powered the *Snapshot* successfully for forty-three days, until an anomalous event (possibly a collision or an internal problem) necessitated premature shutdown.\textsuperscript{139} The reactor is now in a storage orbit with an estimated life of more than 3,000 years.\textsuperscript{140} Re-entry of the reactor

\textsuperscript{135} Id.


\textsuperscript{139} PORTREE & LOFTUS, *supra* note 138, at 30.

The parent body [of the *Snapshot* satellite] sheds pieces but remains largely intact. Six more anomalous events occur in the next 6 years, releasing nearly 50 trackable pieces. Release of radioactives is possible but not confirmed. A collision with another space object has not been ruled out as the cause of the initial event, though an unknown internal malfunction is perhaps more likely.

\textsuperscript{140} Id. “Expected orbital lifetime is more than 3000 years (assuming it avoids a more complete breakup).” Id.
will not occur until the radioactivity of the plutonium fission by-products has decayed to a very low level.\textsuperscript{141}

Following the \textit{Snapshot} mission, American efforts to develop reactors for space power and propulsion have been sporadic. In the 1960s and early 1970s, NASA studied the concept of nuclear thermal propulsion as part of the Rover/NERVA program.\textsuperscript{142} Solid core nuclear rocket engines were built and tested, producing some encouraging results.\textsuperscript{143} (American scientists also briefly studied the possibility of a nuclear pulse rocket propelled by nuclear explosives as part of the now famous Project Orion.)\textsuperscript{144} However, the United States reactor program was put on hold in 1973 because no American space missions required the power production of a nuclear reactor.\textsuperscript{145}

The American reactor program reappeared in the 1980s, with new studies of nuclear thermal propulsion and designs for a gas core nuclear rocket.\textsuperscript{146} The cornerstone of the program, a joint effort of NASA and the Department of Defense known as SP-100, was eventually terminated.\textsuperscript{147}

With the Bush administration’s support of Project Prometheus, nuclear reactors are again being considered for use on space missions.\textsuperscript{148} According to NASA, the portion of Project Prometheus devoted to fission power and propulsion research will “focus on

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\begin{enumerate}
\item RTG Fact Sheet, supra note 20.
\item NERVA research yielded a solid core nuclear rocket with a thrust up to more than half that of the space shuttle chemical rockets. \textit{Solid Core Nuclear Rocket, in ADVANCED PROPULSION CONCEPTS}, supra note 47.
\item Reynolds, supra note 70. Project Orion commenced in 1958 and was terminated in 1963 with the passage of the Partial Test Ban Treaty. \textit{Id.} See infra notes 202-205 and accompanying text for further discussion of the Treaty.
\item Aftergood, supra note 17, at 95.
\item \textit{Id.}
\item See Project Prometheus, supra note 12.
\end{enumerate}
developing the [nuclear] systems needed for revolutionary new capabilities in space exploration," and will "include research on reactors, advanced heat-to-power conversion, and power management and distribution technologies to provide spacecraft flexibility, long-mission durations, and orders of magnitude more power for science instruments."\textsuperscript{149} Initial activity "will focus on defining the near-term technology research goals, and on identifying planetary science missions uniquely enabled by nuclear fission electric power and propulsion."\textsuperscript{150} In particular, Project Prometheus has targeted the Jupiter Icy Moons Orbiter ("JIMO") program for the development of nuclear technologies.\textsuperscript{151} To be launched sometime in or after 2011, the JIMO spacecraft will be powered by a nuclear reactor and propelled by nuclear powered ion engines.\textsuperscript{152} Clearly, the Bush administration has high hopes for the development of nuclear space technologies.

Unlike the United States, the Soviet Union had a long history of powering satellites with nuclear reactors; it launched over thirty nuclear reactors after late 1967.\textsuperscript{153} The Soviet Union used nuclear reactors to power Radar Ocean Reconnaissance Satellites ("RORSATs"), low-orbiting navigation satellites used to track and target American naval vessels.\textsuperscript{154} The low orbit of the satellites led the Soviet Union to forgo solar power; solar panels would have

\textsuperscript{149} Id.
\textsuperscript{150} Id.
\textsuperscript{151} Id. See NASA Space Science, Jupiter Icy Moons Orbit Fact Sheet (Feb. 2003), available at http://spacemath.nasa.gov/missions/JIMO.pdf, for more information about the Jupiter Icy Moons mission.
\textsuperscript{153} Aftergood, supra note 17, at 95-97. The Soviet missions included: the Cosmos 367 in 1970; the Cosmos 402 and 469 in 1971; the Cosmos 516 in 1972; the Cosmos 556 and 626 in 1973; the Cosmos 651 and 654 in 1974; the Cosmos 723, 724, and 785 in 1975; the Cosmos 860 and 861 in 1976; the Cosmos 952 and 954 in 1977; the Cosmos 1176 in 1980; the Cosmos 1249, 1266, and 1299 in 1981; the Cosmos 1365, 1372, 1402, and 1412 in 1982; the Cosmos 1579 and 1607 in 1984; the Cosmos 1670 and 1677 in 1985; the Cosmos 1736 and 1771 in 1986; the Cosmos 1818, 1860, 1867, and 1900 in 1987; and the Cosmos 1932 in 1988. Id.
\textsuperscript{154} Id. at 96.
increased drag, shortened the lifetime of each satellite’s orbit, and necessitated an electrical storage system for operation in the Earth’s shadow. At least three accidents occurred involving space nuclear reactors aboard Soviet RORSATs.

In April 1973, a Soviet RORSAT fell into the Pacific Ocean and created detectable amounts of radioactivity. In January 1978, the Soviet Cosmos 954 RORSAT re-entered the atmosphere over Canada, resulting in the most serious nuclear space accident ever to occur. The Cosmos satellite broke apart over Canada’s Great Slave Lake, spreading radioactive debris over an 800-kilometer long region of the country’s Northwest Territory. Although a number of fragments were highly radioactive, the search, recovery, and cleanup operations were completely successful; subsequent tests revealed no detectable levels of contamination in air, water, and food samples.

In a third incident, the jettisoned reactor core of the Soviet Cosmos 1402 RORSAT (which failed to boost into a storage orbit in late 1982) re-entered the atmosphere above the South Atlantic Ocean in February 1983. The reactor left a radioactive trail through the atmosphere, but it is not known whether any radioactive debris eventually reached the Earth’s surface.

Like the United States, the Soviet Union pursued nuclear thermal rocket technology. Soviet research and development of nuclear thermal propulsion for the upper stages of multi-stage

155 Id.
157 SNP Accidents, supra note 156.
158 Aftergood, supra note 17, at 100; PORTREE & LOFTUS, supra note 138, at 25; SNP Accidents, supra note 156. The Cosmos accident implicated the 1972 Liability Convention. See infra Part IV.B for further discussion.
159 SNP Accidents, supra note 156.
160 Aftergood, supra note 17, at 100.
161 SNP Accidents, supra note 156.
162 Solid Core Nuclear Rocket, in ADVANCED PROPULSION CONCEPTS, supra note 47.
launch vehicles continued from the late 1950s until the collapse of the Soviet Union in 1992.\textsuperscript{163}

III. SAFETY AND THE DANGERS OF NUCLEAR SPACECRAFT

American RTGs have undergone many design improvements since their first use on satellites in the early 1960s.\textsuperscript{164} More recent American RTG designs have employed plutonium-238 instead of other nuclear fuels because of its long half-life (approximately 87.7 years) and high heat-to-mass ratio.\textsuperscript{165} Plutonium-238 also has the advantage of emitting low levels of gamma rays, which are difficult to shield and can be extremely harmful to human beings (especially launch preparation workers, who are exposed to the material for extended periods of time).\textsuperscript{166} Alpha-emitters like plutonium-238 are much easier to shield, as they travel only short distances and cannot penetrate human skin.\textsuperscript{167} Alpha particles can, however, be highly dangerous if ingested in particle form through the mouth or nose.\textsuperscript{168}

A number of safety features are incorporated in NASA’s current crop of RTGs to reduce the dangers posed by the plutonium-238. First, the plutonium in the RTG is in the ceramic form of plutonium dioxide, which is heat resistant and highly insoluble, has low chemical reactivity, and fractures primarily into large, non-respirable particles.\textsuperscript{169} This reduces the probability that

\textsuperscript{164} Furlong & Wahlquist, supra note 25, at 27.
\textsuperscript{168} See Loft, supra note 4.
\textsuperscript{169} Cassini Spacepower, supra note 19.
the plutonium will vaporize during re-entry, and mitigates the negative effects of exposure to the fuel.\textsuperscript{170}

Second, the plutonium dioxide is separated into small cylindrical pellets, each with its own heat shield and impact shell.\textsuperscript{171} This reduces the likelihood that all of the plutonium will be released if an accident were to occur.\textsuperscript{172}

Third, each individual plutonium pellet is covered by "multiple layers of protective materials, including iridium capsules and high-strength graphite blocks."\textsuperscript{173} Altogether, the shielding serves to protect the radioisotopic material from explosions, fires, fragment impacts, and the heat of atmospheric re-entry.\textsuperscript{174}

NASA's basic RHU design contains safety features similar to those incorporated in NASA's RTGs.\textsuperscript{175} Several layers of protective material cover the small plutonium pellet of the RHU: a high-strength platinum-rhodium shell, an external graphite aeroshell, and a graphite insulator.\textsuperscript{176} The plutonium itself is in a ceramic form (the same as that used in RTGs) that minimizes the likelihood of vaporization during re-entry and lessens the negative effects of exposure.\textsuperscript{177}

In its literature on the Cassini spacecraft, the Department of Energy highlighted the impossibility of a nuclear power plant-type accident involving RTGs:

Potential RTG accidents are sometimes mistakenly equated with accidents at nuclear power plants. It is completely inaccurate to associate an RTG accident with Chernobyl or any other past radiation accident involving fission. RTGs do not use either a fusion or fission process and could never explode like a nuclear

\begin{footnotes}
\textsuperscript{170} Id.
\textsuperscript{171} Id.
\textsuperscript{172} Id.
\textsuperscript{173} Id. Iridium is a strong, corrosion resistant metal with a high melting point.
\textsuperscript{174} Id.
\textsuperscript{175} See Cassini Spacepower, supra note 19.
\textsuperscript{176} DOE RPS, supra note 78.
\textsuperscript{177} Id.
\end{footnotes}
bomb under any accident scenario. Neither could an accident involving an RTG create the acute radiation sickness similar to that associated with nuclear explosions.\(^{178}\)

The Department of Energy also highlighted the strong oversight and risk assessment for space missions (including \textit{Cassini}) that carry nuclear materials:

In addition to NASA's internal safety requirements and reviews, missions that carry nuclear material also undergo an extensive safety review involving detailed verification testing and analysis. Further, an independent safety evaluation of the Cassini mission will be performed as part of the nuclear launch safety approval process by an Interagency Nuclear Safety Review Panel (INSRP), which is supported by experts from government, industry and academia.\(^{179}\)

The General Accounting Office ("GAO"), the auditing and evaluation arm of the United States Congress, supported NASA's risk assessment of the \textit{Cassini} mission in 1997.\(^{180}\) "NASA did a good job in trying to ensure the risks were addressed, said Alan Li, associate director at GAO . . . . We're not talking about a handful, but many experts in many areas were consulted."\(^{181}\)

In its risk assessment for the \textit{Cassini} mission, NASA estimated that the likelihood of cancer fatalities due to the launch were one in one hundred thousand.\(^{182}\) It also estimated that the likelihood of cancer fatalities due to an accidental re-entry was one in one million.\(^{183}\) However, these statistics have been disputed by

\(^{178}\) \textit{Cassini Spacepower}, supra note 19.
\(^{179}\) \textit{Id.}
\(^{181}\) Lytle, \textit{supra} note 180.
\(^{182}\) \textit{Cassini FEIS, supra} note 111.
\(^{183}\) \textit{Id.}
critics. "I find that NASA bureaucrats in some sense are living in Fantasyland', says Michio Kaku, a physics professor at City University of New York. 'Pure guesswork has replaced rigorous physics. Many of these numbers are simply made up." Bruce Gagnon of the Global Network Against Weapons and Nuclear Power in Space noted that "[w]hen you look at the average failure rate for rockets, eventually, you are going to have a problem." Others have used the space shuttle Columbia tragedy in Texas to illustrate the strong possibility of an accident. "I think the [Columbia] tragedy definitely raises legitimate questions about the technical risks associated with the current space program," said Edwin Lyman, the head of the Nuclear Control Institute, "and should give anyone pause before we continue to expand nuclear capabilities in space."

Many scientists, however, have emphasized that the dangers posed by the plutonium in RTGs are minor. According to Otto G. Raabe, a radiation specialist at the University of California at Davis and president of the Health Physics Society, under a Cassini "worst-case scenario' where all the plutonium . . . is released into the atmosphere in pulverized form . . . humans would be exposed to no more than 1 millirem of radiation a year for the next 50 years." Considering that humans are exposed to at least two thousand millirems of radiation each year from radon in the Earth and its natural background, "[t]he dose (from Cassini) would be so

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186 Id.
189 Id. An acronym for Roentgen Equivalent Man, a rem is a standard unit that measures the effects of ionizing radiation on humans; a millirem is one thousandth of a rem. See, e.g., U.S. Nat'l Regulatory Comm'n, Glossary, Rem and Millirem, at http://www.nrc.gov/reading-rm/basic-ref/glossary.html (last modified Mar. 9, 2004).
negligible . . . that it would have no real biological effect. There is no risk to anyone in the whole world.”  According to Cassini project manager Richard J. Spehalski, in the unlikely case of such an accident, “[t]he radiation dose an individual would receive over a 50-year period from that exposure would be . . . 15,000 times less than a natural lifetime exposure.” To Cassini scientists, the claims of anti-nuclear activists that Cassini could kill billions of people or lead to a global increase in lung cancer rates were “hogwash.”

Space-based nuclear reactors and nuclear rockets, however, offer more serious safety challenges for scientists and engineers than RTGs and RHUs. A nuclear reactor could be highly destructive to the terrestrial environment if the radioactive by-products of its fission reaction were to reenter the atmosphere. As such, NASA’s Project Prometheus efforts have explicitly limited the use of nuclear reactors to “nuclear safe” orbits, where the orbital decay time of the craft is greater than the fissile material’s radioactive decay time. In other words, the reactor will not be activated until it is certain that the spacecraft will remain in space permanently, or at least until the by-products of the fission reaction will decay to sufficiently small amounts. This will practically eliminate the possibility of a catastrophic re-entry of radioactive materials.

According to NASA-Department of Energy literature, a number of important design features should be considered in any potential space-based fission reactor system, including:

the ability [of the reactor] to operate reliably without continual actions from ground control, the ability to keep the reactor in a subcritical state prior to startup and under various accident scenarios, the ability to

190 Id.
191 Britt, supra note 10.
192 Id.
194 See id.
195 Id. “[W]hile in Earth’s vicinity, the ‘cold’ reactor is not at all dangerous.” Id.
remove operational and decay heat during specified normal and off-normal operating conditions, and the ability to reliably perform all necessary control and safety functions.\textsuperscript{196}

NASA and the Department of Energy also emphasize that rigorous testing and safety assessments should be undertaken before any nuclear reactor is incorporated in a spacecraft.\textsuperscript{197}

IV. INTERNATIONAL SPACE LAW & ENVIRONMENTAL LIABILITY

A. The Legality of Nuclear Power and Propulsion in Outer Space

Activities in outer space are governed by a combination of international treaties, customary international law, and domestic law. The major multilateral space treaties have been drafted and negotiated by the United Nations Committee on the Peaceful Uses of Outer Space ("UN COPUOS"), which acts as the world's legislature for developing international space law.\textsuperscript{198} Created by the UN General Assembly in 1958 shortly after the Sputnik launch, and established as a permanent body in 1959,\textsuperscript{199} UN COPUOS meets annually and has ratified five treaties and five declarations of legal principles regarding activities in outer space.\textsuperscript{200}


\textsuperscript{197} See id.


Several major international treaties prohibit the undertaking of specific nuclear activities in outer space. The Outer Space Treaty of 1967, the first major space treaty, specifically addressed nuclear weapons, prohibiting states from “plac[ing] in orbit around the earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install[ing] such weapons on celestial bodies, or station[ing] such weapons in outer space in any other manner.” The Partial Test Ban Treaty of 1963 addressed nuclear explosions, prohibiting states from “carrying out . . . any nuclear weapon test explosion, or any other nuclear explosion” in the Earth’s atmosphere or outer space.202

html (last modified May. 10, 2004). The five treaties are available at the UN Office for Outer Space Affairs Website. Id. They are: The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, Jan. 27, 1967, 18 U.S.T. 2410 [hereinafter Outer Space Treaty]; The Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, Apr. 22, 1968, 19 U.S.T. 7570; The Convention on International Liability for Damage Caused by Space Objects, Mar. 29, 1972, 24 U.S.T. 2389 [hereinafter Liability Convention]; The Convention on Registration of Objects Launched into Outer Space, Jan. 14, 1975, 28 U.S.T. 695; The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, Dec. 18, 1979, 18 I.L.M. 1434. The United States has signed and ratified each of the first four UN COPUOS treaties, but it has not signed or ratified the Moon Agreement, which regulates activities on the moon and other celestial bodies within the Solar System.

201 Outer Space Treaty, supra note 200, art. IV.
202 Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space, and Under Water, Oct. 10, 1963, 14 U.S.T. 1313, 1317 [hereinafter Partial Test Ban]. Similarly, the Comprehensive Nuclear Test Ban Treaty of 1996 would obligate States not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control ... [and] to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapon test explosion or any other nuclear explosion. Comprehensive Nuclear Test Ban Treaty, Sept. 10, 1996 [hereinafter Comprehensive Test Ban]. However, the Comprehensive Test Ban has not formally entered into effect; only 32 of the requisite 44 nuclear-capable states have ratified the Treaty. Arms Control Ass'n, The Status of the Comprehensive
The Partial Test Ban Treaty presents a serious obstacle to the development of a Project Orion-style nuclear pulse rocket propelled by nuclear explosions. The Treaty clearly prohibits the potential testing or operation of such a craft in outer space or the Earth’s atmosphere; a ratifying nation desiring to do so would be forced to withdraw from the treaty. The Outer Space Treaty, however, would not be an obstacle to such a rocket; the Treaty’s ban of weapons of mass destruction in space would not prohibit a rocket with nuclear explosives designed for propulsion, rather than for use as a weapon.

In terms of nuclear and radiological power sources, however, none of the multilateral space treaties or test ban treaties prohibits the placement of nuclear materials in space for non-weapon or non-explosive purposes. This omission has opened the door for the United States and other spacefaring nations to pursue RTGs and nuclear reactors as power sources for their spacecrafts.


203 Reynolds, supra note 70.
204 A nation must give three months notice prior to withdrawal from the Partial Test Ban Treaty. Partial Test Ban, supra note 202, art. IV. If the Comprehensive Test Ban Treaty were to take effect, it would provide a similar obstacle. Under the Comprehensive Test Ban, a nation must give six months notice prior to withdrawal. Comprehensive Test Ban, supra note 202, art. IX.
205 See Outer Space Treaty, supra note 200, art. IV. See also Reynolds, supra note 70.
206 See Comprehensive Test Ban, supra note 202; Outer Space Treaty, supra note 200; Partial Test Ban, supra note 202.
Among other claims, the plaintiffs alleged that NASA's decision to launch the Cassini mission was arbitrary and capricious, and that NASA did not properly balance the risks of the Cassini mission against its benefits. The court denied the motion, stating that the plaintiffs could not show irreparable injury and were not likely to succeed on the merits.

In the decision, District Judge Ezra stated that:

Plaintiffs' allegations regarding NASA's risk/benefit analysis are essentially conjecture at this point. Plaintiffs may disagree with NASA's decisions, but to meet the extraordinary requirements necessary to obtain a preliminary injunction, Plaintiffs must produce evidence sufficient to support the conclusion that they are likely to succeed on their claim that NASA acted in an arbitrary and capricious manner.

In addition, Judge Ezra held that a preliminary injunction would not be in "the public interest because of the significant scientific contributions the Cassini Mission will advance, and because the

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208 Id. at 1163.
209 Id. at 1167.
210 Id. at 1168-69. The court ruled that the plaintiffs could not show a violation of § 1983 because Clinton, Gibbons, and Goldin were not state defendants. Id. at 1164. To state a claim for violation of 42 U.S.C. § 1983, a plaintiff must show that the defendant acted under color of state law, and that defendant's conduct deprived plaintiff of a constitutional right. See Ketchum v. County of Alameda, 811 F.2d 1243, 1245 (9th Cir. 1987). The court also ruled that the plaintiffs could not show a violation of NEPA because the President is not a Federal agency within the meaning of NEPA; plaintiffs thus could not allege that the President's decision to proceed with the launch was reviewable under NEPA and the Administrative Procedure Act. Hawaii County Green Party, 980 F. Supp. at 1165. See also National Environmental Protection Act, 40 C.F.R. § 1508.12 (2004). Finally, the court ruled that the plaintiffs could not show a violation of due process because their motion for an injunction was heard by the court. Hawaii County Green Party, 980 F. Supp. at 1165.
211 Hawaii County Green Party, 980 F. Supp. at 1167.
public would eventually bear the brunt of the financial burdens and potential danger caused by the delay."\(^{212}\)

The Florida Coalition for Peace and Justice filed similar actions to prevent the *Galileo* launch in 1989\(^{213}\) and the *Ulysses* launch in 1990.\(^{214}\) Both requests were denied, and the launches proceeded as planned.\(^{215}\) These cases set a very high standard for receiving a temporary restraining order or a preliminary injunction to prevent the launch of nuclear materials into space.

**B. Responsibility, Liability, and Compensation for Nuclear Damages**

The Outer Space Treaty of 1967 established the ground rules regarding responsibility and liability for accidents involving space objects, launch vehicles, and their component parts.\(^{216}\) Article VI of the treaty holds that State parties bear international responsibility for their national activities in space, whether undertaken by governmental agencies or non-governmental entities.\(^{217}\) Article VII places liability firmly upon States whose launch of objects causes harm to the property or persons of another nation:

> Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its

\(^{212}\) *Id.* at 1169.


\(^{215}\) *Hawaii County Green Party*, 980 F. Supp. at n.4.

\(^{216}\) See *Outer Space Treaty*, *supra* note 200, art. VI - VII.

\(^{217}\) *Id.* art. VI. In addition, activities by non-governmental entities "[s]hall require authorization and continuing supervision" by each State. *Id.*
natural or juridical persons by such object or its component parts.\textsuperscript{218}

The language of Article VII makes no distinction between nuclear and non-nuclear space objects.

The 1972 Convention on International Liability for Damage Caused by Space Objects ("Liability Convention") amplifies and expands upon Article VII of the Outer Space Treaty.\textsuperscript{219} The Liability Convention establishes that a launching State, including States "from whose territory or facility a space object is launched . . . shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the earth or to aircraft in flight."\textsuperscript{220} In so doing, the Liability Convention has become the only international instrument that establishes original State liability and imposes absolute liability for damages.\textsuperscript{221} International agreements regarding nuclear power plants,\textsuperscript{222} oil pollution,\textsuperscript{223} and the transport of dangerous goods and substances\textsuperscript{224} focus on third party or subsidiary State liability, and provide numerous exceptions and limitations on liability. The Liability Convention exonerates States from absolute liability for damages.

\textsuperscript{218} Id. art. VII.
\textsuperscript{219} Liability Convention, supra note 200.
\textsuperscript{220} Id. art. II. See also id. art. IV (addressing joint and several liability for launch of space objects by nations acting in concert).
\textsuperscript{222} See, e.g., Convention on Third Party Liability in the Field of Nuclear Energy, Jul. 29, 1960, 956 U.N.T.S. 251 (one of several international conventions establishing a limited liability regime for damages from nuclear installations).
\textsuperscript{223} See, e.g., International Convention on Civil Liability for Oil Pollution Damage, Nov. 29, 1969, 973 U.N.T.S. 3 (imposing liability on ship owners for damages resulting from oil discharges).
\textsuperscript{224} See, e.g., Convention on Civil Liability for Damage caused during Carriage of Dangerous Goods by Road, Rail and Inland Navigation Vessels, Oct. 10, 1989 (imposing liability on carriers for damages resulting from the transportation of dangerous goods).
from space objects and launch vehicles only to the extent that the claimant State or its persons are contributorily negligent. In addition, like the Outer Space Treaty, the Liability Convention makes no distinction between nuclear and non-nuclear incidents; the absolute liability standard extends to accidents involving nuclear material.

Articles VIII through XX of the Liability Convention address the presentation of damage claims to a launching State and establish procedures for settling those claims. A State or its persons present claims to the launching State through diplomatic channels or the Secretary-General of the United Nations. If the State Parties cannot reach settlement through diplomatic means, a Claims Commission is established to "decide the merits of the claim for compensation and determine the amount of compensation payable, if any." The Commission's decision "shall be final and binding if the parties have so agreed; otherwise the Commission shall render a final and recommendatory award, which the parties shall consider in good faith."  

According to Article XII of the Liability Convention, compensation is "determined in accordance with international law and the principles of justice and equity" so as to restore the person, State, or international organization "to the condition which would have existed if the damage had not occurred." This follows the standard of the Factory at Chorzow case, which established the principle of international liability that "reparation must, as far as possible, wipe out all the consequences of the illegal act." Article I of the Liability Convention, however, explicitly limits the term

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225 Liability Convention, supra note 200, art. VI.
226 See id.
227 Id. arts. VIII-XX.
228 Id. art. IX. Such claims must be made within a single year of the occurrence of damages or identification of the liable launching State. Id. art. X.
229 Id. art. XVIII. Each Claims Commission is composed of three members: one chosen by the claimant State, one by the launching State, and one member (the "Chairman") chosen by both parties. Id. art. XV, subject to art. XVI-XVII.
230 Liability Convention, supra note 200, art. XIX.
231 Id. art. XII.
“damage” to “loss of life, personal injury or other impairment of health; or loss of or damage to property of States or of persons, natural or juridical, or property of international intergovernmental organizations . . . .” Environmental damages are not specifically mentioned, although some level of compensation for such damages would clearly fall under the remaining parts of the definition. It is not clear whether compensation for damages such as lost earnings, lost profits, search and rescue costs, or pain and suffering are available under the Liability Convention. Such damages would be particularly relevant in the case of a large-scale nuclear incident. However, because the language of the convention explicitly deals with compensation rather than punishment, neither nominal nor punitive damages are possible. Awarding punitive damages to a State in an attempt to make a launching State reform its procedures for launching or operating nuclear powered missions is not possible under the Liability Convention.

The only provision in the Liability Convention that refers specifically to the large-scale environmental effects of a space accident is Article XXI, which discusses immediate aid and assistance to a State facing serious emergencies as a result of damage caused by a space object. The rendering of such aid and

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233 Liability Convention, supra note 200, art. I.
235 See Liability Convention, supra note 200, art. I.
236 Christol, supra note 234, at 367.
237 See id.
238 Liability Convention, supra note 200, art. XXI.

If the damage caused by a space object presents a large-scale danger to human life or seriously interferes with the living conditions of the population or the functioning of vital centers, the States Parties, and in particular the launching State, shall examine the possibility of rendering appropriate and rapid assistance to the State which has suffered the damage, when it so requests. However, nothing in this article shall affect the
assistance is not mandatory, however. If an incident involving a nuclear spacecraft were to pose a large-scale danger to the health and living conditions of a particular nation’s population, the launching State would not be obligated to render immediate assistance to that nation.

Only one case has triggered the Liability Convention: the 1978 crash of the nuclear powered Soviet Cosmos 954 satellite into Canada. Cleanup operations cost the Canadians roughly $14 million. The Liability Convention took effect, and Canada claimed $6 million in damages; the Soviets acknowledged the spacecraft’s existence and eventually paid $3 million.

In addition to addressing responsibility, liability, and compensation issues in the Outer Space Treaty and the Liability Convention, UN COPUOS has given its imprimatur to a declaration of “Principles Relevant to the Use of Nuclear Power Sources in Outer Space” (“NPS Declaration”). Begun in the aftermath of the 1978 Cosmos 954 crash into Canada and finally adopted by the UN General Assembly in 1992, the NPS Declaration provides guidelines for the safe use of nuclear power sources in space. Although not an international treaty, the NPS Declaration is binding to the extent that States act in accordance with its provisions to create customary international law. At this point, the extent to which that has occurred is uncertain. As time passes and the use of

rights or obligations of the States Parties under this Convention.

Id.

See id.

See id.


PORTREE & LOFTUS, supra note 138, at 25.

Id.; GRAHAM, supra note 241.


NPS Declaration, supra note 244.
nuclear power sources in space increases, the NPS Declaration’s passage into customary law will become more apparent.

The NPS Declaration is explicitly limited to non-propulsive nuclear power sources (i.e. ones that provide onboard electrical power); propulsive power sources such as nuclear rockets are not within the declaration’s language. It addresses goals for radiation protection and nuclear safety, nuclear safety assessments, notification of spacecraft re-entry, and specific guidelines for the use and operation of nuclear reactors and radioisotope generators. The declaration also reiterates the language of the Outer Space Treaty and Liability Convention regarding responsibility, liability, and compensation issues for nuclear accidents.

Perhaps the most important provision of the NPS Declaration is Principle 3, which provides substantive guidelines for the safe use of nuclear power sources in space. It endeavors to restrict the use of nuclear power sources to “space missions which cannot be operated by non-nuclear energy sources in a reasonable way.” Although the language is somewhat problematic because of a failure to define “reasonable,” the U.N. resolution explicitly

\[247 \text{Id.} \]

**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 . . . .

\[248 \text{Id. at princ. 2, sec. 1.} \]
\[249 \text{Id. at princ. 4.} \]
\[250 \text{Id. at princ. 5.} \]
\[251 \text{Id. at princ. 3, sec. 1 & 2.} \]
\[252 \text{NPS Declaration, supra note 244, at princ. 3, sec. 1 & 3.} \]
\[253 \text{Id. at princ. 8.} \]
\[254 \text{Id. at princ. 9, sec. 1.} \]
\[255 \text{Id. at princ. 9, sec. 2 & 3.} \]
\[256 \text{Id. at princ. 3.} \]
\[257 \text{Id.} \]

\[258 \text{A broad reading of “reasonable” might indicate that nuclear energy sources could be used whenever a non-nuclear source would have an adverse effect on} \]
endorses the use of nuclear power sources for some space missions. In particular, the declaration states that nuclear reactors may be used "on interplanetary missions; [in sufficiently high orbits . . . [and] [in] low-Earth orbits if they are stored in sufficiently high orbits after the operational part of their mission," and that RTGs may be used "for interplanetary missions and other missions leaving the gravity field of the Earth," and "in Earth orbit if, after conclusion of the operational part of their mission, they are stored in a high orbit."

Principle 3 outlines several limitations on the design and construction of nuclear reactors and RTGs. It limits nuclear reactors to those that use enriched uranium-235 as a fuel, and emphasizes that the fuel "can not 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." It also requires nations to devise containment systems for RTGs that are "designed and constructed to withstand the heat and aerodynamic forces of re-entry in the upper atmosphere under foreseeable orbital conditions" and that "ensure that no radioactive material

the spacecraft's weight, launch cost, operation, or maneuvering. A narrow reading might indicate that an RTG or nuclear reactor should be viewed as an option only where all of the other power source options, including solar energy, are prohibitively expensive or virtually impossible to use.

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 . . . .

Id. at 116.

NPS Declaration, supra note 244, at princ. 3, sec. 2(a).

Id. at princ. 3, sec. 2(c).

NPS Declaration, supra note 244, at princ. 3, sec. 2(e).
is scattered into the environment so that the impact area can be completely cleared of radioactivity by a recovery operation.\textsuperscript{265}

More generally, Principle 3 outlines a general standard of care for the design of space objects with nuclear power sources:

States launching space objects with nuclear power sources on board shall endeavor 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 . . . \textsuperscript{266}

Furthermore, the design and construction of the nuclear power systems "shall take into account relevant and generally accepted international radiological protection guidelines" and "shall, with a high degree of confidence, restrict radiation exposure to a limited geographical region" and to specified radiation levels.\textsuperscript{267}

In addition to establishing guidelines for the design and construction of nuclear power sources, the NPS Declaration requires launching States to "ensure that a thorough and comprehensive safety assessment is conducted," covering all relevant phases of the mission and spacecraft systems,\textsuperscript{268} and that such an assessment "shall be made publicly available prior to each launch."\textsuperscript{269} It also requires a launching State, if it becomes aware of a risk of re-entry of radioactive materials, to provide specific information to other States that may be affected.\textsuperscript{270}

\textsuperscript{265} Id. at princ. 3, sec. 3(b).
\textsuperscript{266} Id. at princ. 3, sec. 1(a). In addition, "[s]uch design and use shall also ensure with high reliability that radioactive material does not cause a significant contamination of outer space." Id.
\textsuperscript{267} Id. at princ. 3, sec. 1(c).
\textsuperscript{268} Id. at princ. 4, sec. 1.
\textsuperscript{269} NPS Declaration, supra note 244, at princ. 4, sec. 3.
\textsuperscript{270} Id. at princ. 5. Among other information, the notification must provide the name of the launching State or States, information regarding the trajectory of the craft and the predicted impact region, the function of the spacecraft, and the
The NPS Declaration addresses the two major flaws of the Liability Convention regarding nuclear powered spacecraft: the failure to require a launching State to render immediate assistance to a State affected by its nuclear spacecraft,271 and the limited definition of “damages” regarding compensation for major accidents.272 Under Principle 7, launching States “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 power source, “to detect the re-entered material and to carry out retrieval or clean-up operations.”273 Under Principle 9, compensation “shall include reimbursement of the duly substantiated expenses for search, recovery and clean-up operations, including expenses for assistance received from third parties.”274 Again, because the status of the NPS Declaration as customary international law is in doubt, the mandatory assistance and extension of damages provisions may not bind States in the same manner as the Liability Convention.

CONCLUSION

Nuclear power and propulsion technologies face few legal barriers to their incorporation in outer space missions. Even at the international level, the United Nations has explicitly recognized that nuclear technologies are useful for, or even essential to, certain civilian space missions. The use of nuclear power and propulsion in space is thus primarily a question of public policy, not of law.

Undoubtedly, the health and safety of the Earth population must be a major factor in the decision to use any nuclear space technology. As the United Nations emphasized in its declaration

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271 Liability Convention, supra note 200, art. XI.
272 Id. art. I.
273 NPS Declaration, supra note 244, at princ. 7.
274 Id. at princ. 9.
of the “Principles Relevant to the Use of Nuclear Power Sources in Outer Space,” a State must conduct thorough safety assessments available to the public, limit nuclear technology to missions involving safe orbits and trajectories, prevent nuclear reactors from becoming critical before the operating orbit, and use proper containment systems for RTGs. Only if these principles have been followed should a particular use of a nuclear technology be approved.

As the Cosmos 954 incident illustrates, accidents involving nuclear technologies are entirely possible. Indeed, risk will never be completely eliminated from any method of space travel. However, the mere possibility of re-entry should not lead policymakers to issue a prohibition of nuclear technologies in space. Through the efforts of mission planners, scientists, and engineers, the probability of a serious accident can be lowered to insignificant levels, and the environmental effects of an actual re-entry can be severely reduced. The Apollo 13 and Nimbus B-1 incidents, in particular, illustrate that efforts to reduce the risk posed by radioactive materials can be enormously effective. What might otherwise be an accident with serious environmental consequences can be reduced to a harmless incident if the proper precautions are taken.

Unfortunately, nuclear power is a bugaboo to many environmentalists. Indeed, to some anti-nuclear activists, virtually any use of radioactive materials is perceived as a Chernobyl in the making. These individuals are only willing to accept virtually unattainable levels of safety—any risk, however limited or unlikely, is seen as an unacceptable danger to the Earth environment. Such opinions should be rejected. Extensive action has been taken by NASA to limit the possibility of accidents, to protect radioisotopic material from explosions, impacts, and the heat of atmospheric re-entry, to choose safe mission trajectories, and to limit the negative effects of fuel in the unlikely event that it was actually released into the Earth environment. In the specific case of the Cassini mission, the possibility of a serious accident involving the craft was exceedingly limited. Environmental groups were wrong in criticizing the use of RTGs, and courts were justified in rejecting efforts to keep the mission grounded.
Many scientists and space enthusiasts see the development of nuclear power and propulsion as the key to man’s future in outer space. They rightly see the Bush administration’s attempt to revamp America’s nuclear space program as an effort with potentially far-reaching positive consequences for science and space exploration. The potential benefits offered by nuclear space technologies to planetary science, geology, astronomy, astrobiology, and space travel in general are strikingly apparent. Chemical propulsion and chemical and solar power, although effective in the immediate vicinity of the Earth, have placed enormous barriers in front of mankind’s exploration and use of outer space. Nuclear reactors and nuclear rockets have the potential to remove those barriers, and open the way for cheaper, more expansive, more effective space travel. Such technologies should not be abandoned because of irrational prejudices about nuclear energy and overheated claims about their risks to human health and the Earth environment.