CHAPTER 3

RADIOISOTOPES POWER PRODUCTION

6/22/2017

3.1 INTRODUCTION

Compact devices using radioisotopes for terrestrial and space power applications have been in use since 1956. They were initially developed under the general designation of Systems for Nuclear Auxiliary Power or SNAP.

The SNAP-3 device was first demonstrated in 1959, it was the size of a grape fruit, weighted 4 lbs, had a power of 2.5 Watts, and was capable of delivering 11.60 Kilowatt-hours of electrical energy over a 280 days period. This would have been the equivalent energy produced by Nickel-Cadmium batteries weighing about 700 lbs. It used as an energy source the Polonium^{210} alpha emitter isotope.

Radioisotope Thermoelectric Generators (RTGs) enabled the National Aeronautics and Space Administration (NASA) to launch missions to explore the solar system as part of the Apollo missions to the Moon, the Viking missions to Mars, the Pioneer, Voyager, Ulysses, Galileo, Cassini and the Pluto New Horizons to the outer solar system.

The RTGs for the Pioneer 10 spacecraft operated flawlessly for three decades until the spacecraft signal was too weak to detect in 2003. The Voyager 1 and 2 missions, operating on RTG power since their launch in 1977 reaching interstellar space. The USA launched 26 missions involving 45 RTGs over a forty years period.

3.2 SPACE APPLICATIONS

In space applications, isotopic power units offer advantages over solar cells, fuel cells and batteries because of the following special circumstances:

1. When the satellite orbits pass through radiation belts such as the Van-Allen belts around the Earth that could destroy the solar cells.
2. Operations on the moon or mars where long periods of darkness require heavy batteries to supply power when solar cells would not have access to sunlight.
3. Space missions in opaque atmospheres such as Venus, where solar cells would be useless because of lack of light.
4. At distances far from the sun, for long duration missions where fuel cells, batteries and solar arrays would be too large and heavy.
5. Heating the electronics and storage batteries in the deep cold of space at minus 245 degrees Fahrenheit is a necessity.

3.3 ISOTOPES FOR POWER GENERATION

A radioisotope power generator must meet stringent safety criteria. Under no circumstance should it subject people to undue radiation exposure. It must also be reliable, operating for long periods of time without failure. Weight and cost are also important performance criteria. For terrestrial applications, weight can be large at the expense of cost. For space applications weight may have to be reduced at the expense of cost. The design of a radioisotope power generator becomes a typical engineering task of optimizing different performance criteria.

The fuel capsule, as shown in Figs. 1-2, must be constructed as a rupture proof container filled with an isotope with a large volumetric power density. The initial activity of the isotope in Becquerels or transformations per second is given by:

$$A_0 = \lambda N_0 \ \text{[Bq]} \tag{1}$$

where $\lambda = \frac{\ln 2}{T_{1/2}}$, is the decay constant of the isotope in sec^{-1},

$T_{1/2}$ is its half-life in seconds,

N_o is the initial number of atoms present at time t = 0.

Figure 1. Radioisotope Heater Unit (RHU) weighs only 40 grams, and is 3.2 cm long and 2.6 cm in diameter. NASA photograph.

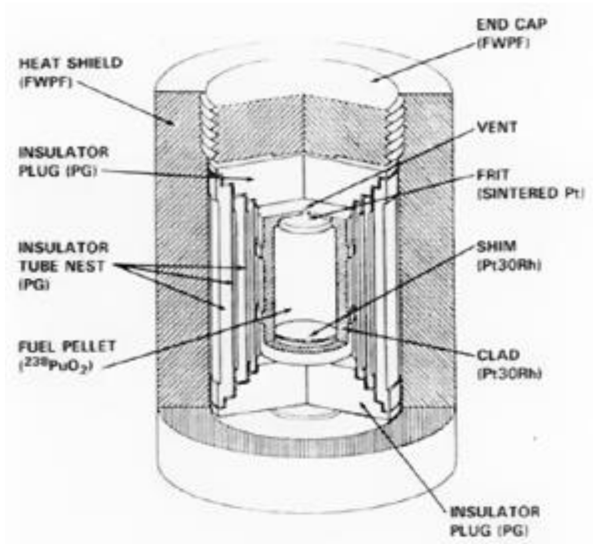

Figure2. Internals of a Radioisotope Heater Unit (RHU).

Figure 3. Plutonium^{238} oxide sphere.

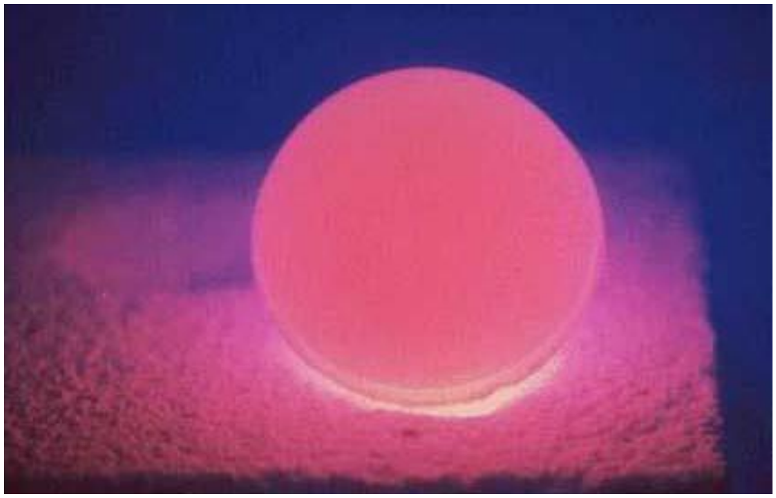

Figure 4. Plutonium^{238} disc that glows red-hot from its internal heat generation.

The specific activity of the isotopes in Becquerels per grams is given by:

$$A_0^{'} = \frac{\lambda N_0}{g} \text{ [Bq/gm]} \tag{2}$$

If the energy release per disintegration is E in MeV, the specific power of the isotope is given by:

$$P^{'} = \frac{E\lambda N_0}{g} \text{ [MeV/(gm.sec)]} \tag{3}$$

Since:

$$N_0 = \frac{gA_v}{M} \text{ [nuclei]} \tag{4}$$

where: A_v is Avogadro's number = 0.6×10^{24} [nuclei/mole],
M is the atomic weight in amus.
One can write for the specific power of the isotope:

$$P^{'} = \frac{E\lambda A_v}{M} \text{ [MeV/(sec.gm)]} \tag{5}$$

where the weight of the isotope (g) cancels out.

We can express the specific power in watts per gram using the conversion factor:

$$1 \text{ [MeV/sec]} = 1.6\times 10^{-13} \text{ [Watts]}$$

as:

$$P' = 1.6 \times 10^{-13} \frac{E\lambda A_v}{M} \text{ [Watts(th)/gm]} \tag{6}$$

These are thermal Watts of power generated as heat. If conversion of thermal energy to electricity is attempted, then the specific electrical power output in electrical Watts per gram becomes:

$$P_e = \eta_{th} P' = 1.6 \times 10^{-13} \frac{\eta_{th} E\lambda A_v}{M} \text{ [Watts(e)/gm]} \tag{7}$$

where: η_{th} is the overall conversion cycle efficiency.

PRODUCTION OF Pu^{238}

The isotope Np^{237} is produced in reactor fuel from U^{238} through the (n, 2n) fast-neutron reaction:

$$\begin{aligned} &{}_0n^1 + {}_{92}U^{238} \rightarrow 2\,{}_0n^1 + {}_{92}U^{237} \\ &{}_{92}U^{237} \rightarrow {}_{-1}e^0 + {}_{93}Np^{237} \end{aligned} \tag{8}$$

It can be separated from reactor fuel and further irradiated in a neutron flux to produce Pu^{238} from the reaction:

$$\begin{aligned} &{}_0n^1 + {}_{93}Np^{237} \rightarrow {}_{93}Np^{238} + \gamma \\ &{}_{93}Np^{238} \rightarrow {}_{-1}e^0 + {}_{94}Pu^{238} \end{aligned} \tag{9}$$

EXAMPLE

For the alpha emitter Pu^{238}, the half life is 87.74 years, and the energy per disintegration is 5.544 MeV, yielding:

$$\begin{aligned} P' &= 1.6 \times 10^{-13} \frac{E\lambda A_v}{M} \\ &= 1.6 \times 10^{-13} \times 5.544 \times \frac{0.6931}{87.74 \times 365 \times 24 \times 60 \times 60} \times \frac{0.6 \times 10^{24}}{238.0495} \\ &= 0.56 \left[\frac{Watts(th)}{gm}\right] \end{aligned}$$

EXAMPLE

For Ni^{63}; a pure beta emitter, the half life is 100.1 years, and the energy per disintegration is 0.067 MeV, yielding:

$$P' = 1.6\times10^{-13}\,\frac{E\lambda A_v}{M}$$
$$= 1.6\times10^{-13}\times0.067\times\frac{0.6931}{100.1\times365\times24\times60\times60}\times\frac{0.6\times10^{24}}{62.92967}$$
$$= 0.0224\ [\frac{Watts(th)}{gm}]$$

Table 1 shows the specific power of different isotopes used in power applications. In a design situation, the mass of a given isotope needed to produce a certain amount of power P in Watts(th), can be estimated from:

$$m = \frac{P}{P'}\ \text{[gm]} \qquad (10)$$

The radioisotope fuel must be inexpensive and easily shielded against gamma radiation that is associated with some beta and alpha emissions. The fuel capsule must be rugged enough to withstand impact against rock at high velocity in case of a rocket launch failure, yet it must melt easily if the generator reenters the Earth's atmosphere. A capsule designed for the containment of the isotope $_{94}Pu^{238}$ is shown in Fig. 1. It weighs 40 grams, is 3.2 cms long and 2.6 cms in diameter, producing a power of 1 Watt(th). Its internal design is shown in Fig. 2.

3.4 SELECTION CRITERIA FOR ISOTOPES

There are at least 1,300 radioactive isotopes both natural and man-made available. Many of them are fission products from the fission of fissile fuel in fission reactors, and others can be manufactured in particle accelerators. If one sets a limit on the half lives:

$$100 \text{ days} < T_{1/2} < 100 \text{ years},$$

the number of choices is reduced to only 100 of them. If one further sets a criterion on the specific power as:

$$P' > 0.1 \text{ [Watt(th)/gm]},$$

and eliminate those with powerful gamma rays emissions, only about 30 isotopes are left. Even though others can be used, attention has been concentrated on 8 isotopes from the potential list of 15 shown in Table 1, which have desirable characteristics and are cheap to produce.

Table 1. Properties of isotopes useful for isotopic power generation.

Isotope	Main modes of radiation emissions	Half life	Specific Power [Watts(th)/gm]	Melting point (^{o}C)
$_{1}$Tritium^{3}	β^-, no γ	12.33 a	0.26	

$_{14}$Silicon^{32}	β^-, no γ	280.00 a		
$_{15}$Phosphorous^{32}	β^-, no γ	14.28 d		
$_{15}$Phosphorous^{33}	β^-, no γ	25.30 d		
$_{16}$Sulfur^{35}	β^-, no γ	87.2 d		
$_{21}$Scandium^{46}	β^-, γ	83.8 d		
$_{27}$Cobalt^{60}	β^-, γ	5.27 a	17.7	1,480.0
$_{28}$Nickel^{63}	β^-, no γ	100.10 a	0.0224	
$_{36}$Krypton^{85}	β^-, γ	10.72 a	0.623	
$_{38}$Strontium^{90}	β^-, no γ	29.00 a	0.93	770.0
$_{38}$Strontium^{90} - $_{39}$Yttrium^{90} (parent-daughter)	β^-, γ	29.00 a		
$_{39}$Yttrium^{90}	β^-, γ	64.00 h		
$_{44}$Ruthenium^{106}	β^-, no γ	1.008 a	33.1	2,310.0
$_{55}$Cesium^{134}	β^-, γ	2.062 a		
$_{55}$Cesium^{137}	β^-, γ	30.17 a	0.42	28.0
$_{58}$Cerium^{144}	β^-, γ	284.4 d	25.60	800.0
$_{61}$Promethium^{147}	β^-, few γ	2.6234 a	0.33	1,300.0
$_{65}$Terbium^{160}	β^-, γ	72.4 d		
$_{69}$Thulium^{170}	β^-, few γ	129 d	13.2	2,375.0
$_{79}$Gold^{198}	β^-, γ	2.696 d		
$_{81}$Thallium^{204}	β^-, no γ	3.77 a		
$_{83}$Bismuth^{210}	β^-, α, γ	5.01 d		
$_{84}$Polonium^{210}	α, few γ	136.38 d	141.00	254.0
$_{94}$Plutonium^{238}	α, γ,SF	87.74 a	0.56	640.0
$_{94}$Plutonium^{241}	β^-, α, γ	14.70 a		640.0
$_{95}$Americium^{241}	α, γ, SF	432.00 a	0.11	

$_{96}Curium^{242}$	α, γ,SF	162.80 d	120.00	950.0
$_{96}Curium^{244}$	α, γ,SF	18.11 a	2.84	950.0

Table 2. Required Pb shielding for radioisotopic sources of 1 kWth power leading to an effective (dose equivalent) of 10 mrem/hr at 1 meter.

Isotopic Compound	Main emission	$T_{1/2}$ [yr]	Spontaneous Fission (FS) $T_{1/2}$ [yr]	Melting Point [^oF]	Density [g/cm^3]	Specific Power [Wth/gm]	Activity per Watt(th) [Ci/Wth]	Pb Shield thickness [in]
$Pu^{238}O_2$	α	87.7	$5x10^{10}$	4,352	10.0	0.39	30	0.1
$Am^{241}O_2$	α	432.0	$2x10^{14}$	3,632	10.47	0.097	30	0.7
$Cm^{244}{}_2O_2$	α	18.1	$1.4x10^7$	3,956	9.0	2.27	29	2.01
$Cs^{137}Cl$	β^-	30.0	-	1,193	3.2	0.12	207	4.6
$Sr^{90}TiO_2$	β^-	28.0	-	3,704	4.6	0.22	148	6.0
Metallic Co^{60}	γ	5.24	-	2,723	8.8	1.74	65	9.5

Table 3. Commercial forms of the isotopes.

Isotope	Form	Percent isotope in metallic element
Co^{60}	Metal	10.0
Sr^{90}	$SrTiO_3$	55.0
Ru^{106}	Metal	3.3
Cs^{137}	CsCl	35.0
Ce^{144}	Ce_2O_3	4.5
Pm^{147}	Pm_2O_3	95.0
Tm^{170}	Tm_2O_3	10.0
Po^{210}	Metal	95.0
Pu^{238}	PuO_2	80.0
Cm^{242}	Cm_2O_3	0.45
Cm^{244}	Cm_2O_3	18.1

$Strontium^{90}$, as well as tritium are pure beta emitters emitting no gamma rays, eliminating the need to shield against them. However, as the beta particles are stopped in the surrounding material, secondary radiation in the form of bremstrahlung radiation is emitted. This requires shielding. A lead casing would have to be about 4 inches thick, depleted uranium, 3 inches thick, and cast iron 8 inches thick.

The negative beta emitters can be recovered abundantly from fission fuel reprocessing plants. The alpha emitters, with weak gammas, are easier to shield. They are more costly than the beta emitters, but they offer the advantage of weight reduction with good specific power. This makes them particularly useful in space applications.

3.5 FUEL FORMS

A chemical form that would contain the radioisotope under all conceivable circumstances is a desired safety feature. In the case of the use of Strontium^{90}, which has a half life of 28 years, and that is available at the megacuries level in the waste from uranium reprocessing, one must contain it effectively before being able to use it, since it is bone seeker, by the fact that it lies under calcium in the periodic table of the elements, and hence possesses chemical properties similar to calcium.

Strontium titanate: $SrTiO_2$ has been identified as a suitable fuel form. Its melting point is 1910 ^{0}C, which is high enough to keep the fuel in the solid state in most fire situations. It is also not very soluble in fresh or salt water, another property that would isolate it from living organisms in the unlikely case of its release to the environment. It is also resistant to shock and physically strong.

Solvent extraction is used to separate the two isotopes Sr^{90} and Sr^{89} from the fission products wastes. Since Sr^{89} has only a half life of 51 days, aging the mixture would lead to the decay of Sr^{89}, leaving a relatively pure Sr^{90} sample in a short time period.

The solvent extraction process produces strontium carbonate: $SrCO_3$, which is later converted into strontium titanate. It is then made into small cylindrical pellets, which are loaded into fuel capsules.

3.6 THERMOELECTRIC CONVERSION

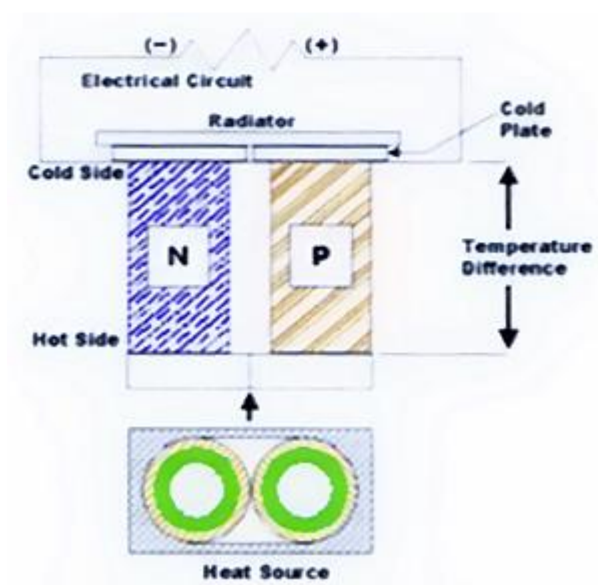

Figure 5. Operation of a Thermoelectric Generator.

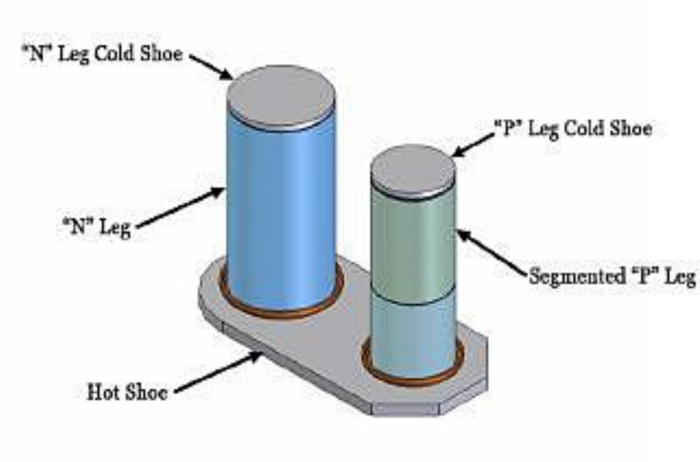

Figure 6. Thermoelectric couple schematic. Source: NASA.

Thomas Johann Seebeck, a German scientist, discovered thermoelectricity. He observed that an electrical voltage is produced when two dissimilar metals are joined in a closed circuit and the two junctions are kept at different temperatures. Such junctions are called thermoelectric couples, or in short, thermocouples.

In a temperature measuring or sensing thermocouple two ordinary metals or alloys are used. For power production, it was discovered that some semiconductors doped by the addition of impurities to produce a deficiency or an excess of electrons provide a greater efficiency. A large number of semiconductor compounds exhibit the thermoelectric effect. The power output of a thermoelectric material is a function of its operating temperature.

In radioisotope generators, a thermoelectric couple is composed of a positive type element and one negative type element designated as p-n junctions as shown in Fig. 6. In positive (p) elements the flow of electrons is toward the hot junction. In negative (n) elements it is away from the hot junction. A photograph of a thermoelectric generator used in space applications with its silicon-germanium junctions is shown if Fig. 7.

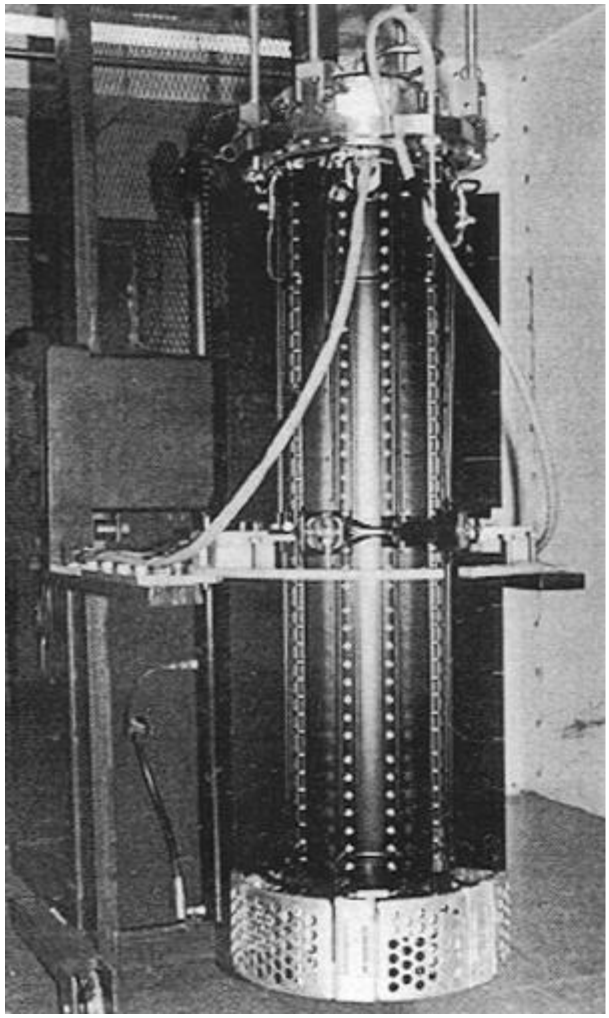

Figure 7. Photograph of a Radioisotope Thermoelectric Generator (RTG). Source: NASA.

Energy losses can occur if the thermal conductivity of the elements is too high. Heat entering the hot end would escape without much conversion to electricity. Joule heating or I^2R losses, where I is the current and R is the resistance, is another source of loss of heat energy. A thermoelectric rating or figure of merit Z can be written for a thermoelectric generator as:

$$Z = \frac{S^2}{Rk} \tag{11}$$

where: S is the Seebeck coefficient, a thermoelectric property of the material that is equal to the voltage produced for each degree of temperature difference,
R is the electrical resistivity of the thermoelectric material,
k is the thermal conductivity of the thermoelectric material.

The higher this figure of merit Z the better the thermoelectric material. Thus a good thermoelectric material is one with high S but low k and R.

Ordinary metals like copper conduct heat too well. Instead, semiconductors like bismuth telluride and germanium silicide make good thermoelectric elements.

3.7 MULTI MISSION RADIOISOTOPE THERMOELECTRIC GENERATOR, MMRTG

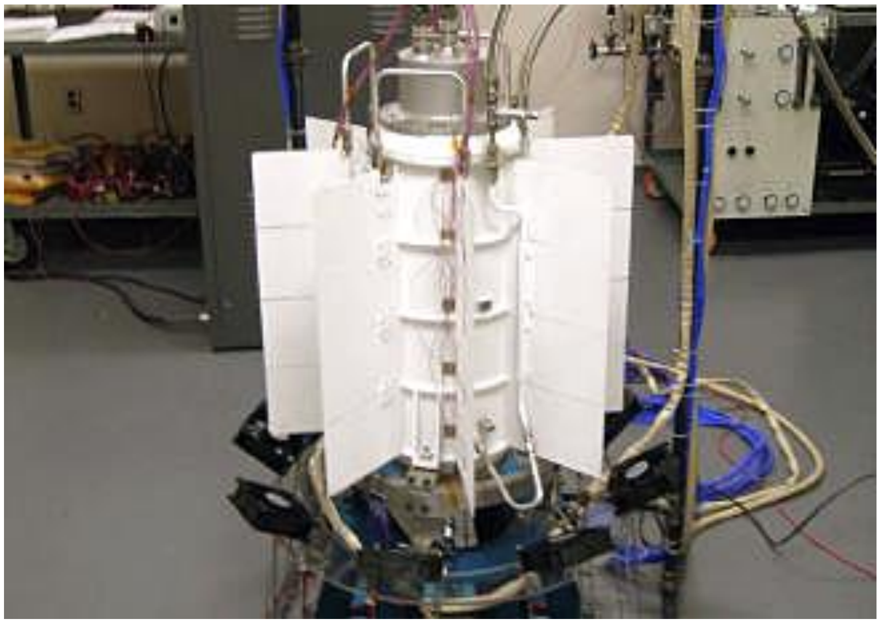

Figure 8. Multi Mission Radioisotope Generator (MMRTG) unit. Source: NASA.

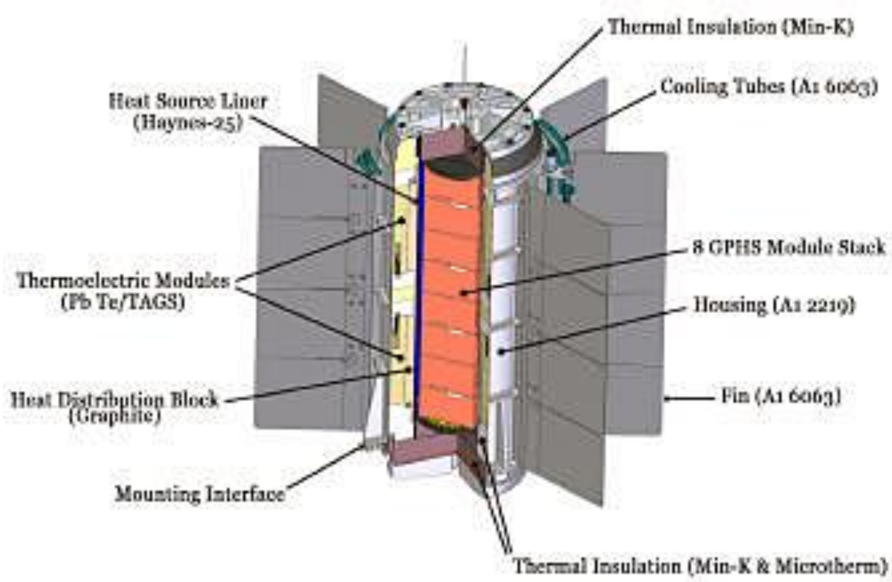

Figure 9. Multi Mission Radioisotope Generator (MMRTG) schematic. Source: NASA.

A Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is meant to operate on planetary bodies with atmospheres such as Mars, as well as in the vacuum of space. It has a flexible modular design capable of meeting the needs of a wider variety of missions as it generates electrical power in small increments above 100 Watts over a minimum lifetime of 14 years.

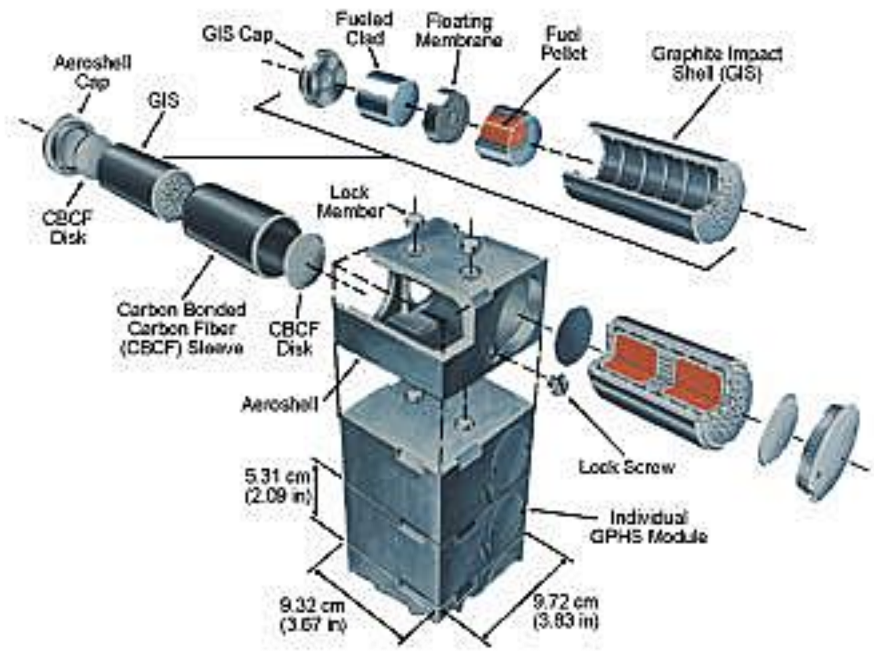

Figure 10. General Purpose Heat Source (GPHS) module. Source: NASA.

It uses a heat source composed of eight General Purpose Heat Source (GPHS) modules. Each MMRTG contains 4.8 kgs or 10.6 lbs of plutonium^{238} dioxide that initially provides 2,000 watts of thermal power and 120 watts of electrical power. An MMRTG generator is 64 cms or 25 in in diameter from fin tip to fin tip, by 66 cms or 26 in long and weighs about 43 kgs or 95 lbs.

3.8 THERMIONIC CONVERTERS

In thermionic direct energy conversion, an electric current is obtained by collecting the electrons emitted by a hot surface. The hot surface would be a high work function emitter.

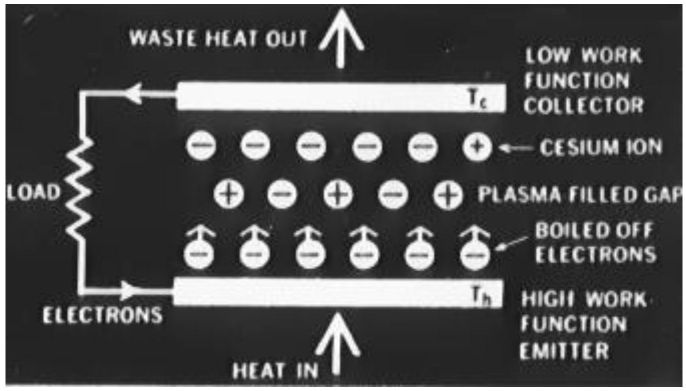

Figure 11. Principle of operation of a flat thermionic generator.

The electrons are collected at a low work function collector. The thin gap of about 0.02 cm between the emitter and the collector is filled with a metallic vapor plasma such a cesium.

Since the hot temperature must be high to boil off the electrons from the emitter, the Carnot cycle efficiency is high. However this is neutralized because that same high temperature causes losses around the converters. Heat is also lost across the narrow gap by thermal radiation. If the electrons boiled off from the emitter strike the collector with too high an energy, their kinetic energy is turned into heat. Reducing the heat losses around the energy converters becomes paramount for a successful design.

The perfect generator would be spherical in geometry, where all heat would have to flow through the converter section. The more practical cylindrical shapes have to be insulated towards the ends. To force the heat through the thermionic converters the curved sides are surrounded with thin metal sheets separated by a vacuum. The practical thermionic generator resembles a multi-layered vacuum bottle operating between a temperature of 1,700 ^{o}C at the emitter and 700 ^{o}C at the collector. A thermionic generator would have an overall efficiency between 15 and 20 percent.

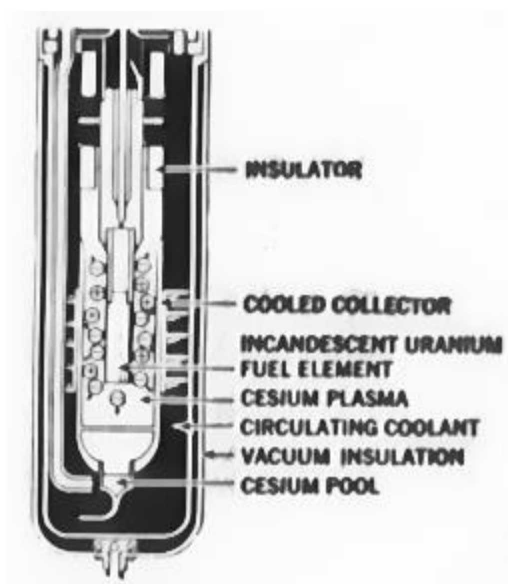

Figure 12. Cylindrical type of thermionic generator.

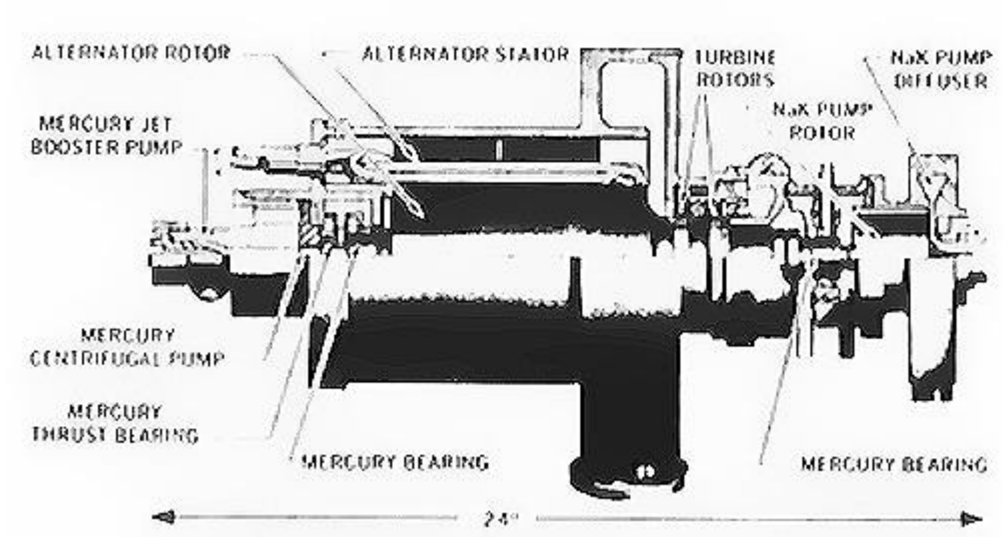

Figure 13. Dynamic converter SNAP 2 uses a high speed turbine, mercury coolant, an electric generator and pumps to produce 3,000 Watts of power from radioisotopes.

The boiled off electrons form a cloud of negative charges that repel subsequently emitted electrons. This space charge effect in a thermionic generator must be circumvented by filling the gap between the plates with a gas containing positively charged particles such as cesium. These positive ions mix with the electrons and neutralize their charge. The mixture of positive and negative charges constitutes a plasma. The plasma makes the gas a good conductor. The emitted electrons can move easily across the plasma and they condense on the cooler surface.

3.9 DYNAMIC ENERGY CONVERSION

This is the most familiar process of using a working fluid such as steam, to produce mechanical energy to drive a turbine, which in turn drives an electric generator as shown in Fig. 13.

When radioisotopes are used, alternate working media could be adopted such as mercury, potassium, sodium and lithium liquid metals, or organic liquids. Closed loop gas systems using helium and argon could also be used. The dynamic converter Snap 2 used a high speed turbine, an electric generator and pumps to produce 3,000 Watts of power from radioisotopes with the NaK eutectic that is liquid at room temperature.

3.10 NUCLEAR BATTERY, BETA CELL

INTRODUCTION

The nuclear battery concept uses the emission of charged particles from a surface coated by a radioisotope to directly produce electrical energy. The energy is minute compared with that from conventional batteries but can be used in special applications requiring small amounts of electrical current. Their application as current sources in nanotechnology to provide power to Micro Electro Mechanical Systems (MEMS) deserves exploration.

MOSELEY GENERATOR

Moseley's generator was a direct charging device consisting of a spherical glass globe silvered on the inside, with a radium isotope emitter installed on the tip of a wire in the center. The charged particles from the radium moved to the inside silvered surface of the sphere.

The current charged the sphere as a capacitor. The spacing could be either a vacuum or a dielectric. Negative beta particles, positive alpha particles positrons or fission fragments could be used. Extremely low currents and high voltages result by the direct charging process. The voltages can be reduced using transformer and oscillator devices followed by rectifiers to transform the alternating current to a direct current as needed.

A very little known fact is that beta particles ejected from an insulated radioactive source leave it with a positive charge. This is the principle of operation of the Henry Moseley generator that dates back to 1913.

VOLTAGE PRODUCTION BATTERIES, BETA VOLTAICS

The Moseley generator could be 1 inch in height and consist of a radioisotope such as Sr^{90} enclosed in a polystyrene capsule within an aluminum collector. A Monel wire transmits the positive charge to an anode. The system would be surrounded by a copper cylinder around a lead radiation shield to which the cathode is connected.

The maximum voltage can reach up to 7 kilovolts and is about 1 percent efficient. For 10 milli curies of Sr^{90}, a current of 40 $\mu\mu A$ at zero voltage is produced.

Another design consists of a rod in the center that is coated with an electron-emitting isotope such as tritium. The electrons cross the gap between two concentric cylinders and are collected on a metallic sleeve and directed to the load.

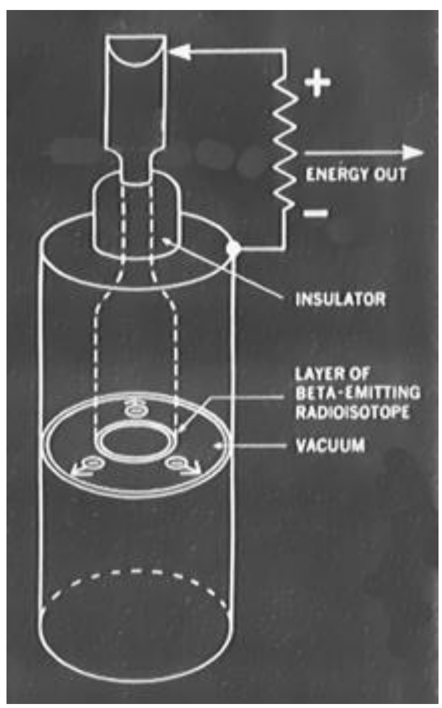

Figure 14. The nuclear battery uses the emission of charged particles from a surface coated by a radioisotope.

Space charge effects are not noticeable since the energy of the electrons far exceeds those that are emitted by thermionic devices.

Voltage production nuclear batteries are simple and rugged but can generate only microamperes of current at a high voltage of 10 to 100 kVolts. These high voltages can be used as particle accelerators but are unsuitable for consumer devices requiring lower voltages. We proposed an inverse Marx Generator as a voltage step down device.

The beta particles can be made to pass through a silicon diode generating power in a way similar to that used in photovoltaics cells.

ELECTROMECHANICAL PIEZOELECTRIC GENERATOR

A charge buildup is created between two adjacent plates with one coated with a radioisotope, and the other bendable. The bendable plate touches the other plate as a result of the electrostatic charge buildup and discharges it returning back to its original position and creating a vibration mechanical motion. The use of a piezoelectric material or an electrical linear generator can create power in the range of milliwatts at a 35 Hz frequency.

OPTOELECTRIC BATTERY

A beta emitter such as Tc^{99m} can be used to excite an excimer mixture of argon and xenon in a composite carbon fiber pressure vessel with an inner mirrored surface generating light that can then transformed into electricity using a photocell. An intermittent ultrasonic source would stir a fine Tc^{99m} powder from which the beta particles would escape illuminating the photocell that has a bandgap tuned to the used excimer.

CURRENT PRODUCING BATTERIES

Instead of directly collecting the electrons, one can take advantage of the secondary ions multiplication principle. The high energy electrons could be used to bombard a pea sized silicon P-N junction or a dielectric. The P-N junction in turn can release 200,000 slow moving electrons for each high energy electron striking it.

In this case a low magnitude voltage is produced at about 10 mV; strong enough to cause an audible signal in a telephone receiver and can definitely be used in nanotechnology in MEMS applications.

A battery using the S^{90} isotope would be the size of a thimble and can have an operational life of more than 20 years. Other pure beta emitter isotopes such as tritium can be used avoiding the need for shielding against gamma radiation, with just shielding against the lower energy bremstrahlung radiation in the x rays region of the electromagnetic spectrum. The use of $Thallium^{204}$ would allow a recharging of the nuclear battery by reirradiating it in a nuclear reactor.

RADIATION SHIELDING

The use of low energy pure beta emitter isotopes would eliminate the need to shield aginst gamma radiation. Low energy beta particles would also generate low energy bremstrahlung x rays that is easy to shield against. This suggests isotopes such as T^3, Ni^{63}, Sr^{90}, Tc^{99m}, and Pm^{147}. Pu^{238}, $Curium^{242}$, and $Curium^{244}$ are other possibilities.

3.11 ALKALI METAL THERMAL TO ELECTRIC CONVERTER, AMTEC

This is an electromechanical device using the β-alumina electrolyte used in the sodium sulfur type of battery. It is a sodium concentration cell using the ceramic polycrystalline β -alumina solid electrolyte as a separation between a high pressure Na vapor region at 900-1300 ^oK and a lower pressure liquid sodium region at 400-700 ^oK.

3.12 SPACE PROBES HEAT AND ELECTRICAL POWER SUPPLIES

On a typical interplanetary spacecraft, between 300 Watts and 2,500 Watts(e) of electricity are required to power all the computers, radio transmitters, receivers, motors, valves, data storage devices, instruments and a multitude of sensors. For instance the Cassini spacecraft shown in Fig. 15 sent to Saturn, uses 1 kW of power. This power generation must be supplied reliably over a period of years or decades. Battery power is an option only on short missions such as the Huygens atmospheric entry probes. Even when batteries are used, solar photovoltaic and radioisotopes thermo electric generators must be used to charge the batteries before their deployment. The batteries and the electronic equipment must also be kept from freezing in the cold of space, so that radio isotopic heating units, shown in Fig. 16, are also needed for heating the batteries and equipment.

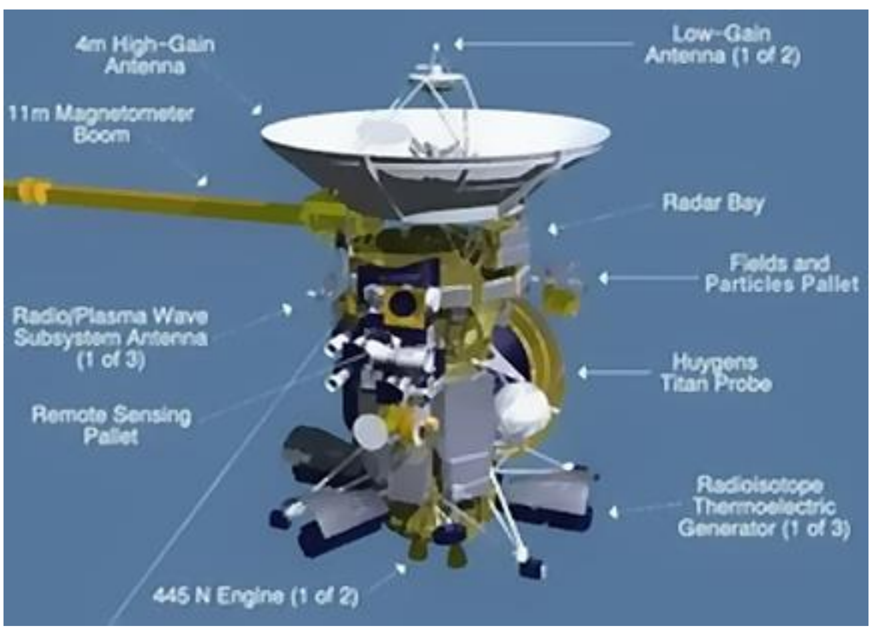

Figure 15. The Cassini Space craft showing its three thermoelectric radioisotope generators. Photo: NASA.

Radioisotope heating units (RHUs) normally use the isotope Pu^{238} these systems are highly reliable since they do not use moving parts. They are very compact and lightweight, resist radiation damage and the heat produced is independent of the distance from the sun as opposed to solar heating units.

Photovoltaic materials are capable of converting solar energy directly into electricity at an efficiency reaching 29 percent. Crystalline silicon and gallium arsenide are typical choices for deep space applications. At a distance of one Astronautical Unit (AU), corresponding to the distance between the Earth and the sun, a 6 cm diameter silicon cell can produce a current of about 1 ampere at a voltage of 0.25 volt.

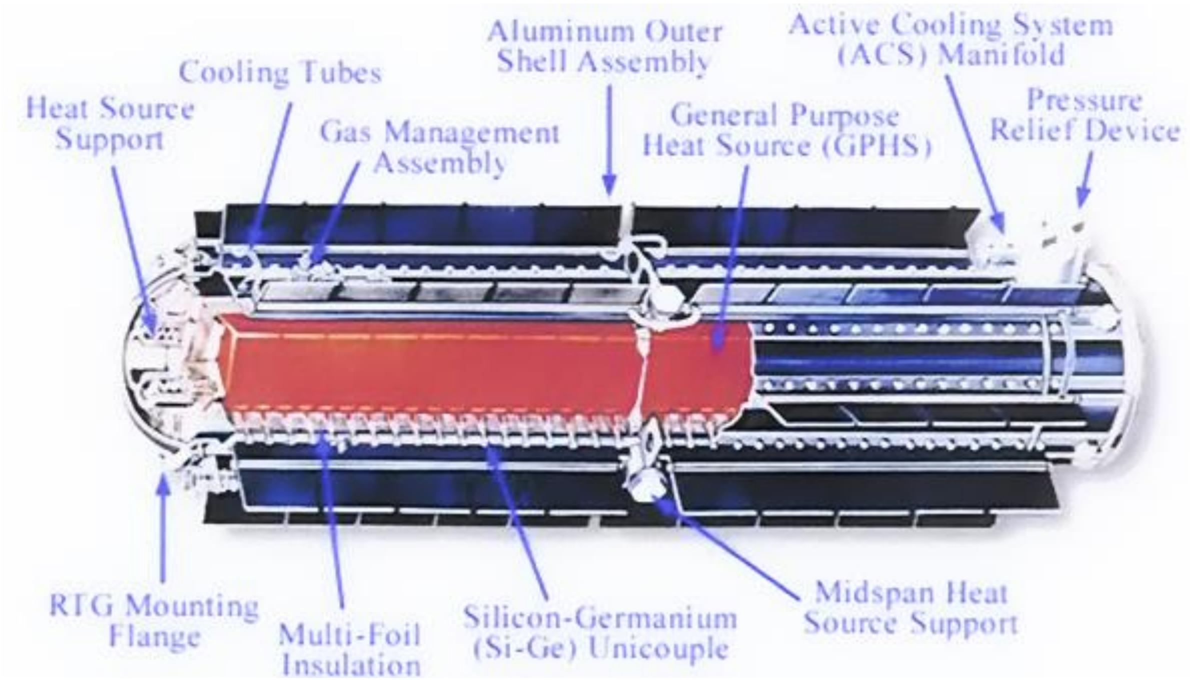

Figure 16. General purpose Heat Source (GPHS) Radioisotope Thermoelectric Generator (RTG).

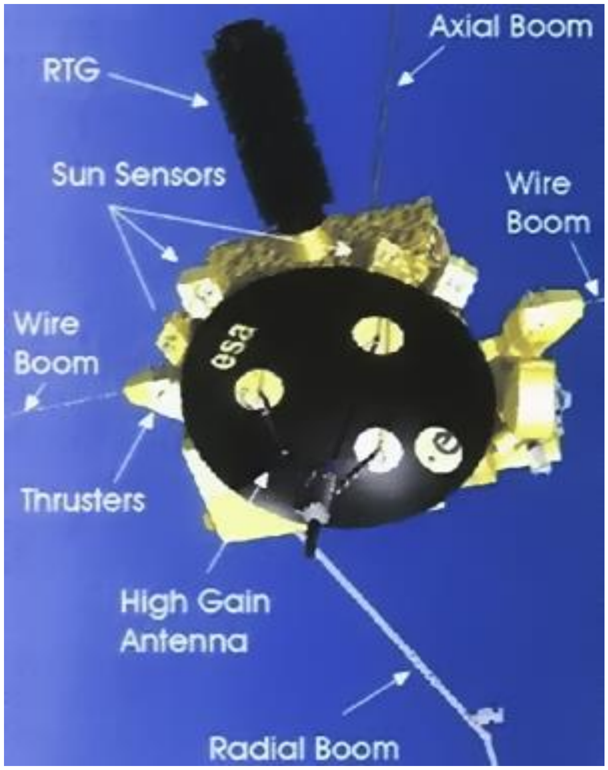

Figure 17. The Ulysses solar probe with a Radioisotope Thermoelectric Generator (RTG).

Solar cells are manufactured from crystalline ingots that are grown then sliced into wafer thin circles with metallic conductors deposited as a grid facing the sun, and a flat sheet on the other side. Solar panels or solar arrays are constructed of the cells trimmed into appropriate shapes and attached to a substrate, then normally enclosed in protective glass covers. The cells are connected in series and parallel combinations to reach the total desired voltage. The substrate and cement must conduct heat since the cells absorb solar energy and can reach high temperatures, yet they are more efficient when they operate at low temperatures.

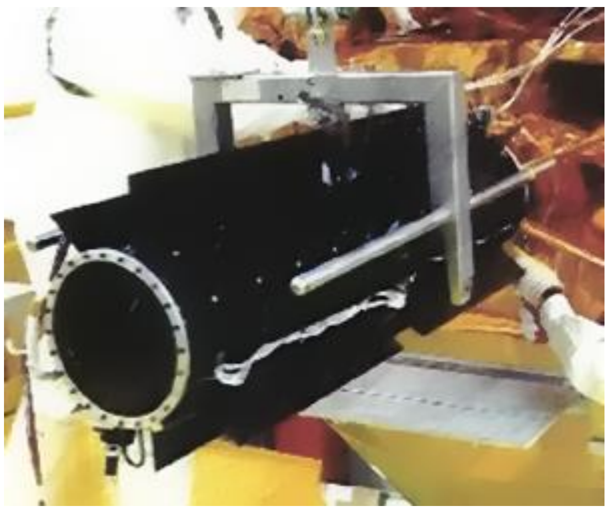

Figure 18. A Radioisotope Thermoelectric Generator (RTG) being fitted to the Ulysses solar probe.

Even when photovoltaics are feasible, missions close to the sun such as the Ulysses solar probe shown in Fig. 17 used thermoelectric generators to avoid the interference effects of strong magnetic fields and intense fluxes of radiation close to the sun. Ulysses explored the northern portion of the sun and mapped it. It also explored the magnetic fields associated with the sun.

Beyond the orbit of Mars, the weaker intensity of solar radiation would require solar panels larger in size and weight than is practicable, because of the increased and more costly launch mass. In addition if the panels become excessively large, it becomes difficult to support, deploy and articulate them. One of the panel designed for the Spacelab satellite failed to deploy successfully.

Prolonged exposure to sunlight causes the photovoltaics performance to degrade at a rate of 1 to 2 percent per year. They degrade much faster if they are exposed to particle radiation from solar flares or from radiation belts.

When solar panels cannot be used efficiently, radio-isotopic power sources become the best available alternative. The Thermoelectric unicouple is a semiconductor type device with P and N type material in the legs. Heat from the decay of a radioactive isotope is applied at the hot junction. Cooling through radiation in space produces an electrical potential difference between the materials, according to the Seebeck Effect. Connecting the cold side terminals through a resistive load causes a current to flow in the electrical external circuit.

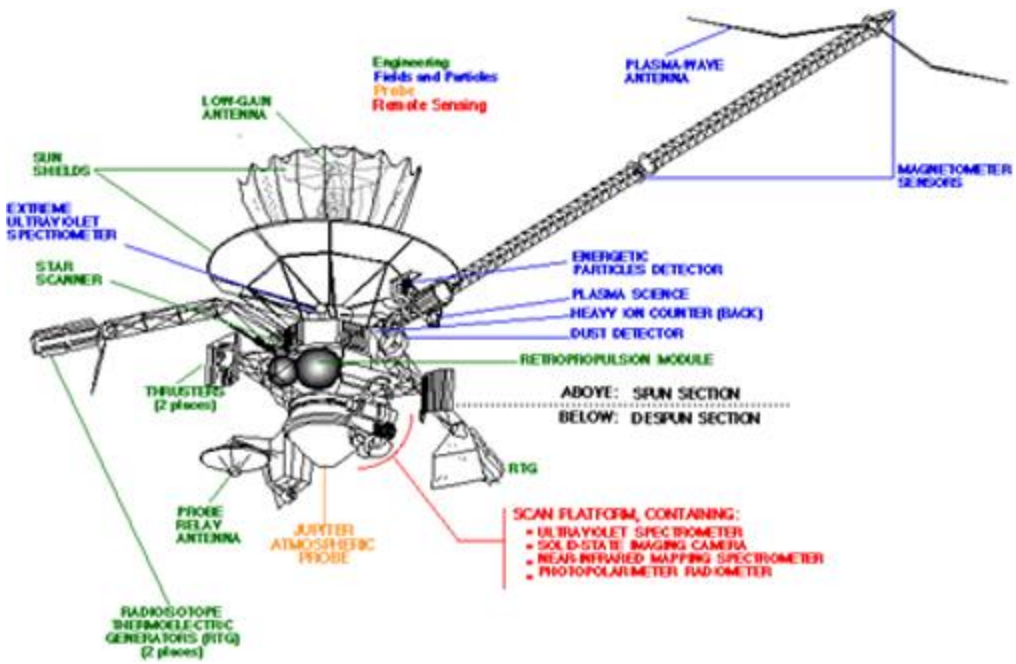

Figure 19. Galileo Space craft showing its Radioisotope Thermoelectric Generators (RTGs). Source: NASA.

The Galileo space probe shown in Fig. 18 used RTGs in its mission to study the Jovian environment. As Jupiter is far from the sun and Earth, solar cells cannot be used, and RTGs provided a reliable long lasting source of electricity which is insensitive to the cold of space and is almost invulnerable to high radiation fields such as the Earth's Van Allen belts and the Jupiter's magnetosphere.

In Galileo each RTG weighted 55 kgs and contained about 11 kg of Plutonium^{238} dioxide fuel. The fuel was pressed into 72 solid ceramic cylindrical 2.5 by 2.5 cm pellets. The RTGs are located in such a way as to minimize their impact on the infra-red detecting science instruments, since radioactive decay is accompanied by electromagnetic radiation mostly in the form of infrared radiation, since the RTGs reach considerable temperatures. Galileo RTGs were mounted behind shades to hide the near-infrared mapping spectrometer from their radiant heat.

The alpha decay of Pu^{238} leads to U^{234} with an energy release of 5.59 MeV per transformation, provides the probe with 570 Watts(th) of power at launch. The power generation of Galileo would decrease to 480 Watts(th) at its Jupiter destination. The power degradation is in fact around 2-3 percent per year, a little more than for solar panels.

If solar collectors would have been used, Galileo, which weighted 2.23 tons, would have needed a minimum of 700 to 1,600 square feet of solar panels, which is about the size of a house. Galileo was launched in October of 1989 and reached Jupiter in December of 1995. Galileo dropped instrumental probes into Jupiter's atmosphere, and sent photographs of the icy surface of its moon Europa, which suggest that it had a salt-water ocean beneath its icy surface. It proved that the Ganymede and Calisto moons have layers of liquid water as well. This is the only known possibility other than Mars of existence of life in the rest of our solar system.

3.13 PLANETARY EXPLORATION

The planet that has the most plausible possibility of having life in the past or the present is Mars. In the future, with planetary engineering, Mars could be made to harbor life in some form. Measurements by the spacecraft Viking I and II determined that Mars is a self-sterilizing planet. This is due to the high ultra violet radiation it receives from the sun and explains its dry soil and soil chemistry, which cannot sustain life on its surface. That does not exclude the possibility of life in more protected areas in its canyons or under its surface.

Figure 20. Mars Sojourner sampling a Martian rock. It uses Radiosiotopes Heating Units (RHUs) to maintain a desirable operating temperature of its electrical components during the cold Martian nights.

Figure 21. Mars rover as part of the Mars Surveyor program requires Radioisotope Heating Units (RHUs). Source: NASA.

Figure 22. Spirit Mars rover. Source: NASA.

With the robotics probes used to explore Mars such as the 1997 Mars Pathfinder rover Sojourner shown in Fig. 21 and the rover depicted in Fig. 22, solar energy is insufficient to power the vehicles and keep its batteries from freezing during the Martian night. Thus RTGs were used to generate enough heat to warm their batteries and its electronic circuits which are charged by its solar collectors during the Martian day. The Sojourner rover weighted 23 pounds and was equipped with three cameras and an alpha, proton, and X-ray spectrometer. It landed on Mars using a parachute and airbags. It used solar arrays and batteries in addition to the RHUs for its power and heat generation.

The Lander and rover can use solar arrays and batteries for power but would need RHUs to keep the electrical components warm enough to survive the cold Martian nights. These robotic explorers were able to trek up to 100 meters across the surface each Martian day. Each rover carried a set of instruments to search for evidence of liquid water that may have been present in the planet's past. The rovers were identical to each other but landed in different regions of Mars. The science instruments included a panoramic camera, a miniature thermal emission spectrometer, a Mössbauer Spectrometer, an alpha, proton x-ray spectrometer and a microscopic imager.

3.14. MARS SCIENCE LABORATORY, MSL

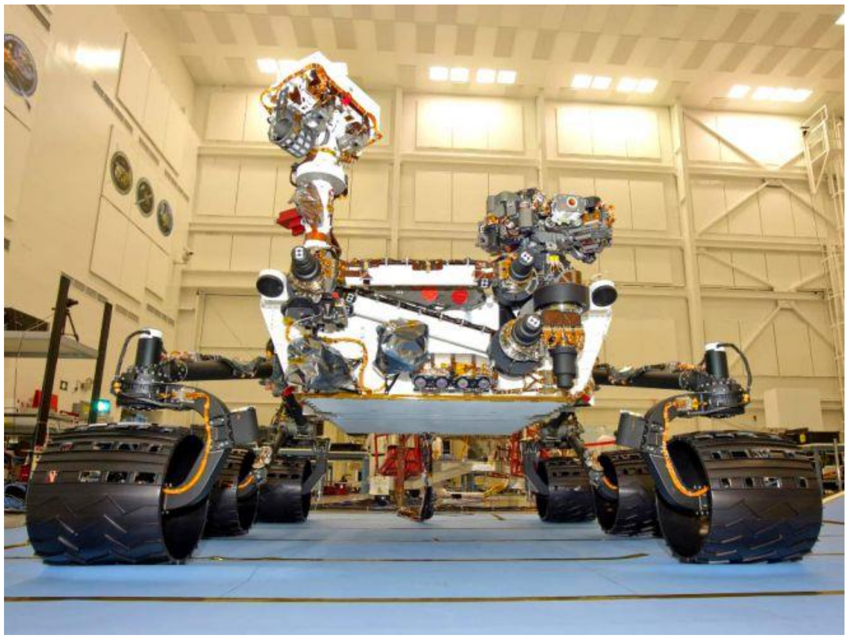

Figure 23. Curiosity rover under assembly. Source: NASA.

Figure 24. Rocket landing of Curiosity rover on Mars. Source: NASA.

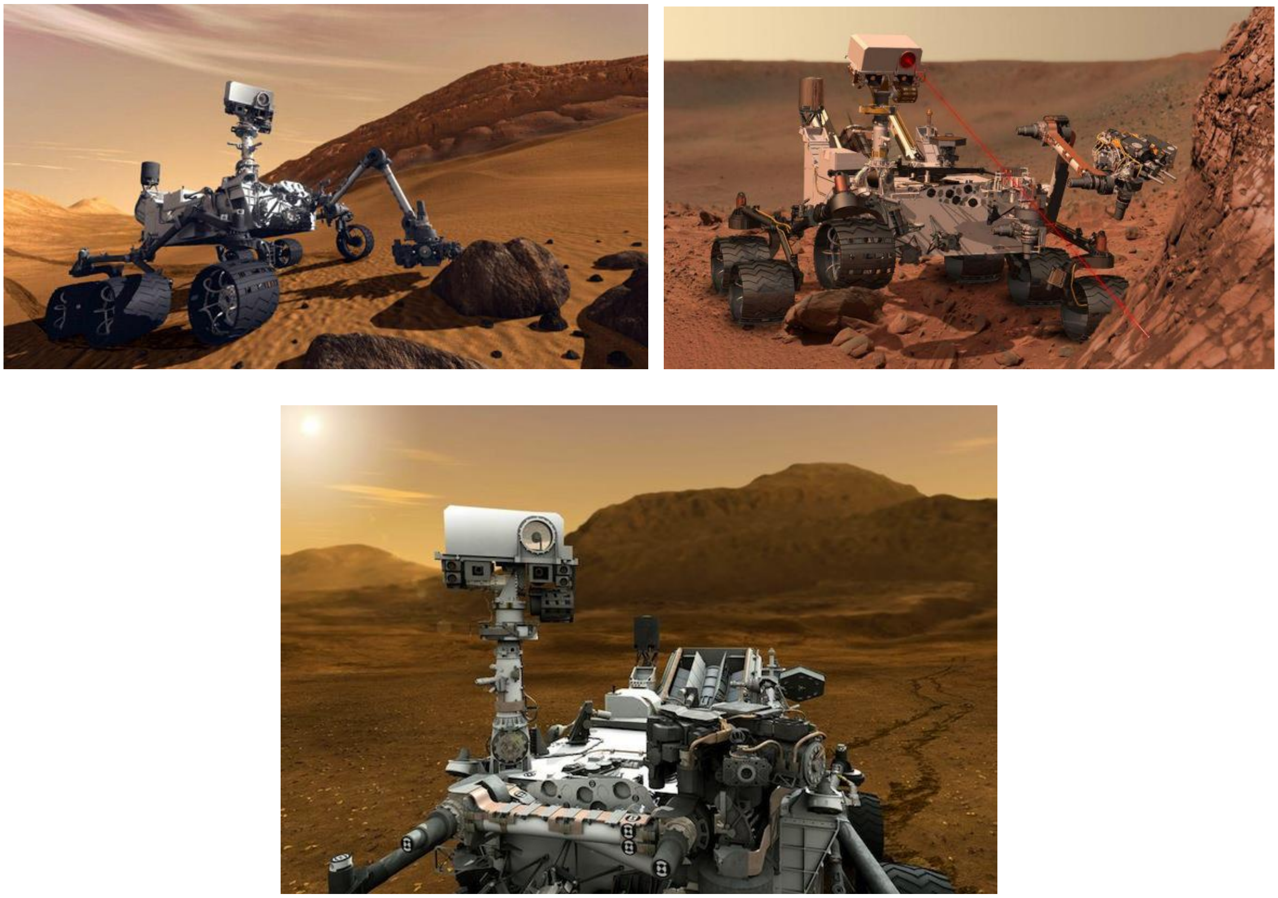

Figure 25. Mars Science Laboratory mission Curiosity rover uses its Chemistry and Camera, Chem Cam, instrument to investigate the composition of a rock surface. It fires infrared laser pulses at a target and views the resulting spark with a telescope and spectrometers to identify chemical elements. Source: NASA.

Mars Science Laboratory (MSL) Curiosity rover was launched on November 26, 2011 using an Atlas V rocket toward Mars on a search for evidence that the red planet might once have harbored life. It takes 8 1/2 months for Curiosity to reach Mars following a journey of 354 million miles. The landing on Mars was at 10:32 Pacific time on August 5, 2012. It seeks to answer questions about Mars' wet history, current atmosphere and climate, and the possibility of ancient or contemporary life on Mars.

The 1-ton Curiosity is as large as a car. It is a mobile, nuclear-powered laboratory holding 10 science instruments that will sample Martian soil and rocks, and analyze them right on the spot. It has a drill as well as a stone-zapping laser machine. The primary goal of the $2.5 billion mission is to see whether cold, dry, barren Mars might have been hospitable for microbial life once upon a time, or might even still be conducive to life now. No actual life detectors are on board; rather, the instruments will hunt for organic compounds.

With an average surface temperature of -82 degrees Fahrenheit, Mars has a cold environment. The Curiosity rover is the largest and most advanced machine to ever touch down on another planet. Rather than opting for photovoltaic solar panels for power generation, as NASA has done for past missions, the MSL will use nuclear energy to make it more productive during its treks over the Martian surface.

Pu-238 in undergoing nuclear decay, provides heat to warm the MSL's electronics and keep it generating data even at night. Unlike previous missions, the rover will be able to ride over to areas without sunlight, giving it wider range of possibilities for exploration.

The Pu-238 thermoelectric generator generates about 110 Watts of electricity through thermoelectric lead tellurite. This power can keep the rover operating along for years if needed, though MSL's current mission is only scheduled to last 23 months.

Idaho National Laboratory, which assembled the nuclear generator, has assured that multiple layers protect the nuclear fuel and that extensive testing has been done to ensure safety. NASA has reliably used nuclear generators for 26 missions over the last 50 years.

Curiosity is 10 feet in length and 9 feet in width. Its 7-foot arm has a jackhammer on the end to drill into the Martian red rock, and the 7-foot mast on the rover is topped with high-definition and laser cameras. No previous Martian rover has been so sophisticated or capable. NASA will use Curiosity to measure radiation at the red planet. The rover also has a weather station on board that will provide temperature, wind and humidity readings; a computer software app with daily weather updates is planned.

The rover is lowered onto the Martian surface via a jet pack and tether system similar to the sky cranes used to lower heavy equipment into remote areas on Earth. It is too heavy to use air bags like its much smaller predecessors, Spirit and Opportunity, did in 2004. Astronauts will need to make similarly precise landings on Mars one day.

Curiosity will spend a minimum of two years roaming around Gale Crater, chosen as the landing site because it is rich in minerals. Scientists reason that if there is any place on Mars that might have been ripe for life, it would be there.

Reliable power from its MMRTG would allow it to operate for at least one Mars year or 687 Earth days. It is able to go farther and work harder than any previous Mars explorer because of its power source consisting of 10.6 pounds of the plutonium^{238} isotope. The nuclear generator was encased in several protective layers in case of a launch accident. The nuclear-powered battery will allow it to rove day and night. Over the course of its two-year initial mission, the probe will climb up a 3-mile-high mountain in the middle of Gale Crater, poking, prodding, and drilling into the soil and rocks.

INSTRUMENTATION

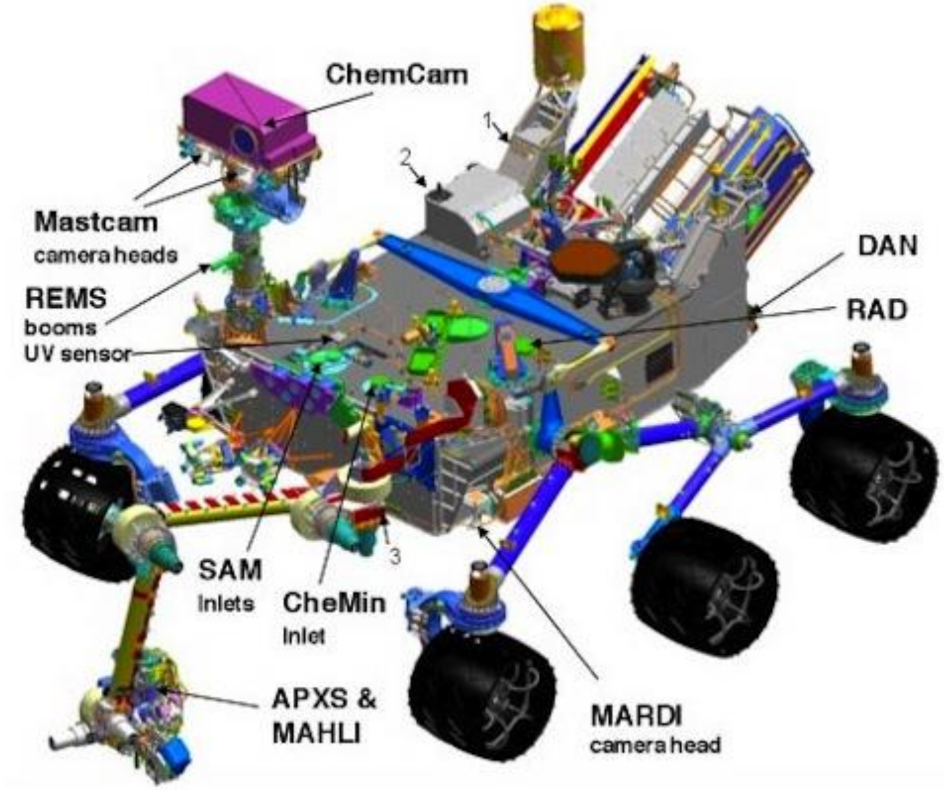

Figure 26. Instruments on the Mars Science Laboratory, MSL, Curiosity Rover. Source: NASA.

MARS SCIENCE LABORATORY ENTRY DESCENT AND LANDING INSTRUMENT, MEDLI

As the rover hits the Martian atmosphere, it will start taking data. Studded in 14 locations around the probe's heat shield are devices known as the Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI). This equipment will provide information about Mars' atmosphere and the dynamics of the rover's descent, analyzing Curiosity's trip to the surface and providing information helpful in designing future Mars missions.

MARS DESCENT IMAGER, MARDI

A special camera, the Mars Descent Imager (MARDI) will be watching the view as the ground rushes up at Curiosity. By taking high-resolution color video during the probe's landing sequence, MARDI will provide an overview of the landscape during descent and allow geologists back on Earth to determine exactly where Curiosity lands.

CHEMCAM LASER INSTRUMENT

The ChemCam instrument uses a laser beam to shoot rocks in order to vaporize a small sample. A spectrograph will then analyze the vapor, determining the composition and chemistry of the rocks. Situated on Curiosity's head, ChemCam can shoot up to 23 feet and should provide unprecedented detail about minerals on the Martian surface.

CHEMISTRY AND MINERALOGY, CHEMIN

The Chemistry and Mineralogy (CheMin) instrument will look at various minerals on the Martian surface. Specific minerals form in the presence or in the absence of water, revealing the history of an area and helping scientists to understand whether or not liquid existed there. Curiosity will drill into rocks to obtain samples for CheMin, pulverizing the material and transporting it into the instrument's chamber. CheMin will then bombard the sample with X-rays to determine its composition.

ROVER ENVIRONMENTAL MONITORING STATION, REMS

The Rover Environmental Monitoring Station (REMS) is Curiosity's weatherman, providing data about daily atmospheric pressure, wind speed, humidity, ultraviolet radiation, and air temperature. REMS will sit on Curiosity's neck and also help assess long-term seasonal variation in Mars' climate.

ALPHA PARTICLE X-RAY SPECTROMETER, APXS

The Alpha Particle X-Ray Spectrometer (APXS) sits the end of Curiosity's arm, allowing the rover to place it right up against rocks and soil. It will then shoot X-rays and alpha particles or He nuclei at the materials to identify how they formed.

SAMPLE ANALYSIS AT MARS, SAM

The Sample Analysis at Mars (SAM) is one of the most important instruments and the reason that Curiosity can be called a mobile laboratory. Taking up more than half of the rover's body, SAM contains equipment found in top-notch labs on Earth:

1. A mass spectrometer to separate materials and identify elements,
2. A gas chromatograph to vaporize soil and rocks and analyze them,
3. A laser spectrometer to measure the abundances of certain light elements such as carbon, oxygen, and nitrogen – chemicals typically associated with life.

SAM will also look for organic compounds and methane, which may indicate life past or present on Mars.

DYNAMIC ALBEDO OF NEUTRONS, DAN

The other experiment important in Curiosity's search for Martian habitability is the Dynamic Albedo of Neutrons (DAN) instrument, which will look for water in or under the Martian surface. Water, both liquid and frozen, interacts with neutrons slowing down and thermalizing them differently than other materials. DAN will be able to detect layers of water up to six feet below the surface and be sensitive to water content as low as one-tenth of a percent in Martian minerals.

MAST CAM CAMERAS

Perched atop its head is the MastCam, two cameras capable of taking color images and video, as well as stitching pictures together into larger panoramas. One of these two cameras has a high-resolution lens, allowing Curiosity to study the distant landscape in detail.

MARS HAND LENS IMAGES, MAHLI

The Mars Hand Lens Images (MAHLI) instrument will provide close-up views of rocks and soil samples near the rover. MAHLI sits at the end of Curiosity's long, flexible arm, and can image details down to about 12.5 micrometers, roughly half the diameter of a human hair. The instrument is able to see in the ultraviolet light part of the electromagnetic spectrum, which will come in handy during night exploration.

HAZARD AVOIDANCE HAZCAMS AND NAVIGATION NAVCAMS

Curiosity's other cameras are the hazard-avoidance Hazcams and navigation Navcams. The Hazcams will watch underneath the rover to prevent it from crashing into any large objects while the Navcams will be mounted on the rover's mast to help it steer. Both camera sets will be capable of taking stereoscopic 3D images.

RADIATION ASSESSMENT DETECTOR, RAD

Future Mars missions may rely on data from the Radiation Assessment Detector (RAD). The first instrument that Curiosity fires up when it lands on Mars, RAD will measure radiation at the Martian surface, determining how plausible it is that microbes exist there. One of RAD's main selling points is its ability to assess how safe or dangerous the Martian surface would be to future human explorers, calculating the radiation dose future astronauts may receive.

3.15 DISCUSSION

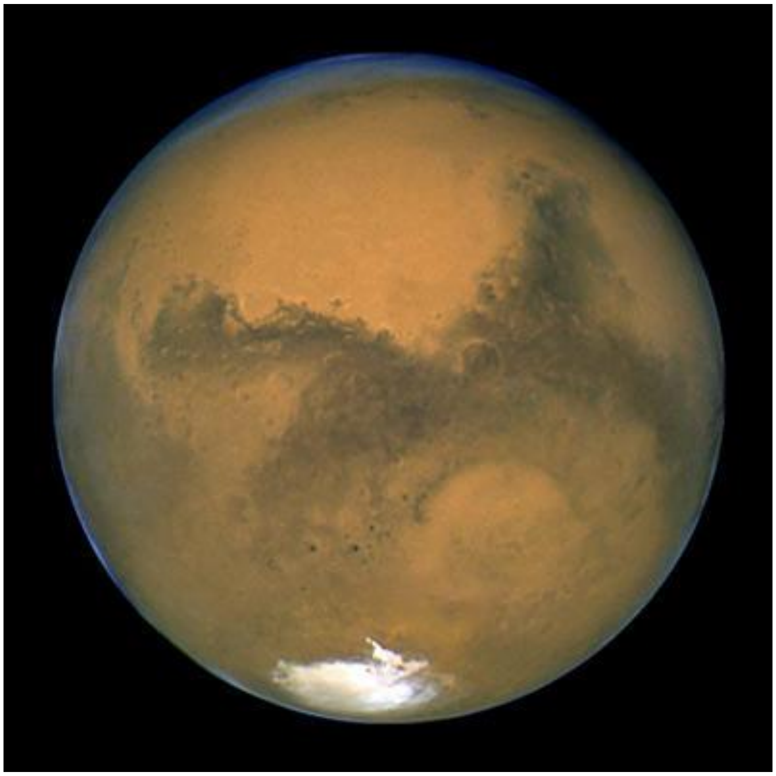

Figure 27. Mars at its closest approach to Earth. Source: NASA.

The use of power as heat and electricity from radioisotope will continue to be indispensable for space exploration. As technology evolves, the need for more power and more heat will undoubtedly grow along with it. At some point for a manned mission to Mars the need would arise for a nuclear reactor system to provide power at a magnitude that isotopes alone cannot provide. In addition because of its higher specific impulse compared with a chemical one, a nuclear rocket may in fact be used to propel the space-ship to Mars reducing its travel time from a year to a few weeks or months.

EXERCISES

1. A space probe needs a Radioisotope Heating Unit (RHU) to heat its equipment in the cold of space away from the sun. The isotope Pu^{238}, an alpha emitter is used in space applications and can produce the needed thermal energy. For a thermal power of 5 Watts what would be the weight needed for this generator in grams?
2. If thermoelectricity can be used at a conversion efficiency of 40 percent, what would be the needed weight be to produce 5 Watts of electrical power?
3. If the radioisotope Sr-90 is used instead of Plutonium-238, what would be the weight of the isotope in the two cases above?
Access the Table of the Nuclides and mine for the data concerning its half-life, and the energy emitted in the radioactive decay.
4. The isotope ${}_{81}\text{Thallium}^{204}$ has a half life of 3.78 years. It decays through beta decay to ${}_{82}Pb^{204}$ with a branching ratio of 97.1 percent with decay energy of 0.764 MeV. It also decays through electron capture to ${}_{80}Hg^{204}$ with a branching ratio of 2.9 percent with decay energy of 0.347 MeV.
    a. Calculate its total specific activity in [Becquerels/gm].
    b. Calculate its total specific activity in [Curies/gm].
    c. Calculate the specific power generation in thermal [Watts(th)/gm].
    d. For a 100 Watts of thermal power in a Radioisotope Heating Unit (RHU) power generator, how many grams of ${}_{81}\text{Thallium}^{204}$ are needed?
    5. After 3.78 years of operation, what would its power become?
5. The isotope ${}_{38}\text{Strontium}^{90}$ is a pure beta emitter without gamma rays emissions. This makes it particularly suitable for radio isotopic power generation. Its half-life is 29 years and its average beta energy per disintegration is 0.21 MeV. It decays into Yttrium^{90} which has a half life of 64 hours and average beta particle energy per disintegration of 0.89 MeV. The two isotopes are in secular equilibrium or have the same activity. The Yttrium^{90} isotope decays into stable Zirconium^{90}.
    1. Calculate the total specific activity in Becquerels per gram of a mixture of Sr^{90} in secular equilibrium with its Y^{90} daughter nuclide.
    2. Calculate the specific power generation in thermal Watts/gm.
    3. For a 100 Watts of thermal power in a radioisotope heating unit (RHU) power generator, how many grams of ${}_{38}Sr^{90}$ in equilibrium with Y^{90} are needed?
    4. After ten years of operation, what would its power become?

Use: 1 MeV/sec=$1.602\text{x}10^{-13}$ Watts, $A_v=0.602\text{x}10^{24}$ [nuclei/mole].

6. A radioisotope power generator uses the isotope $_{84}Polonium^{210}$. If its specific thermal power is 141[Watts(th)/gm], its half-life is 0.38 year, and the thermal to electrical conversion efficiency is 20 percent, determine:

1. The weight of the isotope needed to produce 30 Watts(e) of electrical power.
2. The electric power after 0.76 year of operation.
3. The electric power after 1.52 years of operation.

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