Nuclear Energy Spacecraft

The human race has been enthralled by the exploration of space, but performing major long distance flights proved to be a major challenge since technology in the early stages of space exploration was limited. This frontier of space exploration was finally broken with the use and advancement of nuclear energy. There are several means of creating enough energy to power a spacecraft; however, none are as reliable and as favored as nuclear power when it comes to exploring the solar system past the moon. Innately, space provides for extreme temperatures, dark environments, exposure to radiation, etc. These punishing conditions are not conducive to conventional energy sources. While regular means of power prove to be unsustainable in deep space, nuclear energy provides spacecraft with sufficient power to complete deep space flights.
This report will explore the various power sources that could be used in space travel focusing on the propulsion choice and illustrates a brief historical background of nuclear reactors and radioisotopes for space.

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Nuclear rocket propulsion

One of the main features of spacecraft modelling is the propulsion choice which has been debated since the beginning of the spatial era.
The advantage of nuclear rocket propulsion lies in the reactor's unlimited energy supply that can be used to heat a propellant to a high temperature and, therefore, to very high exhaust velocities resulting in a superior rocket performance.
Rocket engines can be separated into two main categories: nuclear engines and chemical engines. The chemical engines can also be divided into two areas depending upon whether they use solid or liquid propellant. Solid propellants are inherently simpler in design and operation as liquid propellants. However, liquid propellants are presently capable of producing higher specific impulse and have greater flexibility. The advantages of each system are:
Solid Propellant.

1. simpler in design and construction;
2. lighter for low total impulse applications;
3. fewer servicing problems;
4. believed to be more reliable.

Liquid Propellant.

1. capable of higher specific impulse;
2. lighter for long duration or high thrust;
3. engine can be switched on and off and have variable thrust control;
4. less sensitive to ambient temperature variations.

Operation of a rocket engine is based upon the reaction principle-for every action there is an equal and opposite reaction. The thrust of a rocket is the reaction on its structure due to ejection of high-velocity matter. All kinds of rocket engines are self-sufficient in the sense that they are not dependent upon the medium in which they operate, being therefore especially suited for space missions. A schematic diagram of a nuclear rocket is shown in Fig. 1.

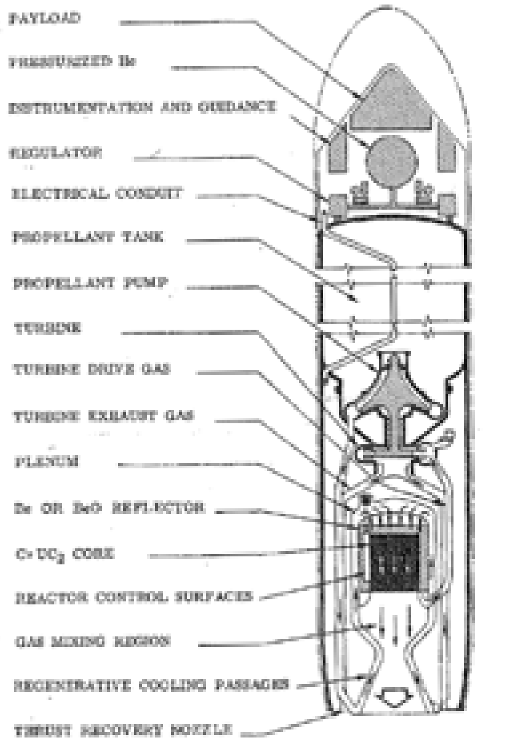


Fig. 1

Schematic diagram of a nuclear rocket.

The nuclear rocket uses a solid fluid element reactor to heat a single propellant. This is the basic difference between chemical and nuclear powered rockets. The propellant for the nuclear rocket provides no intrinsic energy but is heated by the kinetic energy of the fission fragments released during operation of the nuclear reactor. The main components of a nuclear rocket engine, as shown in Fig. 2, are: propellant tank, turbine driven pump, reactor core, reflector, and nozzle. Liquid hydrogen is stored in the insulated propellant tank and is replaced by helium as hydrogen is drawn off the pump. From the pump the hydrogen flows under high pressure (1000-1500 psia) through pipes to the exit end of the nozzle where it is used to cool the nozzle, pressure shell, and reflector before it enters the reactor plenum. From the plenum the hydrogen flows down through the core and out of the nozzle at about 1000-1500 °F. A small amount of hydrogen at 1000-1500 °F is diverted at the nozzle and used to drive the turbine. A bypass valve in the line regulates the turbine speed. From the turbine the gas is exhausted through thrust recovery auxiliary nozzles.

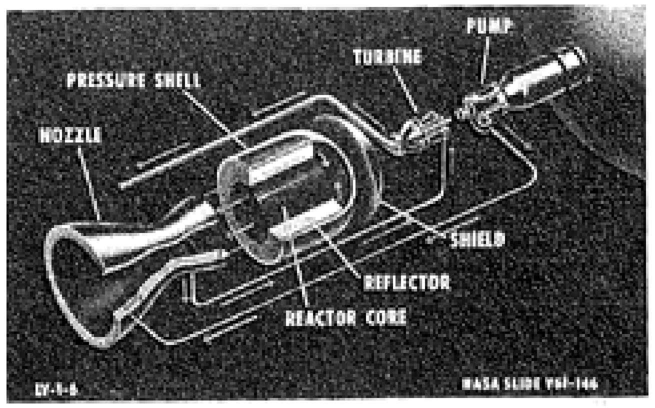


Fig. 2

Nuclear rocket engine.

Specific impulse I_{sp} is related to the amount of energy released to the propellant ΔH, called the *enthalpy change*, and the mean molecular weight of the exhaust products ejected from the noozle, $\overline{M}$.

$$I_{sp} = \sqrt{\frac{2J\Delta H}{gm}}\ \text{sec}$$

where *J=778ft-lb/Btu* is the mechanical equivalent of heat.
From the above relationship between energy, molecular weight, and specific impulse it is seen that:

1. for a given amount of available energy, the lower the mean molecular weight of the propellant, the higher will be the specific impulse. It is therefore important to use a propellant of low molecular weight such as hydrogen (H_2).
2. for a given molecular weight of the propellant, the higher the enthalpy change, the higher will be the specific impulse. Thus, the greater the thermal energy transferred to the propellant, the higher will be the specific impulse.

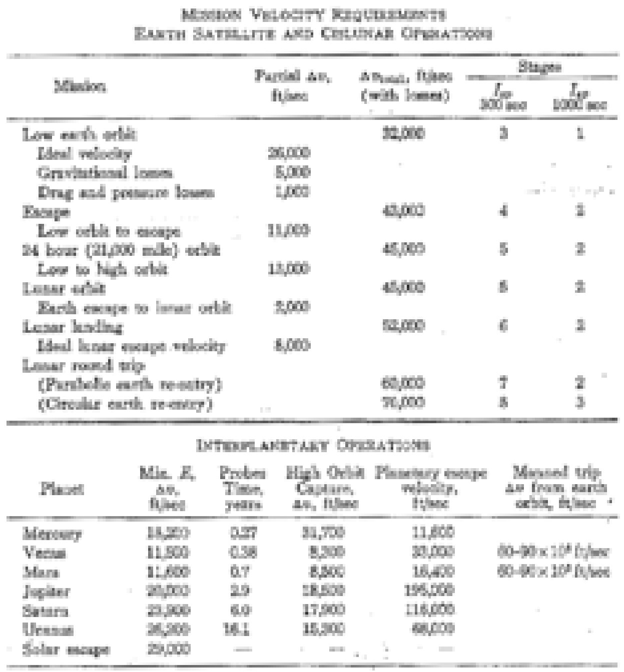
The above equation explains why the specific impulse of a nuclear rocket can be at least twice that of the best chemical rockets.
Analysis of the size, weight, and flight performance of different nuclear rocket vehicles allows choice of the optimum design conditions for a given required performance. For example, although lighter than those using other propellant, nuclear rockets which use liquid hydrogen may be considerably larger because of the low density of the liquid propellant.

Specification of the optimum vehicle for a given job is clearly not an analytical procedure, since much must be left to the judgement of the vehicle designer and the ultimate user. However, the relative usefulness of nuclear and chemical rockets can be assessed on the basis of a comparison of the vehicle weight required to carry a given payload or lead load to any desired velocity. Such a comparison results in determination of an optimum performance region of interest for each type of vehicle. Other studies can be made to show the effect of varying the selected design parameters such as reactor specific weight, operating pressure, vehicle initial acceleration, tank pressure, and others. These are often called *optimization studies* although it is not always possible to achieve a true optimum in the mathematical sense of maxima or minima.

For chemical rockets the maximum burnout velocity is about 10,000 ft/sec whereas for nuclear rockets the value is about 25,000 ft/sec or higher. Multiple-stage rockets are required for missions reaching very high velocities. A simple two-stage rocket consists of a booster stage and a sustainer stage. The booster stage is dropped when its propellant is exhausted and the sustainer stage carrying the payload is then fired to obtain the final burnout velocity.

Nuclear energy is essential to the long-range picture of space exploration. The nuclear rocket offers order of magnitude improvements in performance over chemical systems for the interplanetary missions. The performance advantage of the nuclear rocket lies in its high specific impulse-2 or 3 times the impulse possible with chemical systems. The high impulse means that potentially the nuclear rocket can accomplish a given mission with a smaller amount of propellant so that the ratio of dry weight for the system can be larger. Although some of this dry weight is taken up by the extra weight of the nuclear propulsion unit, the greater dry weight can make possible significant increases in payload for nuclear systems compared with chemical ones on many missions of interest.

The required mission velocities for earth satellites, lunar operations, and interplanetary operations already performed are listed in Table 1. Also shown in the table are the number of stages required for the various missions. It was then assumed that the chemical rockets have a specific impulse of 300 sec, and the nuclear rockets have a specific impulse of 1000 sec. as shown in the table for a lunar round trip, three nuclear stages were required for the mission compared to eight stages for the chemical rocket. A summary of the major space propulsion systems and their performance limits for various space missions is shown in Fig. 3.



MISSION VELOCITY REQUIREMENTS
EARTH SATELLITE AND CISLUNAR OPERATIONS

Mission	Partial Δv, ft/sec	Δv_{total}, ft/sec (with losses)	Stages I_{sp} 300 sec	Stages I_{sp} 1000 sec
Low earth orbit		32,000	3	1
Ideal velocity	26,000			
Gravitational losses	5,000			
Drag and pressure losses	1,000			
Escape		43,000	4	2
Low orbit to escape	11,000			
24 hour (21,000 mile) orbit		45,000	5	2
Low to high orbit	13,000			
Lunar orbit		45,000	5	2
Earth escape to lunar orbit	2,000			
Lunar landing		52,000	6	2
Ideal lunar escape velocity	8,000			
Lunar round trip				
(Parabolic earth re-entry)		60,000	7	2
(Circular earth re-entry)		70,000	8	3

INTERPLANETARY OPERATIONS

Planet	Min. E, Δv, ft/sec	Probe Time, years	High Orbit Capture, Δv, ft/sec	Planetary escape velocity, ft/sec	Manned trip Δv from earth orbit, ft/sec
Mercury	18,200	0.27	31,700	11,600	
Venus	11,500	0.38	8,300	33,000	60–90 × 10³ ft/sec
Mars	11,600	0.7	8,800	16,400	60–90 × 10³ ft/sec
Jupiter	20,000	2.9	18,500	195,000	
Saturn	23,900	6.0	17,900	116,000	
Uranus	26,200	16.1	15,300	68,000	
Solar escape	29,000	—	—	—	

Table 1

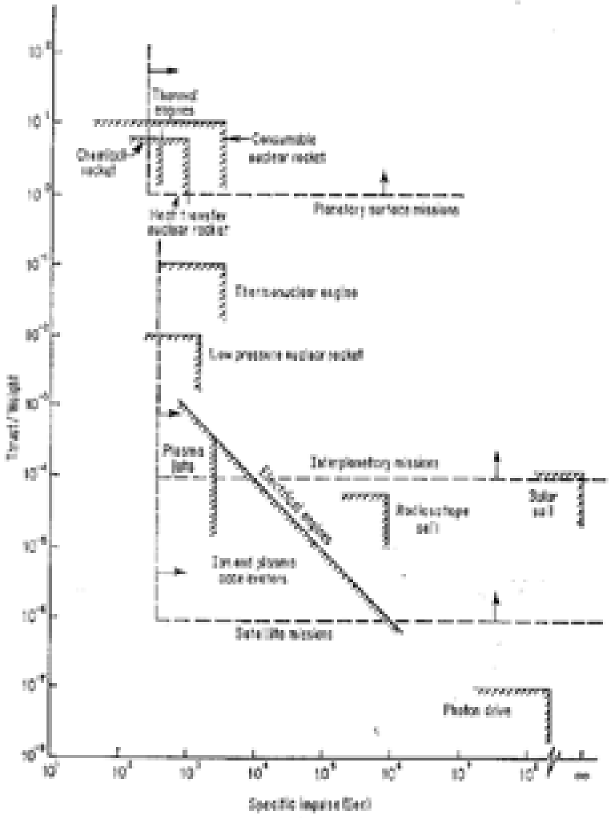


Fig. 3

Summary chart showing the major propulsion systems.

Propellant analysis: general characteristics

Propellant are the working substance of rocket engines and constitute the material that undergoes thermodynamic changes in the reactor and noozle. Since heating of the propellant in a nuclear rocket is accomplished by a reactor rather than by combustion processes as in chemical rockets, it is not necessary to utilize a chemically reactive mixture. The following characteristics are considered important in the selection of a propellant for a nuclear rocket:

- low molecular weight of the exhaust gas;
- low vapor pressure;
- low viscosity;
- high bulk density. A dense propellant permits reducing missile size and structural weight: this, in turn, increases the mass ratio and burnout velocity;
- low freezing point: this will permit rocket operation without heating at high altitudes;
- good heat transfer characteristics. This is important for heat transfer in the nuclear core and cooling of the nozzle and structure;
- desirable banding and storage characteristics. Low toxicity to personnel, low fire hazard, low corrosivity to materials are desirable practical considerations for a propellant;
- readily available and low cost. Propellants must be available in large quantities at a reasonable cost.

There are three groups of propellants that could be considered for use in a nuclear rocket-solid, gaseous, and liquid. In case of the solid and gaseous propellants, the problems of handling, storing, and utilization for nuclear rockets are so formidable compared to those associated with use of liquids that only liquid propellants are covered here.

Water. Water is an excellent nuclear moderator because of its high nuclear density. Because of water's stable molecular structure, the molecular weight of gaseous water is about 18 at elevated temperatures and pressures.

Alcohols. Methyl CH_3OH, and ethyl C_2H_3OH are readily available with some properties similar to those of water. The molecular weight of decomposed alcohols will be 9 to 10 or half of that of water, Alcohols decompose at about 3000 °F at moderate pressure to form hydrogen, carbon monoxide, acetylene, and free oxygen.

Hydrocarbons. Hydrocarbons such as CH_4 to CH_2 may be used as propellants provided that appreciable dissociation takes place in passing through the reactor. The molecular weight of hydrocarbons varies from 5.5 to 8 at high temperatures and pressures.

Nitrogen compounds. Ammonia, NH_3, and hydrazine N_2H_4 are useful propellants. They present a health hazard after prolonged inhalation and may form combustible mixtures with air. Both ammonia and hydrazine decompose rapidly at about 2500 °F. The free hydrogen present after dissociation will attack most metals. The molecular weights of the products of decomposition are about 8.5 for ammonia and 10.5 for hydrazine.

Hydrogen. Liquid hydrogen has several of the most and least desirable characteristics for use as a propellant. Its main advantage is its low molecular weight. Hydrogen is stable up to 4000 °F at moderate pressures. Hot hydrogen is highly reducing and will react with graphite and some metals. The molecular weight of hydrogen is about 2 at most temperatures and pressures experienced in a nuclear rocket. The variation of specific impulse in vacuum with temperature for gaseous hydrogen is shown in Fig. 4. As seen from the curve, the temperature of hydrogen has a very strong influence on the specific impulse I_{sp}.

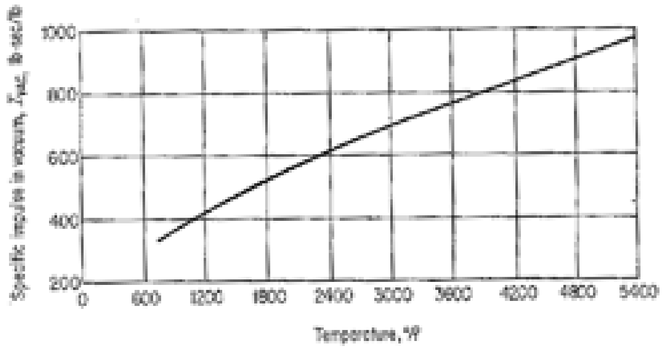


Fig. 4

Specific impulse in vacuum for gaseous hydrogen.

Nuclear Reactors and Radioisotopes for Space

There are only two practical ways to supply electrical power for multi-year space missions: the sun's rays or heat generated by natural radioactive decay. Radioisotope power systems-which directly convert heat generated by the decay of plutonium-238 into electric power-use the latter, and are essential for long missions to distant parts of the solar system, where solar-powered space travel may be impractical or impossible.

Plutonium-238 works well as a space power source for several reasons. It has a half-life of 88 years, meaning it takes that long for its heat output to be reduced by half. It's stable at high temperatures; can generate substantial heat in small amounts; and emits relatively low levels of radiation that is easily shielded, so mission-critical instruments and equipment are not affected. This type of plutonium is different than those used for nuclear weapons or nuclear power plant reactors.

In a radioisotope power system, commonly called a "space battery," the plutonium is processed into a ceramic form-similar to the material in your morning coffee mug. Just like a shattered mug, it breaks into large chunks instead of being vaporized and dispersed, preventing harm to people and the environment in the unlikely event of a launch or reentry accident. For more than 50 years, every radioisotope power system launched into space has worked safely and exactly as designed.

Nuclear space power systems

In 1961, the U.S. Navy's Transit 4A navigation satellite became the first U.S. spacecraft to be powered by nuclear energy. Transit 4A was powered by a radioisotope thermoelectric generator, or RTG, developed by the Atomic Energy Commission, the predecessor to the Energy Department. Since then, eight more generations of radioisotope power systems were developed by the Energy Department for use in space by NASA, the U.S. Navy and the U.S. Air Force.

With no moving parts, RTGs convert heat from plutonium-238 decay into electricity using devices called thermocouples. 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 RTG on the Navy's Transit 4A satellite produced 2.7 watts of electrical power. Transit 4A held the record for oldest broadcasting spacecraft for its first decade in orbit, during which time it traveled nearly 2 billion miles and circled the Earth more than 55,000 times.

In 1969, NASA launched the RTG-powered Nimbus III, the first U.S. weather satellite to measure air pressure, solar ultraviolet radiation, the ozone layer and sea ice during both day and night. Nimbus also included on-board infrared sensors that took early satellite photographs of the Earth. Aside from its RTGs, Nimbus also drew power from 10,500 built-in solar cells. 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 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) (Fig. 5) 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. 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.

MMRTG technology is being used in the NASA Mars Science Laboratory mission's rover *Curiosity* (Fig. 6), which at 890 kg is about five times the mass of previous Mars rovers. Another rover project, Mars 2020, will utilize the MMRTG, and is planned for launch in 2020.

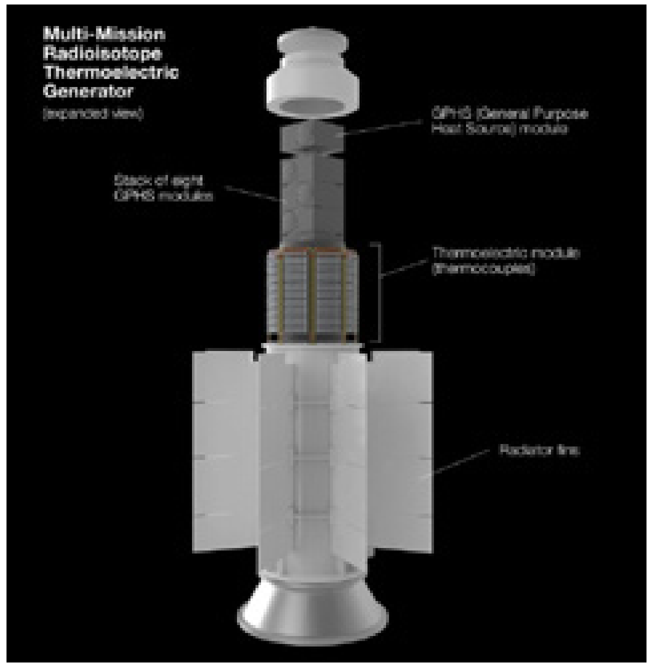


Fig. 5

Multi Mission Radioisotope Thermoelectric Generator (MMRTG). Source NASA.

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 utilize 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.

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 meter 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.

The Apollo missions to the moon included experimental packages known as ALSEP-for Apollo Lunar Surface Experiment Package-containing scientific instruments that were left on the moon by U.S. astronauts to send data back to Earth. The first package was solar-powered but relied on two 15-watt radioisotope heater units (RHUs) to keep its instruments warm enough to function. The subsequent packages were each powered by 70-watt SNAP-27 radioisotope thermoelectric generators. The ALSEPs contributed to a significant amount of what we now know about the moon including data on solar wind and radiation, and the observation that the moon is geologically active. The five ALSEP stations were shut down in 1977. Pioneer 10 and Pioneer 11, launched in the early 1970s, were precursors to the Voyager missions that followed. The spacecraft were designed to travel far-each powered by four RTGs and kept warm by 12 RHUs-and to withstand intense radiation from planets further out in the solar system. Voyager 1 and 2 built on Pioneer's legacy in the late 1970s. Taken together, these two missions have yielded some of the most important discoveries in U.S. space exploration history. Each spacecraft uses nine RHUs to stay warm and draws power from three multi-hundred watt radioisotope thermoelectric generators, or MHW-RTGs-a type of power system specific to these two missions. The power systems are still operating today, more than 35 years after they were deployed. As the Voyager spacecraft slowly loses power, mission controllers back on Earth may turn off instruments one by one to conserve energy as long as possible. Viking 1 and 2, launched separately in 1975, were NASA's first effort to harvest data directly from the surface of the red planet. Each mission had

Fig. 6

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

two parts: an orbiter and a lander. Both Viking missions sent back photographs of the surface of the red planet and helped scientists back on Earth learn more about elements present there (carbon, nitrogen, hydrogen, oxygen and phosphorus-all essential to life on our own home planet). The two 42.6-watt RTGs on Viking 1 and 2 were designed to last at least 90 days but lasted for six and four years, respectively.

Interestingly, Viking 1 was not the first spacecraft to land on Mars - although it was the first successful one. A failed Soviet mission touched down on the Martian surface in 1971 but only survived for seconds before losing communication. Between Viking 1 and 2, more than 55,000 images of Mars were transmitted back to Earth-including the first space "selfie" on Mars, taken by Viking 2 itself. The image is one of the most famous pictures in the history of the U.S. space program.

NASA took Mars exploration one step further in 1996, launching the microwave oven-sized Mars Pathfinder rover. Designed to last seven days, the mission endured 12 times longer-demonstrating a cost-effective way to send a scientific mission to the red planet. Pathfinder used solar panels for electric power and relied on three RHUs to keep its scientific instruments warm.

In 2003, NASA separately launched twin rovers Spirit and Opportunity, designed to search Mars for evidence of water, climate changes and other clues that the planet may have once supported life. Both rovers used solar panels for power and RHUs to support on-board scientific instruments. 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[1]. Meanwhile a beryllium core would store heat energy required for the explosive vaporization needed for the next hop. When ready for the next hop, nuclear heat would rapidly vaporize the carbon dioxide, creating a powerful jet to propel the craft up to 1000 meters 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.

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 kilometers, 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 meters. The rover will also be equipped with 16 small stations to study the regolith and seismic activity of the Moon.

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.

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 minimizes 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 and current US programs

Early on, from 1959-73 there was a US nuclear rocket program-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).

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.

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 ionize 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. 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 kilometers and make flybys of the asteroid Braille and the comet Borelly.

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 200 kW 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.

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[2] to transfer energy from the reactor core to make electricity using Stirling or Brayton cycle converters. A smaller version of this kind of reactor is the HOMER-15-the Heatpipe-Operated Mars Exploration Reactor. Another small fission surface power system for the moon and Mars was announced by NASA in 2008.

In 2002 NASA announced its Nuclear Systems Initiative for space projects, and in 2003 this was renamed Project Prometheus and given increased funding. 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. In 2003 Project Prometheus successfully tested a High Power Electric Propulsion (HiPEP) ion engine. This operates by ionizing xenon with microwaves.

More recently space reactors designated as KiloPower by NASA have been developed, 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. 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. 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.

Russian fission systems

Between 1967 and 1988 the former Soviet Union launched 31 low-powered fission reactors in Radar Ocean Reconnaissance Satellites (RORSATs) on Cosmos missions. They utilized 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. 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.

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.

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

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[1] 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.

[2] A heatpipe is a heat transfer device combining thermal conductivity with phase change.

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 was tested in 2018.

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 was developed in 2015, then life-service tests were 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.

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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