WORLD NUCLEAR ASSOCIATION

Nuclear Reactors and Radioisotopes for Space

(Updated April 2020)

- **Radioisotope power sources have been an important source of energy in space since 1961.**
- **Nuclear fission reactors for space have been used mainly by Russia, but new and more powerful designs are under development in both the USA and Russia.**
- **Plutonium-238 is a vital power source for deep space missions.**

Nuclear power reactors use controlled nuclear fission in a chain reaction. With the use of neutron absorbers, the rate of reaction is controlled, so the power depending on the demand.

Radioisotope Thermoelectric Generators (RTGs) are an alternative source of power where a chain reaction does not take place. The power depends on the initial amount of the radioisotope used as fuel and the power is provided by converting the heat generated by radioactive decay of the radioisotope into electricity using thermocouples. Most RTGs use plutonium-238. With the use of RTGs, the power generated cannot be varied or shut down so supplementary batteries need to be taken into account for the peak times. RTGs are used when spacecraft require less than 100 kW. Above that, fission systems are much more cost effective than RTGs.

The United Nations has an Office for Outer Space Affairs (UNOOSA)* which implements decisions of the Committee on the Peaceful Uses of Outer Space (COPUOS) set up in 1959 and now with 71 member states. UNOOSA recognises “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” and “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.” It has adopted a set of principles applicable “to nuclear power sources in outer space devoted to the generation of electric power on board space objects for non-propulsive purposes,” including both radioisotope systems and fission reactors.

* UNOOSA has the dual objective of supporting the intergovernmental discussions in the Committee and its Scientific and Technical Subcommittee (S&T) and Legal Subcommittee, and of assisting developing countries in using space technology for development. In addition, it follows legal, scientific and technical developments relating to space activities, technology and applications in order to provide technical information and advice to Member States, international organizations and other United Nations offices.

Radioisotope systems – RTGs

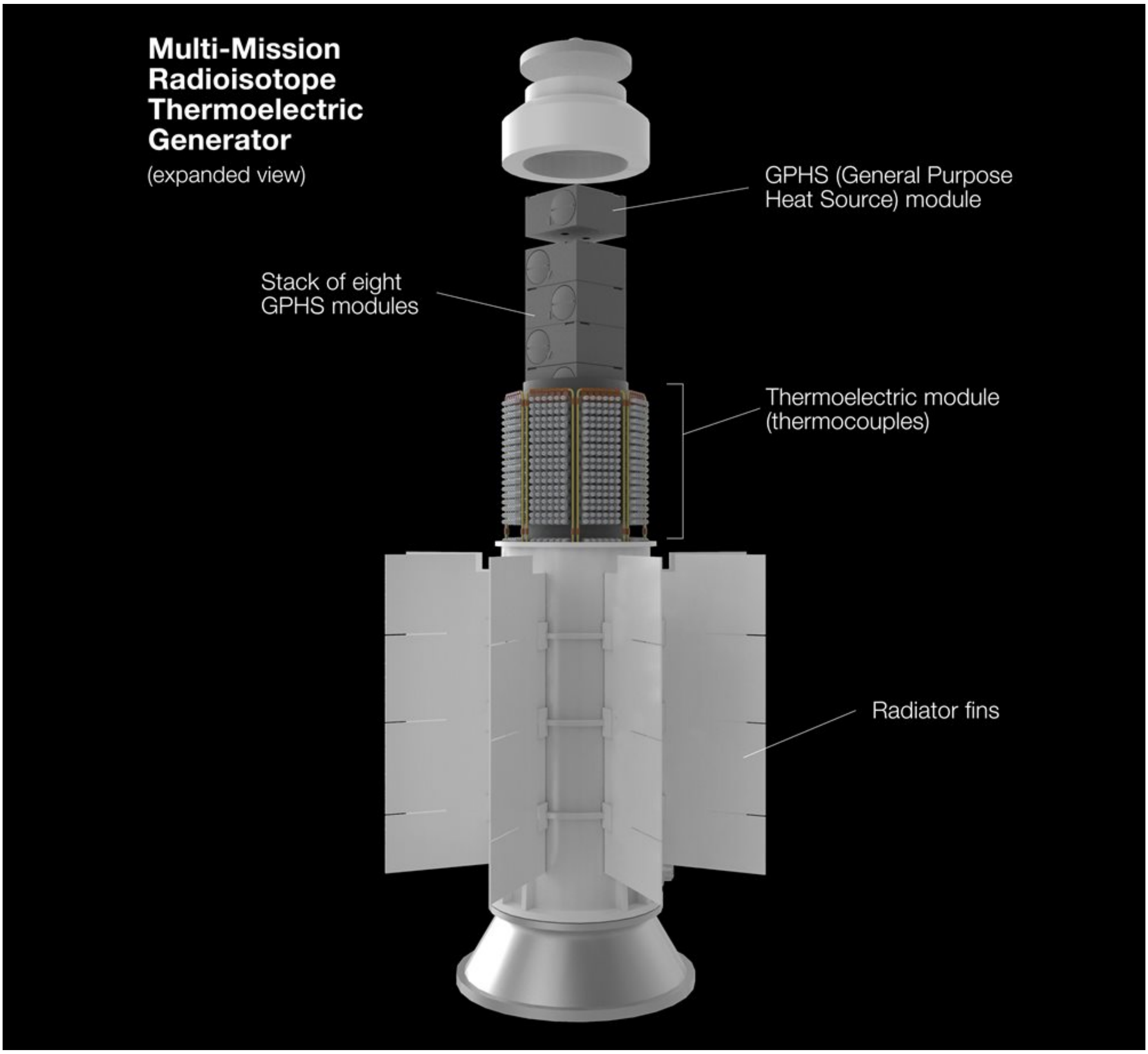
Radioisotope Thermoelectric Generators **(RTGs)** have been the main power source for US space work since 1961. The high decay heat of Plutonium-238 (0.56 W/g) enables its use as an electricity source in the RTGs of spacecraft, satellites and navigation beacons. Its intense alpha decay process with negligible gamma radiation calls for minimal shielding. Americium-241, with 0.15 W/g, is another source of energy, favoured by the European Space Agency, though it has high levels of relatively low-energy gamma radiation. Heat from the oxide fuel is converted to electricity through static thermoelectric elements (solid-state thermocouples), with no moving parts. RTGs are safe, reliable and maintenance-free and can provide heat or electricity for decades under very harsh conditions, particularly where solar power is not feasible.

The importance of such power sources was illustrated by the European Space Agency's **Rosetta** mission, which successfully landed the **Philae** probe on comet 67P/Churymov–Gerasimenko in 2014. Equipped with batteries and solar panels, the position in which Philae came to rest on the comet's surface – shielded from the Sun's rays by cliffs – meant that the lander was unable to make use of solar energy and was only able to send 64 hours' worth of data before its battery power ran out.

So far over 45 RTGs have powered in excess of 25 US space vehicles including Apollo, Pioneer, Viking, Voyager, Galileo, Ulysses and New Horizons space missions as well as many civil and military satellites. The **Cassini** spacecraft carried three RTGs providing 870 watts of power from 33 kg plutonium-238 oxide as it explored Saturn. It was launched in 1997, entered Saturn’s orbit in 2004, and functioned very well until it was terminated in September 2017. **Voyager 1 & 2** spacecraft which have sent back pictures of distant planets have already operated for over 35 years since 1977 launch and are expected to send back signals powered by their RTGs through to 2025. **Galileo**, launched in 1989, carried a 570-watt RTG. The **Viking** and **Rover** landers on Mars in 1975 depended on RTG power sources, as does the Mars Science Laboratory rover launched in

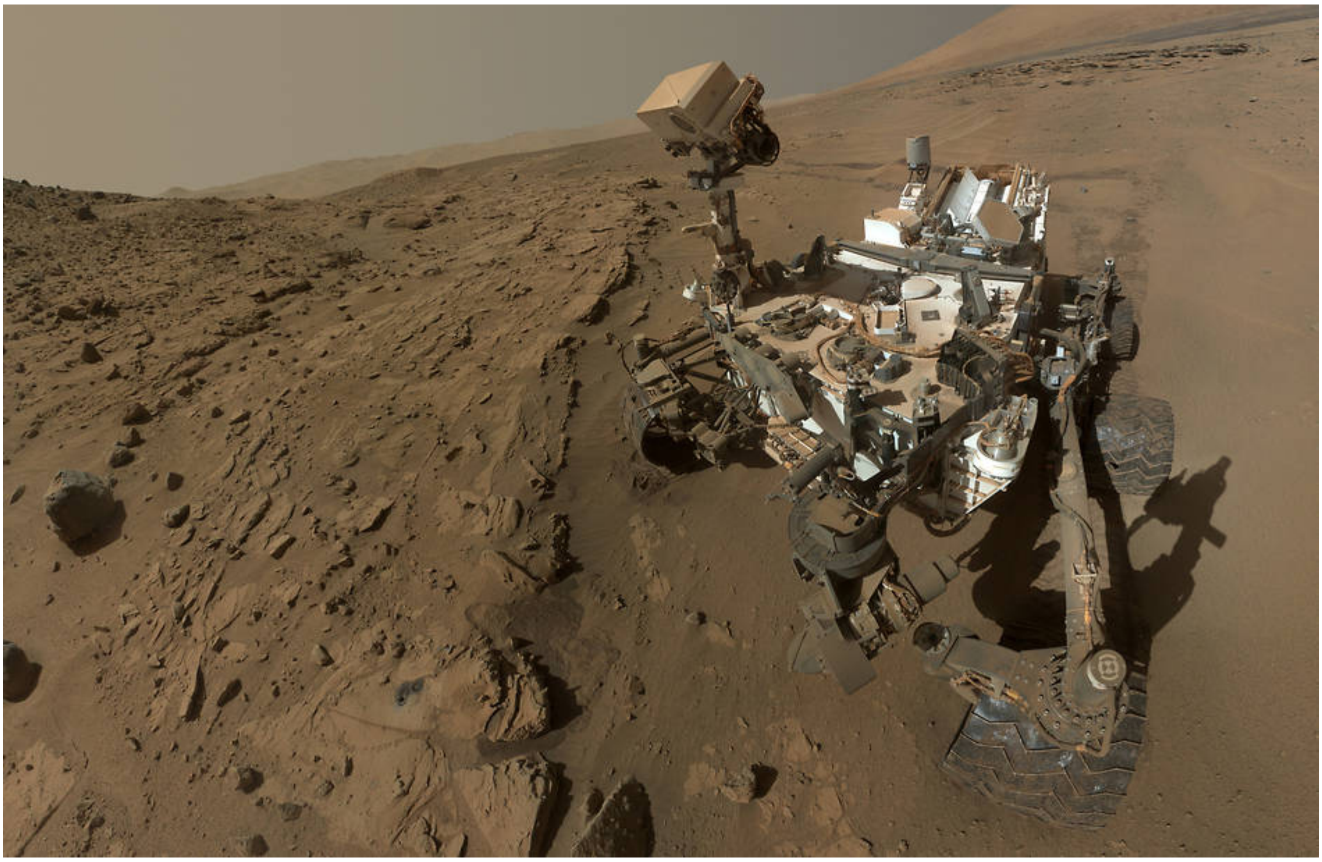
2011. Three RTGs (each with 2.7 grams of plutonium-238 dioxide) were used as heat sources on the Pathfinder Mars robot lander launched in 1996, producing 35 watts. Each produced about one watt of heat. (The 10.5 kg Pathfinder rovers in 1997 and the two Mars rovers operating 2004-09 used solar panels and batteries, with limited power and life.)

The latest plutonium-powered RTG is a 290-watt system known as the **GPHS RTG**. The thermal power for this system is from 18 general purpose heat source (GPHS) units. Each GPHS contains four iridium-clad ceramic Pu-238 fuel pellets, stands 5 cm tall, 10 cm square and weighs 1.44 kg. The **multi-mission RTG** (MMRTG) (see below image) uses eight GPHS units with a total of 4.8 kg of plutonium oxide producing 2 kW thermal which can be used to generate some 110 watts of electric power, 2.7 kWh/day.



Multi-Mission Radioisotope Thermoelectric Generator (MMRT). Source: NASA

MMRTG technology is being used in the NASA Mars Science Laboratory mission's rover *Curiosity (see below image)*, which at 890 kg is about five times the mass of previous Mars rovers. Another rover project, Mars 2020, will utilise the MMRTG, and is planned for launch in 2020.



NASA's Curiosity Mars rover. Source: NASA/JPL-Caltech/MSSS

Russia's Institute of Space Research (IKI) of the Russian Academy of Sciences and the Bauman Moscow State Technical University are developing three types of lunar rovers, one of them a heavy, 'nuclear-powered' lunar rover. This will weigh 550-750 kg and is designed to study polar regions of the Moon. In addition to solar panels and batteries, a nuclear power source is to be installed on the rover to enable it to operate for up to 400 kilometres, including in the shade. It will carry up to 70 kg of scientific equipment, including special drills to extract soil samples from a depth of 1.5 metres. The rover will also be equipped with 16 small stations to study the regolith and seismic activity of the Moon.

ExoMars is a joint project between the Russian space agency Roscosmos and European Space Agency (ESA) to research evidence of life on Mars, and will utilise RTGs. The mission will ultimately deliver a European rover and a Russian surface platform to Mars. The first part of the mission was launched in 2016, the primary purpose of which is to test for evidence of methane and other trace atmospheric gases. The second part of the mission is planned to launch in 2020.

The New Horizons spacecraft which flew by Pluto in July 2015 has a 250 watt, 30 volt GPHS RTG which would have decayed to about 200 watts by the time of the Pluto flyby (it was launched in 2006). It uses 10.9 kg of Pu-238 oxide and is less powerful than originally designed, due to production delays. There are 16 Aerojet thrusters controlling trajectory and attitude of the 478 kg craft. Four of the thrusters generate 4.4 N, while 12 generate 0.9 N thrust. The fuel for these is 65 kg of hydrazine

The Stirling Radioisotope Generator (SRG) is based on a 55-watt electric converter powered by one GPHS unit. The hot end of the Stirling converter reaches 650°C and heated helium drives a free piston reciprocating in a linear alternator, heat being rejected at the cold end of the engine. The AC is then converted to 55 watts DC. This Stirling engine produces about four times as much electric power from the plutonium fuel than an RTG. Thus each SRG will utilise two Stirling converter units with about 500 watts of thermal power supplied by two GPHS units and will deliver 130-140 watts of electric power from about 1 kg Pu-238. The SRG and Advanced SRG (ASRG) have been extensively tested but have not yet flown. NASA planned to use two ASRGs for its probe to Saturn's moon Titan (Titan Mare Explorer, TiME) or that to the comet Wirtanen, though these missions have been postponed in favour of the Mars InSight mission originally scheduled for March 2016, now likely mid-2018. In November 2013, after spending $270 million on it, NASA halted development of the ASRG due to budget constraints, claiming that it had enough Pu-238 for MMRTGs.

NASA also said that **production of Pu-238** was being ramped up to 1.5 kg/yr by the mid-2020s, and by the end of 2015 over $200 million had been spent on this (see information paper on Plutonium). Since the 1990s the USA has relied on Russian supplies of Pu-238 produced at Mayak, and has bought 16.5 kg of it. However, Russia no longer produces or sells it.

Russia has developed RTGs using Po-210, two are still in orbit on 1965 Cosmos navigation satellites. But it concentrated on fission reactors for space power systems. China's Chang'e 3 lunar lander apparently uses RTGs with Pu-238.

Americium-241 can be used for RTGs. It has about one-quarter of the energy of Pu-238, but is cheaper and readily available from the clean-up of aged civil plutonium stocks such as in the UK. It also has a longer half-life – 432 years compared to 88 years. However it has some gamma activity (8.48 mSv/hr/MBq at one metre is quoted) and has been disregarded. However the European Space Agency is setting out to use it and is paying for Am-241 recovered from the UK's civil plutonium by the National Nuclear Laboratory to be used for its RTGs. About twice the mass of pure Am-241 is needed in an RTG relative to Pu-238 (which normally has some impurities). In May 2019 National Nuclear Laboratory and University of Leicester generated usable electricity from americium, extracted from the UK's plutonium stocks.

As well as RTGs, radioactive heater units (**RHUs**) are used on satellites and spacecraft to keep instruments warm enough to function efficiently. Their output is only about one watt and they mostly use Pu-238 – typically about 2.7g of it. Dimensions are about 3 cm long and 2.5 cm diameter, weighing 40 grams. Some 240 have been used so far by the USA and two are in shutdown Russian lunar rovers on the moon, these using polonium-210. Eight were installed on each of the US Mars Rovers *Spirit* and *Opportunity*, which landed in 2004, to keep the batteries functional. China's *Chang'e 3* lunar rover Yutu apparently uses several RHUs.

The Idaho National Laboratory's (INL) Centre for Space Nuclear Research (CSNR) in collaboration with NASA is developing an RTG-powered hopper vehicle for Mars exploration. When stationary the vehicle would study the area around it while slowly sucking up carbon dioxide from the atmosphere and freezing it, after compression by a Stirling engine. Meanwhile a beryllium core would store heat energy required for the explosive vaporisation needed for the next hop. When ready for the next hop, nuclear heat would rapidly vaporise the carbon dioxide, creating a powerful jet to propel the craft up to 1000 metres into the 'air'. A small hopper could cover 15 km at a time, repeating this every few days over a ten-year period. Hoppers could carry payloads of up to 200 kg and explore areas inaccessible to the Rovers. INL suggests that a few dozen hoppers could map the Martian surface in a few years, and possibly convey rock samples from all over the Martian surface to a craft that would bring them to Earth.

Both RTGs and RHUs are designed to survive major launch and re-entry accidents intact. Nimbus B-1 in 1968 and the Apollo 13 lunar module in 1970 did so.

Stirling engine

A Stirling engine uses any external heat source through a gaseous working fluid to drive a reciprocating piston which turns a crankshaft to do mechanical work. The working fluid is permanently contained, and through a regenerator with heat exchanger can recycle continuously. The working gas is expanded in the hot portion and compressed in the cold portion of the engine, thus converting heat to work. The larger the temperature difference between the hot and cold sections of a Stirling engine, the greater its efficiency. In single-cylinder designs a displacer piston moves the working gas back and forth between the hot and cold heat exchangers.

Fission systems – heat and propulsion

For higher power requirements, fission power systems (FPS) have a distinct cost advantage over RTGs. As currently conceived, FPS would be launched cold, with essentially no radioactive hazards. Reactor start-up is after the device is in orbit. Then the reactor automatically responds to thermal load changes and maintains safe operating temperatures based on negative temperature reactivity feedback, giving it load-following capability. Low reactor power would reduce thermal stresses and provide tolerance to potential damaging transients. The low fuel burn-up minimises fission products that would cause adverse radiation effects on reactor materials and spacecraft components.

After a gap of several years, there is a revival of interest in the use of nuclear fission power for space missions. While Russia has used over 30 fission reactors in space, the USA has flown only one – the SNAP-10A (System for Nuclear Auxiliary Power) in 1965.

Early US program: 1960s to 1980s

Early on, from 1959-73 there was a US **nuclear rocket programme** – Nuclear Engine for Rocket Vehicle Applications (NERVA) – which was focused on nuclear power replacing chemical rockets for the latter stages of launches. NERVA used graphite-core reactors heating hydrogen and expelling it through a nozzle. Some 20 engines were tested in Nevada and yielded thrust up to more than half that of the space shuttle launchers. Since then, 'nuclear rockets' have been about space propulsion, not launches. The successor to NERVA is today's nuclear thermal rocket (NTR).

Another early idea was the US Project Orion, which would launch a substantial spacecraft – about 1000 tonnes – from the earth using a series of small nuclear explosions to propel it. The project was commenced in 1958 by General Atomics and was aborted in 1963 by the Atmospheric Test Ban Treaty. The Orion project gave ideas for other projects for example ICAN-II and AIMStar as other means of generating the propulsive pulses are considered.

The US SNAP-10A launched in 1965 was a 45 kWt thermal nuclear fission reactor to produce 650 watts with ZrH moderator (or UZrH fuel) and eutectic NaK coolant feeding thermoelectric converter panels. It operated for 43 days at 590 watts, but was shut down due to a voltage regulator (not reactor) malfunction. It remains in orbit.

The last US space reactor initiative in this period was a joint NASA-DOE-Department of Defense program developing the SP-100 reactor – a 2 MWt fast reactor unit and thermoelectric system delivering up to 100 kWe – as a multi-use power supply for orbiting missions or as a lunar/Martian surface power station. This was terminated in the early 1990s after absorbing nearly $1 billion. The reactor used uranium nitride fuel and was lithium-cooled.

There was also a Timberwind pebble bed reactor concept under the Department of Defense Multi-Megawatt (MMW) space power programme during the late 1980s, in collaboration with the DOE. This had power well beyond any civil space programme requirements. But see MegaPower below.

For spacecraft propulsion, once launched, some experience has been gained with **nuclear thermal** rocket (NTP or NTR) propulsion systems, which are said to be well-developed and proven. Nuclear fission heats a hydrogen propellant which is stored as liquid in cooled tanks. The hot gas (about 2500°C) is expelled through a nozzle to give thrust (which may be augmented by injection of liquid oxygen into the supersonic hydrogen exhaust). This is more efficient than chemical reactions. Bimodal versions will run electrical systems on board a spacecraft, including powerful radars, as well as providing propulsion. Compared with nuclear electric plasma systems, these have much more thrust for shorter periods and can be used for launches and landings.

Later US programs: 1990s on

In the late 1980s attention turned to **nuclear electric** propulsion (NEP) systems, where nuclear reactors are a heat source for electric ion drives expelling plasma out of a nozzle to propel spacecraft already in space. Superconducting magnetic cells ionise xenon (or hydrogen), heat it to extremely high temperatures (millions °C), and use very high voltage to accelerate it and expel it at very high velocity (*e.g.* 30 km/s) to provide thrust. While the thrust is miniscule relative to a rocket, its application in space over a long period (*e.g.* years) can lead to high velocity of the spacecraft. NASA's *Dawn* spacecraft operating between Mars and Jupiter since 2007 uses an ion thruster, as do over 100 geosynchronous Earth orbit communication satellites. They both extend the operating lifetimes of satellites and reduce launch and operation costs. Xenon is used because it is easily ionised and has relatively high atomic mass, as well as being inert and having high storage density.

The first NASA space mission with an ion thruster was from 1998 to 2001. The NASA Solar Technology Application Readiness (**NSTAR**) ion propulsion system enabled the Deep Space 1 mission, the first spacecraft propelled primarily by ion propulsion, to travel over 260 million kilometres and make flybys of the asteroid Braille and the comet Borelly. The NASA Evolutionary Xenon Thruster (NEXT) and the Annular Engine are developments of this. NEXT is a high-power ion propulsion system designed to reduce mission cost and trip time, operating at three times the power level of NSTAR. NASA's patented Annular Engine has the potential to exceed the performance capabilities of NEXT and other electric propulsion thruster designs, with a total (annular) beam area that is twice as great.

Research for one version, the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) draws on that for magnetically-confined fusion power (tokamak) for electricity generation, but here the plasma is deliberately leaked to give thrust. The system works most efficiently at low thrust (which can be sustained), with small plasma flow, but shorter high thrust operation is possible. It is very efficient, with 99% conversion of electric to kinetic energy, though only 70% is claimed for the short thrust firings. The VX200, a 200kW version, was being tested in 2015 with a view to deployment on space missions for nuclear electric propulsion. It could also be used for removal of space debris, pushing into low orbit for burn-up. NASA has contracted Ad Astra Rocket Co to develop a new version, VX-200SS ("SS" stands for "steady state"), featuring a new core design and thermal controls, operating at temperatures of 1,000,000 ºC while almost entirely eliminating the need for vast quantities of rocket fuel.

Heatpipe Power System (HPS) reactors are compact fast reactors producing up to 100 kWe for about ten years to power a spacecraft or planetary surface vehicle. They have been developed since 1994 at the Los Alamos National Laboratory as a robust and low technical risk system with an emphasis on high reliability and safety. They employ heatpipes* to transfer energy from the reactor core to make electricity using Stirling or Brayton cycle converters.

* A heatpipe is a heat transfer device combining thermal conductivity with phase change. At the hot end a liquid vapourises under low pressure and at the other end it condenses, releasing its latent heat of vapourisation. The liquid then returns to the hot end, either by gravity or capillary action, to repeat the cycle. (If using gravity, they are sometimes called two-phase thermosiphons, but capillary 'pumping' using surface tension is the main mechanism used.)

In the 1990s design, energy from fission is conducted from the fuel pins to the heatpipes filled with sodium vapour which carry it to the heat exchangers and then in hot gas to the Stirling or Brayton power conversion systems to make electricity. The gas is 72% helium and 28% xenon. The reactor itself contains a number of heatpipe modules with the fuel. Each module has its central heatpipe with rhenium-clad fuel sleeves arranged around it. They are the same diameter and contain 97% enriched uranium nitride fuel, all within the cladding of the module. The modules form a compact hexagonal core. Control is by six stainless steel clad beryllium drums each 11 or 13 cm diameter with boron carbide forming a 120 degree arc on each. The drums fit within the six sections of the beryllium radial neutron reflector surrounding the core, and rotate to effect control, moving the boron carbide in or out.

Shielding is dependent on the mission or application, but lithium hydride in stainless steel cans is the main neutron shielding.

The **SAFE-400** space fission reactor (Safe Affordable Fission Engine) is a 400 kWt HPS of 100 kWe to power a space vehicle using two Brayton power systems – gas turbines driven directly by the hot gas from the reactor. Heat exchanger outlet temperature is 880°C. The reactor has 127 identical heatpipe modules made of molybdenum, or niobium with 1% zirconium. Each has three fuel pins 1 cm diameter, nesting together into a compact hexagonal core 25 cm across. The fuel pins are 70 cm long (fuelled length 56 cm), the total heatpipe length is 145 cm, extending 75 cm above the core, where they are coupled with the heat exchangers. The core with reflector has a 51 cm diameter. The mass of the core is about 512 kg and each heat exchanger is 72 kg. SAFE has also been tested with an electric ion drive.

A smaller version of this kind of reactor is the **HOMER-15** – the Heatpipe-Operated Mars Exploration Reactor. It is a 15 kW thermal unit similar to the larger SAFE model, and stands 2.4 metres tall including its heat exchanger and 3 kWe Stirling engine (see above). It operates at only 600°C and is therefore able to use stainless steel for fuel pins and heatpipes, which are 1.6 cm diameter. It has 19 sodium heatpipe modules with 102 fuel pins bonded to them, 4 or 6 per pipe, and holding a total of 72 kg of fuel. The heatpipes are 106 cm long and fuel height 36 cm. The core is hexagonal (18 cm across) with six BeO pins in the corners. The total mass of reactor system is 214 kg, and diameter is 41 cm.

Another small fission surface power system for the moon and Mars was announced by NASA in 2008. The 40 kWe system could utilise one of two design concepts for power conversion. The first, by Sunpower of Athens, Ohio, uses two opposed piston engines coupled to alternators that produce 6 kilowatts each, or a total of 12 kilowatts of power. The second, by Barber Nichols of Arvada, Colorado, is for development of a closed Brayton cycle engine which uses a high-speed turbine and compressor coupled to a rotary alternator that also generates 12 kilowatts of power. NASA itself will develop the heat rejection system and provide the space simulation facility. In mid-2012 NASA reported successful tests of power conversion and radiator components of this 40 kWe system, which is based on a small fission reactor heating up and circulating a liquid metal coolant mixture of sodium and potassium. The heat differential between this and the outside temperature would drive two complementary Stirling engines to turn a 40 kWe generator. Some 100 square metres of radiators would remove process heat to space.

US Project Prometheus: 2003-2007

In 2002 NASA announced its Nuclear Systems Initiative for space projects, and in 2003 this was renamed Project Prometheus and given increased funding. Its purpose was to enable a major step change in the capability of space missions. Nuclear-powered space travel will be much faster than is now possible, and will enable manned missions to Mars. (See section below.)

One part of Prometheus, which was a NASA project with substantial involvement by the DOE in the nuclear area, was to develop the Multi-Mission Thermoelectric Generator and the Stirling Radioisotope Generator described in the RTG section above.

A more radical objective of Prometheus was to produce a space fission power system (FPS) such as those described above for both power and propulsion that would be safe to launch and which would operate for many years with much greater power than RTGs. Power of 100 kW is envisaged for a nuclear electric propulsion system driven by plasma.

The FY 2004 budget proposal was for $279 million, with $3 billion to be spent over five years. This consisted of $186 million ($1 billion over five years) building on FY 2003 allocation plus $93 million ($2 billion over five years) towards a first flight mission to Jupiter – the Jupiter Icy Moon Orbiter (JIMO), was expected to launch in 2017 and explore for a decade. However, Project Prometheus received only $430 million in the 2005 budget and this shrank to $100 million in 2006, most of which was to compensate for cancelled contracts, so it is effectively stalled. A similar project has been initiated and planned to launch in 2022 named the JUpiter ICy moons Explorer (JUICE), as an interplanetary spacecraft in development by the European Space Agency (ESA) with Airbus Defence and Space as the main contractor.

In 2003 Project Prometheus successfully tested a High Power Electric Propulsion (HiPEP) ion engine. This operates by ionizing xenon with microwaves. At the rear of the engine is a pair of rectangular metal grids that are charged with 6,000 volts of electric potential. The force of this electric field exerts a strong electrostatic pull on the xenon ions, accelerating them and producing the thrust that propels the spacecraft. The test was at up to 12 kW, though twice that is envisaged. The thruster is designed for a 7 to 10-year lifetime with high fuel efficiency, and to be powered by a small nuclear reactor.

Current US programme

Space reactors in the kilowatt class are designated **KiloPower** by NASA, and may include a variety of designs of comparable power and mass to RTGs. They use liquid metal heatpipes to transfer fission heat to either thermoelectric or Stirling power conversion. Los Alamos National Laboratory and NASA Glenn Research Center completed a proof-of-concept test at the Nevada National Security Site in 2012 using the Flattop reactor and two small Stirling convertors to produce 24 watts.

In December 2014 NASA's Glenn Centre announced progress with its 4 kWt/1 kWe KiloPower project, using high-enriched uranium powering a heatpipe system and Stirling engine to generate electricity – Kilopower Reactor Using Stirling Technology (KRUSTY). This is a fast reactor relying entirely on negative thermal feedback for control, the objective being to design self-regulation as a major feature and demonstrate that it is reliable. The design is scalable up to 10 kWe. Los Alamos Nuclear Laboratory (LANL) with NASA in April 2018 announced completion of full-power testing of a prototype KRUSTY unit. The testing ran from November 2017 to March 2018, during which time the unit successfully handled multiple simulated failures, including power reduction, failed engines and failed heat pipes. This was the first US nuclear-powered ground test on an in-space nuclear reactor for several decades.

Prior to testing, NASA had appealed to the US National Nuclear Security Administration (NNSA) to let it proceed. The testing is being carried out under the Department of Energy's Criticality Safety Program working with NASA. The optimum fuel for the fast reactor was proposed as an HEU (93% enriched) alloy with 7% molybdenum as a solid casting, 129 mm in diameter and 300 mm long*. A 250 mm diameter beryllium oxide reflector would surround this, with 18 sodium heatpipes between the fuel and the reflector. Criticality is achieved by raising the BeO reflector to generate fission in the reactor core. Once fission has begun, the BeO reflector would be slowly raised to increase the temperature in the system to 800°C. There is a single central boron carbide control rod. The heatpipes will deliver 13 kWt heat from the core to eight free-piston Stirling engines and allow each to produce about 125 watts of electric power. The Stirling engine would have a cylindrical radiator of nearly 10 m^2. The system mass is about 750 kg, and the length about 5 m. The science payload is assumed to be about 10 m from the core, and shielded by 45 kg of depleted uranium and 40 kg of lithium hydride.

* The 1 kWe test reactor in November 2017 is reported to use an alloy of 92% uranium, 8% molybdenum, with enrichment to 95%, and diameter 11 cm with 4 cm central hole and eight heat pipes recessed. There are two axial neutron reflectors and one radial one, total 70.5 kg beryllium.

NASA estimates that about 40 kWe would be needed for power on Mars, using ten 4 kWe KiloPower units.

Experience of the KiloPower project will be fed to a **MegaPower** project, with 2 MWe units. Features would include reactor self-regulation, low reactor core power density and the use of heatpipes for reactor core heat removal. The reactor would be attached to an open air Brayton cycle power conversion system using air as the working fluid and as the means of ultimate heat removal. The reactor would weigh about 40 tonnes including 3 t of LEU fuel (16-19% enriched), and be 4 m long, 2 m diameter. It would be scalable to 10 MWe, and could also be used in military bases, with 72-hour installation.

Russian fission systems

Between 1967 and 1988 the former Soviet Union launched 34 low-powered fission reactors in Radar Ocean Reconnaissance Satellites (RORSATs) on Cosmos missions. They used **thermoelectric** converters to produce electricity, as with the RTGs. Romashka reactors were their initial nuclear power source, a fast spectrum graphite reactor with 90%-enriched uranium carbide fuel operating at high temperature. Then the Bouk or Buk fast reactor produced 3 kW for up to four months. This programme was led by the Krasnaya Zvezda design bureau in Moscow. Later reactors, such as on Cosmos-954 which re-entered over Canada in 1978, had U-Mo fuel rods and a layout similar to the US heatpipe reactors described above. Most Russian military reconnaissance satellites used Bouk reactors.

These were followed by the multi-cell Topol or Topaz-1 reactors with **thermionic** conversion systems using caesium vapour, generating about 5 kWe of power over 3-5 years for on-board uses from 12 kg of fuel. Reactor mass was about 320 kg. This was a US idea developed during the 1960s at the Kurchatov Institute in Russia and first tested in 1971. Topaz-1 was flown in 1987 on Cosmos 1818 & 1867 for ocean surveillance. One reactor ran for six months, the other for a year, and the Topaz-1 program was then halted.

The single-cell ENISY or Topaz-2 reactor was developed by the Central Design Bureau of Machine Building in Leningrad, with the fuel from Luch Design Bureau. In this, each fuel pin (96% enriched UO_2) sheathed in an emitter is surrounded by a collector and these form the 37 fuel elements which penetrate the cylindrical ZrH moderator. This in turn is surrounded by a beryllium neutron reflector with nine rotating control drums and three rotating safety drums in it. NaK coolant surrounds each fuel element, driven by an electromagnetic pump. It operated at about 10 kWe (minimum 6 kWe net at 27 volts over three years) and the mass of the reactor was about 1060 kg. Later Topaz-2 units were aiming for 40 kWe via the Topaz International Program (TIP) undertaken largely in the USA from 1990, which tested six reactors. Two Topaz-2 reactors (without fuel) were sold to the USA in 1992. Budget restrictions in 1993 forced the cancellation of the Nuclear Electric Propulsion Spaceflight Test Program associated with this. Four more Topaz-2 reactors were shipped to the USA for testing in 1994.

In 2010 the Russian Presidential Commission on Modernization and Technology Development of Russia's Economy allocated federal funds to design a nuclear power propulsion unit (NPPU) in the megawatt power range, capable of powering a craft on long-haul interplanetary missions. In particular, SC Rosatom was to get RUR 430 million and Roskosmos (Russian Federal Space Agency) RUR 70 million to develop a Transport and Energy Module based on the NPPU, though it was reported that Roskosmos did not include the project in its space programme budget for 2016-2025. N.A. Dollezhal NIKIET (Research & Development Institute for Power Engineering) in Moscow was appointed the sole contractor for the NPPU, based on previous developments including those of nuclear rocket engines. In November 2015 NIKIET reported that the engineering design of the reactor was complete, and tests had "confirmed the integrity of the reactor vessel" and checked for leaks and deformation. The tests had also validated the "reliability of design calculations" to determine the ability of the vessel to withstand stress. The prototype propulsion reactor for space applications is expected to be tested in 2018. The total cost of the project of the propulsion and power module based on the propulsion reactor is estimated at RUR 20 billion (US$ 274 million) with the reactor part of it RUR 7 billion.

Russia's S.P.Korolyov Rocket and Space Corporation Energia space corporation started work in 2011 on standardized space modules with nuclear-powered propulsion systems, initially involving 150 to 500 kilowatt systems. A conceptual design in 2011 led to the basic design documentation and engineering design. The idea now being pursued by Russia's Keldysh Research Centre is to use a small gas-cooled fission reactor aboard the rocket to turn a turbine and generator set and thereby produce electricity for a plasma thruster. The reactor unit should be developed about 2015, then life-service tests are planned for 2018. The first launches, are envisaged for about 2020.

The Director of Roskosmos says that development of megawatt-class nuclear space power systems for manned spacecraft is crucial if Russia wants to maintain a competitive edge in the space race, including the exploration of the moon and Mars. The NPPU appears to meet this requirement. Energia earlier said that it is ready to design a space-based nuclear power station with a service life of 10-15 years, to be initially placed on the moon or Mars. It is also working on a concept of a nuclear-powered space tug, which could be used for launching satellites.

Space Reactor Power Systems

	SNAP-10 US	SP-100 US	Romashka Russia	Bouk Russia	Topaz-1 Russia	Topaz-2 Russia-US	SAFE-400 US	ERATO* France
Start decade	1960s	1980s	1960s	1970s	1980s	1990s	2000s?	1980s
kWt	45.5	2000	40	<100	150	135	400	
kWe	0.65	100	0.8	<5	5-10	6	100	20
Converter	t'electric	t'electric	t'electric	t'electric	t'ionic	t'ionic	t'electric	t'electric
Fuel	$U\text{-}ZrH_x$	UN	UC_2	U-Mo	UO_2	UO_2	UN	UO_2, UN
Reactor mass, kg	435	5422	455	<390	320	1061	512	
Neutron spectrum	thermal	fast	fast	fast	thermal	thermal/ epithermal	fast	fast/ epith
Control	Be	Be	Be	Be	Be	Be	Be	
Coolant	NaK	Li	none	NaK	NaK	NaK	Na	Na, gas
Core temp., °C max	585	1377	1900	?	1600	1900?	1020	840

* In the 1980s the French ERATO program considered three 20 kWe turboelectric power systems for space. All used a Brayton cycle converter with a helium-xenon mix as working fluid. The first system was a sodium-cooled UO_2-fuelled fast reactor operating at 670°C, the second a high-temperature gas-cooled reactor (thermal or epithermal neutron spectrum) working at 840°C, the third a lithium-cooled UN-fuelled fast reactor working at 1150°C.

Radiation in space

The 2011-12 space mission bearing the Mars Science Laboratory - the rover Curiosity - measured radiation en route. The spacecraft was exposed to an average of 1.8 mSv/day on its 36-week journey to Mars. This means that astronauts would be exposed to about 660 mSv on a round trip. Two forms of radiation pose potential health risks to astronauts in deep space. One is galactic cosmic rays (GCRs), particles caused by supernova explosions and other high-energy events outside the solar system. The other, of less concern, is solar energetic particles (SEPs) associated with solar flares and coronal mass ejections from the sun. One way to reduce the crew exposure would be to use nuclear propulsion, reducing the transit time considerably.

The radiation dose on the International Space Station orbiting Earth is about 100 mSv over six months.

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