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THE FEASIBILITY OF CONTROLLED RATE OF RELEASE OF ENERGY 1/1

BY NUCLEAR ALPHA-EMITTERS(U) INSTITUTE FOR DEFENSE
ANALYSES ALEXANDRIA VA D A SPARROW JUN 88 IDA-M-442

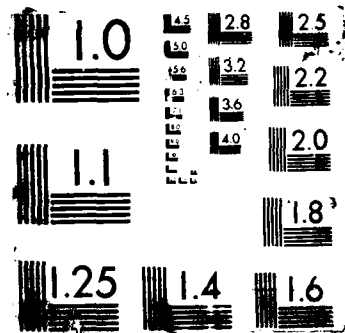
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IDA MEMORANDUM REPORT M-442

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OF ENERGY BY NUCLEAR ALPHA-EMITTERS

David A. Sparrow

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REPORT DOCUMENTATION PAGE				
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY N/A		3. DISTRIBUTION/AVAILABILITY OF REPORT This document is unclassified and suitable for public release.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A				
4. PERFORMING ORGANIZATION REPORT NUMBER(S) IDA Memorandum Report M-442		5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Institute for Defense Analyses	6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State, and Zip Code) 1801 N. Beauregard Street Alexandria, VA 22311		7b. ADDRESS (CITY, STATE, AND ZIP CODE)		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER IDA Independent Research Program		
8c. ADDRESS (City, State, and Zip Code)		10. SOURCE OF FUNDING NUMBERS		
		PROGRAM ELEMENT	PROJECT NO.	TASK NO.
11. TITLE (Include Security Classification) The Feasibility of Controlled Rate of Release of Energy by Nuclear Alpha-Emitters				
12. PERSONAL AUTHOR(S) David A. Sparrow				
13. TYPE OF REPORT Final	13b. TIME COVERED FROM 12/87 TO 6/88	14. DATE OF REPORT (Year, Month, Day) June 1988	15. PAGE COUNT 11	
16. SUPPLEMENTARY NOTATION				
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Nuclear power production, alpha emitters, compact power sources		
FIELD	GROUP SUB-GROUP			
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Energy is approximately one million times more densely stored in atomic nuclei than in chemical bonds. This has been exploited in nuclear reactors which can supply varying amounts of electrical power, but which have a minimum size, and in radioisotope thermoelectric generators (RTGs) which can be small, but have very limited power range despite their large energy density. This paper looks at some possibilities for externally varying alpha decay rates, in an attempt to design an RTG which would be a light, compact, variable electric power source for space applications with peak power much greater than presently available. We consider using alpha particles to stimulate decay, and microwave absorption to reduce the angular momentum barrier and hasten spontaneous decay. Neither of these approaches seems feasible.				
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL David A. Sparrow		22b. TELEPHONE (Include Area Code) (703) 578-2992	22c. OFFICE SYMBOL	

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ACKNOWLEDGMENTS

Conversations with Thomas Paterson, Robert C. Oliver and Francis X. Hartmann of the Science and Technology Division staff at IDA were very helpful in the beginning stages of this project. The author also thanks Bohdan Balko for a critical reading of the text. Formal IDA review was conducted by Ivan C. Oelrich, Leslie Cohen, and Francis X. Hartmann. Their valuable comments are gratefully acknowledged.

ABSTRACT

Energy is approximately one million times more densely stored in atomic nuclei than in chemical bonds. This has been exploited in nuclear reactors which can supply varying amounts of electrical power, but which have a minimum size, and in radioisotope thermoelectric generators (RTGs) which can be small, but have very limited power range despite their large energy density. This paper looks at some possibilities for externally varying alpha decay rates, in an attempt to design an RTG which would be a light, compact, variable electric power source for space applications with peak power much greater than presently available. We consider using alpha particles to stimulate decay, and microwave absorption to reduce the angular momentum barrier and hasten spontaneous decay. Neither of these approaches seems feasible.

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I. INTRODUCTION

Radioisotope thermoelectric generators (RTGs) utilize the energy from nuclear alpha decay trapped as heat to generate electricity. They have theoretical energy density comparable to nuclear reactors, and can be made much smaller, since there is no critical mass requirement. Their drawback is that despite the large energy density power is limited by the decay rate. The purpose of this investigation is to determine if there is a way to externally enhance the decay rate to make a power supply with a larger range of operating powers.

The use of these systems dates to the beginning of the space program. The first systems launched were SNAP-3Bs in 1961. (SNAP stands for Space Nuclear Auxiliary Power.) These units generated 2.7 W with a mass of 2.1 kg, and both operated for 10 years or more. By the time of the Voyager missions in the late 1970s, the multi-hundred-watt RTG was generating 150 W from a mass of only 37.6 kg. At the upper end of the power scale the dynamic radioisotope power system (DIPS), which uses a mechanical heat engine rather than the thermoelectric effect, is designed to produce up to 2 kW, and has been ground tested (Refs. 1 and 2).

Although the DIPS system has mechanically variable output, none of the systems allows for power generation above the ambient level given by the radioactive decay. If an efficient method could be found for triggering the decays two important benefits would accrue. First, high peak powers would be obtainable, even with modest sized systems. Second, for a given lifetime much less of the expensive radioisotope fuel could be used, since the decay rate could be enhanced continuously to maintain power. The original purpose of this investigation was to determine if this triggering was feasible either by using alpha particles themselves to stimulate the decays, or by using microwave radiation to manipulate the angular momentum barrier. A sufficiently efficient method of triggering decay would lead to great savings since some very cheap materials (e.g., all the stable lead isotopes) have an energetically allowed alpha decay, which could in principle be triggered. (These isotopes have very low decay energies, leading to such long barrier penetration times that their decays have never been observed.)

Section II opens with a discussion of the technical features of the two proposed triggering schemes. In Section III, two related approaches which emerged during the research are examined. None of the schemes appears to be workable. In Section IV we summarize the problems with the triggering schemes, and conclude that triggering of nuclear energy to be released in alpha decay does not seem feasible.

II. TRIGGERING MECHANISMS

We will consider two mechanisms for increasing the alpha emission rate of a nucleus. These are, first, stimulated emission and, later, microwave absorption.

Stimulated emission is in principle a mechanism for increasing the decay rate of any system which emits elements of a quantized boson field (integral spin particles) as its decay mode. To date the effect has only been observed with photons, although there have been theoretical studies on the possibilities with pions (Ref. 3). The advantages photons have are, first, that it is relatively easy to create and control a source of photons to use in stimulating the decay of an available sample. Second, the created photons have a relatively long mean free path in matter, so they travel far enough to be effective.

Although alpha particles cannot be created from pure energy like photons they are helium nuclei, and can be created by ionizing atomic helium. The practical difficulty will lie in their short mean free path, or high energy loss rate. Even though alpha particles are known to lose energy rapidly in matter, this possibility seemed worth investigating. In principle, since alpha particles are not point-like field elements, treating them as such will neglect form-factors. This means the calculations give upper limits on rates.

In order for the ionized helium nuclei to stimulate alpha decay effectively they would have to be accelerated to the decay energy and maintained at that energy as they moved through the material. A typical nuclear alpha decay energy is in the 5-8 MeV range. As our first plausibility test we ask what is the rate of energy loss of a 5 MeV alpha particle through matter, and what magnitude electric field would be needed to maintain the alpha particle at constant velocity.

The energy loss for 5 MeV alpha particles ranges from several hundred MeV/cm in carbon and other light materials to a few GeV/cm in lead and denser materials. Maintaining fields of this magnitude is clearly not a feasible approach to triggering. The energy loss decreases with increasing alpha particle energy, but a fifty-fold increase in decay energy is required for an order of magnitude decrease in required field strength. There simply are no alpha emitters with a decay energy anywhere near that large. Stimulation of alpha decay

using alpha particles of the right energy founders on the extremely large field strengths needed to maintain the alpha particles at the right energy.

The second approach we consider is to stimulate the decay by using microwaves to change the angular momentum of the alpha particle. Alpha decay is a complicated many-body process; however, it has been successfully modeled by assuming that a small percentage of the time there is a preformed alpha particle in the nucleus, and that this alpha particle has a definite rate of escape by tunneling through the combined Coulomb/angular momentum barrier. To the extent that this model is valid, it should be possible to change the angular momentum of the alpha particle, and hence the magnitude of the barrier it sees. Alpha decay rates are a very sensitive function of the size of the barrier that the alpha particle must penetrate. Absorption of a low-energy microwave photon would change the effective height of the barrier by much more than the energy of the absorbed photon. Thus, it would appear possible to manipulate the decay rate by applying a microwave field.

In order to determine whether or not this effect could be useful, it is instructive to estimate the effect of the angular momentum barrier on the lifetime. This has been worked out in the limit of large Coulomb potential energy compared with escape kinetic energy, which is the situation for all reasonably long-lived alpha decays. In this case the lifetime is increased by a factor F given by (Ref. 4):

$$F = \exp \left(\frac{h L(L+1)}{\pi \sqrt{2mzZe^2R}} \right)$$

where h is Planck's constant, L is the angular momentum, m is the reduced mass of the alpha particle, e is the charge of the electron, z and Z are the atomic numbers of the alpha particle and the daughter nucleus, and R is the inner radius of the barrier. Evaluating this expression for isotopes in the transuranium region indicates that changing L by one unit would change the lifetime by approximately a factor of two due to the change in the barrier height.

To obtain a net power gain the coupling of microwave energy to the alpha decay mode would need an efficiency greater than 50 percent, which is extremely improbable. Even assuming 100 percent efficiency, this relatively modest effect would probably not be worth the effort of complicating the proven RTG designs with the electronics for microwave generation. To make matters worse, there are additional effects resulting from the changes in the alpha particle wave function in the nuclear interior which tend to cancel

the effect of the barrier. These effects would be very difficult to calculate, or even estimate. These effects simply reinforce the impracticality of this approach.

III. OTHER APPROACHES

In the course of this research, two other approaches to utilization of radioisotopes in power generation were investigated. One involved searching for an isotope mix that would have a power output that was constant or even increasing with time. The second involved using beta emitters, which are known to have great sensitivity to angular momentum, as the radioisotopes and attempting to trigger beta decay with microwaves.

The isotope of choice for the U.S. space program has been ^{238}Pu , which has an 86-year lifetime, and emits a 5.6 MeV alpha particle. The daughter isotope, ^{234}U , emits a 4.9 MeV alpha and has a 250,000-year lifetime, and hence is effectively stable so far as power generation is concerned. Most alpha emitters with "useful" lifetimes (between 10 and 1000 years) follow this pattern, decaying to a nucleus with a lower alpha decay energy and a longer lifetime. However, an isotope which decayed to a daughter with a shorter lifetime would have a heat energy output which increased with time.

A search through the data on alpha emitters indicated that only ^{232}U had the desired type of sequence. Calculations on mixing traces of this isotope with ^{238}Pu indicated that the energy available as a function of time would only change by a few percent over the first few years of operation. Unfortunately, ^{232}U is currently unavailable from Oak Ridge, and has been for many years. It is unlikely this isotope would be made available to facilitate a few percent stabilization of future space-based nuclear power levels.

Triggering alpha decay with microwaves proved impractical because the alpha decay rate was essentially independent of angular momentum. For beta decay, there is a large angular momentum dependence, and we have performed calculations to estimate the feasibility of increasing beta decay rates with microwave radiation. Unlike alpha particles, the products of beta decay do not exist "preformed" in the nucleus. As a result, changing the angular momentum available for the decay is a level mixing process rather than a simple absorption process. A detailed discussion of how to perform these calculations for photons far below the resonance energy is given in the IDA Gamma Ray Laser Annual Summary Report (1986), IDA Report P-2004. Here we simply want to state the salient points.

The most desirable transition from the point of view of exciting the nucleus and not the atomic electrons is magnetic dipole. For such a transition, the kinematic factors associated with the decay width and the off resonance energy all cancel. This makes possible a general estimate of the power required to halve the spontaneous lifetime, which should be accurate within a factor of a few. Our estimate of the incident power flux to double the spontaneous lifetime for 1mm microwaves is $7 \times 10^{20} \text{W/cm}^2$. This requirement is clearly much too great for any small-scale efficient power supply.

IV. CONCLUSIONS

We have examined a variety of methods which could be used to enhance radioactive decay with a view to designing radioisotope thermoelectric generators which could generate peak powers far in excess of the heat released by spontaneous decay. These included stimulated alpha decay and microwave triggering of both alpha and beta decay. None of these were found to be feasible.

In addition, we considered using different isotopes to devise a mix which would have essentially constant heat release, at least for several years. The only reasonable candidate for admixture is ^{232}U . Improvements obtained by mixing this isotope with ^{238}Pu were marginal. The current unavailability of ^{232}U makes this impractical as well.

The only practical scheme which has emerged from this investigation is use of a chain of decay in which the daughters decay faster than the parent isotope for use in long-term power supplies. The unavailability of the one identified isotope makes this an unlikely approach to improving the constancy over time of current systems. However, for long-term space exploration this approach could be used for power supplies which increased their output with time, perhaps for as long as 10 or 20 years. Some further investigation in this area might be warranted.

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