Nuclear Power for Space Exploration

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USING its own launch vehicle, India has placed its satellite in geo-synchronous orbit. Also, its successful Lunar mission proves its capability to enter deep space missions. In space research, probably the next major-step for India is its entry into advanced deep-space exploration.

The use of nuclear power appears to be almost inevitable for deep-space exploration.

The purpose of this Article is to discuss the types of nuclear power sources used for deep-space exploration and to review the developments in these by the USA and the former Soviet Union.

Spacecraft Power-Units

For a spacecraft to function in space, different power-supply units are needed to deliver thermal-, electrical-, and mechanical-powers. Thermal-power is required to keep certain compartments of spacecraft at desirable temperatures. Electrical power actuates on-board scientific equipment, cameras, radio communication systems, and computers. And, mechanical power, through thrust force from rocket engines on-board, changes the position of spacecraft as and when needed.

Earth Orbits

For the spacecraft in the Earth orbits (low Earth-orbits and geo-synchronous orbits), thermal- and electrical-power are derived generally from solar power with chemical-batteries backup. And, for the mechanical power, mostly the stored chemicals (propellants) are burned in the chemical rocket engines that accelerate and eject the gaseous products of combustion at high speeds in the form of a jet to produce a thrust force.

Alternatively, under certain special circumstances, the required mechanical power can be obtained from electric rocket engines, powered by the electrical power derived from solar power. These engines accelerate and eject electrically-charged particles at very high speeds in the form of a jet to produce a thrust force.

In all, we see that, for the different power-supply needs, spacecraft in the Earth orbits generally depend on solar power and the chemicals stored on-board.

Deep Space Missions

Apart from the spacecraft in the Earth orbits, there are spacecraft that undertake deep-space missions: lunar and planetary surface missions, and outer-planetary and extra solar-system missions. Considering the present "fast-forward" growth in “space civilization”, such deep-space missions are expected only to increase to larger numbers, that too with heavier payloads.

In the deep-space missions, spacecraft travel to environments where the solar power is either too feeble or too harsh to supply the required electric power — solar power varies as the reciprocal of square of the distance from the Sun.

In this connection, NASA has documented as follows in one of its fact sheets. “Sometimes it is not possible to use arrays of solar cells for space missions. This is especially true when a mission is constrained by being:

(1) too far from the Sun to make use of solar power,
(2) in a space-radiation environment too harsh to allow sustained use of solar cells (e.g., very near the Sun),
(3) landing near a planet’s poles, where solar illumination is insufficient,
(4) in night environments with time frames beyond practical battery capacity, and
(5) on a dust- or cloud-enshrouded world, or in a subsurface application, where the solar power is impractical or impossible.”

Nuclear Space-Power

Among the available power sources from the proven or near-term technologies, the nuclear power is the only one that is available for deep-space missions.

A report of the US National Research Council identifies the nuclear power systems in space as one of six key technologies that the space program will need in the 21st Century.

Nuclear power can be derived from any one of the three types of nuclear reactions:

(1) radioactive decay of a radioisotope such as plutonium-238,
(2) fission of a radioactive heavy-element such as uranium-235, and
(3) fusion of two light elements such as deuterium and tritium or deuterium and helium-3.

Basically, all these reactions are directed to produce energy in the form of useful heat. The technology of realizing this heat in a sustained and controlled manner is available for the first two types. But the technology for the last one is not yet ripe.

While the deep-space missions of low-power demand may use radioactive-decay units, the ones of high-power requirement adopt nuclear-fission reactors.

A radioisotope is an unstable form of an element that decays through radioactivity. More than 1300 natural and manmade radioisotopes have been identified.

For the radioactive-decay unit to produce power in space, the most common radioisotope adopted is the non-weapons grade plutonium-238. This isotope is obtained in a nuclear reactor by irradiating the manmade neptunium-237 with neutrons.

Plutonium-238 (stored in a convenient chemical form, say, plutonium dioxide) slowly decays into uranium-234 releasing ionized high velocity helium particles. Bringing these particles to "rest" using a suitable medium produces useful heat. Half the initial mass of plutonium thus gets decayed in about 87 years and 9 months, the so called "half life".

In view of this relatively long half-life, radioactive decay-units of plutonium-238 are able to supply essentially constant power even for a few tens of years from the beginning to the end of a space mission.

As mentioned previously, heat is required to keep certain compartments of spacecraft at desirable temperatures. For this, the heat from a radioactive-decay unit can be used directly and the unit is known as radioisotope heater-unit (RHU).

A fission of a radioactive heavy-element produces generally two light elements and the heat energy that is much larger than that in a radioactive decayprocess. For example, a single fission in uranium-235 produces about forty times more heat than a single decay does in plutonium-238.

A nuclear reactor is a device in which the nuclear fission takes place in a sustained and controlled manner to release useful heat. Uranium-235, in a convenient chemical form (uranium zirconium hydride, uranium nitride, uranium carbide, uranium molybdenum alloy, or uranium oxide) is adopted in all the space-flown nuclear reactors.

Direct Conversion of Heat to Electricity

The heat energy obtained from the radioactive decay or fission can be directly converted into electricity by the use of either thermoelecric- or thermionic-materials.

In thermoelectric converters, the direct conversion of heat into electricity occurs when the junctions of two dissimilar thermoelectric materials are maintained at two different temperatures — in fact this is the basis for temperature measurement using thermocouples.

For thermoelectric conversion special semiconductor thermoelectric materials have been developed. These materials include lead telluride, silver-antimony-germanium telluride, silicon germanium, and silicon germanium with gallium-phosphorus.

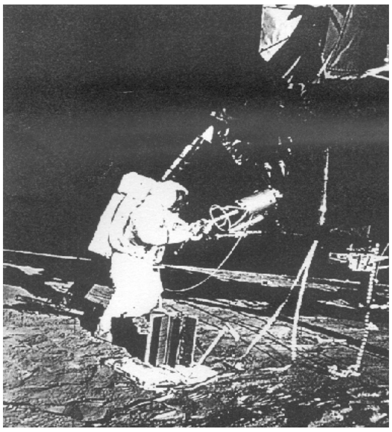
The system that directly converts the heat from radioactive decay into electricity using a thermoelectric material is known as radioisotope thermoelectric generator (RTG). Recently radioisotope units are constructed to supply heat as well as electricity (using thermoelectric materials) and such units are known as general purpose heat source radioisotope thermoelectric generators (GPHS-RTGs).

Recent RTGs developed in the USA have used silicon germanium or silicon germanium with gallium-phosphorus. RTGs of thermoelectric-conversion efficiency of 6 to 7% with specific power of 5 to 6 Watts of electricity per kg of RTG have been used in flights.

However, advanced RTGs, using improved thermophotovoltaics (essentially gallium antimonide photovoltaic cells) or alkali metal thermal-to-electric conversion, are being developed to have specific power of about 13 Watts of electricity per kg.

Thermionic converter is a device that works in a manner similar to that of the vacuum-tubes of yesteryears. In this, electrons are "boiled off" a hot emitter surface (typically of 1500^{o}C) and gathered at a somewhat cooler collector surface (of about 750^{o}C) across a small inter-electrode gap of about half a millimeter. These electrons travel through the complete electrical circuit that has the load.

Tungsten, molybdenum, or rhenium, and niobium or molybdenum can be emitter- and collector-material respectively in thermionic converters.



Apollo 12 mission (November 1969): Astronaut Alan L. Bean is removing the nuclear heat-source module for insertion into the RTG shown in the foreground.

Space Missions

The USA has so far flown one nuclear-fission unit and more than 40 radioactive decay units. And, the former Soviet Union flew six radioactive decay units and more than 30 nuclear-fission units.

Some of the well-known space missions in which the USA has used RTGs are:

(1) Apollo (12, and 14 to 17) for lunar trajectory,
(2) Pioneer (10 and 11) and Voyager (1 and 2) for solar system escape trajectory,
(3) Viking (1 and 2) for trans-Mars trajectory,
(4) LES (8 and 9) for geo-synchronous orbit,
(5) Galileo for trans-Jupiter trajectory,
(6) Ulysses for solar polar orbit, and
(7) Cassini for trans-Saturn trajectory

The maximum power realized in a spacecraft through RTGs is 888 Watts. This is in Cassini spacecraft that was launched in 1997 to reach Saturn by 2004. This spacecraft has three GPHS-RTGs, containing totally 33 kg of plutonium dioxide.

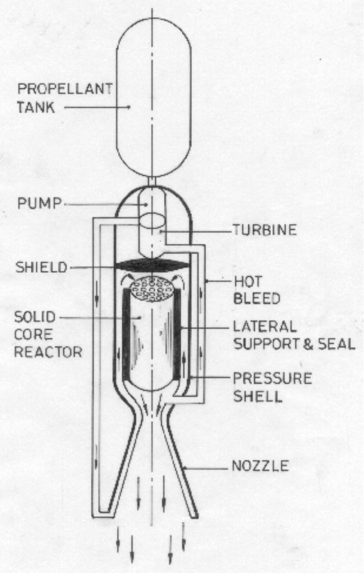
The first and the only nuclear fission reactor flown by the USA is SNAP-10A. This powered the SNAPSHOT spacecraft launched in 1965 into a low Earth-orbit. The reactor unit delivered a maximum 650-Watts of electricity using 1.3 kg of uranium-235 (in uranium zirconium hydride) and 2880 silicon-germanium thermoelectric elements.

SP-100, the ambitious space reactor program by the USA, was carried out from 1983 to 1994 to develop nuclear space-power systems from 10 kW to 1 MW.

At the termination of the SP-100 program, the USA more or less realized the components of a nuclear space-power system that could deliver 100 kW of electricity using 140 kg of uranium-235 (in uranium nitride). The modular construction of SP-100, permits the use of the reactor as a power source to electric rocket engines or as a base electric power station on a planet's surface.

To meet the nuclear power needs in space, while the Americans chose mostly RTGs the Russians opted for fission-reactors. The space reactors of the former Soviet Union are Romashka (0.8 kW), RORSAT (~ 5 kW), and TOPAZ-I (5-10 kW).

All these space-flown Russian reactors use uranium-235 as the fuel and serve as electrical power units. While the first two reactors use thermoelectric materials (probably a combination of lead telluride and silicon germanium), the third one uses thermionic materials.



Schematic sketch of a nuclear rocket with a solid-core reactor — a more advanced version will use a gas-core reactor.

Nuclear Rocket Engine

As previously seen, using the nuclear heat directly or to generate electricity has been well demonstrated in space. In addition, by constructing nuclear rocket engines, this heat can be used to produce large mechanical power.

In a nuclear rocket engine, the heat from nuclear reaction is used to heat up, accelerate, and eject a gas, say hydrogen, at high speeds in the form of a jet to produce thrust force.

During the 1960s, the USA entered into nuclear rocket engine development by its projects named KIWI and NERVA. Almost $1.4 billion (in 1960s dollars) was spent up to 1972 on nuclear rocket engine development.

The nuclear rocket engine had the graphite-based reactor. The final engine used a reactor core containing a mixture of uranium/zirconium carbide in a graphite matrix. At the termination of the projects in 1972, this engine developed about 114 metric ton of thrust for 90 minutes continuously at a specific impulse of 850 seconds and a thrust to mass ratio of 40 N/kg.

A chemical rocket, with its characteristic high thrust-to-mass ratio, can produce practically unlimited jet-power, or in other words unlimited thrust-force. But, it can operate only for a very short duration — at the maximum for a few tens of minutes.

This performance of the chemical rocket engine (practically unlimited power but limited energy) makes it ideally suitable for launching a spacecraft into an orbit against a large gravitational force. But, it does not make it suitable for powering a spacecraft on a deep-space mission

Globally, the most important next step in space exploration is to realize a deep-space mission of a large payload and not too long a mission time (say, a manned spacecraft to Mars with a mission time of a few years). The key to this step lies in finding a rocket engine of reasonably high thrust to mass ratio that can produce reasonably a large thrust force continuously for a long duration (many months).

Among the near-term technologies, a nuclear rocket engine, which basically has no limitation on its energy, will be the best to meet this requirement. Other future technologies, better than nuclear power, may be antimatter or faster than light concepts.

And, to realize these future technologies we "will require technical breakthroughs and safety management that will surpass humanity's technological leap from fire to nuclear power," says Gary L. Bennett, who retired from NASA as its manager of advanced space propulsion systems.

For India to enter into deep space exploration, developing the technology of nuclear thermoelectric- and thermionic-generators appears to be important. This technology may be at least an order of magnitude more complicated than that of "uncontrolled" nuclear power release on the Earth. However, the international objection to this development may be the least, if not altogether absent!

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