Nuclear Technologies for Space Exploration: an overview on nuclear thermal and electric propulsion, radioisotope power generators and fission surface power

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ABSTRACT

Nuclear power sources have enabled or enhanced some of the most challenging and exciting space missions ever conducted. Since 1961, 47 radioisotope thermoelectric generators and 36 space nuclear reactors were successfully flown to provide power for 62 space systems. Yet, the future of nuclear technology for space exploration promises even more remarkable journeys and more amazing discoveries.

Space fission nuclear systems can be divided in radioisotope power generators, nuclear thermal propulsion, nuclear electric propulsion and fission surface power technologies. Space radioisotope power systems use radioisotope decay to generate heat and electricity for space missions. For the last fifty-four years, radioisotope thermoelectric generators (RTGs) have provided safe, reliable electric power for space missions where solar power is not feasible. The new advanced sterling radioisotope generators (ASRGs) are sought to do an even more efficient job on heat and electricity generation for future space missions. But future space missions will need increased power for propulsion and for surface power applications to support both robotic and human space exploration missions. Nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) are the most technically mature, advanced propulsion systems that can enable a rapid access to different regions of interest throughout the solar system. The latter is possible by its ability to provide a step increase above what is feasible using a traditional chemical rocket system. Nuclear fission-based power systems are the best suited power sources for surface missions requiring high power in difficult environments where sunlight is limited and reliability is paramount.

An overlook of such technologies and activities is presented.

KEYWORDS: *space nuclear systems, nuclear, power, space, RTG, MMRTG, ASRG, FSP, NTP, NEP, advanced propulsion, nuclear propulsion, electric propulsion, radioisotope, space exploration.*

INTRODUCTION

The advantage of nuclear power in space applications manifests itself where continuous operation, comparatively high power and the non-dependency of external energy sources is needed. Unlike solar cells, nuclear power systems function independently of sunlight, which is necessary for deep space exploration. Sun intensity reduces as the square of the distance from the Sun and solar panels need to have direct access to sunlight, making them not an alternative for operation during long dark periods. As an example, the solar energy flux on Mars reduces to 50% compared to that available on Earth and in the Jovian system the solar energy flux reduces to ~ 0.3% than that on Earth, Fig. 1.

In space applications, it is a great advantage that a small amount of nuclear fuel produces a large amount of energy (low weight-to-capacity ratio). Therefore, nuclear power systems take up much less space than solar power systems and nuclear spacecrafts are easier to orient and direct in space when precision is needed. Furthermore, space nuclear systems can power life support and propulsion systems effectively reducing cost and mission length.

Power sources can be divided in internal and external sources. Among the former, we find chemical and nuclear energy sources whilst among the latter we find solar and beamed power energy as an energy source, Fig. 2. Depending on the type of nuclear energy conversion, nuclear power systems can be broadly separated in reactor sources and radioisotope sources. The energy released by reactor power sources are orders of magnitude higher than their radioisotope counter-part.

- Power of reactor nuclear sources is determined by the rate of heavy nuclei fission and can be controlled over a wide range.
- Thermal power of isotope sources cannot be controlled and it is determined by the type and quantity of radionuclides and decreases in time due to radioactive decay.
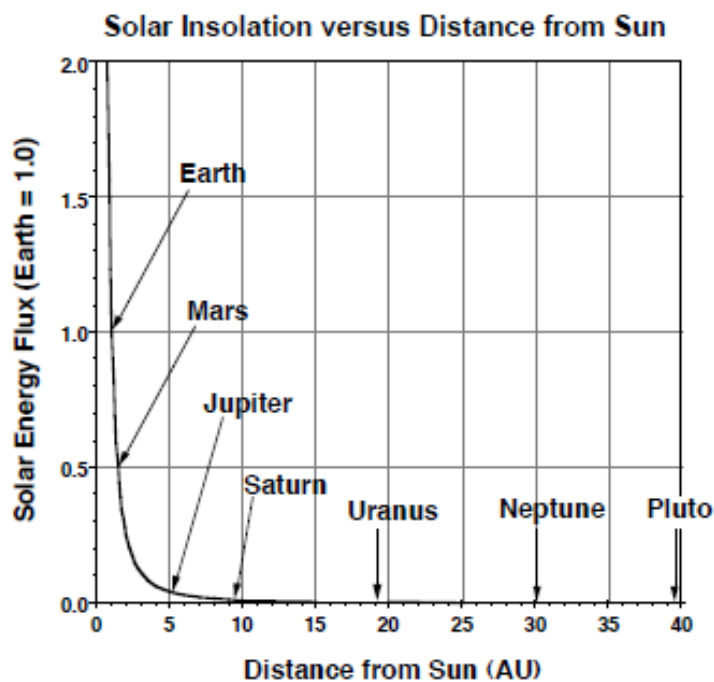

Figure 1 : Solar energy flux as a function of distance from the Sun in astronomical units (Earth = 1 AU). Source: NASA

Independently of the source, nuclear power is converted into the thermal power that can be absorbed by a working fluid to produce thrust, as in the case of nuclear propulsion systems, or converted into

electricity, as in the case of nuclear power sources, through dynamic conversion (i.e. a turbine generator) or by static conversion (i.e. a thermo-ionic convertor or thermo-couples). In general, space fission nuclear systems can be divided in

- radioisotope power generators,
- nuclear thermal propulsion,
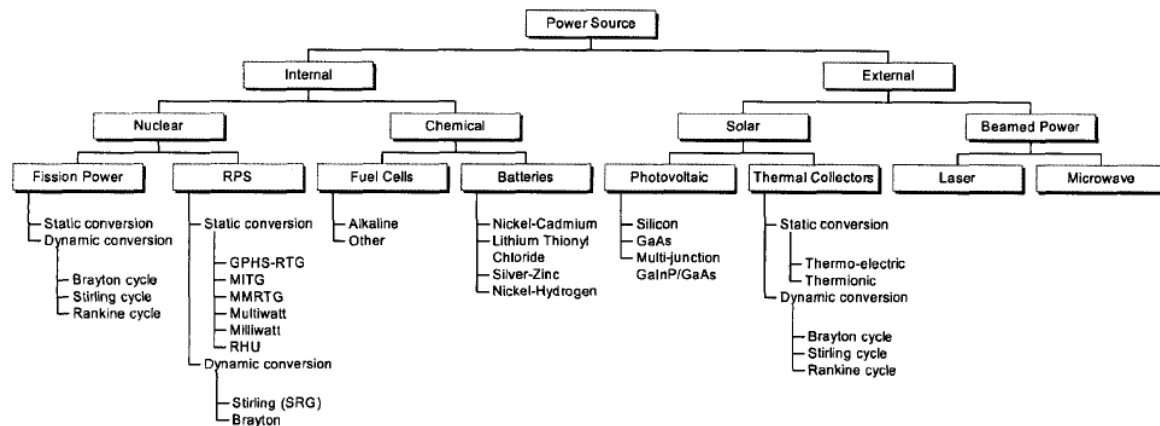- nuclear electric propulsion and
- fission surface power technologies.

Figure 2 : Tree diagram showing internal and external power sources types and their sub-categories.

Since 1961, the United States has successfully flown 45 radioisotope thermoelectric generators (RTGs) and one reactor to provide power for 25 space systems. The former Soviet Union has reportedly flown at least 35 nuclear reactors and at least two RTGs to power 37 space systems. The latter constitutes a total of 47 radioisotope thermoelectric generators and 36 space nuclear reactors successfully flown to provide power for 62 space systems.

RADIOISOTOPE POWER GENERATORS

Radioisotope thermoelectric generators (RTGs) are devices that transform the heat produced by a radioactive source into electricity. This is done by the use of an array of thermocouples through Seebeck effect, which is the conversion of temperature differences directly into electricity. Radioisotope heater generators (GHGs) are devices used only to provide heat for the scientific and technical instruments to operate under the low temperatures found in space. Currently RTGs add the functionality of RHGs to their design.

Alpha emitting radioisotopes, having a long half-life compared to the mission lifetime, are generally considered the most attractive nuclear fuels for space applications because of their relatively low shielding requirements and high power densities. Isotopes must not produce significant amounts of gamma, neutron radiation or penetrating radiation in general through other decay modes or decay chain products which would require heavy shielding. Plutonium-238 has the lowest shielding requirements and longest half-life; its power output is 0.54 kilowatts per kilogram and it needs less than 2.5 mm of shielding, so it has become the most widely used fuel for RTGs, in the form of plutonium(IV) oxide (PuO_2). Its half-life is 87.7 years; it has a reasonable power density, and exceptionally low gamma and neutron radiation levels. Americium-241 is a potential candidate isotope with a longer half-life than ^{238}Pu: 432 years. The power density of ^{241}Am is a quarter that of ^{238}Pu, and because it produces more penetrating radiation through decay chain products than ^{238}Pu, it needs about 18 mm of lead shielding (only ^{238}Pu requires less). RTGs using a material with a half-life λ will

diminish in power output by $1-0.5^{1/\lambda}$ of their capacity per year. We can also calculate the power decay using the equation: $P_1 = P_0 * 0.9919^Y$ where P_1 is the current power output [W], P_0 is the power output when the RTG was constructed [W] and Y are the years since the RTG was constructed (i.e. If a new RTG outputs 470 watts, in 23 years it will output 470 x 0.9919^23 = 470 x 0.83 = 390 W).

The first radioisotope generator, SNAP-3P, was launched in 1961 having a power of only 2.7 W_e while the latest spacecraft using an RTG, the Mars Science Laboratory, was launched on 2011 providing approximately 2000 W of thermal power and 120 W of electrical power. Its multi-mission RTG (MMRTG) uses eight general purpose heat source (GPHS) units with a total of 4.8 kg of plutonium oxide. Curiosity, the Mars Science Laboratory rover, uses one RTG to supply heat and electricity for its components and science instruments.

Stirling radioisotope generators uses free-piston Stirling engines coupled to linear alternators to convert heat to electricity with an average efficiency of 23%. Greater efficiency can be achieved by increasing the temperature ratio between the hot and cold ends of the generator. Vibration can be eliminated as a concern by implementation of dynamic balancing or use of dual-opposed piston movement. To minimize the risk of the radioactive material being released, the fuel is stored in individual modular units with their own heat shielding. They are surrounded by a layer of iridium metal and encased in high-strength graphite blocks. These two materials are corrosion and heat resistant. Surrounding the graphite blocks is an aero-shell, designed to protect the entire assembly against the heat of re-entering the Earth's atmosphere. The plutonium fuel is also stored in a ceramic form that is heat-resistant, minimising the risk of vaporization and aerosolization. The ceramic is also highly insoluble.

Figure 3 : In the clean room at NASA's Kennedy Space Center's Payload Hazardous Servicing Facility, technicians prepare the New Horizons spacecraft for a media event. The RTG seen in this picture is only a mock-up. The real RTG was installed shortly before launch. Photo: NASA.
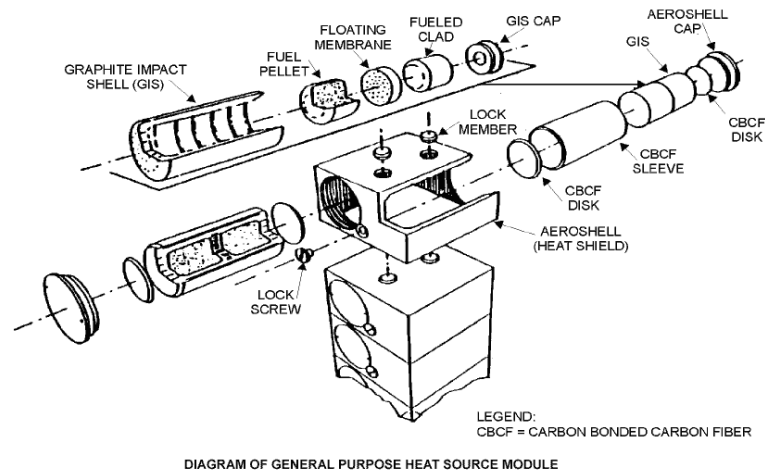
Figure 4 : Diagram of general purpose heat source module used in RTGs. Courtesy: NASA.
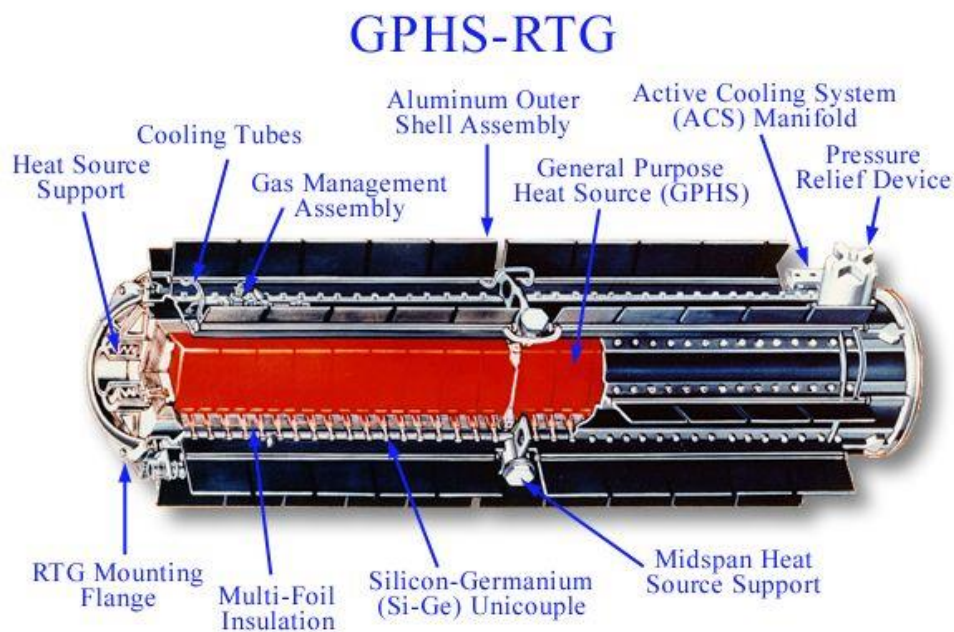

Figure 5 : A cut drawing of the general purpose heat source (GPHS) - RTG used for Galileo, Ulysses, Cassini-Huygens and New Horizons space probes.

FISSION SURFACE POWER

Currently, power is usually generated in space by solar arrays that convert the Sun's energy into electricity or by radioisotope power systems that convert the heat from naturally decaying plutonium-238 into electricity. In order to meet the large power needs for some future NASA missions, solar or radioisotope power systems may be impractical. Space missions will need increased power for propulsion and for surface power applications to support both robotic and human space exploration

missions. Nuclear fission reactors are the only reliable power source where sunlight is limited. These reactors are small modular reactors (SMR) with a minimum requirement of 3kWe and an average of a 30 - 40 kWe system with 8 or 9 years design life suitable mainly for lunar and Mars surface applications. For the particular case of lunar surface applications an emplaced configuration with regolith shielding augmentation permits near-outpost sitting (<5 rem/yr at 100 m separation).
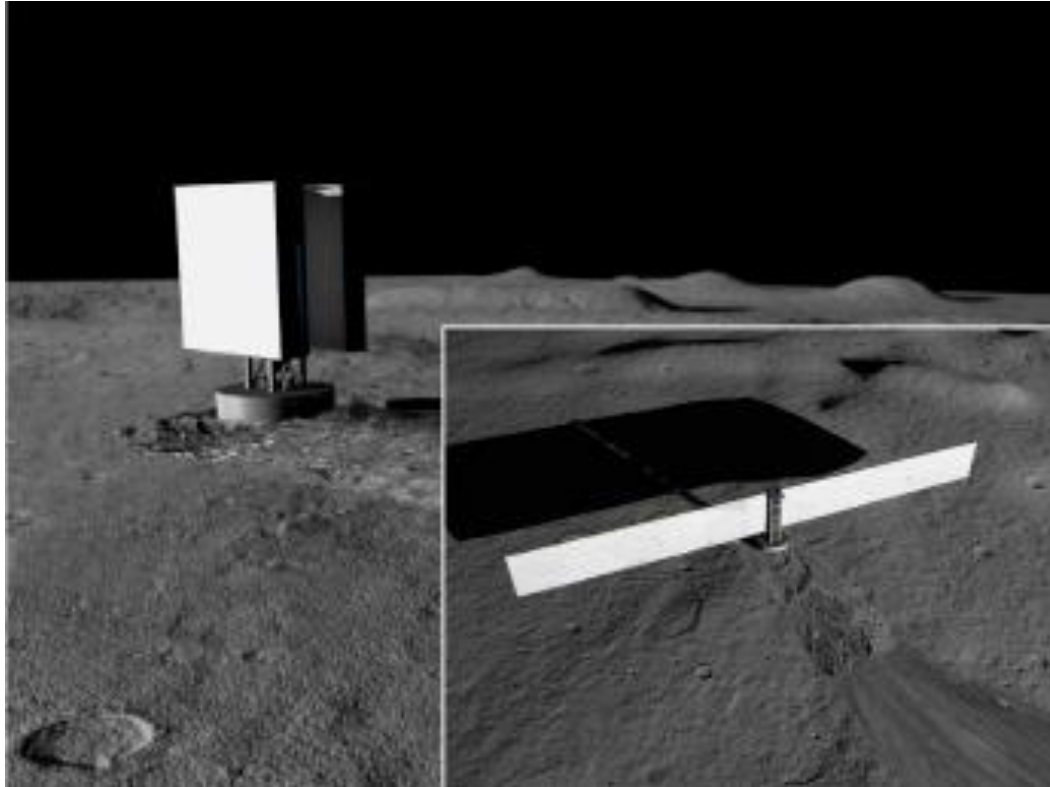

Figure 6 : Artistic representation of the NASA/U.S. DoE Fission Surface Power technology unit.

These FSP units should be low temperature, low development risk, liquid-metal cooled reactors and of stainless steel construction. The best options for the nuclear fuel are uranium oxide or uranium metal fuel in stainless steel cladding. Both fuels have extensive fuel performance databases and both fuels bound anticipated performance range for FSP. Uranium oxide is the preferred option mainly for three reasons: it is used as the standard for commercial reactors, the technology is well understood and few commercial entities (none in the United States) are currently making oxide pellet fuel using highly enriched uranium. The flow rate for small 40 kWe FSP units as the one designed by NASA/DoE, Fig. 7, is in the order of 80 gpm or $5.03 \ 10^{-3} \ m^3$/s and the operating temperature in the order of 850K. The working fluids considered for FSP units are Na, Li and NaK78. The disadvantage of NaK78 compared to the other options is the fact that it requires more pumping power than Na or Li but when we study other characteristics of these liquid metals we find a series of advantages that NaK78 has over the other elements for space applications. Among the characteristics that lead to the selection of NaK78 as the working fluid are:

- NaK78 is liquid at 261K while Li at 454K and Na at 361K;
- Li readily dissolves Nickel at the temperature of interests so it is not suitable to use with steels or super-alloys;
- Neutron capture of ^{6}Li and ^{7}Li produces He gas that would have to be removed from the reactor in space;
- NaK78 activates less strongly than Na.

The heat differential between the 850 K operating temperature and the outside temperature would drive two complementary Stirling engines to turn a 40 kWe generator. Some 100 m^2 of radiators would remove process heat to space.
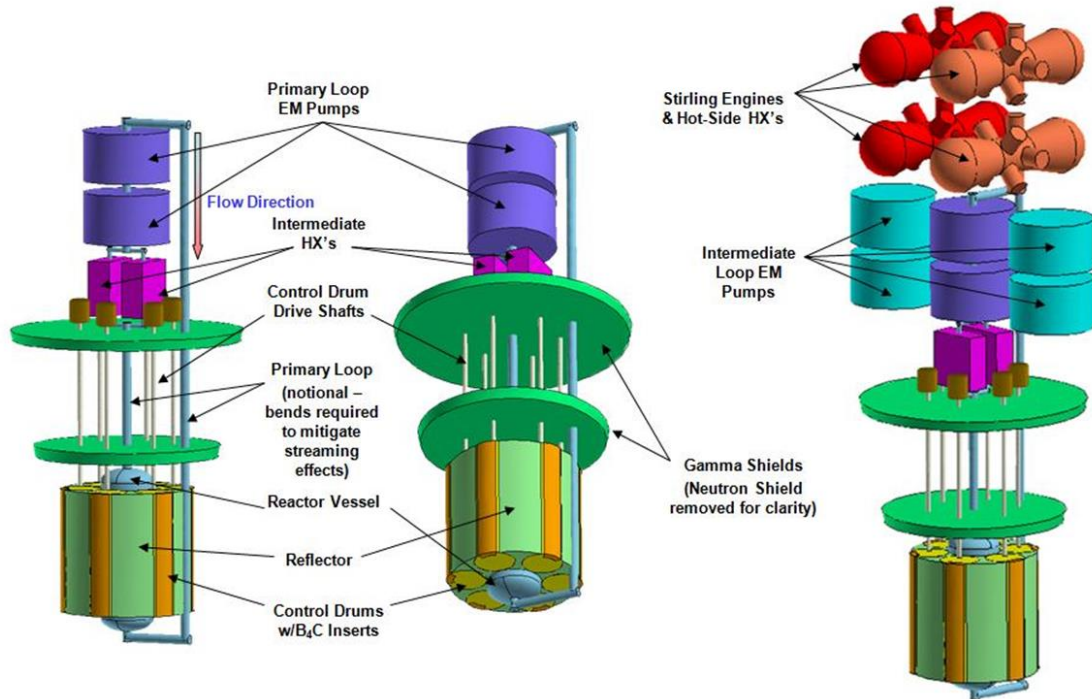

Figure 7 : Internal view of the systems that compose the NASA/DoE Fission Surface Power (FSP) technology units.

NUCLEAR THERMAL PROPULSION

Chemical rocket propulsion has been the main method of space propulsion: the combustion of a propellant, consisting of fuel and oxidizer components, produces a high speed fluid exhaust that is released by the rocket engines producing thrust. Although this method seems to work extremely well, it has limitations. These limitations make more demanding missions, such as trips to Mars, cumbersome and extremely inefficient. One way to overcome such limitations is the use of nuclear thermal rockets. While in chemical rockets hot gases are created by chemical combustion, in nuclear thermal rockets the hot gas is created by heating the propellant in a nuclear fission reactor.

The ratio of the amount of thrust to the amount of fuel is one key factor when determining a rockets overall effectiveness; this ratio is called the specific impulse. The specific impulse, I_{sp}, is defined as the change in momentum per unit mass of propellant and has SI units of m/s (thrust [Newtons]/mass flow rate [kg/s]) which can be normalized using g_0 (mean acceleration of gravity at Earth's surface) to obtain the engineering units, seconds. In the case of a chemical rocket, the specific impulse is around 500 s while in a nuclear thermal rocket is around 1000 s. The specific impulse, a measure of engine performance, increases with higher chamber temperatures and lower-weight exhaust gases. Higher specific impulse results in decreased amounts of propellant needed for a given mission.

The basic nuclear thermal rocket engine concept consists of a nuclear reactor heating a low molecular weight gas such as Hydrogen, H_2, to the highest possible temperature, a nozzle for gas expansion and a pump (usually electromagnetic) to make the propellant and cooling circulate through the system. The thrust may be augmented even more by injection of liquid oxygen into the supersonic hydrogen exhaust. In practice, the design becomes quite complex due to the efficiency, weight, temperature and

power density requirements. Bimodal versions run electrical systems on board a spacecraft, including radars, as well as provide propulsion.

Testing on nuclear thermal propulsion (NTP) systems began in the 1960's when the former Soviet Union was searching for a better way to reach space. In the middle of the cold war and in the beginning of the space race, the United States created the program Nuclear Engine for Rocket Vehicle Application (NERVA) in the late 1960's, Fig. 8 . After a few years of development, the engine was built and tested by NERVA in a remote desert area, with very promising results. NERVA demonstrated that nuclear thermal rocket engines were a feasible and reliable tool for space exploration and at the end of 1968 the U.S. Space Nuclear Propulsion Office certified that the latest NERVA engine, the NRX/XE, met the requirements for a manned Mars mission. The NERVA NRX/EST engine test objectives included:

- Demonstrating engine system operational feasibility
- Showing that no enabling technology issues remained as a barrier to flight engine development.
- Demonstrating completely automatic engine start-up.

The objectives also included testing the use of a new facility for flight engine qualification and acceptance. Total run time was 115 minutes, including 28 starts. The Rover/NERVA program accumulated 17 hours of operating time with 6 hours above 2000 K.
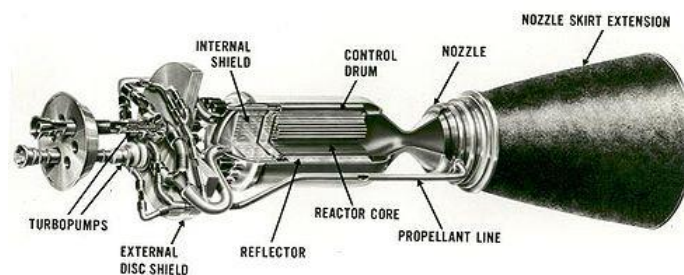

Figure 8 : NASA NERVA diagram

Several other designs have been made during the years, including small nuclear thermal propulsion engines with an approximate weight of 800 kg but political and financial constraints have always limited the development of NTP. The current interest in developing a human mission to Mars made public the inadequacy of pure chemical propulsion systems for space exploration missions to Mars and beyond. The United States space agency, NASA, has partnered with the U.S. Department of Energy and private organizations to continue investigating and to develop nuclear space systems in general and nuclear propulsion systems in particular. This project will test power conversion and thermal management technologies for in-space nuclear power and propulsion systems during the years 2012-2017. Non-nuclear testing will validate the performance of integrated systems. Over the five-year budget, the project will address five project elements: thermal power conversion, thermal management systems, reactor simulators, thermal propulsion and fission reactors.

NUCLEAR ELECTRIC PROPULSION

In nuclear electric systems, nuclear reactors are a heat source for electric ion drives expelling plasma out of a nozzle to propel spacecraft already in space. Magnetic cells ionize hydrogen or xenon, heat it to extremely high temperatures (millions °C), accelerate it and expel it at very high velocity to provide

thrust. Nuclear electric propulsion (NEP) is a combination of magnetoplasmadynamics (MPD) and nuclear power systems. Nuclear power systems are the only alternative for any thruster that consumes more than 100 kW of power. A nuclear electric propulsion system uses a nuclear heat source coupled to an electric generator. The power processing unit converts the electrical power generated by the power source into the power required for each component of the ion thruster. It generates the voltages required by the electromagnetic optics, the discharge chamber and the high currents required for the hollow cathodes. The power management system controls the propellant flow from the propellant tank to the thruster and hollow cathodes. Typically, NEP and NTR can accomplish the same lifting task with similar mass in LEO. When compared to chemical propulsion, NEP was found to accomplish the same missions with 40% less mass in LEO.

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is based on systems for magnetically-confined fusion power 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 high thrust operation is possible. It is very efficient, with 99% conversion of electric to kinetic energy and specific impulse of 5000 s. VASIMIR is a design for heavy orbit transfer from Low Earth Orbit (LEO).
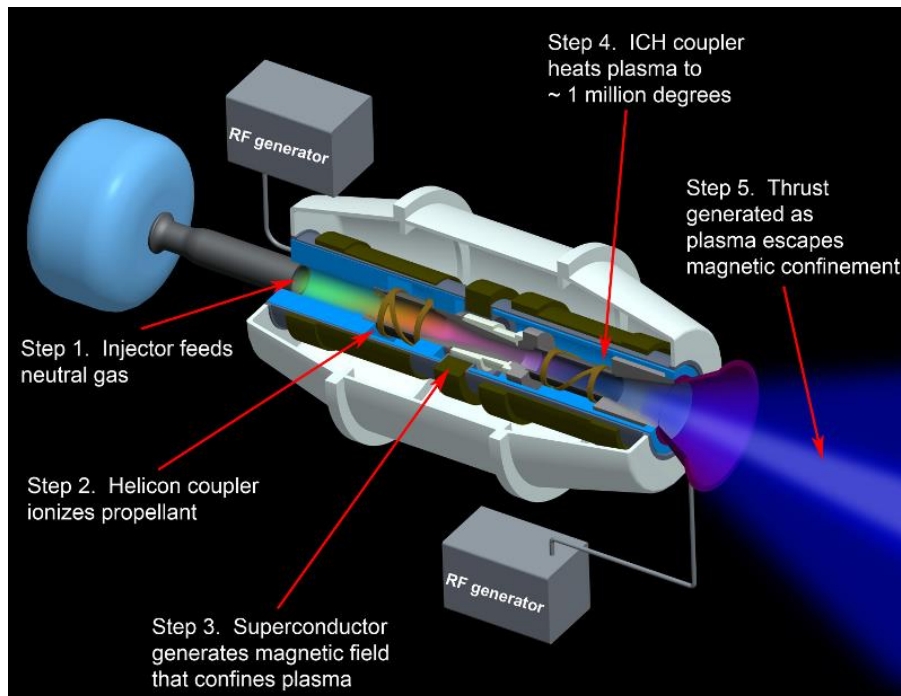

Figure 9 : VASIMIR concept. Courtesy: Ad Astra Rocket Company.

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