NUCLEAR POWER TECHNOLOGIES FOR DEEP SPACE AND PLANETARY MISSIONS

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ABSTRACT

Photovoltaic cells are well established as the appropriate primary power source for most space missions. For long duration missions that cannot rely on harnessing the external power of the sun, electrochemical processes are simply too low in energy density to provide useful sustained power. Nuclear processes, however, can have huge energy densities, and for this reason, nuclear power systems (NPS) are the only current alternative to solar arrays for long–term generation of power in space.

Although nuclear power has been in use since the beginnings of spaceflight, it remains a niche technology that has not enjoyed the visibility and commercial-sector development effort of solar photovoltaics. However, as our space science and exploration programmes look to the outer planets or to long-duration lander missions, nuclear power becomes a key enabling technology.

It is logical and useful to divide space nuclear power systems into three categories. In order of increasing complexity, these are:

- Direct production of heat by radioactive decay.
- Electrical power generation via radioactive decay heat.
- Nuclear reactor systems.

Past and future mission applications for these are briefly considered before examining, in greater detail, the technology challenges presented by the first two classes of NPS; the radioactive decay heat systems. Of particular current interest are the various methods for conversion of heat to electrical power. For space nuclear power systems, thermoelectricity has been the dominant technology, due to its long-term reliability and vibration-free operation. However, the cost, mass, and safety implications of radioisotopic fuel provide a strong driver to move towards higher-efficiency conversion techniques that could greatly reduce the fuel quantities required.

This paper reviews the established technologies used in space nuclear power systems, and then looks to the future, summarising the main areas of worldwide development and considering the requirements that will influence the direction of work in this field in the coming years.

1. INTRODUCTION

This paper aims to provide a broad insight into the crucial but niche technology that is, at present, unavailable to European space projects other than through collaboration with the USA or Russia. It considers the full range of space nuclear power systems (NPS), but focuses primarily on those exploiting the heat of radioisotopic decay (as opposed to fission reactor systems). The various technologies for converting heat to electricity are assessed, and the applications for space nuclear power are analysed, both generically and in the frame of ESA programmes.

2. CLASSES OF SPACE NUCLEAR POWER SOURCE

2.1. Heat Generation

The simplest nuclear power sources used in space are Radioisotopic Heater Units (RHUs). These devices contain an amount of radioactive material to generate heat directly via natural radioactive decay.

In a radioactive decay process, a nucleus emits radiation in the form of photons and/or elementary particles. This emitted radiation carries electromagnetic or kinetic energy that, if absorbed in the immediate surroundings of the device itself, is manifested as localised heating. Therefore, favoured isotopes are often alpha emitters. This is because alpha particles (^{4}He nuclei) are both highly energetic and display very low penetration through matter. This low penetration means that the heat energy is manifested within the device where required, and that the unwanted side effect of external radiation emission is kept to a minimum. Consideration of suitable isotopes can be found in Section 4.

An RHU, therefore, is a fundamentally 100% reliable device, in the sense that its heat output cannot fail, but will only fall according to the known half-life of the radioactive isotope. The downside of this is that the heat output cannot be deactivated during, for example, ground operations or launch phase.

The primary technological challenge of RHUs is the encapsulation of the radioactive material. Most significantly, it is necessary to ensure that the RHU is sufficiently robust against accident scenarios that would threaten to expose the radioactive material to the Earth

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environment or population.

Typically, RHUs are low power devices, containing less than 20g of radioisotope, and producing less than 10W of heat. The Ulysses probe contained 35 USA-provided RHUs, with power of only $1W_t$ each. These small units could be placed directly where heat was required, avoiding or limiting the use of electrical heaters. Fig. 1 shows an (unfuelled) $8.5W_t$ Russian "Angel" RHU. This type of RHU was used on the "Mars 96" mission (which was unfortunately subject to a launch failure). The same design of RHU is proposed for use on ESA's ExoMars mission. The PuO_2 fuel in the "Angel" unit is encapsulated first in refractory metal, and subsequently in various layers of carbon-based insulating and structural materials.

The use of RHUs is an issue closely related to electrical power system sizing. Whilst RHUs do not generate electrical power, they provide power budget savings by removing the need for electrical heaters.

Figure 1. Russian "Angel" $8.5W_t$ RHU (unfuelled simulator)

2.2. Radioisotopic Power Systems

The heat generated by the decay of a radioisotope can be used to generate electricity. The usual way of doing this is via the thermoelectric (Seebeck) effect. Such a device is called a radioisotope thermoelectric generator (RTG). RTGs are an established technology for both space and terrestrial applications. On Earth, RTGs were used most widely in the former Soviet Union to power remote lighthouses and navigation beacons. In space, RTGs have been used most extensively by the USA, with the Soviet Union favouring reactor power sources.

Since 1961, the USA has flown 41 RTGs [1]. All of these flight models used ^{238}Pu fuel, although other isotopes were used in several development or demonstration models.

The earlier U.S. RTGs used telluride thermoelectric materials. From 1976 onwards, silicon-germanium alloys were used [1]. The main technical weakness of RTGs is their low power conversion efficiency, which is in the region of 7% for modern devices. The c.a. $300W_e$ GPHS RTG is optimised for use in vacuum, and is not suitable for use in planetary atmospheres (it uses light-weight multi-layer insulation). This is one reason why the USA is now developing the "Multi-Mission RTG" (MMRTG), which will be suitable for both environments, but at the cost of a significantly lower specific power (W_e/kg) [2]. The $125W_e$ MMRTG is expected to be flight qualified on the 2009 Mars Science Laboratory Mission.

Other power conversion technologies have been coupled to radioisotope decay heat sources. The early U.S. system SNAP-1 used a mercury Rankine-cycle heat engine, and SNAP-13 used caesium vapour diodes for thermionic conversion (neither were flown) [3]. More recently, NASA's development of Stirling heat engines for radioisotopic generation has neared maturity, and the U.S agency has publicly stated its intention to fly a Stirling system in the next few years [4]. Heat engines promise greater efficiencies than thermoelectrics, but the dynamic nature of the devices brings challenges in terms of reliability and vibration damping.

NASA's current research activities in this field are focussed mainly on thermoelectrics and Stirling engines, and to a lesser degree on thermophotovoltaics and Brayton-cycle turbines. [5][2].

2.3. Nuclear Reactor Systems

The only U.S. fission reactor known to fly in space was the SNAP-10A. This was a thermal[*] reactor, using Uranium-Zirconium Hydride (U-ZrH_x) fuel, and a sodium-potassium (Na-K) liquid-metal primary coolant. SNAP-10A developed $42kW_t$, and was coupled to a SiGe thermoelectric power converter producing ~$600W_e$. The system provided power to the SNAPSHOT spacecraft, which was equipped with an ion thruster. SNAP-10A operated in space for 43 days in 1965, until a failed voltage regulator triggered a shutdown [6][7].

The U.S. space reactor programme also produced the SNAP-2 and SNAP-8 reactors. These were also thermal reactors with U-ZrH_x fuel and Na-K coolant, but were coupled to a Rankine-cycle power conversion system

[*] Utilising moderated, thermal-energy neutrons to induce fission. As opposed to a *fast* reactor, which has no moderator, and uses fission-energy neutrons to sustain the chain reaction.

(see Section 5.3). These were ground-tested, but never flown [3][6]. More recently, between 1978 and 1995, the USA developed a fast reactor design known as SP-100. This was originally proposed with a Si-Ge thermoelectric system, but has also been linked, on paper, to closed Brayton cycle conversion. The SP-100 programme was cancelled before any reactor testing took place.

The USSR space programme made more extensive use of fission reactors, with 35 believed to have been launched between 1967 and 1988 [8]. Most of the Russian reactors have been coupled to thermoelectric generators, and used for short duration low-earth-orbit military satellites. Some higher power systems have used in-core thermionic generation. [8]

Whilst reactor systems clearly have the potential to power various forms of electrical propulsion systems, they can also be used for *nuclear thermal propulsion*. This involves the direct heating of a propellant gas (such as H_2) within the reactor core, which is then ejected from a convergent-divergent nozzle to provide thrust. From 1955 to 1973 the USA was engaged in the development of nuclear rocket engines in the *Rover/NERVA* programme. The development reactor families were known as KIWI, NRX, PHOEBUS and PEWEE. The PHOEBUS-2A reactor ran at over 4GW thermal power for 12 minutes in June 1968 [6]. Remarkably, this is a similar power to today's largest electrical utility power reactors.

3. APPLICATIONS FOR SPACE NUCLEAR POWER SYSTEMS

3.1. Planetary landers and rovers

Solar power is disadvantaged in planet surface applications by the day/night cycle and atmospheric attenuation. On Mars, the seasonal dust storms cause both a transient increase in atmospheric attenuation and some attenuation due to settled dust on the solar arrays.

These variabilities in the solar flux also create a thermal control challenge, which would traditionally require electrical heaters to overcome. This places further strain on the electrical generation system, which is already challenged by the factors described above. It can be seen, therefore, that both nuclear heating and nuclear power generation can bring great advantages.

3.2. Outer Solar System and Deep Space Exploration

Satellites in Earth orbit can generate kW of electrical power from photovoltaic arrays of reasonable size (a few square metres). However, the inverse-square relationship between solar radiation flux and distance means that the situation is very different for the outer planets (Jupiter and beyond). Considering that state-of-the-art solar arrays are less than 30% efficient, we can easily calculate that one square metre of array will generate approximately 13W at Jupiter, and less than 4W at Saturn. Therefore, Jovian missions are at the very limit of the useful range of photovoltaics. For Saturn and beyond, solar power can be discounted, regardless of future improvements in solar cell technology. Surface science missions to distant moons such as Titan are a prime candidate for the use of radioisotope power systems.

The 1990 Ulysses probe is an interesting example of a mission enabled by nuclear power systems. The Ulysses mission was to orbit and observe the sun, from a polar orbit. Therefore, a gravitational swing-by of Jupiter was required to bring the spacecraft out of the ecliptic plane. This long cruise phase to Jupiter, as well as the subsequent aphelic parts of the elliptic solar orbit, required the use of a $290W_e$ GPHS RTG, as well as 35 1-Watt RHUs for thermal support.

3.3. Nuclear Electric Propulsion

Nuclear electric propulsion (NEP) is a notable case of a potential application for nuclear/radioisotopic power systems. NEP will be critically important for deep-space science and exploration missions for the following reasons:

Firstly, electric propulsion itself is already a mission enabler compared to chemical propulsion when high delta-V requirements are combined with a need to limit the orbit transfer to a reasonable timeframe, therefore practically excluding time-consuming gravity-assist manoeuvres. However, due to physical size constraints, the supply of power to electrical thrusters cannot be achieved by solar panels beyond Jupiter.

At the lowest level of power, NEP is just conceivable with power from a radioisotopic system. The largest RTG flown to date is the one used on Cassini (GPHS-RTG, $295W_e$). For instance, a few GPHS-RTGs on a single craft would allow the use of a small ion engine (as used on Artemis and GOCE) or a mini Hall-effect thruster (under development). However, NEP is most often linked, on paper, with higher power reactor systems.

The Russian liquid-metal cooled thermionic-reactor system "TOPAZ" provides 5 kW_e for 1 year, or potentially for longer at lower power. Its mass is greater than 1 ton, including 27 kg of enriched ^{235}U fuel, and it has a length of nearly 4m. This range of power could supply the already flight-proven Hall-effect thruster (as used on SMART-1 and Alphabus).

An up-scaling of the Topaz design has been already proposed as feasible. This would result in the 25-30 kW_e range, with a 2.5 ton system mass, and 40 kg of enriched ^{235}U. This would allow the use of a cluster of

"T6" high-power electric thrusters (under qualification for the Bepi-Colombo mission) or PPS-5000 thrusters (under development) or even very high-power Hall-effect thruster in the 20-25 kW_e range (under preliminary design). High-power reactor NEP systems such as these are undoubtedly an exciting future concept.

4. RADIOISOTOPES FOR SPACE POWER

Leaving aside the subject of fission reactors, and concentrating on radioisotope decay heat, there are some important considerations that limit the number of potentially suitable isotopes. These are considered below.

4.1. Decay Modes and Radiation Types

Most unstable isotopes decay by either alpha or beta particle emission. These charged particles can be absorbed quite easily in small thicknesses of solid material, especially alpha, which can be effectively stopped by a sheet of paper.

However, most beta decay is accompanied by gamma rays (high energy photons) as a result of internal relaxation of the daughter nucleus. Furthermore, beta particles produce *bremsstrahlung* photons as they are slowed within a shielding material. The penetration of photons depends entirely on their energy, but is typically much greater than that of charged particles. This is important for space applications, because gamma ray attenuation is achieved by mass alone. Heavy metals such as lead are typical shielding materials primarily because their density makes them volume-efficient.

The heavy nuclei that typically undergo alpha decay also tend to have a spontaneous fission decay mode. Whilst the prevalence (*branching ratio*) of the fission mode is low compared to the alpha mode, the highly penetrating neutrons produced in the fission process can be very significant in terms of external radiation dose. Furthermore, alpha-neutron (α,n) reactions with light nuclei such as oxygen will add to the neutron emission. Neutron shielding is a more subtle process than gamma shielding. Firstly, the fast neutrons must be thermalised (slowed) by scattering from light nuclei such as hydrogen or carbon. Once thermalised, the neutrons must be absorbed in a material of high neutron capture 'cross section'. Boron, gadolinium and cadmium are some common examples, and hydrogen (^1H) is also reasonably effective when in the form of a dense hydrogenous compound.

There will also be some degree of gamma or x-ray production from an alpha-active isotope, albeit at much lower intensity than with a typical beta emitter.

4.2. Half Life and Specific Power of Radioisotopes

The half-life, $T_{½}$, (years), and the specific power output P_{sp} (W/g) of an isotope are fundamentally inversely related as per Eq. 1:

$$P_{sp} = \frac{\ln 2}{T_{\frac{1}{2}}} . \frac{E_d . N_A}{A} \quad (1)$$

Where E_d = average released energy per decay, excluding neutrinos,
N_A = Avogadro's number,
A = relative atomic mass.

Therefore, a balance must be struck between a desirable high power density, and a half-life long enough to suit the space mission. It is advantageous if an isotope undergoes a chain of multiple decays, provided that the daughter products have short half-lives. In such a case, the power output is multiplied whilst the effective half-life remains that of the parent isotope.

The average energy released per decay, E_d, varies from isotope to isotope, but is significantly larger for alpha emitters than for beta. This relationship is presented graphically in Fig. 2. The beta emitters do not fit to a smooth curve because two of them (^{90}Sr and ^{144}Ce) have major energy contributions from the decay of daughter products.

In the past, short-lived isotopes such as ^{144}Ce (285 days) and ^{210}Po (138 days) have been envisaged for, or used in, short mission applications, namely low-earth orbit and moon landers. Isotopes such as these would be unsuitable for use in a NPS device that must meet the transfer time requirements of planetary and outer solar system missions.

4.3. Radioisotope Chemical Form

The isotope must be available in a form that is thermally and chemically stable. In an accident scenario, the aqueous solubility of the compound is very important when calculating the effect upon the population and environment. For instance, a soluble compound will enter the ecosphere more readily, but dilution may nullify its toxicity. In operation, the compound must not corrode the encapsulating material, even when operating at very high temperature.

It is important to note that the use of chemical compounds reduces the weight-specific power of the radioisotope fuel. The greatest reduction comes when using very light radioisotopes. Elemental tritium (^3H) has a reasonable specific power of more than 0.3 W_t/g. However, other than for very small-scale applications, it is impractical to use hydrogen gas, and a hydrogen compound such as LiH must be employed. This reduces the specific power to less than 0.1 W_t/g.

4.4. Radioisotope Availability

As well as the various technical considerations, a suitable isotope must be obtainable and affordable. Isotopes that must be manufactured in a nuclear reactor are inevitably very expensive, and in addition, many nuclear materials are subject to various national or international regulations and restrictions. These restrictions may apply to the manufacture, ownership, use, storage and transport of the material.

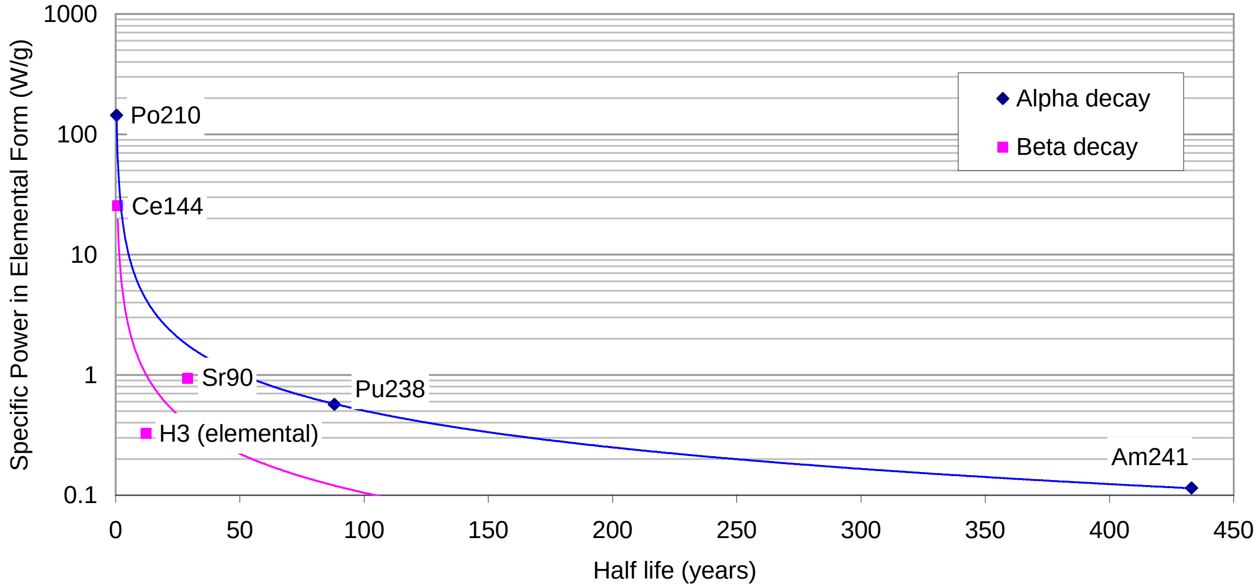

Figure 2. Isotope Specific Power as a Function of Half Life.

Historically, some space radioisotope generators have employed beta-active fission products that are far from ideal in terms of shielding requirements, for reasons of cost and availability [3]. However, none of these models were flown. In terrestrial applications, where the mass of shielding is not so problematic, ^{90}Sr has been the favoured isotope for RTGs. A quantified assessment of shielding requirements in the context of modern radiological safety standards is necessary to establish if ^{90}Sr can be used in space with a useful power-to-mass ratio.

^{238}Pu is technically the best radioisotope heat source for anything other than very short space missions. However, ^{238}Pu forms only a few percent of standard reactor-grade plutonium, and cannot be separated. Therefore, it must be specially manufactured by irradiation of other actinides (normally ^{237}Np) in nuclear reactors, followed by chemical purification. This means it is very expensive and the worldwide supply is extremely limited. The USA has stated an intention to recommence ^{238}Pu manufacture in the future, but has always refused to make this material available for export. It is understood that production of ^{238}Pu in Russia has also ended, and existing stocks are limited.

^{241}Am has never been employed as a radioisotopic heat source, probably because it has only 20% - 25% of the power output of ^{238}Pu (depending on the specifics of compounds, purities, etc.) However, it is an alpha-decaying isotope with only a minor low-energy gamma output, and may be available within Europe as an unwanted by-product of the nuclear fuel reprocessing cycle. Following the chemical separation of mixed plutonium isotopes from the other components of spent nuclear fuel, the plutonium is usually stored in the form of PuO_2. During storage, the ^{241}Pu decays, with a half-life of 14 years, to ^{241}Am. Hence, ^{241}Am is said to "grow in" to the plutonium. Chemical processing techniques can subsequently be used to extract the americium, in a purification cycle.

Given the severely restricted availability of ^{238}Pu, the use of ^{241}Am may warrant further investigation, particularly if an autonomous European NPS capability is required, and ^{238}Pu remains unavailable or prohibitively expensive.

Those isotopes potentially suitable for decay-heat nuclear power systems are listed in Table 1.

5. POWER CONVERSION TECHNIQUES FOR SPACE RADIOISOTOPIC POWER SYSTEMS

Many different techniques may be used to convert heat energy into electrical energy. For space applications, it is clear that light weight, high efficiency systems are desirable. However, the qualities that have effectively dominated the selection of space power conversion systems in the past are reliability and lack of vibration. Military "spy satellites" were the early driving force for the development of RPS, and systems with no moving parts, such as thermoelectrics and thermionics, were ideal for providing motionless and reliable power. The low efficiencies of these techniques resulted in high nuclear fuel costs and associated launch weight costs, but these could be accommodated in military budgets. However, for modern civil space applications, increased efficiency is hugely important.

Table 1. Isotopes potentially suitable for Decay-Heat NPS. (Nuclear data from references [9][10][11])

Isotope	Half-life	Specific Power. (W_t/g in elemental form)	Decay Mode and Radiative Emissions	Suitable Chemical Form(s)	Production Route and availability.
^{238}Pu	88 years	0.568	α. Some neutrons from spon-fiss and (α,n).	PuO_2 Pu_2C_3	Reactor irradiation of ^{237}Np or ^{241}Am. World supplies virtually exhausted.
^{241}Am	433 years	0.115	α. Some neutrons from spon-fiss and (α,n). Significant soft γ.	AmO_2	Chemical separation from aged reactor-grade Pu. (Carried out in civil reprocessing operations in France.)
^{90}Sr	29 years	0.935	β. Plus bremsstrahlung photons from β shielding.	$SrTiO_3$ SrO $SrZrO_3$	Fission product –Could potentially be obtained from a nuclear reprocessing plant.
^{210}Po	138 days	144	α. Some neutrons from (α,n).	HgPo PbPo Po	Reactor irradiation of ^{209}Bi. Availability is very unlikely. Included in this table only because of previous space use*.
^{144}Ce	285 days	25.5	β. Also γ, mainly at 134keV. Bremsstrahlung photons from β shielding.	CeO	Fission product –Could potentially be obtained from a nuclear reprocessing plant.
^{3}H	12.3 years	0.326 elemental 0.098 as LiH	β. Plus bremsstrahlung photons from β shielding.	LiH	Reactor irradiation of ^{6}Li.

Fig. 3 illustrates the inverse relationship between fuel requirement and system efficiency, assuming the use of $^{238}PuO_2$, with an illustrative comparison line for ^{241}Am The efficiency range for several different conversion technologies is indicted on the curve. It is clear that there is a strong incentive to improve the efficiency of radioisotopic power sources from the ~7% (thermoelectrics) region up to 20-30%. This will bring a factor of three saving in fuel cost and weight, and would be vital if a low power isotope such as ^{241}Am was used.

5.1. Thermoelectricity

Thermoelectricity is by far the most applied power conversion technology for space nuclear power systems. Whereas metals are normally used to form thermocouples used for temperature measurement, a thermocouple designed for power production is formed from two semiconductor "legs". The technology of thermoelectric generation is dominated by the search for the optimum p-type and n-type semiconductor materials. The performance of a thermoelectric material is quantified by the figure of merit "Z" as follows: [12]

$$Z = \frac{\alpha^2 \sigma}{\lambda} \qquad [K^{-1}] \tag{2}$$

where,
α is the Seebeck coefficient or 'thermopower' ($\mu V.K^{-1}$),
σ is the electrical conductivity ($A.\mu V^{-1}.cm^{-1}$), and
λ is the thermal conductivity ($W.cm^{-1}.K^{-1}$)

Whilst all conductors and semiconductors exhibit thermoelectric properties to some extent, a material is usually considered to be 'thermoelectric' if its value of Z is greater than $0.5\times10^{-3}\ K^{-1}$.

Different thermoelectric materials are optimal in different temperature regions. From around 450 to 850K, lead telluride alloys are the established material of choice, but at higher temperatures up to 1300K, silicon germanium alloys are more efficient. [12]

Some other materials that are in the development stage have still higher figures of merit. A notable example is the class of compounds known as filled skutterudites. Skutterudites are binary compounds of the composition MX_3, where M is a metal such as Co, Rh or Ir, and X is a pnicogen such as P, As or Sb. Another active field of research is that of nanostructured or "low dimensional" materials. In this context, the application of nano-

* Po metal was used to fuel SNAP-3B, but the melting point is only 254°C.[3]

technology is normally via the introduction of "nanoparticles" within the bulk semiconductor material. These particles are used to modify the thermal or electrical properties of the material, typically the thermal conductivity [12].

Thermoelectric conversion systems have no moving parts, generate DC power, and demonstrate proven long-term reliability. These factors are strong advantages for space applications. On the downside, even state-of-the-art systems have a conversion efficiency of less than 7%. This low efficiency has a threefold negative impact: firstly on the mass of the device, secondly on the cost of the nuclear fuel, and thirdly on the quantity of waste heat which has to be rejected. RTGs are invariably mounted on booms external to the spacecraft body. This is partly to limit the effect of emitted radiation on the spacecraft systems and payload, but also to allow effective heat rejection.

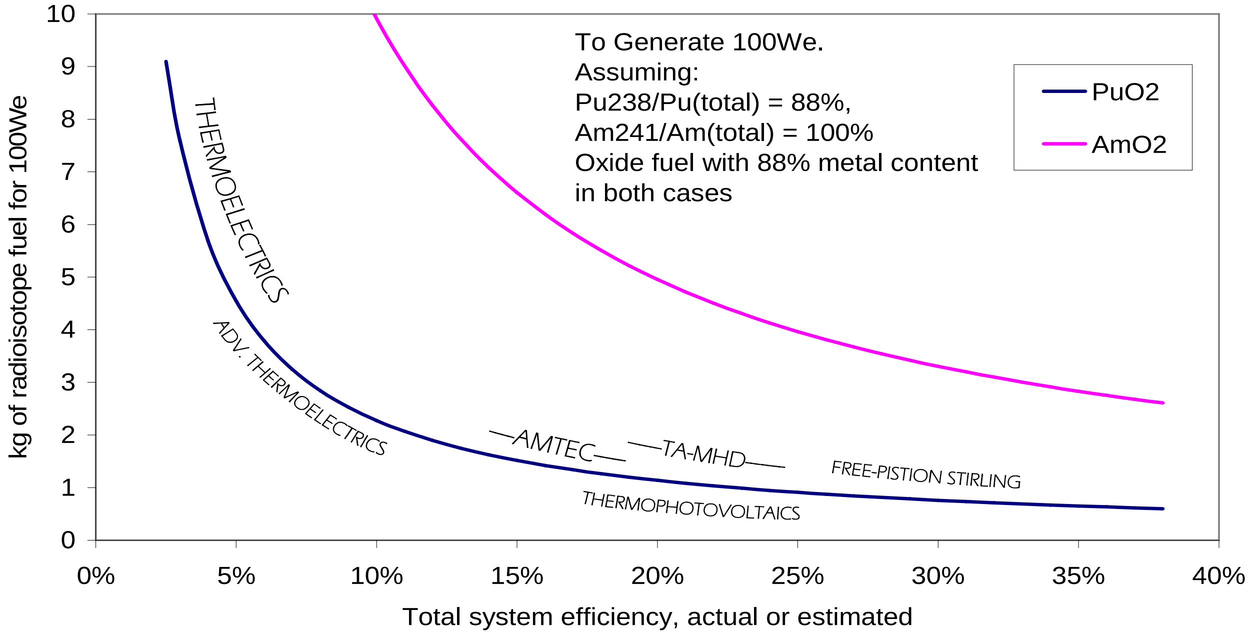

Figure 3. Isotopic fuel requirement vs. converter system efficiency.

The established USA GPHS-RTG has a specific power just above 5 W_e/kg at BOL. However, the as-yet un-flown MMRTG only achieves 2.8 W_e/kg [13], due partly to its smaller scale (125W_e as opposed to 285W_e), and partly to its heavier insulation required for use in planetary atmospheres.

5.2. Thermionics

A thermionic converter produces electrical work directly from heat by the phenomenon of thermionic emission. No intermediate energy form or working fluid (other than a flow of electrons) is required. In its simplest form, a thermionic converter consists simply of a hot cathode (emitter) and a colder anode (collector), separated by an evacuated or vapour-filled space. For power production devices, it is most usual for the inter-electrode space to be filled with low-pressure caesium vapour.

The efficiency of thermionic converters has a strong positive dependency on working temperature. This is one reason why, in the context of space nuclear power, they have been most widely used (by the USSR) directly inside reactor cores. For radioisotopic generation, thermionics can produce acceptable efficiencies only when used with a very high "hot side" temperature. This makes long-term reliability difficult to achieve. For this reason, there is no significant current interest in thermionics for space RPS.

5.3. Dynamic Heat Engines

A heat engine is a dynamic mechanical system for the conversion of heat into work. The laws of thermodynamics state that the efficiency of such a process is fundamentally limited to be no more than the *Carnot Efficiency*, η_c, a function of the temperatures of the hot and cold reservoirs (heat source and heat sink) between which the engine is operated:

$$\eta_c = 1 - \frac{T_c}{T_h} = \frac{T_h - T_c}{T_h} \qquad (3)$$

where T_h and T_c are the absolute temperatures of the hot and cold reservoirs.

Therefore, in a realistic situation in which an engine's hot source is at twice the absolute temperature of the cold source (e.g. 600K and 300K), 50% is the maximum efficiency that could ever be achieved.

In practice, thermodynamic cycles in real engines deviate from the idealised Carnot cycle, and most have a theoretical efficiency less than η_c, even before 'engineering losses' such as friction and heat leakage are considered.

The first class of dynamic heat engine to be applied to space nuclear power systems was the Rankine cycle. This is the cycle commonly used in electrical power stations, in which a liquid is heated to form a gas which drives a turbine before being condensed and reused. The Rankine cycle was developed in the USA for both space fission reactor and radioisotopic systems, but was never flown. Mercury was used as the working fluid.

The closed Brayton cycle (a closed loop gas turbine) has been proposed in principle as a suitable technique for high power systems, such as those that would be required for a space missile defence system (e.g. the U.S. Strategic Defence Initiative "Star Wars") [7].

The class of heat engine to have commanded the most research in recent decades is the Stirling engine. Ironically, this engine was most popular in terrestrial applications in the nineteenth century, before continued development of the steam engine rendered it obsolete. The Stirling cycle is a reversible thermodynamic cycle that normally uses reciprocating pistons and a single-phase gaseous working fluid. It is attractive because of its high efficiency, which is theoretically equal to that of the Carnot cycle [14].

NASA has recently focussed a great deal of effort on the development of Stirling engines for space applications [15]. The problem of reliability has been tackled primarily by using a high-frequency "free piston" design, in which gas bearings can eliminate sliding surfaces, and a linear alternator can be used for electrical conversion, eliminating mechanical linkages. Also important for reliability is the use of high-temperature creep-resistant materials at the hot end of the engine. Vibration is reduced by the use of synchronised, opposed, dual-engine units, and with active balancing/damping systems. Recent NASA-funded development by Sunpower Inc. of Ohio has produced demonstration devices with efficiencies of up to 38% for the Stirling converter unit (engine + alternator). The full-system efficiency for a $140W_e$ DC radioisotopic generator is projected to be 30%, with a specific power of over $7W_e$/kg. The system is generally referred to as the ASRG (Advanced Stirling Radioisotope Generator). A recent NASA paper concludes that specific power in the range 8 to $10W_e$/kg appears achievable with this technology [13].

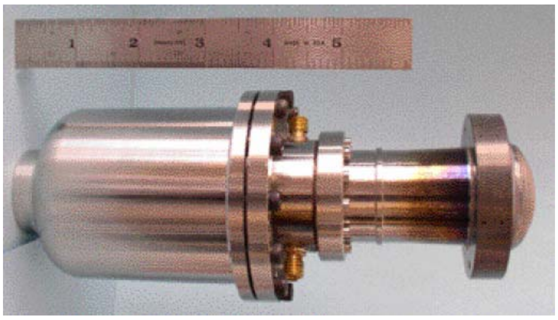

Figure 4. NASA/Sunpower Advanced Stirling Generator unit, containing a Stirling engine and linear alternator. Two such units are used in an "ASRG".

It is important to note that, whilst there is not yet any flight experience with Stirling generators, Stirling cryocoolers employing very similar technology have been used extensively on USA and European missions. These coolers operate with very low vibration, as low as mN levels if active damping is used.

5.4. Thermoacoustics

In a thermoacoustic generator, heat energy is converted first to mechanical (acoustic) energy, which must then be converted to electricity by some means. In this respect, a thermoacoustic system has more in common with a dynamic heat engine than with a thermoelectric or thermionic converter. Thermoacoustic engines can be considered in two categories, depending on whether the pressure-motion phasing of the fluid within the acoustic cavity is characteristic of a standing-wave or travelling-wave. This distinction is not as arbitrary as it may first seem, because the two types of engine have fundamentally different thermodynamic cycles. [16, 17].

A standing-wave thermoacoustic engine employs a simple resonating cavity, such as a closed tube with length equal to half the acoustic wavelength. Hot and cold heat exchangers are separated by a "stack", which is essentially a solid surface with which the fluid can exchange heat. The effective temperature gradient is maintained across the length of the stack. In this case, the stack matrix is relatively coarse, to introduce a small delay in the fluid↔solid heat transfer, so that the movement of the fluid molecules along the stack takes place in quasi-adiabatic conditions.

A travelling-wave engine uses a much more efficient "stack" of a very fine matrix with large surface area. This means that thermal expansion and contraction of the fluid takes place during the movement along the temperature gradient. The resultant reversible thermodynamic cycle is actually the Stirling cycle (see above). For this reason, travelling wave engines are sometimes called Thermoacoustic Stirling Engines, and the stack is referred to as a *regenerator*. Travelling wave engines are intrinsically more efficient than the standing-wave type.

Whichever category of thermoacoustic engine is used, the acoustic power must be converted to electricity by one of several potentially suitable technologies. Piezo-electricity and high-frequency linear alternators are both realistic candidates. However, if a liquid is used as the working fluid, it is possible to combine the thermoacoustic engine directly to a magneto-hydro-dynamic (MHD) generator without any membranes or mechanical moving parts of any type. This concept is attractive for space applications, as it should be intrinsically reliable and should be capable of an overall conversion efficiency in excess of 20%. A device of this type has already been the focus of ESA research contracts that have demonstrated the feasibility of the technology. However, further work is required to assess the power levels and efficiency that may be achievable.

5.5. Beta-Voltaic Systems and Nuclear Batteries

The generic term *nuclear battery* is usually taken to mean a small device that generates electrical power via some direct conversion technique that does not use heat as an intermediate energy form. The simplest such concept directly exploits the emission of charged alpha or beta particles to form a potential difference across a pair of concentric or parallel conductors. Such a device can be thought of as a self-charging capacitor. By their nature, these devices are more voltage generators than power generators, and the steady state current delivery capability is very low.

Most of the modern interest in nuclear batteries is centred on beta-voltaic semiconductor devices. These typically use gaseous tritium (^3H) in direct contact with the surface of a semiconductor "diode" structure. The impact of beta electrons on the p-n junction causes a forward bias in the semiconductor. Such devices are invariably in the μW or mW class of power production, and the author is not aware of any credible proposals for significant up-scaling of the technology.

Perhaps the most likely space application for beta-voltaics is for localised supply of low power at, for instance, instrument detector heads.

5.6. AMTEC

An Alkali Metal Thermal to Electric Converter is a sodium concentration cell which uses a ceramic, polycrystalline β"-alumina solid electrolyte as a separator between a high-pressure region containing sodium vapour at 900 - 1300K and a low pressure region containing a condenser for liquid sodium. During thermal expansion of the sodium vapour through the solid electrolyte, the atoms are ionised, generating electrical power. Therefore, an AMTEC converter is essentially motionless, having the potential for vibration-free operation.

Efficiency of AMTEC cells has reached 16% in the laboratory and was predicted to reach 20% or more [18]. AMTEC was briefly subject to NASA research for radioisotopic generation, but was discontinued in 1999. Long-term reliability and materials stability issues were the main problems.

5.7. Thermophotovoltaics

Thermophotovoltaic (TPV) cells are similar in principle to solar cells, but operate in the infra-red region, converting heat directly into electricity. A heat source is used to heat a selective emitter material, which has wavelength characteristics matched to a suitable low-bandgap semiconductor PV cell. Clearly, this power conversion technique is motionless and vibration-free. Furthermore, it has the attraction that it is based on photovoltaic technology, of which there is plentiful space heritage.

In recent years, NASA has placed at least three R&D contracts on TPV for radioisotope power application [19]. This work is targeting conversion efficiencies in excess of 20%, but is at very low TRL (Technology Readiness Level) compared to the Stirling engine "ASRG" system. In the USA, development companies have made widely varying estimates of the specific power of $100W_e$ TPV RPS systems (8 to 15 W_e/kg). However, a recent NASA paper has concluded that 5 to 7 W_e/kg is realistic [13].

6. SAFETY ISSUES

Any work involving the use of radioactive substances is necessarily subject to a high degree of regulation, for two main reasons:

- To ensure the safety of workers, the public and the environment.
- To prevent the diversion of nuclear material towards non-peaceful uses (with regard to criminal, terrorist or state nuclear proliferation).

Regulatory and safety systems, processes and procedures for the terrestrial use of nuclear material are well established in most developed nations. However, the use of nuclear material in space is far less common, and only the USA and Soviet Union/Russia has launched nuclear material on civilian space missions*.

Specifically, Europe has no experience of launching space nuclear power systems, and no European country has an established regulatory framework to control such a launch. Furthermore, any safety case for the launch of NPS will certainly be very different from terrestrial nuclear safety cases, due to the possibility of the NPS

* Discounting small radioactive sources used in scientific instruments.

being subject to a high-energy accident (launcher failure).

Therefore, it is essential that any European NPS programme be accompanied by the development of a regulatory and safety framework. This must involve close liaison of the nuclear and launch regulatory authorities, especially in France. .

7. THE FUTURE

The science and robotic exploration programmes of the European Space Agency include future missions to the outer planets, and missions with planetary landers and rovers. Nuclear power sources are a key enabling technology for such missions. ESA's Aurora programme has a long-term goal of manned missions to the Moon and/or Mars. It is widely acknowledged that human presence on Mars would require nuclear power, probably reactors.

ExoMars will use Russian RHUs for thermal control within both the rover and the static lander module, and as such, will be the first European led (and launched) mission to use NPS. As RHUs are the simplest form of space nuclear power system, and contain only small amounts of radioisotopic fuel, the ExoMars approach is a sensible first step for Europe, and opens the debate on whether more complex radioisotopic power generators could be used on European missions.

8. REFERENCES

1. G.L. Bennett, *Space Nuclear Power: Opening the Final Frontier*. AIAA-2006-4191. Proceedings of the 4th IECEC, June 2006.
2. National Research Council. *Priorities in Space Science Enabled by Nuclear Power and Propulsion*. 2006. ISBN 0-309-65337-1. The National Academies Press, Washington, D.C. (www.nap.edu).
3. W.R. Corliss & D.G. Harvey. *Radioisotopic Power Generation.* 1964.
4. *Space News.* 29th October, 2007.
5. D.J. Anderson et al. *NASA's Advanced Radioisotope Power Conversion Technology Development Status.* 2007 Aerospace Conference, Big Sky, Montana. March 3-10 2007. IEEEAC Paper 1610. NASA/TM-2007-214487.
6. J.A. Anglio, Jr. & D. Burden. *Space Nuclear Power.* 1985. ISBN 0-89464-000-3.
7. *Advanced Power Sources for Space Missions.* Committee on Advanced Space Based High Power Technologies. National Research Council (USA). ISBN 0-309-03999-1.
8. G.L. Bennett. *A Look at the Soviet Space Nuclear Power Program*. Energy Conversion Engineering Conference, 1989. IECEC-89. Proceedings of the 24th Intersociety. 1187-1194 vol.2.
9. E. Browne & R.B. Firestone. *Table of Radioactive Isotopes.* 1986. ISBN 0-471-84909-X.
10. The JEF2.2 Evaluated Data Library, as "JEF-PC", Nov 1994. OECD/NEA.
11. A.L. Nichols, D.L. Aldama*, M. Verpelli, I.A.E.A. International Nuclear Data Committee. H*andbook of Nuclear Data for Safeguards*. January 2007. NDC(NDS)-0502.
12. D.M. Rowe (Ed.). *Thermoelectrics Handbook – Macro to Nano.* 2006. CRC Press. ISBN 0-8493-2264-2.
13. L.S. Mason. (NASA GRC) *Realistic Specific Power Expectations for Advanced Radioisotope Power Systems.* Journal of Propulsion and Power Vol. 23, No. 5, September–October 2007.
14. M.W. Zemansky & R.H. Dittman. *Heat and Thermodynamics.* Sixth Edition, 1981. ISBN 0-07-072808-9.
15. R.K. Shaltens & W.A.Wong. *Advanced Stirling Technology Development at NASA Glenn Research Centre.* NASA Science Technology Conference, Adelphi, Maryland, June 2007. NASA/TM-2007-214930.
16. S. Backhaus & G. Swift (Los Alamos National Laboratory). *New Varieties of Thermoacoustic Engines.* 9th International Congress on Sound and Vibration, July 2002. LA-UR-02-2721.
17. T.D. Rossing (Ed). *Springer Handbook of Acoustics*, Chapter 7. 2007.
18. M.A. Ryan & J.P. Fleurial. *Direct Thermal-To-Electric Energy Conversion For Outer Planet Spacecraft.* 12-May-2002. 201st Meeting of the Electrochemical Society Philadelphia, PA, USA.
19. D.J. Anderson. *NASA Radioisotope Power Conversion Technology NRA Overview*. NASA/TM-2005-213981. November 2005.