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Prepared for the U.S. Department of Energy
Assistant Secretary for Nuclear Energy

Westinghouse
Hanford Company Richland, Washington

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THULIUM HEAT SOURCES FOR SPACE POWER APPLICATIONS

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ABSTRACT

Reliable power supplies for use in transportation and remote systems will be an important part of space exploration terrestrial activities. A potential power source is available in the rare earth metal, thulium. Fuel sources can be produced by activating Tm-169 targets in the space station reactor. The resulting Tm-170 heat sources can be used in thermoelectric generators to power instrumentation and telecommunications located at remote sites such as weather stations. As the heat source in a dynamic Sterling or Brayton cycle system, the heat source can provide a lightweight power source for rovers or other terrestrial transportation systems.

INTRODUCTION

The Space Exploration Initiative (SEI) is America's program to explore the universe and from that exploration, gain knowledge and a better understanding of how we relate to it and how we can use it to our benefit. In the grandest form, the SEI includes manned missions to the moon and to Mars, first for scientific exploration and then for mining and manufacturing.[1] All this implies a terrestrial base from which to direct activities. Base power will be supplied by a nuclear reactor. Remote power is expected to be supplied by photovoltaics and fuel cells.

Over the last 25 years, radioisotopes have provided a heat source from which to extract power. Generally, the isotopic source of choice has been plutonium-238 (Pu-238). Its long half-life makes it ideal for supplying power to remote satellites and space craft such as Voyagers I and II and, most recently, the Galileo. However, the United States is no longer producing P-238, and what quantities exist, are already slated for use in the space program.

Thulium, a rare earth metal, may be capable of making isotopic heat a viable option for space power production. It can be launched from the earth in a chemically stable, nonradioactive form. The targets can be activated in-flight or once they are received at the space station. In a matter of months, the newly created heat sources can be placed directly into power generators.

DESCRIPTION

In current space Radioisotope Thermoelectric Generator (RTG) and Dynamic Isotope Power Supply (DIPS) designs, heat producing isotopes are activated and installed into the generator prior to launching from Earth. Plutonium decays by neutron and gamma emission requiring shielding to limit personnel dose and to protect radiation sensitive equipment leading to heavier launch loads. Although the 87 year half-life keeps power relatively constant, the specific power of 0.56 W/g-Pu-238 limits the amount of useful electric power that can be produced when radiation shielding is added. The cost to NASA for existing plutonium has been approximately $1300 per gram. This source is already committed to other projects and, should the U.S. begin producing Pu-238 again, the cost is expected to at least triple. Other potential sources are foreign suppliers with short-term availability and unknown purity and costs.

Westinghouse Hanford Company proposes a concept in which the heat source leaves the earth as an isotopically and chemically stable target. The target does not become radioactive until it is activated at the space station for one to three months. This eliminates shielding requirements during launch, making handling significantly simpler and safer and lightens the total payload. The design is presently based on thulium (Tm), a rare earth metal found in nature in the single, stable isotope Tm-169. Although not particularly abundant, it is found in deposits of bastnasite, monazite and xenotime ores. Combined with oxygen, it forms one of the most stable known compounds, thulium sesquioxide, Tm_2O_3, which has a 2650 K (4310 °F) melting point. It has a low vapor pressure and a thermal expansion similar to graphite.

When irradiated, Tm-169 transmutes to Tm-170. Thermal heat generated in pure Tm-170 has been calculated in the range of 11.6 kWt/kg to 12.1 kWt/kg. It decays primarily through beta decay (99.8 % of the time) to ytterbium-170 with a half-life of approximately 129 days. Of the beta decay, 76% produce betas of 0.968 MeV and the remaining 24% produce 0.884 Mev beta particles. These betas also produce 70% of the dose.[2] An 84 keV gamma is emitted with the 0.884 Mev beta, however this gamma is highly converted internally. Another decay product, erbium-170, is produced by the gamma decay of Tm-170. Both ytterbium and erbium are isotopically stable, simplifying disposal requirements. Bremsstrahlung, producing about 70% of the radiation dose,[2] can be inhibited by shielding with a low atomic number material such as graphite.

A small amount of Tm-171 is produced in the irradiation process which must be considered in the disposal along with activated impurities. It has a half life of 1.9 years and decays by beta decay to ytterbium-171. Because of its longer half-life, it has a minor effect on the total power. The primary impurities found in Tm_2O_3 are erbium, ytterbium, iron, calcium, silicon magnesium and aluminum. Under current regulation on Earth, the used heat source would be classified as Class B low-level waste after 129 days of decay (one half-life).

Targets could be fabricated in such a manner as to be used as a heat source requiring little to no intermediate processing steps. A mixture of Tm_2O_3 and graphite create a light weight target that minimizes bremsstrahlung.

Once irradiated, no chemical or isotopic separations would be required as the newly created heat source could be put to use in the same form. The size, shape and cladding would be conducive to insertion and removal from the space reactor with immediate insertion into the generator. The fuel could be activated as the energy needs demanded. Launching the thulium RTG components from earth requires handling only non-radioactive, chemically benign materials. This reduces the payload weight and significantly reduces the risks to the flight crews, ground crews, radiation sensitive equipment, and the general population in the event of a launch accident.

Evaluation of this concept has consisted of two studies, physics and system studies. In the physics studies, we appraised the feasibility of producing Tm-170 in a space reactor such as SP-100. System studies evaluated their use and handling of such heat sources in the SEI.

PHYSICS STUDIES

Westinghouse Hanford Co. performed physics calculations for Lawrence Livermore National Laboratory to evaluate thulium heat source power supplies for autonomous underwater vehicles for the U. S. Navy.[3,4] These calculations were used as a starting point in our space power analysis. The SP-100 was used as the source reactor for the target irradiation (2.4 MWt, lithium-cooled, fast reactor). Radial reflectors external to the reactor core are designed to control power in the high-leakage reactor core. For analyses, the reflector was replaced by a target consisting of a 0.5 cm Tm_2O_3 slab sandwiched between 3-cm layers of yttrium-hydride ($YH_{1.7}$) for neutron moderation.

Converting 10% of the Tm-169 to Tm-170 produces a specific heat in the range of 1 kWt/kg of Tm_2O_3. To maximize the production rate of Tm-170, no thulium was actually included in the model of graphite and oxygen (no self-shielding). This over estimates the production rate and will be lower when thulium is added back into the model. Figure 1 shows that an SP-100 neutron flux of 2.86×10^{13} n/cm^2-s can produce about 0.1 kWt/kg in about 1.5 months.

A thermal neutron spectrum (0.025 eV), raises production by approximately 20%. By tailoring neutron moderation to the 1 eV to 10 eV range, production goes up by almost an order of magnitude, producing over 1 kWt/kg in three months of irradiation.

We then found the flux level required to achieve higher production levels, assuming the same $YH_{1.7}$ moderated SP-100 neutron spectrum. We performed a parametric study of the neutron flux required to activate the target within six months time. Figure 2 shows that to produce approximately 6.7 kWt/kg of oxide within three months, the flux level in the reflector region must be in the range of 3×10^{15} n/cm^2-s. At more moderate flux levels, power densities of 2 kWt/kg and 3 kWt/kg can be achieved at flux levels of 3×10^{14} n/cm^2-s and 5×10^{14} n/cm^2-s, respectively, after six months of irradiation.

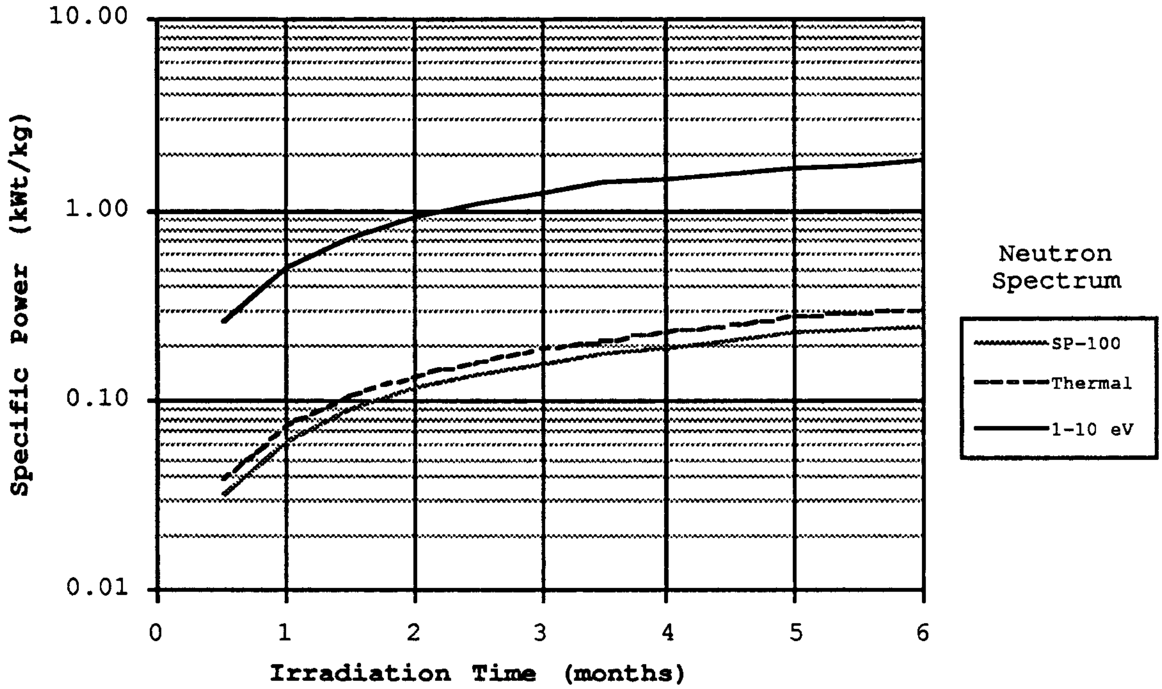

Figure 1 Specific Power of Tm_2O_3 as a Function of Irradiation Time and Flux Level in the SP-100

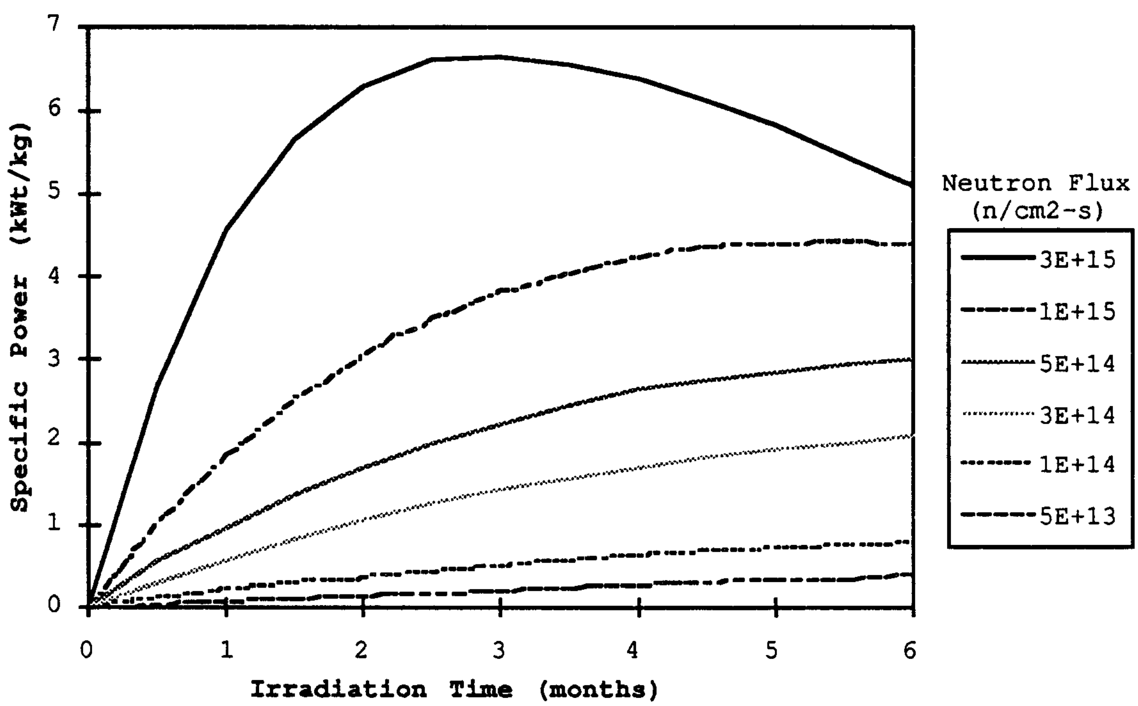

Figure 2 Specific Power of Tm_2O_3 as a Function of Irradiation Time and Flux Level in a Filtered SP-100 Neutron Spectrum

If the flux level at the target were to increase by stepping up the reactor flux, production of Tm-170 at higher power levels becomes feasible. These two charts show that if the neutron spectrum is optimized and the flux is between 1 and 3 x 10^{14} n/cm^2-s, the targets could be activated to 1 kWt/kg within a few month's time.

The potential exists to recycle the heat sources. If 10% or less of the thulium atoms are activated, we may be able to reirradiate the source once it has decayed below usable levels, allowing more than one use for the target prior to disposal. More analysis must be performed on activation rates, activation products, and material properties.

SYSTEMS STUDIES

Space power needs range from low powers to relatively large power levels. Instrumentation, such as that aboard past space probes, will require power up to 10 kWe. Medium power systems, between 10 and 100 kWe, are required for surface operations such as advanced rovers and advanced science missions. Higher power levels are required for earth orbital missions, permanent base power source and nuclear propulsion systems.

Heat Source Uses

Thulium-170 could provide a valuable heat source for the low and mid-power range equipment. As can be seen in Table I,[5] a variety of power needs can be met by an appropriately powered radioisotope heat source.

Table I
Power Needs for the SEI Mission

Up to 10 kWe	
Low Power Rovers	RTG, DIPS, Fuel Cells
Remote, Unmanned Stations	RTG, Fuel Cells
Thermal Heating Units	Shielded Tm_2O_3 Thermal Unit
10 kWe to 100 kWe	
Pressurized Scientific Rovers	DIPS, Fuel Cells
100 kWe to 1.0 MWe	
Base Power	Nuclear Reactor
Construction/Mining Machinery	DIPS

The high power density of 12.1 watts/gram makes Tm-170 a good candidate for rovers and other space systems which need high power levels over longer time periods. It can also be useful in supplying lower power needs. As a thermoelectric generator it can trickle charge battery supplies which may be required for emergency backup power or to supply a short-term power boost. The RTG can power instrumentation and telecommunications located at remote sites such as weather stations. As the heat source in a dynamic system, it can provide a light-weight power source for rovers or other terrestrial transportation systems.

The current design for RTGs requires 9.63 kg of Pu (≈11 kg PuO_2) to produce 300 We. At 1 kWt/kg, only five kg of Tm_2O_3 would be needed to produce that same power. Generator design modifications are needed to accommodate more frequent and simpler reloading of the fuel. The generator design, as well as dynamic generator designs, would have to be such that the fuel is easily accessible and quickly replaced. Because of the need for fuel replacement and the harsh environment in which the generators will operate, the design must be more rugged than that used for deep space probes.

Rover power requirements are expected to vary from 0.5 kW for initial unmanned scientific rovers up to 30 kWe for piloted rovers and construction and mining machines.[5,6] Regenerative fuel cells which currently produce 250 W-hr/kg are expected to improve to 1 kW-hr/kg by the year 2000. Fuel cells with 100 kWe-hr storage capacity would be required for the low power, 1 kWe, rover (100 kWe-hr will provide power for four days). The 1 kWe-hr/kg fuel cells would be required to carry 100 kg of fuel, along with the hardware for storing the fuel as well as for storing water produced by the fuel cell reaction, for later conversion back to hydrogen and oxygen.

To produce the same power using a Tm-170 dynamic system with 30% efficiency in which the Tm_2O_3 is producing heat at 2 kWt/kg, the power output is 600 We/kg. This means only 1 kg of Tm_2O_3 would supply more than enough power at the initial loading. Even if the fuel produced heat at a rate of 0.1 kW/kg, only 17 kg of Tm_2O_3 is needed. Using Tm_2O_3 can extend the range and trip duration without impacting fuel loading requirements.

Space heating can also be met with heat sources. Properly shielded, they can produce radiant heat required to keep instrumentation properly functioning as well as maintain personnel comfort.

With fuel cells, rovers requiring greater power will be limited in the amount of time they can be active before more fuel is needed. More fuel and water storage would be required as well. Dynamic Tm_2O_3 systems will last significantly longer than two to three days and require relatively simple upsizing. Comparatively, dynamic Tm_2O_3 systems show a distinct advantage over fuel cells.

Fuel Handling

The physics studies suggest that in a properly designed reactor, enough neutrons can be available external to the core in the reflector region. This allows the target to be activated outside the reactor liquid metal coolant, further simplifying the handling. If the cladding does not have to come into contact with coolant, the choice of acceptable cladding materials increases and may allow for a single cladding layer. Ideally, a gas coolant could be used in the reflector. Another benefit of this is the absorption of the neutrons.

Targets would be fabricated to be used as heat sources requiring little or no preparation. Targets would be a mixture of Tm_2O_3, graphite, and possibly a neutron moderator. The target would be inserted and removed from the reactor through a rapid insertion system. Once irradiated, the newly created heat source would be handled remotely. A relatively simple automated system could be used to remove the targets from the reactor, nondestructively analyze and clean them. Loading the sources into the generator can be performed with a remote or automated system. Small targets might be placed into a secondary package for insertion into the generator. This would simplify processing especially if only part of a generator's fuel is replaced at refueling time.

The generator, whether an RTG, DIPS or a thermal generator, could be brought into the hot cell or, alternatively, remain external to the cell with a sealed docking port through which to access the heat source. The decayed source could be removed and immediately replaced by a new heat source. The used source would be either prepared for disposal or reinserted into the reactor for another cycle. Either way, once the generator is reloaded, it can immediately begin producing power.

Remote, semiautomated handling is anticipated for a number of reasons. Personnel need to be protected from the radiation as well as from the heat produced by the activated source. There may be some thermal shock protection required of the heat source and the components it contacts, suggesting that some controlled heating and cooling may be needed. The generators have historically required a high quality internal environment to minimize degradation of the RTG unicouples. They must be kept inert with argon gas or under a vacuum of at least 10^{-6} torr. Unless the generator is could be redesigned to seal off the unicouples from the heat source allowing access to the fuel without compromising the interior atmosphere, an inerted or evacuated atmosphere will be required.

Throughput

We can get a feel of the throughput of Tm_2O_3 if we look at a conservative effort to maintain a relatively stable 1 kWt heat source. The first year, Table II, in which a quarter of the fuel is replaced each month, 5.25 kg of Tm_2O_3 would be required. In subsequent years, this would be reduced to 4.20 kg per year. This causes a variation of 170 Wt which results in approximately 12 We for RTGs with a 7% efficiency and 51 We for dynamic systems with 30% efficiency. In a unit with 30% efficiency, the power would vary only 51 We. If a specific power of 6 kW/kg can be obtained, Tm_2O_3 requirements can drop to as low as 0.70 kg annually. To produce power for a single 1 kWe rover, this results in approximately 14 kg annually for a 1 kWt/kg heat source and only 2.3 kg for a 6 kWt/kg source. A supplier of such materials quotes a cost of \$30/kg of Tm_2O_3 on an annual basis of 400 to 500 kg. If the need for the material rises, production can be increased to effectively reduce unit costs.

Assuming launch prices to lift material into low Earth orbit are approximately \$7700/kg and that it takes about 10 kg of fuel to get 2 kg to the lunar surface, the cost to get fuel to the moon is approximately \$38,500/kg. Assuming that half the weight of the target/heat source is graphite, based on the discussion above for producing power for a 1 kWe rover, it takes 12 times more mass to fuel the rover with fuel cells. Even though the waste product from the fuel cells can be reprocessed, the hardware required to perform that effort must also be delivered. Recycling the targets requires no extra equipment.

Table II
Power and Fuel Use for a 1 kWt Tm_2O_3 Heat Source

Month	Power Level (kWt) of Fuel Batch at Reload				First of Month	End of Month
	1	2	3	4		
1	0.35	0.35	0.35	0.35	1.400	1.192
2	0.35	0.30	0.30	0.30	1.244	1.059
3	0.30	0.35	0.25	0.25	1.155	0.983
4	0.25	0.30	0.35	0.22	1.117	0.951
5	0.22	0.25	0.30	0.35	1.117	0.951
6	0.35	0.22	0.25	0.30	1.117	0.951

Although thulium is a rare earth material, Rhone-Poulenc, one supplier of such materials, quotes a cost of \$3000 per 100 kg of Tm_2O_3 on an annual basis of 400 to 500 kg. This is low when compared to the \$4000/g price of Pu-238. Also, if the need for the material rises, they can step up production and the cost will drop as time progresses. The availability of the material is not a problem.

Compared to Pu-238 and fuel required for fuel cells, the Tm_2O_3 quantities are exceedingly small and at \$30 per kg, this fuel is a bargain.

CONCLUSIONS AND RECOMMENDATIONS

Results of this initial evaluation of the feasibility of a Tm-170 heat source for space power application show the idea looks promising. Compared to fuel cells, Tm_2O_3 heat sources show some significant advantages. They can supply power for longer durations for a significantly smaller quantity of fuel. The heat source fits in well with the SEI goals and revitalizes the use of radioisotope power supplies. Although a fair amount of development needs to be performed, much of it is based on established technology. RTGs have been used for over 30 years and a modular DIPS design is well under way. The following activities are required to fully evaluate this concept and complete the design:

By starting now, an integrated system can be designed to meet the terrestrial space power needs of the future.

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