NASA VISION MISSIONS
Nuclear Systems Program Office
"Project Prometheus"

Project Prometheus, the Nuclear Systems Program, is developing the means for enabling revolutionary increases in the power available to spacecraft, thereby fundamentally improving our capability for Solar System exploration. These unprecedented levels of sustained power would enable a new era of Solar System missions that could not only travel farther or faster, but would allow for greater scientific return through improved spacecraft maneuverability, mission flexibility and longevity, and high-powered, active science instruments. In the longer term, such dramatic increases in power would help pave the way for future human exploration of the solar system.

To support the next generation of spacecraft requires a bold approach to energy production. Project Prometheus's efforts focus on two sources of energy: 1) radioisotopes that make use of the heat produced by the natural decay of a radioisotope (specifically, plutonium-238) and 2) nuclear reactors that make use of the heat produced by nuclear fission. The development of these systems is expected to support the Office of Space Science's Vision Missions.

RADIOISOTOPE POWER SYSTEMS

Radioisotope Power Systems (RPS) generate electrical power by converting the heat released by the nuclear decay of radioactive isotopes into electricity. First used in space by the United States in 1961, these devices have consistently demonstrated unique capabilities over other types of space power systems at power levels up to several kilowatts. A key advantage of RPS is its ability to operate continuously, independent of orientation and distance from the Sun. The systems are also long-lived, rugged, compact, highly reliable, and relatively insensitive to radiation and other environmental effects. As such, they are ideally suited for missions involving long-lived, autonomous operations in the extreme environments of space and planetary surfaces outside of earth orbit

The RPS units employed by NASA have used plutonium (Pu-238) fuel and thermoelectric devices to convert decay heat into electricity. Forty-four Radioisotope Thermoelectric Generators (RTGs) have been launched on 25 U.S. missions over the last three decades. The Apollo missions to the Moon, the Viking missions to Mars, and the Pioneer, Voyager, Ulysses, Galileo, and Cassini missions to the outer solar system have all used RTGs. As a testament to their reliability and longevity, the RTG for Pioneer 10, which was launched in 1972, has operated flawlessly now for over three decades and continues to generate power well beyond the orbit of Pluto.

Most RPS concepts consist of two principal elements: a heat source and a power conversion system. The heat source includes the radioisotope fuel encapsulated within a protective clad that prevents its release into the environment, and a series of protective shells that prevent damage to the clad during inadvertent atmospheric re-entry and impact. Figure 1 shows the heat source used in NASA's most recent RTG (fuel in red). This General Purpose Heat Source (GPHS) is designed modularly to enhance the safety of the RTG system and to allow for system designs with different thermal outputs and power levels.

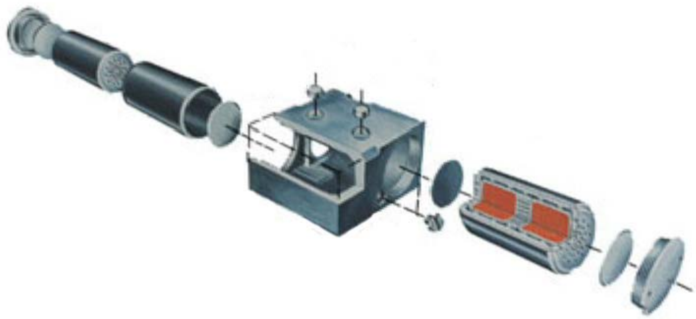

Figure 1: General Purpose Heat Source (GPHS)

The heat produced from this thermal source flows via radiative transfer to a power conversion system, which transforms a portion of the heat into electricity. The remaining unconverted heat is removed, and ultimately rejected to space via radiators. The thermoelectric power converters in RTGs consist of two dissimilar, electrically conductive materials joined in a closed circuit. When the two junctions of the device are kept at different temperatures, a current and voltage are induced in the circuit, which is then used for electrical power. The power output for an RTG is a function of the temperatures at the junctions as well as properties of the thermoelectric materials.

The state-of-practice RPS is the GPHS-RTG, shown in Fig. 2. Used on Galileo, Ulysses and Cassini, it generates at least 285 We (watts electric) at launch from a stack of 18 GPHS modules. Other principal characteristics of the GPHS-RTG are shown in Table 1. The GPHS-RTG is designed to operate only in space. The next planned use of one of these units is on the upcoming New Horizons Pluto mission, which will launch in the 2006-2008 timeframe. Because the future mission needs for power systems include surface exploration of planetary bodies, such as Mars, as well as missions in deep space, the Department of Energy (DOE) and NASA have initiated development of two new RPS that would accommodate a broader range of missions. In addition, NASA and DOE are supporting studies and technology development to enable new applications, such as radioisotope-powered electric propulsion systems for small, high-performance spacecraft, and modest power sources for small surface experiments.

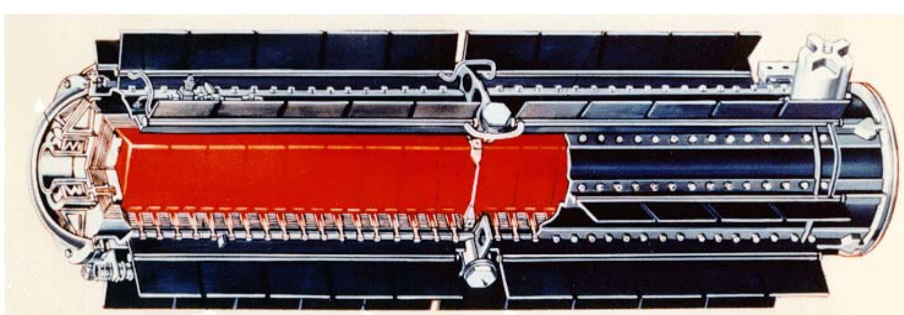

Figure 2: GPHS-RTG

Systems Under Development

NASA is currently developing two RPS that could be considered for Space Science Vision Missions. The first of the next generation of RPS is the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). It differs from the older GPHS-RTG in two important aspects: it is roughly half the size of the GPHS-RTG (uses 8 GPHS units and delivers 110-140W of electric power), and it is being designed to operate on planetary bodies as well as in space. The smaller modular design provides more flexibility in meeting the needs of a wider variety of missions. The design requirements and goals for the MMRTG, summarized in Table 1, include ensuring a high degree of safety (equivalent to or greater than that of the GPHS-RTG), ensuring the ability to operate on solar system bodies with atmospheres as well as in space, optimizing power levels over a minimum lifetime of 14 years, and minimizing mass. The power conversion technology for the MMRTG is similar to previous RTGs, i.e., using thermoelectric materials configured in a series/parallel arrangement that provides redundancy. This approach draws on the design heritage from units in the past and minimizes development risk through use of flight-proven technology.

Development of the MMRTG is structured to enable delivery of 3 flight units for potential use on the Mars 2009 mission, which is planned for launch in late-2009. NASA envisions continued use of MMRTGs on subsequent space science missions, and DOE can initiate the fabrication of more units as required.

DOE and NASA are also developing another, more advanced RPS that would use much less fuel than the MMRTG, while producing the same amount of electrical power. This system, the Stirling Radioisotope Generator (SRG), uses a dynamic (i.e., uses moving parts) Stirling cycle for power conversion, which is roughly four times more efficient than thermoelectric conversion. Although dynamic systems are inherently more complex than their static counterparts, RPS technology programs and Stirling cryocooler flight applications over the last several decades have proven that these systems can be designed to meet RPS reliability and lifetime goals. Figure 3 shows the SRG concept, along with its major components. The SRG is being designed to the same power and operational requirements as the MMRTG: $\geq$110W electric, operation in planetary atmospheres and deep space, safety margins equal to or greater than that of the GPHS-RTG, optimization of power levels over a minimum lifetime of 14 years, and minimization of mass. These parameters are further shown in Table 1.

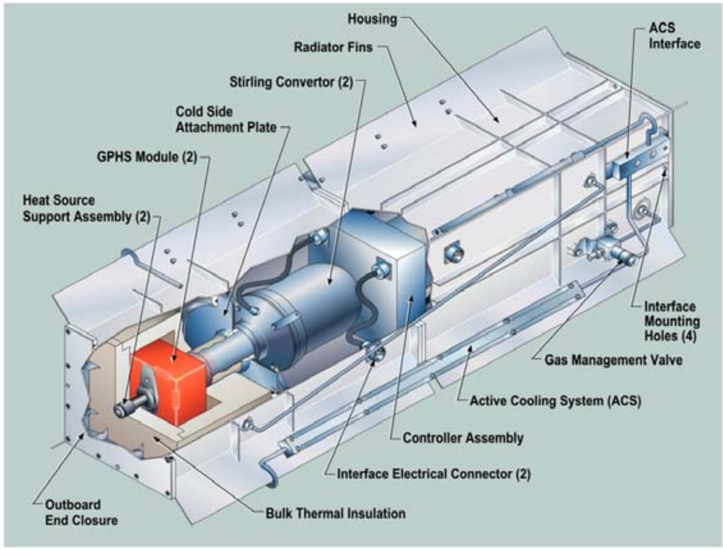

Figure 3: Stirling Radioisotope Generator (SRG)

Like the MMRTG, SRG is being developed to support the Mars 2009 mission. Although both the SRG and MMRTG will be available for use by 2009, only one system will be used on the Mars 2009 mission (4 flight units will be produced). However, both systems could be fabricated and made available for use on other missions scheduled from 2009 and beyond.

Future Systems

It is foreseen that NASA's work on both static and dynamic power conversion technologies could be incorporated into a derivative MMRTG or SRG for consideration by Space Science Vision Missions by as early as 2013. This 2nd generation MMRTG or SRG would have roughly the same power level as its predecessor, but would operate at a higher efficiency and have about half the mass (i.e., twice the specific power).

Additionally, recent mission assessments, particularly for Mars surface science, have pointed to potential benefits in having access to smaller RPS units in the 1-10 watt and 10-100 milliwatt range. Early analysis has shown that RPS can be readily scaled down to smaller systems, since the heat rate per unit mass of fuel is independent of the size of the system. Even though very small RPS can be designed, the specific power (i.e., power per unit mass of the system) tends to decrease with reduced size due to the higher proportion of system mass devoted to insulation, structural support, and control equipment.

It is important to note that flight units of this type do not exist at this time, and no development work has been initiated to provide them. However, DOE and NASA are considering development of such systems in the future pending an identified need in the user community. Such development could pursue the following two options. One option would be the multiwatt-class unit, which could provide power in the 1-10 watt range. Design concepts for this type of unit were developed in the early-1990's, and if a need is defined, it is expected that DOE and NASA could develop a flight-ready system within a 6-8 year time frame. It is reasonable that units of this type could be provided by 2011 to meet the needs of several different NASA space science programs. These systems would use either a single GPHS unit or a fractional unit based on the same Pu-238 fuel form. With current thermoelectric technology, the power levels for such systems could be 3 watts, 6 watts and 12 watts (for a 1/4, 1/2 and single GPHS, respectively). With more advanced static technologies, such as thermophotovoltaics (TPV), the respective power levels could be 5 watts, 10 watts and 20 watts.

Another avenue of development is milliwatt-class units. These systems would likely use the Pu-238-fueled heat sources used in the Radioisotope Heater Units (RHUs) that have been used extensively on many NASA science missions. Each RHU heat source contains 2 grams of fuel and yields 1 watt of thermal power. Conceptual and technology development work has pointed to efficiencies of 2% at these small sizes, which could yield single RHU electric power systems of 20 milliwatts. These units could also be combined for additional power. An alternative approach would be to package multiple RHU thermal sources into a new aeroheating/impact protective shell. A unit such as this could achieve 0.1 watts or more of electric power. The technological maturity of these systems is considered high, with development times of 6-8 years.

Small RPS of either class could be designed to be very compact and robust, able to withstand impacts and high-g loading for deployment on planetary surfaces. These are certainly options that could be considered for missions involving remote, autonomous sensor stations and small robotic vehicles.

Table 1: Radioisotope Power Sources

	Phasing Out	Under Development		Possible Future Developments		
Power Source	GPHS-RTG	MMRTG	SRG	2nd Gen SRG or MMRTG	Multiwatt RPS	Milliwatt RPS
Power (We)	240 (BOL) TBD (EOL)	~120 (BOL) ~110 (EOL)	>114 (BOL) ~95 (EOL)	≈ SRG or MMRTG	1-20	0.02-0.10
Ops Environment	Space Only	Space & Atmos	Space & Atmos	Space & Atmos	Space & Atmos	Space & Atmos
Mass (kg)	75	34	27	≈ 1/2 SRG or 1/2 MMRTG	≈ Power/ Specific Pow	≈ Power/ Specific Pow
Specific Power (We/kg)	5.5	4.12	4.22	8-10	≤2.0	≤0.5
Envelope		58 cm long x 84 cm wide	35" long x 10.5" wide	≈ SRG or MMRTG	TBD	TBD
Voltage (Vdc)	28 +/- 0.2	28 +/- 0.2	28 +/- 0.2	28 +/- 0.2	TBD	TBD
Lifetime (yrs)	≥15	10-14 (space) >3 (Mars)	10-14 (space) >3 (Mars)	≈ SRG or MMRTG	≥10	≥5
Availability	None after 2006	2009	2009	≥2013	≥2011	≥2011
Pu-238 (kg)	~8	~4	~1	~SRG or MMRTG	~0.1	~0.002-0.010

NUCLEAR FISSION POWER AND PROPULSION

NASA recently initiated work on Nuclear Electric Propulsion (NEP) system technology that is planned for use on future missions. A set of technology options, including nuclear reactor, power conversion and propulsion system designs, is being traded over a range of system power levels and operational constraints. Three reactor types have been baselined for the trade study – heat pipe cooled, liquid-metal cooled, and gas cooled – while several ion thrusters are under consideration for the propulsion system. Under current planning assumptions, which are subject to change based on budget appropriations, it is expected that an NEP system would be ready for deployment in the first half of the next decade.

A broad range of NEP perfomance and capabilities could be considered for Space Science Vision Missions. The specific impulse of these systems could range from 2000 to 9000 seconds, while the full power lifetime could equal or exceed 10 years. Estimates of the system mass as a function of power for these NEP systems is shown in Table 2. This data is for mission study purposes only, and subject to revision. The system dry mass includes all nuclear electric propulsion system components used to produce thrust, except the Xenon propellant tank mass, which must be estimated based upon the required propellant for the specific mission. In addition, it does not include spacecraft bus subsystems, such as avionics, communications, or attitude control. Dry mass for systems with intermediate power levels can be interpolated. The power levels in Table 2 represent the electric power delivered by the power conversion system. It can be assumed that a significant portion of this would be available to science instruments, particularly during non-propulsive operational modes.

Table 2: NEP Power/Mass Characteristics

Power (kWe)	System Dry Mass (kg)
50	4500
100	7000
300	15000

Although NASA is presently not developing nuclear reactor power systems for planetary surface applications, the agency is interested in gaining a better understanding of how future space science missions could benefit from such systems. These reactor power systems would deliver 3 to 20 kWe of electricity over full power lifetimes greater than or equal to 10 years. Reference power versus mass characteristics for such systems has not been developed yet. However, at a power level of 3 kWe, the system dry mass should approximate 775 kg. This system mass includes the mass of system components used to produce power, and does not include bus or lander subsystems.

NASA is also interested in understanding how future space science missions could benefit from high-thrust nuclear propulsion technologies. These technologies could provide thrust accelerations greater than 1 m/sec^2 for up to 2 hours with specific impulses between 700 to 900 seconds (approximately 2 times greater than current chemical propulsion technologies). Estimates of engine thrust/weight as a function of thrust is shown in Table 3. This data is for mission study purposes only, and is subject to revision. The Table 3 engine mass includes all nuclear propulsion system components used to produce thrust except the propellant tank mass, which must be estimated based upon the required propellant for the proposed mission. The propulsion system described in Table 3 does not include spacecraft bus subsystems such as avionics, communications, or attitude control. Engine mass for systems with intermediate thrust levels can be interpolated.

Table 3: High-Thrust Nuclear Propulsion Parameters

Thrust (kN)	Engine Thrust/Weight Ratio (g)
5	0.5
25	2
75	3