Nuclear Propulsion in Space

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1. Introduction

Much has been said and only some has been implemented in utilizing nuclear, as a means of propulsion for space exploration. In most cases the term nuclear has been associated with fission, fusion and weaponry; therefore, a definition is warranted for nuclear, that states "…. anything that relates to, or pertains to, the nucleus of an atom."

This treatise will discuss any component of an atom that would, or may, produce propulsive energy. The sources are;

- The ionization of gases, or metals, which are then ejected, they are known as ion thrusters.
- Hydrogen, super-cooled to be metallic; still under laboratory tests.
- Radioisotope decay of Plutonium-238. But that is only a heat source and thrust is required for propulsion. Hence, a means of converting heat into electrical generation is used in combination with any of the above methods is used to provide thrust.
- Generating Power from Pu-238.

1.1 Historical

The idea of using nuclear energy (from weaponry) as a mode of propulsion in space was promoted decades ago but was not pursued for technical and impractical reasons. In the USA, a more vigorous approach was taken in 2003 with Project Prometheus to develop nuclear powered systems for space applications and even had a budget of US$430M. That project was demised in 2006.

More pragmatic approaches were develop ion propulsive systems; with electrical power from RTGs (Radioisotope Thermoelectric Generators) based on radioactive decay of isotopes where the decay heat converts directly to electricity.

2. Ion thrusters

A propellant, often xenon gas, is ionized by stripping its electrons to become a plasma. This can be done via radio waves applied to the gas, or by high energy electron bombardment of the propellant gas. Its electrons are released and the atom becomes a positively charged plasma that is affected by electric and magnetic fields. The plasma is then accelerated to about 145000 kph as an ion beam and ejected via magnetic fields to produce thrust. The assembly incorporates a hollow cathode that expels an equal amount of electrons to neutralize the exhaust beam without which a negative charge would eventually build up in the spacecraft and draw the ejected ions back to the spacecraft …. and that, reduces the thrust. A comparison of some ion thrusters is shown in Table 1 with the power required to produce an amount of thrust.

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Table 1 Test Data Comparisons of Some Ion Thrusters				
Engine	**Propellant**	**Specific Impulse I_{sp} (s)**	**Power (kW)**	**Thrust (mN)**
NEXT	Xenon	4190	6.9	236 max.
Annular Engine	Xenon	5000	14	under test Ref. 3,4
VASIMR	Argon	3000-30000	200	~5000
Hall Effect	Bismuth	8000	140	2500
Hall Effect	Xenon	2900	75	2900
Dawn Spacecraft	Xenon	3100	Solar Panels	90
Specific Impulse (I_{sp}) is a way to describe the efficiency of a rocket. It represents the impulse (change in momentum) per unit amount of propellant fuel used. The higher the specific impulse, the less propellant needed to gain a given amount of momentum. The units are Time i.e. in seconds.				

Another comparison is made for different types of propulsions. Fig. 1 shows the I_{sp} (Specific Impulse) for ion engines is high enough to be a good candidate for propulsion. NASA's ion thrusters are used to keep over 100 geosynchronous satellites in desired location and orbits.

2.1 Forthcoming Ion Thrusters

NASA is currently evolving two other versions of ion thrusters, viz. the NASA Evolutionary Xenon Thruster (**NEXT**) and the **Annular Engine**.

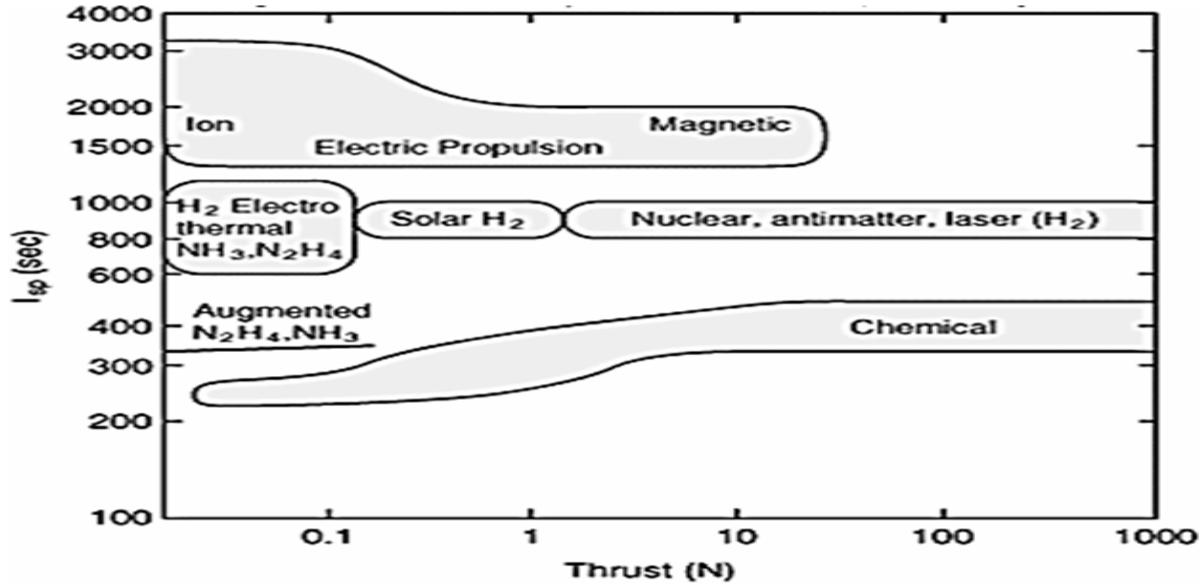

Fig. 1 I_{sp} for Different Propulsion Systems and Their Range of Thrust. *Source JPL Refs. 1, 5*

NEXT, Fig. 2 is three times more powerful than the ion engine that launched the Dawn mission in 2007 to Ceres and to Vesta in the Asteroid Belt between Mars and Jupiter. NEXT has logged 51000h (about 6y) of ground tests without failure Ref. 2. Table 1 shows its performance. Xenon propellant is ejected by a High Pressure and by Low Pressure gimballed assemblies to provide improved maneuverability. The **Annular Engine** is a follow-on to NEXT and works on the same principle but the thrusters are built on an annulus that gives a flatter ion plume thereby giving more thrust Ref. 3. Performance is compared in Table 1; and it is already patented.

VASIMR Variable Specific Impulse Magnetoplasma Rocket, was invented by an ex-astronaut of multiple missions, Franklin Chang Diaz. It uses Argon, Xenon or even Hydrogen as the propulsive medium. The propellant is ionized by radio waves, RF couplers, that turn the cold gas into superheated (>5800 °K) plasma; and that is channelled through a nozzle to produce thrust Fig. 4. A second coupler heats the plasma to some 10M °K. Magnetic field lines accelerate the plasma to some 180000 km/h and ejected to produce thrust.

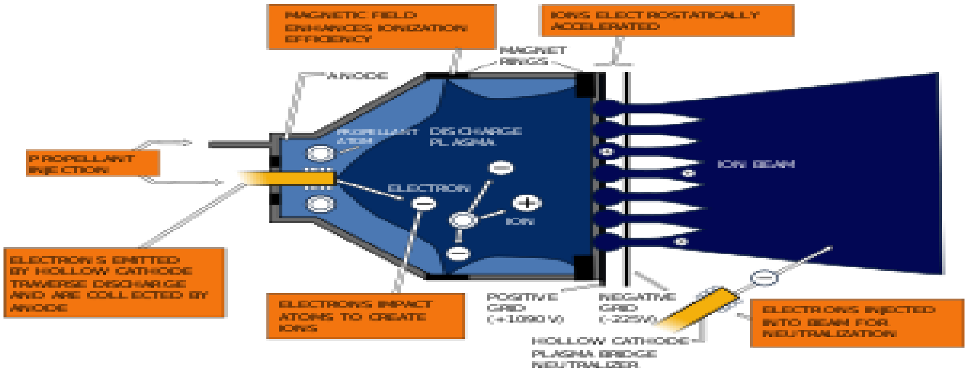

Fig. 2 NASA’s Evolutionary Xenon Thruster *Source NASA Glenn Research Center*

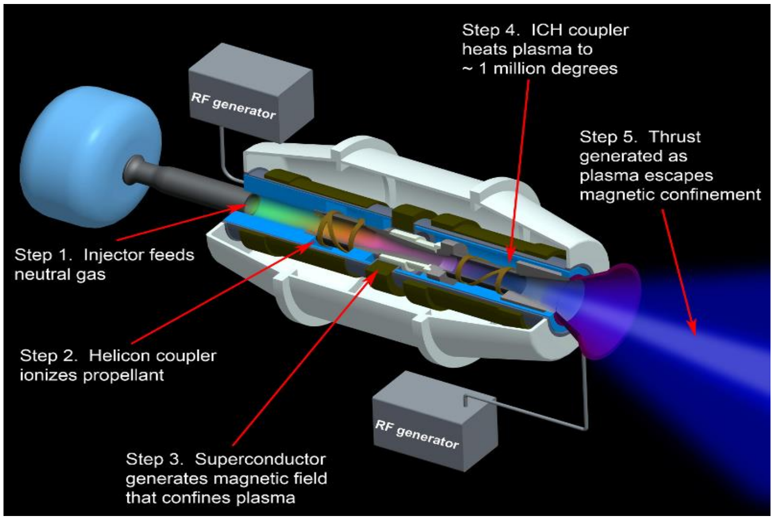

Fig. 4 The VASIMR Ion Engine Showing Its Components.
Source Ad Astra Rocket Co.

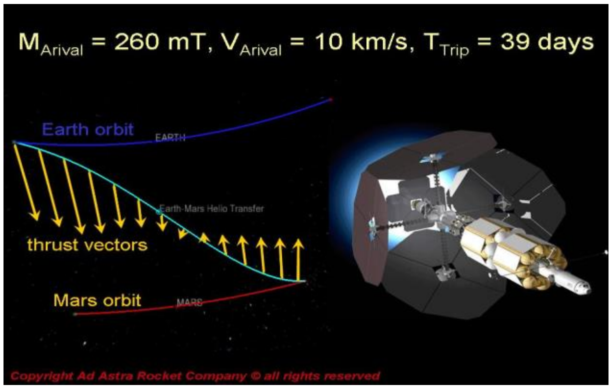

Fig. 5 Accelerate Then Decelerate on route to Mars by VASIMR *Source Ad Astra Rocket Co.*

VASIMR is powered by solar panels. These gradually lose effectiveness as the spacecraft gets further from the sun. Hence its operation is limited to the inner planets but would most likely be used to clean up the space debris circling Earth. It is claimed that spacecraft speeds of 10 km/s are achievable and can get to Mars in 39 days Fig. 5. Nuclear power, described later in the text, is considered if the VASIMR engine is to fly further afield into space.

Hall-effect thrusters: In this format electrons are entrapped in a magnetic field and then used to ionize a propellant creating a plasma. The plasma is then accelerated to produce thrust. The ejected ions are also neutralized in the plume. Hall thrusters are able to accelerate their exhaust to speeds between 10 and 80 km/s, having a specific impulse of 1,000–8,000 s. Most models operate between 15 and 30 km/s i.e. with a specific impulse of 1,500–3,000 s. The thrust produced by a Hall thruster varies depending on the power level. Devices operating at 1.35 kW produce about 83 mN of thrust. Typical values are shown in Table 1. High-power models have demonstrated up to 3 N in ground tests. Power levels up to 100 kW have been demonstrated by xenon Hall thrusters.

Hall Effect Xenon Thrusters. Xenon is preferred. It is easily ionized, has a high atomic mass and can generate a desirable level of thrust when ions are accelerated. It is also an inert gas, has a high storage density; therefore, it is well suited for storing on spacecraft and is most suitable as a propellant.

Hall Effect Bismuth Thruster. Bismuth is the next favoured propellant because it has a larger atomic mass, is cheaper to use, is plentiful, and has a larger cross-section area for easier impact ionization i.e. bombarding with electrons. It is heated to above its melting point of 271 °C, channeled to a chamber where impact ionization occurs. The vaporized bismuth is then accelerated and discharged. The discharge duct is heated to prevent bismuth condensation.

DAWN Mission. The Dawn Mission spacecraft that orbited the mini planets of Ceres and Vesta was empowered by a propulsive system shown in Fig. 5. This system is noted for its efficiency. It comprises three 30 cm diameter thrusters movable in two axes. Any two units can operate and one is spare. They are powered by solar panels. After the beam is accelerated and ejected electrons are injected into the beam to neutralize the plasma. Speeds of 7-10 times that by a chemical rocket were achieved by using a mere 3.25 mg/s of xenon at maximum thrust. The Dawn spacecraft carried 425 kilograms of xenon propellant at launch. Each unit produced 90 mN (millinewtons) of thrust Ref. 5, about a force of holding a single piece of note paper. Not much, but over hundreds of days …. the thrust mounts. Power is/was from two solar panels, each being 8.3m x 2.3m and each is covered by 5740 photo voltaic cells. The conversion of solar energy into electricity is about 28%. On Earth they can produce 10 kW.

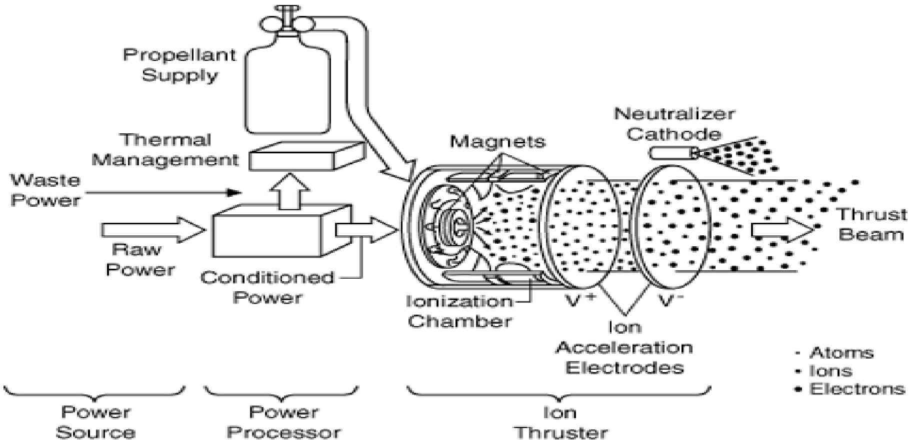

Fig. 5 The DAWN Mission Ion Thruster

3. Metallic Hydrogen

Is another means of propulsion under study at Harvard University is metallic hydrogen as an alternate power source. Hydrogen is a common element on Earth and in space. In its super cold liquid form, it has been used to propel rocketry and also used in semiconducting material. Hydrogen can be cooled even further, and when subjected to extremely high pressures it freezes into a metallic solid form. A comparison of pressures are shown in Table 2 where the Carnegie Institution achieved a pressure of 50 million psi by using diamond anvils, Fig.6, to squeeze the element. The elements displayed different characteristics e.g. Oxygen turned blue, then scarlet and finally into a shiny metal. The anvil uses two diamonds, each a quarter of a Carat and shaped to cupped points. Pressure is applied as in a vertical vice and as the atoms are squeezed electrons are squirted into different locations in the lattice work turning some atoms into superconductors transmitting current without resistance. This transformation seems to occur about 45 Mpsi for Oxygen where it turns into a shiny metal like steel and having a high reflectivity of 0.91. This phenomena was not fully observed in hydrogen, yet Harvard physicists Diaz and Silvera, stated that metallization occurs between 465 and 500 GPa

Table 2. Pressure Comparisons

Location	Typical pressure psi lbs/sq. in.	Typical Pressure Kg/sq. cm
At sea level	14.7	1.03
Marianna Trench deepest with 7 miles of water above it	7 miles of salt water 8 tons=17920 lbs/sq.in	1260
Carnegie Institution diamond anvils	50 M	3.52 M
Centre of Jupiter	10^9	0.72 x 10^9
Neutron Star	10^{21}	0.72 x 10^{21}

(67.44 Mpsi and 72.52 MPsi) at 5.5 °K. [Ref. 6], [Ref. 7]. The energy density can be about 270 kJ/cm^3 which would be about 35 times more explosive than TNT. Their experiments have yet to be verified.

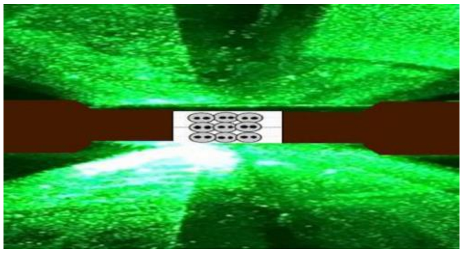

Fig. 6 diamond anvils shaped to a point with a sandwich of gas in-between

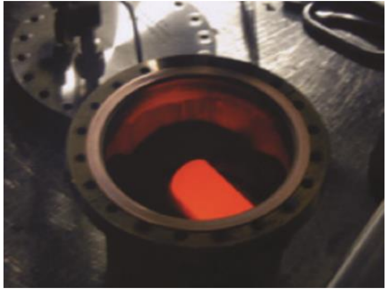

Fig. 7 Pu-238 glows by its own decay heat. Melting point of Pu-238 is 639.5 °C

4. Radioisotope decay

Plutonium Pu-238 was selected in preference to Pu-239 because it releases greater energy per disintegration as it decays. Another criteria of selecting Pu-238 is that it cannot sustain a nuclear reaction and hence cannot be used in a nuclear reactor nor in a nuclear weapon.

A comparison of energy released per disintegration is compared:
Pu-238 β decay to U-234 releases 5.593 MeV per disintegration
Pu-239 β decay to U-235 releases 5.245 MeV per disintegration

Even the small amounts indicated per disintegration add up; and a small slug of P-238 can glow by its own, steady decay heat Fig. 7.

Pu-238 is an abundant Alpha emitter (second only to Polonium). It is processed in a ceramic format into PuO_2 where its decay heat is converted to provide electrical power via the Radioisotope Thermoelectric Generators (RTGs). The rationale of the ceramic format is that in case of accidents, it is less likely to release powdery alpha emitting particles that can be lethal to humans if inhaled or ingested. The PuO_2 is further contained within a cladding of iridium-based DOP-26 alloy.

4.1 Energies expected in PU-238

The decay heat of Pu-238 is 0.56 W/g (compare densities: Pu = 19.86; PuO_2 = 11.5; water = 1). This enables its use as the heat source in RTGs (Radioisotope Thermoelectric Generators) to generate power to cardiac pacemakers, space satellites, navigation beacons, and has powered some 30 US space vehicles including the Voyager spacecraft. The Cassini spacecraft carries three generators with 33 kg of plutonium oxide providing 870 watts power as it orbits around Saturn.

More efficient versions of Multi-Mission RTG's (MMRTG) use eight 290-watt RTG units with a total 4.8 kg of plutonium oxide to produce 2 kW_t thermal that can be used to generate some 110 watts of electric power, at 2.7 kWh/day. This powers the rover Curiosity on Mars which weighs 890 kg. The modus operandi is that the decay of Pu 238 produce a bounty of alpha. When enclosed in a noble gas, the alpha strips the gas of electrons which then migrate to an anode, generating electricity. Decay heat is also used keep the instruments warm within their operating range.

4.2 Scarcity of Pu-238

Due to non-proliferation treaties both Russia and the United States stopped producing Pu-238. But Fig. 8 shows that demand is depleting the inventory and outstripping supply. In February 2017 Ontario Power Generation and its venture arm, Canadian Nuclear Partners, announced plans to produce Pu-238 for space exploration at the Darlington nuclear power plant. OPG is now seeking regulatory approvals to begin Pu-238 production by 2020, using a similar process that produce cobalt-60 at the Pickering units. Ref.8.

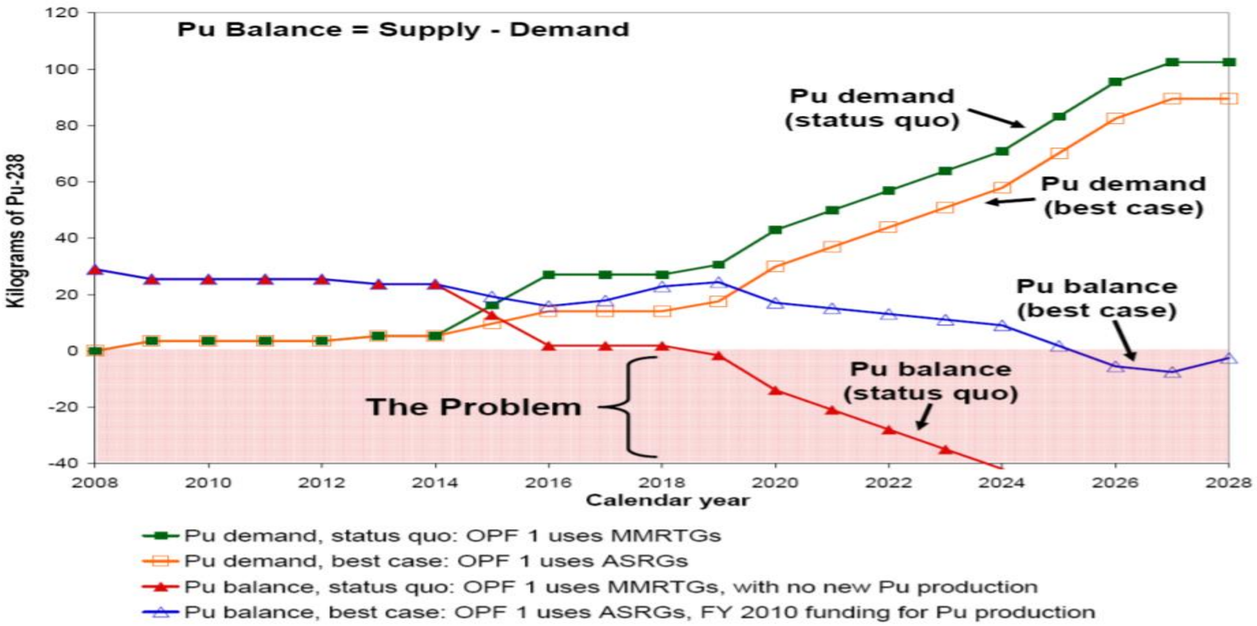

Fig. 8 Projected Demand for Pu-238. Current production is ~1.5 kg/a. the DOE demand is 5 kg/a leading to severe shortages. *Ref. 9*

4.3 Inventory and Requirements

Pu-238 used in American spacecraft has been purchased from Russia since 1993 totaling 16.5 kg produced at Mayak. The US will soon take delivery of Russia's last shipment, Ref. 9. By Mar. 2015, only 35 kg of Pu-238 was available for civil space uses but only half of this supply meets the power specifications. However this is sufficient to power the 2020 Mars Rover Mission. It is anticipated that Pu-238 production at the Darlington nuclear station will help boost the dwindling supply of this material.

ORNL (Oak Ridge Nuclear Labs) also announced on 22 Dec. 2015 that it had successfully produced 50 gm of Pu-238. This production will be scaled up to 300-400 gm/a, and with further automation will be increased to about 1.5 kg/a. The DOE requirement is 5 kg/a.

4.4 How to produce Pu-238

Pu-238 was first synthesized in 1940 by Nobel Laureate Glenn Seaborg by bombarding Uranium-238 with Deuterons (Heavy Water hydrogen) to obtain Neptunium. The method nowadays is to start with the fissionable U-235, irradiate it to U-237 which decays (6.75 days) to Np-237, which in the oxide form, is mixed with Aluminum and pressed into pellets. As per equation sequence below, Neptunium-238 is only an intermediate product which then beta decays to form Pu-238. In usage the Plutonium-238 (half-life 87.7 years) then decays to Uranium-234 and then follows the decay chain series to eventually become Lead-206 after eons of time.

$$^{235}\mathrm{U} + {}^{1}\mathrm{n} \longrightarrow {}^{236}\mathrm{U}_{m\ (120\ ns)} \longrightarrow {}^{236}\mathrm{U} + \gamma$$

$$^{236}\mathrm{U} + {}^{1}\mathrm{n} \longrightarrow {}^{237}\mathrm{U}\ (6.75\ days) \xrightarrow{\beta^{-1}} {}^{237}\mathrm{Np}$$

$$^{237}\mathrm{Np} + {}^{1}\mathrm{n} \longrightarrow {}^{238}\mathrm{Np}\ (2.1\ days) \xrightarrow{\beta^{-1}} {}^{238}\mathrm{Pu}$$

4.5 Generating power from Pu-238

A Radioisotope Thermoelectric Generator (RTG, RITEG) is designed for the purpose. In reality this is an array of thermocouples converting the decay heat released by the PU-238 into electricity by the Seebeck effect. Silicon-Germanium thermocouples were used. This format of generator has no moving parts.

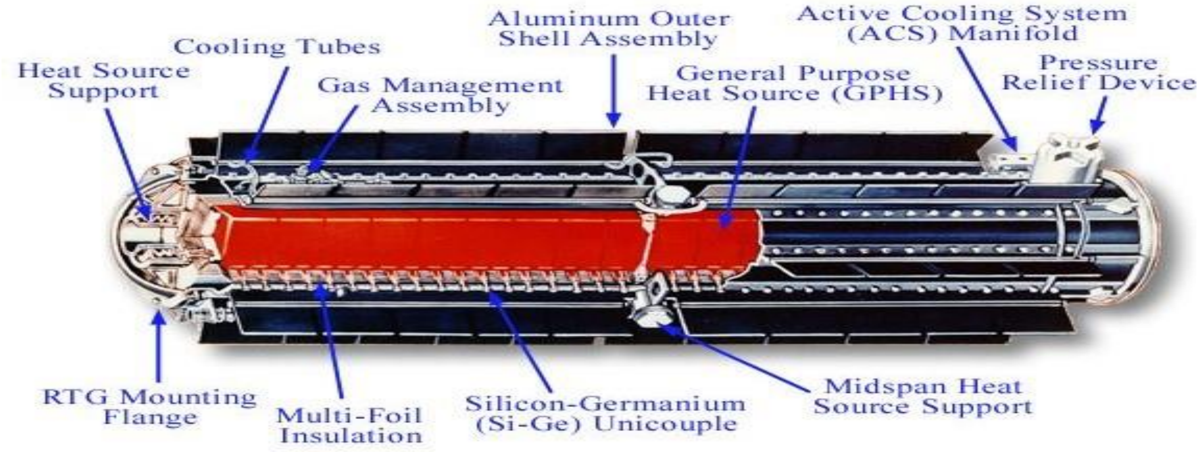

Fig. 9 Radioisotope Thermoelectric Generator using an array of thermocouples to convert the decay heat into electricity. It weighs 55.9 kg and has no moving parts. The dimensions are 1.14 m long, 0.422 m dia. and uses 572 thermocouple elements. Hot junction at 1000 °C and cold junction at 233 °C. Total Power per RTG is around 4410 W_t. the PU-238 is enriched to around 83.5% whilst the decay rate is 0.8%/a approximately *Source JPL-NASA-DOE*

The RTG in Fig. 9 powered the Galileo mission to Jupiter at a cost of US$1.6B, and the European Space Agency (ESA) mission Ulysses to orbit the Sun. Galileo was launched on October 18, 1989 and arrived at Jupiter on December 7, 1995. It was powered by two RTGs, each mounted on a 5-metre long booms Fig. 10, and carried Pu-238 fuel in the ceramic oxide format producing 245 W_t (thermal Watts). It reached a maximum speed of 173800 km/h and orbital speed of 48 km/s around Jupiter.

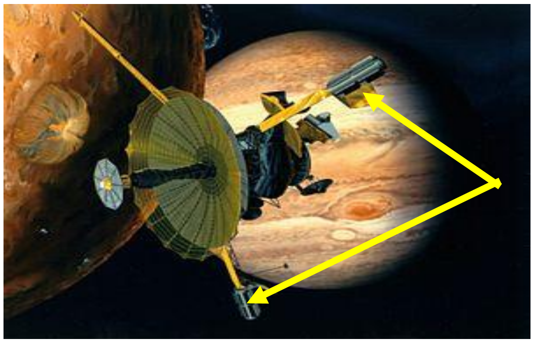

Fig. 10 Galileo Spacecraft Showing Two RTG's. Each is Mounted on 5 m Long Booms.*Source JPL-NASA*

The Mars rover Curiosity used a Multi Mission RTGs (MMRTG) with 768 thermocouples encircling the Pu-238 that generated the heat a steady 110 watts. More efficient power conversion modules are being researched to achieve a higher power output using new materials and alloys. This is the Enhanced Multi Mission Radioisotope Thermoelectric Generator (eMMRTG) which could be aboard NASA's next mission, named InSight launch date in 2018. It would provide 25% more power, degrade more slowly and still have 50% more power at the end of a 17 year design life.

4.6 Performance under radiation

The decaying PU-238 is also a source of neutron radiation. A test unit of the RTG in Fig. 9 showed a rate of neutrons release of 5.9 x 10^3/s per gram of Pu-238. In that configuration, the neutron rate varied from

0.2 – 0.5 mSv/h. The gamma dose rate also varied from 0.05 mSv/h (twice allowable in nuclear power plants) to 0.10 mSv/h. These are not considered high on radiated equipment.

Table 3. RTG Power for Space Missions

Mission	Destination	Longevity After BOM	Quantity of Pu-238	BOM Electrical Output	Flight Mass kg	Operating Voltage	Internal Resistance OHMS
Galileo	Jupiter orbiter	4.2 years (71000 h)	8.1 kg per RTG	470 We for **two** RTG's	55.95	30	2.197
Ulysses	Sun's Polar Mission	4.7 years(42000 h)	8.1 kg per RTG	245 We	55.81	28	2.279
Cassini	Saturn and Moon Titan	At BOM After 16 y	8.1 kg per RTG	826 We 596 We	56.31	30	2.229
New Horizons	Pluto and Moon Charon; then to Kuiper Belt 2016-2020	At BOM On-going 9.5 y and encounter with Pluto	8.1 kg per RTG	237 We 191 We	57.91	30	2.229

Acronyms: BOM: Beginning of Mission. Longevity and hours do not match due to fuel enrichment and what decay had already occurred.
EOM: End of Mission *Source Ref. 10 and others*

Table 3 indicates the RTG power for successful missions around the universe. It shows the power at the Beginning of Mission (BOM).

5. Thermocouples

Thermocouple produce a voltage and hence the current. A typical type K thermocouple has an output of about 46.8µV/°C and can generate 1µA/°C depending on its internal impedance. These are much below the Silicon-Germanium junctions that can produce >300 µV/°C.

For the modules tested in Table 3, the measured currents under vacuum conditions varied from 10A to 8.75A from the tested RTG assembly. It also showed current declines due to Pu-238 decay over an 18 month period. To maximize the current output, the load impedance needs to be as low as possible. The conversion rate is in the region of $0.12W_e/W_t$.

5.1 Skutterudite

Higher power ratings seem to come from Skudderudite material, named after the City of Skotterud in Norway. Skutterudite is a cobalt arsenide $CoAs_3$ mineral that has variable amounts of nickel and iron substituting for the cobalt content. Skutterudites with zinc antimonide are being developed at JPL, and exhibit a higher conversion efficiency Ref. 11. Skutterudite thermocouple electricity generators are also

Fig. 11 A Thermoelectric Skutterudite Generator With Multiple modules That Can Work Up To 500 °C
Source: Fraunhofer for Physical Measurement Techniques IPM

being developed to convert automobile exhaust heat into electricity to recharge batteries and do other functions where these materials can achieve 15 % conversion efficiency. A cluster of Skutterudite thermocouples is shown in Fig. 11. The performance and output is shown in Fig. 12.

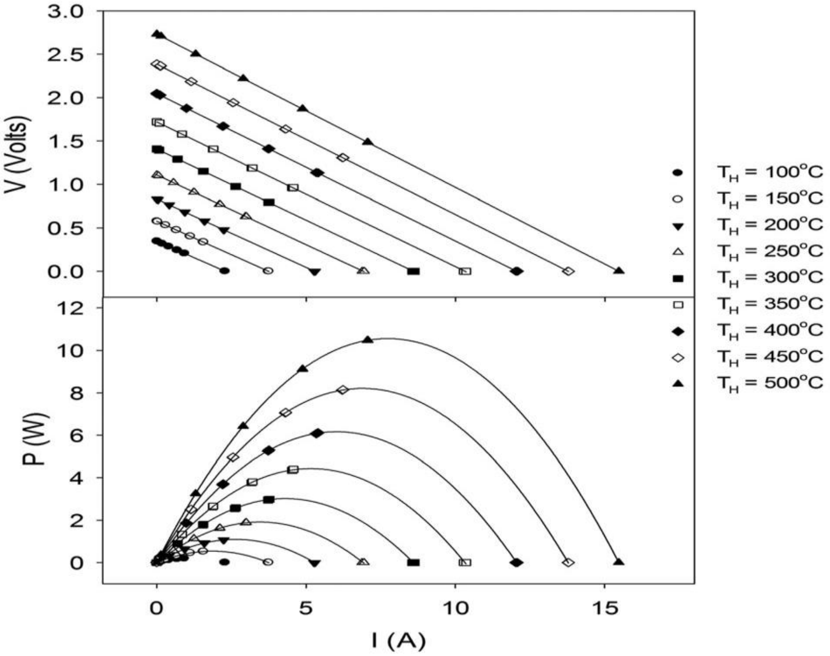

Fig. 12 shows the Volt-Amp relationship of a 32 thermocouple Skutterudite module at different temperatures, top graph. The Lower graph shows the Watts-Amps.
Source Ref. 11

6. References

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Ref.3 Rohit Shastry, Michael Patterson, Daniel A. Herman. NASA Glenn Center, Cleveland, Ohio. “Current Density Measurements of an Annular-Geometry Ion Engine.”

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Ref.6 Isaac Silvera, Ranga Dias. “Metallic Hydrogen”, Nature 542, 17 (02 February 2017), doi:10.1038/nature 2017.21379.

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Ref.8 Ontario Power Generation Announcement 1 March 2017; and World Nuclear Association, March 2017.

Ref.9 Economical Production of Pu-238: Feasibility Study NASA NIAC Phase I Steven D. Howe Douglas Crawford Jorge Navarro Terry R. Centre for Space Nuclear Research.

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Ref.11 Conversion Efficiency of Skutterudite-based Thermoelectric Modules.