DOE F 1325.28
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United States Government **Department of Energy**

memorandum

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Date: August 4, 1992 **SECRETARIAL ACTION REQUESTED BY:**

Orig. Office: NE-1 (NE-50:A. R. Newhouse:903-4306)

Transmittal: INFORMATION: Alternatives to Plutonium-238 for Space Power Applications

To: The Secretary

Issue: Are there radioisotopes other than Plutonium-238 (Pu-238) that could be used to power Radioisotope Thermoelectric Generators (RTGs) used for space missions?

Discussion: In response to your request, the attached technical information paper discusses the feasibility of using radioisotopes other than Pu-238 to fuel thermoelectric power systems for space missions. The major points of this paper are summarized below.

Since the 1950s, virtually all naturally occurring and man-made radioisotopes have been evaluated to determine which are suitable to use as heat sources for thermoelectric power applications. Suitability generally requires long half-life, low radiation levels, high power density, and a stable fuel form at high temperatures. A number of radioisotopes possess some of these characteristics and several prototypic power systems employing radioisotopes other than Pu-238 were taken to the development stage. However, Pu-238 is the only radioisotope which has been actually utilized in space power systems. Candidate radioisotopes which have been investigated include Cerium-144, Polonium-210, Strontium-90, Curium-242, Curium-244 (Cm-244), Thulium-170, Thulium-171, and Cesium-137. None of these radioisotopes are suitable for current space power application because they either possess too short a half-life for long duration missions, or have sizeable neutron and gamma emissions that result in excessive weight for the shielding required to protect a spacecraft's scientific instruments.

Projected National Aeronautics and Space Administration missions requiring RTGs all have nominal mission lifetimes of 15 to 25 years. The half life of the radioisotope fuel for these RTGs needs to be in the range of 15 to 100 years. Of the over 1400 radioisotopes in the most current chart of radionuclides, only sixteen meet this criterion. After further sorting to select those exhibiting the other necessary characteristics described above, only two candidate fuels remain for long duration, deep space missions - Pu-238 and Cm-244. However, there is currently no available source of Cm-244, and its production requires reactor irradiation and chemical processing operations very similar to those for Pu-238. Additionally, there are disadvantages which make it a less attractive fuel than Pu-238, e.g., it has a shorter half life (18 years, as opposed to 87 years for Pu-238), and its spontaneous fission, with associated neutron and gamma emissions, significantly increases shielding requirements and reduces the power-to-weight ratio of the power system, as compared to Pu-238. Therefore, it is concluded that there is no advantage to using Cm-244 instead of Pu-238, which already has a proven design and safety record.

The technology for production of Pu-238 fuel and its use in radioisotope power systems has been clearly demonstrated over the past 30 years. Pu-238 fueled power systems have been through rigorous testing and safety evaluations; approximately $40 million to $50 million has been expended in qualifying these power systems for space applications. Any new radioisotope fuel would need to be qualified by the same rigorous methodology, which could be expected to be even more costly in today's regulatory environment.

A recent review of historical data and evaluation of existing radioisotopes and their characteristics supports the conclusion that there are no preferred alternatives to Pu-238 for RTGs. While some new production techniques are being worked on which could make some previously difficult to manufacture isotopes easier to acquire, no isotope has been identified to date that is preferable to Pu-238 for space applications. Nevertheless, we shall continue to monitor the issue should any new information or prospects arise.

for William H. Young
Assistant Secretary
for Nuclear Energy

DOE F 1325.8
(8-89)
EFG (07-90)

United States Government Department of Energy

memorandum

DATE: August 4, 1992

REPLY TO ATTN OF: NE-1

SUBJECT: INFORMATION: Alternatives to Plutonium-238 for Space Power Applications

TO: The Secretary

INTRODUCTION

Plutonium-238 (Pu-238) fueled power systems have been used on important national space missions for over 30 years. In the 1950's and 1960's, existing radioisotopes were evaluated to determine which were suitable to use as heat sources for thermoelectric power generation applications. In the early 1960's, the Atomic Energy Commission (AEC) selected Pu-238 as the fuel for the first thermoelectric power systems. To date, Pu-238 is the only radioisotope fuel to have actually been deployed by the U.S. in space nuclear power systems. It was produced as a by-product of defense material production in DOE facilities at Savannah River. Recent reductions in defense material requirements have led to a decision to phase out operation of these facilities, with no further new Pu-238 production. There are currently no practical alternatives to the use of Radioisotope Thermoelectric Generators (RTGs) for powering spacecraft on scientific exploration missions to or beyond the outer planets. In light of this, it is appropriate to review whether or not there are suitable alternative radioisotopes which could be used to fuel RTGs for space missions.

Projected future National Aeronautics and Space Administration (NASA) missions to the outer planets beyond Mars will require RTGs which can sustain power production for a nominal generator lifetime of 15 to 25 years. The half-life of radioisotope fuel for deep space exploration missions should be approximately 15 to 100 years to ensure sufficient power is available at end of mission. Of the over 1400 known radioisotopes, only the sixteen listed in Table 1 have half-lives in this range. This paper presents a historical perspective on the work which has been done in the development of radioisotope fueled power systems for space. It also discusses the criteria used to select radioisotope fuel for space nuclear power systems, especially those for long duration, deep space exploration.

HISTORICAL PERSPECTIVE

Development of radioisotope power systems began in the early 1950s and a variety of radioisotopes were evaluated for space and terrestrial applications. The isotope initially selected for demonstration was Cerium-144 (Ce-144) for use in a military surveillance satellite. The 290 day half-life of Ce-144 made it an acceptable fuel for this short duration mission. However, the Air Force requirement for this power system did not materialize and it was never deployed. The high radiation field and short half-life of Ce-144 make it unsuitable for current and future space power applications.

By the late 1950s, Polonium-210 (Po-210) was used to fuel small developmental RTGs to demonstrate the Systems for Nuclear Auxiliary Power (SNAP) technology. Po-210 is an alpha emitter, with minimum shielding requirements, and a very high power density. However, its short half life (138 days) makes it suitable for only limited duration space power applications. Due to the limited availability of Pu-238 at this time, Po-210 and Strontium-90 (Sr-90) were considered by the Air Force, but never used. Although Sr-90 has a sufficiently long half-life (29 years), its low power density and heavy shielding requirements make it unsuitable for current or future space power applications, particularly deep space exploration where weight considerations are critical. However, Sr-90 can be (and has been) used for terrestrial power systems, where weight restrictions are not as important.

In the early 1960s, radioisotope fueled power systems were first successfully used in space. By this time, Pu-238 had been identified as the preferred radioisotope fuel for space power applications. The first radioisotope powered space mission was a joint venture between the Department of Defense and the AEC. SNAP generators were developed and used to provide power on navigational satellites for the Navy's Transit Program. The first Transit satellite was successfully launched in 1961.

Curium-242 (Cm-242) was pursued for development of thermionic power systems which were never launched. The 162 day half-life of the Cm-242 isotope and its high heat output made it suitable for this application. However, due to its short half-life, Cm-242 could not be considered for current or future space power applications, especially for missions to deep space. Curium-244 (Cm-244) was also investigated as a potential radioisotope fuel. It was considered an attractive fuel choice because it has a relatively long half-life (18 years), a power density five times higher than that of Pu-238, and has a stable fuel form for use at high operating temperatures. However, its high radiation emissions and shorter half-life made Cm-244 less desirable than Pu-238, especially for long duration missions.

Pu-238 has historically been shown to have the best characteristics for isotopic power systems for space missions. This was clearly demonstrated by the performance of the SNAP generators on the Transit satellites and many other subsequent missions, including the Apollo lunar surface experiment packages, the Viking landers, and the Pioneer and Voyager space probes. The advantages of Pu-238 as a fuel for space, as compared to the several isotopes discussed above, are shown in Table 2. Its high power density (high heat output per unit of mass), long half life (87.7 years) and low radiation levels make it clearly superior to other isotopes which have been proposed or tested. No new isotopes have been identified in recent years that change this conclusion.

RADIOISOTOPE FUEL SELECTION CRITERIA AND EVALUATION

Selection of a suitable radioisotope fuel for space nuclear power systems focuses mainly on three areas - half-life, radiation emissions, and power density/specific power. Space power systems must be lightweight, long lived, and efficient (high power to weight ratio). An overriding consideration is the ability to produce and use the fuel safely for space missions, with minimal risk to personnel and the environment.

Half-life Considerations:

Radioisotopes decay in a totally predictable and unalterable process which releases energy as heat and/or radiation. It is accompanied by emission of particles and/or photons including alpha, beta, and gamma radiation. Energy absorbed from these emissions by the fuel itself or its containment is transformed into useful heat. For radioisotopes which deposit similar amounts of energy per disintegration, the weight and size of a heat source are directly proportional to the half-life of the fuel. The half-life of the fuel should be at least as long or longer than the mission lifetime, to reduce the amount of excess fuel required initially to offset radioactive decay, and to provide mission scheduling flexibility. If the half-life is too long, radioactive decay occurs slowly and the amount of heat produced is too low to drive the thermoelectric conversion process. For projected NASA missions with lifetimes of 15 to 25 years, a half-life over 100 years is not required, and would adversely impact the generator efficiency.

Radiation Emission Considerations:

Low penetrating radiation emissions are required for any radioisotope fuel used for space applications. Reduction of weight is a critical consideration in spacecraft design, so a low shielding requirement is a critical consideration in the selection of a radioisotope fuel. A fuel with low radiation emissions is required to minimize shielding weight, reduce worker exposure, minimize risk of exposure to the general populace in the event of a launch accident, and to avoid interference with sensitive particle and photon detectors used on these spacecraft.

Four of the sixteen isotopes listed in Table 1 decay purely by gamma radiation emission, a highly penetrating form of radiation, and therefore can be eliminated from consideration as a fuel source for space applications. Although beta particle emissions are easily shielded, some of the beta particle energy is converted to bremsstrahlung radiation (X-rays), which must be shielded. Beta decay also provides less useful energy than decay by highly energetic alpha emissions. Therefore, beta emitting isotopes are not suitable for space power applications, and the seven beta emitting radioisotopes listed in Table 1 can be eliminated. The radiation level from Ce-137 is doubly high because it is both a beta and gamma emitter, and therefore can be eliminated from consideration.

The four remaining radioisotopes are alpha emitters - Uranium-232 (U-232), Pu-238, Curium-243 (Cm-243), and Cm-244. Both Cm-243 and daughter products of U-232 emit a significant level of gamma radiation, with higher dose rate levels than either Cm-244 or Pu-238 heat sources of comparable size; therefore, they can be eliminated from consideration. From a radiation emission perspective, Pu-238 and Cm-244 are the only isotopes suitable for consideration for space power applications.

The comparable rate of neutron production and associated dose rate for three of the alpha emitting isotopes is shown in Table 3. It is clear from this illustration that Pu-238 once again has superior characteristics for use as a radioisotope fuel. Nearly all the gamma dose from Pu-238 is attributable to the decay chain of the Pu-236 isotope impurity in the fuel, which is limited to very small amounts by Pu-238 fuel quality specifications.

Power Density/Specific Power Considerations:

The power density (watts/cubic centimeter) and specific power (watts/gram) of radioisotope fuel is directly proportional to the energy absorbed per disintegration and is inversely proportional to half-life. Higher power density leads to smaller volume heat sources for comparable power levels and higher specific power leads to lighter weight heat sources. Both characteristics are highly significant for space power heat sources. For radioisotope fuels with comparable half-lives, a beta emitting heat source will be larger and heavier than an alpha emitter.

Fuel Form Considerations:

The radioisotope fuel must be used in a fuel form which has a high melting point, and which remains stable during postulated launch pad accidents (i.e., fires) and accidental reentries into the Earth's atmosphere. The fuel form must also be chemically compatible with its containment material (metallic cladding) over the operating lifetime of the power system. It is desirable that the fuel form have a low solubility rate in the human body and the natural environment. Daughter products and the decay process must not affect the integrity of the fuel form. All of the alpha emitting isotopes listed above form very stable, high melting temperature oxides which are acceptable for space applications.

Availability and Cost Considerations:

Any radioisotope fuel selected for space power applications must be producible in sufficient quantities and on a schedule to meet mission power needs. Appropriate types and amounts of target materials and facilities for processing them are needed. Chemical processing technology to produce the proper fuel compound is required, as well as fuel form fabrication processes and facilities.

The proposed fuel form must be extensively tested to support launch safety approvals. The fueled heat source/power system must undergo an extensive analysis and test program to qualify it for use in space. Development of a fuel production and fuel form fabrication capability for a new fuel is very costly and time consuming. To qualify a new fuel form/heat source for flight use is also a large effort in terms of cost and time. To date, approximately $40 million to $50 million has been spent on safety qualification of the Pu-238 fueled General Purpose Heat Source.

Producibility and cost of the two most acceptable radioisotopes, Cm-244 and Pu-238, are compared as follows. Cm-244 is more difficult to produce as it requires extended irradiation of Pu-239 or Am-241, with more neutron captures per gram than required to produce Pu-238 from Np-237. Both require chemical processing of fuel into an oxide form. The major difference would lie in developing and qualifying a new Cm-244 oxide fuel form, and in design, development, and qualification of the new heat source/power system. Ultimately, Cm-244 would cost more and be less beneficial to the NASA users for long duration, deep space missions. Finally, while some new production techniques are being worked on which could make some previously difficult to manufacture isotopes easier to acquire, most of these advances are in the medical isotope field and do not result in any isotope becoming more advantageous than Pu-238 for space applications.

SUMMARY

In the final analysis, no other radioisotope is available that meets or exceeds the performance characteristics of Pu-238, particularly for long duration, deep space exploration missions due to its high heat to mass ratio, relatively long half-life, and low neutron and gamma emissions. Pu-238 has played a major part in establishing the United States' technological superiority and unique capability to conduct deep space exploration, including such missions as Pioneer 10 and 11 and Voyager 1 and 2. Finally, while some new production techniques are being worked on which could make some previously difficult to manufacture isotopes easier to acquire, most of these advances are in the medical isotope fields and do not result in any isotope becoming advantageous to Pu-238.

The technology for producing and processing Pu-238 fuel, as well as for handling it during fabrication of power systems, has been clearly demonstrated over the past thirty years. These power systems have performed safely and reliably, and have been through rigorous testing and safety evaluations. Changes in the Department's defense complex are eliminating our historical sources of Pu-238 (Savannah River K Reactor and processing facilities). Therefore, if these types of power systems are to continue to be available, new sources of fuel must be found.

The recent review of historical data and evaluation of radioisotopes has failed to disprove the advantages of Pu-238 as the best radioisotope fuel for space power applications. Similarly, no new isotopes have been identified as a replacement for Pu-238. Numerous research and development activities continue within DOE and NASA, as well as within commercial companies, to develop nuclear and nonnuclear power systems suitable for space applications. As yet, no other technology has been identified that could replace Pu-238 fueled radioisotope power systems in the foreseeable future.

for William H. Young
Assistant Secretary
for Nuclear Energy

Attachments

TABLE 1

Radioisotopes with 15 to 100 Year Half-Life

Isotope	Half-life (Years)	Type Emission
1. Promethium-145 (Pm-145)	17.7	Gamma
2. Curium-244 (Cm-244)	18.11	Alpha, SF*
3. Actinium-227 (Ac-227)	21.77	Beta, some Alpha
4. Lead-210 (Pb-210)	22.26	Beta, some Alpha
5. Curium-243 (Cm-243)	28.5	Alpha, Gamma
6. Strontium-90 (Sr-90)	28.6	Beta
7. Cesium-137 (Cs-137)	30.17	Beta, Gamma
8. Argon-42 (Ar-42)	33	Beta
9. Bismuth-207 (Bi-207)	33.4	Gamma
10. Titanium-44 (Ti-44)	47.3	Gamma
11. Platinum-193 (Pt-193)	50	Gamma
12. Uranium-232 (U-232)	72	Alpha, SF
13. Tin-121m (Sn-121m)	76	Beta
14. Plutonium-238 (Pu-238)	87.75	Alpha, SF
15. Samarium-151 (Sm-151)	90	Beta
16. Nickel-63 (Ni-63)	100.1	Beta

*SF = Spontaneous Fission

TABLE 2

Isotope Fuel Characteristics

Isotope	Plutonium-238	Strontium-90	Curium-244	Polonium-210
HALF-LIFE (yrs)	87	28	18.1	0.38
TYPE EMISSION	Alpha	Beta	Alpha	Alpha
FUEL FORM	Oxide	Oxide	Oxide	Metal
MELTING POINT (Degrees C)	2,150	2,457	1,950	254
SPECIFIC POWER (Watt/g)	0.40	0.42	2.42	140
POWER DENSITY (Watt/cc)	4.0	1.94	26.1	1316
ACTIVITY (Curies/Watt)	30.73	147.61	29.12	31
FUEL LOADING/300 We RTG*:				
Thermal Output (Wt)	4,500	5,788	7,092	3.5 x 10 E15***
Weight of Fuel (kg)	11.250	13.781	2.931	2.5 x 10 E10***
Volume of Fuel (cc)	1,125	2,984	272	2.7 x 10 E12***
Activity (curies)	1.38 x 10 E5	8.54 x 10 E5	2.06 x 10 E5	1.1 x 10 E17***
RADIATION LEVELS (BOL):				
Gamma Dose Rate (mr/hr@1m)	5	10,000,000	900	5.4 x 10 E14
Gamma Shield Thickness** (cm of uranium)	0	10.3	5.6	****
Fast Neutron Flux @1m (n/cm/cm/sec)	260	0	116,000	7.1 x 10 E12

* Basis: Same thermal output as Pu-238 fifteen years after fueling (3,993 Wt).
** Gamma shielding to reduce dose rates to about 5 mr/hr@1m (Pu-238 equivalent)

*** Extremely large quantities of fuel would be required due to the short half-life of the isotope; this would not be feasible but is listed for illustration purposes.

**** Shielding was not calculated, weight would prohibit consideration for space applications.

TABLE 3

Neutrons From Spontaneous Fission and (alpha,n) Reactions

	Cm-244	U-232	Pu-238
Alpha Decay Half-life (yrs)	18.11	72	87.75
Spontaneous Fission Half-life (yrs)	1.4 x 10E+7	8 x 10E+13	4.9 x 10E+10
SF Neutrons (n/g-s)	10,242,000	1.9	3,000
(alpha,n) Neutrons * (n/g-s)	11,815	3,128	2,500
Neutron Dose Rate (mr/hr-g@1m)	10.59	0.0032	0.00568

* Oxide Enriched in O-16

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