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PROJECTED LARGE-SCALE USE OF RADIOISOTOPES BY NASA

by Robert E. English
Lewis Research Center
Cleveland, Ohio

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TECHNICAL PAPER proposed for presentation at American Nuclear Society Meeting on Large-Scale Production and Application of Radioisotopes
Augusta, Georgia, March 23, 1966

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1966

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INTRODUCTION

For investigation of the problems connected with the design of large, isotope heat sources, the particular thermal power of 50 kW was selected. In general, the analysis is relevant for thermal powers ranging from 10-100 kW. The selected time period is the decade of the 1970's. The potential demand for isotopes during this period is estimated, and various candidate isotopes are compared on the basis of hazard and required weight.

Such a projection of demand for isotopes into the 1970's is highly speculative. NASA has as yet no approved missions that require large amounts of isotopes. Even the level of NASA's budget in this period is a debatable matter. The justification for such a speculative projection is that economical production of the most attractive isotopes also requires a similar long-range projection of demand. Without some early planning for this future need, the results would be either a lack of the best isotopes when the demand materializes or an expensive crash program to produce these isotopes in a short period of time.

If the isotopes are available, the extent of their use is still an open question, for this use will depend on the merits of isotope power systems in relation to the merits of competitive power systems. If mission duration is of the order of a year or more and if the required electric power is of the order of 10 kW, solar photocells are the primary competitive source of electric power. The nature of this competition between isotope and solar power systems will be discussed.

Ultimately, the extent to which isotopes will be used in space power systems will depend on the solutions found for the problems of isotope systems. Chief among these problems is the hazard associated with the isotopes themselves. An attack on this problem of safety is presented, and this approach then provides the basis for comparative evaluation of several isotopes.

REENTRY

For an isotope heat source burned up on reentry into the Earth's atmosphere, the extent of atmospheric contamination is given in Table I. The complete source was assumed to be reduced to particles of the order of a micron in size at an altitude high enough to permit wide dispersion by the wind. The maximum fraction of the initial inventory that is contained

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in the troposphere is directly related to the half-life; among the isotopes considered, Pu-238 yielded the highest concentration and Po-210 the lowest. In general, these concentrations for a 50 kW source range from 10^{-4} to 10^{-2} of the maximum permissible concentration in air. Although none of these levels of contamination would be a serious hazard to any given individual, widespread contamination of the atmosphere, even at these levels, is not desirable. Because several such isotope sources may be flown, intact reentry was selected as the preferred design criterion.

HELIUM CONTAINMENT

If the capsules containing alpha-emitting isotopes are to remain hermetically sealed indefinitely, some void volume must be provided for the helium that accumulates. The size of this void is shown in Fig. 1. The void volumes were chosen to limit the maximum internal pressure to either 100 or 1000 atm. In order to include some allowance for isotope decay during the mission, two mission times were selected, viz., 1 yr and 1 half-life. In general, the helium void volumes exceed the volumes required for the isotope. As will be shown later, void volumes greater than about 0.1 cc/W result in a significant penalty in weight. For purposes of comparison, the corresponding power per unit void volume is also shown in Fig. 1.

PASSIVE HEAT REJECTION

If an isotope source is to remain intact under the variety of conditions associated with launching, space flight, and reentry, some passive means of cooling the source is required. In general, active cooling methods introduce some risk of failure of the cooling system. For this reason, the isotope heat source was postulated to be cooled by thermal radiation in the absence of any other more effective cooling method. Thermal radiation has the merit that it also functions in space in case of failure or shutdown of the power conversion system.

The geometry assumed for the source is shown in Fig. 2. The source was chosen to be a thin slab of area sufficient to reject all the generated heat from a single face of the slab. The heat-radiating capability of the slab was estimated from the temperature distribution in a solid homogeneous slab of material with uniform heat generation per unit volume; this power density was one-third that of the isotope and its required void.

The effect of isotope power density on mass of the slab is shown in Fig. 3. Slab mass is in inverse proportion to power density. For power density of 10 W/cc, slab mass is low enough that further reduction in slab mass is of little significance in relation to, say, shield mass. For selected maximum temperatures of the slab, the resulting slab geometries are shown in Fig. 4. For each maximum temperature, the allowed power per unit slab area is limited by the thermal radiation at that temperature; only the thinnest slabs approach these limiting values. At reduced power density, the increased slab thickness required to obtain a given surface power results in a greater temperature drop through the slab and thus in a reduction in its ability to radiate heat. Isotope power densities of 1 W/cc are required to obtain slabs as thin as 10 cm; much lower power density would yield excessively thick and heavy slabs.

The effect of isotope power density on slab area is shown in Fig. 5. At the slab temperature of 1340° F, the approximate minimum slab area is obtainable with a power density of 10 W/cc. For the slab maximum temperature of 2060° F, slab area decreases rapidly until power density reaches 10 W/cc. and decreases more slowly for power density as high as 100 W/cc. Although power density above 10 W/cc has only a minor effect on slab weight (Fig. 3), its effect on slab area (Fig. 5) can markedly affect shield weight, as will be discussed later.

HEAT SINKS

Although isotope sources considered herein were provided with surface area adequate for thermal radiation of the generated heat, this ability to radiate heat may be lost temporarily. Occasions during which such radiant cooling is ineffective are the brief period of atmospheric reentry and in the event of fire on the launch pad. During such temporary losses of radiation cooling, a material of high heat capacity could absorb the generated heat. Examples of such materials are listed in Table II. Three of the materials were chosen for their high heat fusion and their melting point near 2500° F. Although silcon has the highest heat of fusion, the containment of molten silicon is an unsolved problem. On the other hand, the mixed salts were investigated briefly and showed promise of successful containment in molybdenum, tungsten, rhenium, or alloys of these materials. The sensible heat of materials such as beryllium oxide can also be used as a heat sink.

If the required mass of heat-sink material be taken as 10 lb/kW-hr, a heat sink of 1000 lb would be capable of absorbing all the heat from a 50 kW source for 2 hr.

UNSHIELDED DOSE RATES

Some isotopes result in comparatively low radiation dose during brief exposure to an unshielded source. If this desirable quality can be achieved, an operational flexibility might then be obtained that could be exploited for a brief time under either emergency or normal conditions. Consider, for example, an isotope source being inserted into the spacecraft atop a launching vehicle on the launch pad, and consider that the source insertion mechanism jams. In such a case, use of a man for adjustment or repair would be highly desirable. If the dose rate were low enough, a man might be able to work in such an unshielded zone for an hour or so.

The dose rates from several unshielded sources are given in Table III. Of these dose rates, only those from Pm-147, Pu-238, and Po-210 are low enough to be really useful. Determination of whether or not the unshielded dose rate of 100 rems/hr for Cm-244 would be a serious restriction on its use requires a more thorough evaluation than presented herein. For Pm-147, exposures of several hours appear practical.

SOURCE AND SHIELD WEIGHTS

For five isotopes, weights of heat source and shield were determined for the geometry shown in Fig. 6, and the results are presented in Table IV. For Po-210, enough isotope was supplied to produce 50 kW at the end of a 90-day mission plus a 90-day launch window. For the other isotopes, the initial loading is adequate for a 1-yr. mission plus a 90-day launch window. For the alpha emitter, helium volume was chosen to limit gas pressure to 1000 atm. Shields of constant thickness were added to limit dose rate to 1 mrem/hr at a distance of 1 m from the source. As an approximation of the mass of a 2π shield, each slab overhangs by a radial distance equal to its thickness. Po-210, with its short half-life, requires only a small volume for helium; its effective power density is thus high and its source weight low. The total weight required for a 90-day mission with Po-210 is thus the lowest. If mission duration were to increase to a year, however, the starting power of Po-210 would be about four times as great; accordingly, slab area and shield weight would also then roughly quadruple.

Among the longer lived isotopes, Pm-147, Pu-238, and Cm-244 are competitive; although Cm-244 requires the greatest weight of the three isotopes, its weight warrants some discussion. Although Cm-244 has the thickest shielding, its shield weight is not as large as this high thickness implies. The reason for this lies in both the power density (27 W/cc) and half-life of Cm-244 (18 yr). For a maximum helium pressure of 1000 atm and mission duration of 1 yr., the void required for Cm-244 is only 0.1 cc/W. Thus, the effective power density of Cm-244 is 7 W/cc, which is a value high enough to produce a thin and small slab. Correspondingly, shield area is also low.

MISSIONS

Availability is a factor affecting use of isotopes in space missions. For this reason, NASA has requested the AEC to produce 500 kW of Pu-238 by 1980. This rate of production will support one or two major isotope missions a year during the 1970's.

Historically, NASA's unmanned flights have not required the power levels of the manned flights, and this will probably remain generally true. The possible exceptions are communications satellites for television or radio broadcasting directly to home receivers. In general, these unmanned needs for large blocks of power will probably be infrequent and not be a major addition to the demands of the manned flight program. Solar cell systems are also strong contenders for these unmanned applications. In order for the supply of the valuable and scarce Pu-238 to be stretched, isotope heat sources will be reused, specifically, through recovery on reentry, transfer between spacecraft, and extended use on the lunar surface.

It thus appears that 500 kW of Pu-238 spread over the 1970's will satisfy the principal needs of NASA predictable this far in advance. A problem with Pu-238, on the other hand, is the slow response of production to a change in demand. What do we do for isotopes if in the 1970's a presently unexpected but urgent mission arises? There is a need for an isotope the supply of which can be rapidly increased to satisfy a new demand. For some missions, the lead time for isotope production may be as short as 3 to 5 yr.

EVALUATION OF ISOTOPE POWER SYSTEMS

In order for as much power as possible to be extracted from these comparatively heavy sources, an efficient power conversion system is desired. The Brayton cycle system appears capable of an efficiency of 20 percent for a thermal power of 50 kW, or a useful output of 10 kW.

The general characteristics of solar-cell and isotope-Brayton power systems are compared in table V for power systems in a 300-mile orbit about the Earth. Solar cells have a weight advantage of roughly 50 percent. On the other hand, the area required for oriented solar cells is double the radiator area for the isotope Brayton system. If the isotope Brayton radiator is a plane able to reject heat from both surfaces, the radiator area is then one-fourth the area of the solar array. In either event, the radiator requires no special orientation. The high cost of solar cell systems (about $800/W) is occasionally claimed to be a disadvantage. If just the isotope for heat source is to match this cost, the isotope must cost only $160 per thermal W, conversion efficiency again being taken as 20 percent and decay being neglected. Hence, isotope power systems probably do not have any advantage on the basis of cost alone. The characteristic that isotopes have to offer to NASA's mission groups is the flexibility in mission planning that independence of the Sun and space environment can provide. Large and oriented surfaces need not extend from the spacecraft, and thereby atmospheric drag may be decreased as well as interference with rendezvous maneuvers, communication, or observation. If rotation of the spacecraft is required in order to provide artificial gravity, an isotope system can readily tolerate this rotation. The goal in designing a competitive isotope power system is thus to realize this potential operational freedom within the limits imposed by nuclear safety.

TABLE I. - TROPOSPHERIC BURDEN AND FRACTION OF MPC

AFTER HIGH-ALTITUDE BURNUP

[Mission, 1 yr; window, 90 days.]

Isotope	Time to maximum tropospheric burden, days	Maximum fraction of inventory in troposphere	Maximum fraction of MPC in air for 50 kW release
Pu^{238}	1600	6.0×10^{-3}	1.13×10^{-2}
Sr^{90}	1460	5.6	5.5×10^{-3}
Cm^{244}	1410	5.3	3.25
Co^{60}	1040	3.9	6×10^{-5}
Pm^{147}	785	2.9	3×10^{-4}
Po^{210}	322	5.7×10^{-4}	4×10^{-4}

TABLE II. - HEAT STORAGE MATERIALS

Substance	Melting point		Heat of fusion, cal/g	Specific mass lb/kW-hr
	^{o}K	^{o}F		
Si	1693	2588	420	4.5
$3BeO\cdot2CaO$	~1650	~2500	~273	7
$3MgO\cdot B_2O_3$	1630	2475	~220	9
BeO	$\Delta T = 500^{o}$ F			14

TABLE III. - DOSE RATES FOR UNSHIELDED

50-kW ISOTOPE SOURCES

Isotope	Initial dose rate at 1 m, rem/hr
Co^{60}	2×10^{6}
Sr^{90}	5×10^{4}
Pm^{147}	1
Po^{210}	10
Pu^{238}	4
Cm^{244}	1×10^{2}

TABLE IV. - HEAT-SOURCE AND SHIELD WEIGHTS

[Maximum P, 1000 ATM; maximum T, 1400° K (2060° F); shield angle, 2π; dose rate, 1 mrem/hr at 1 m.]

Nuclide	Power, kW	Weight, lb		
		Slab	Shield	Total
Po^{210}	123	100	2000	2100
Pm^{147}	69	2200	1500	3800
Pu^{238}	50	2100	2100	4200
Cm^{244}	52	400	4900	5300
Sr^{90}	51	2800	6100	8900

TABLE V. - COMPARISON OF SOLAR AND ISOTOPE SYSTEMS

	Solar cells	Isotope Brayton
Weight, lb/kWe	300	600
Area, ft^2/kWe	200	100(50)
Oriented	Yes	No
Radiation hazard	No	Yes

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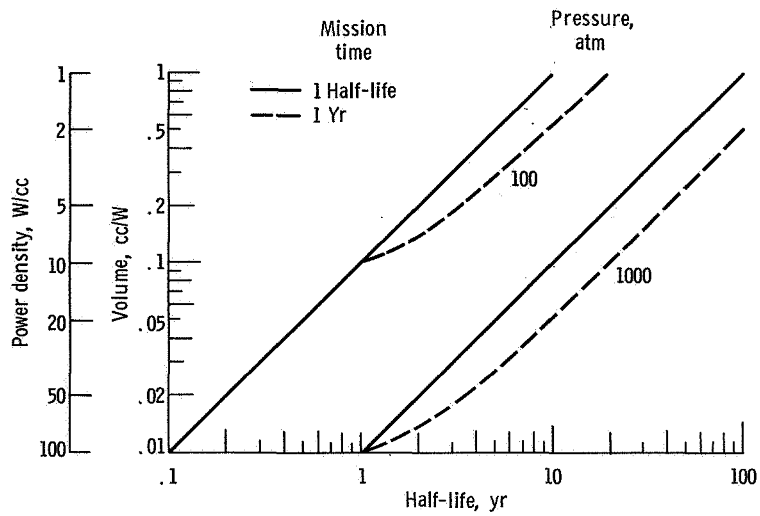

Figure 1. - Void volume for helium containment.

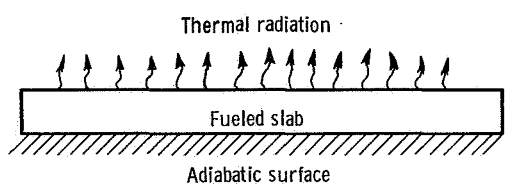

Figure 2. - Source geometry.

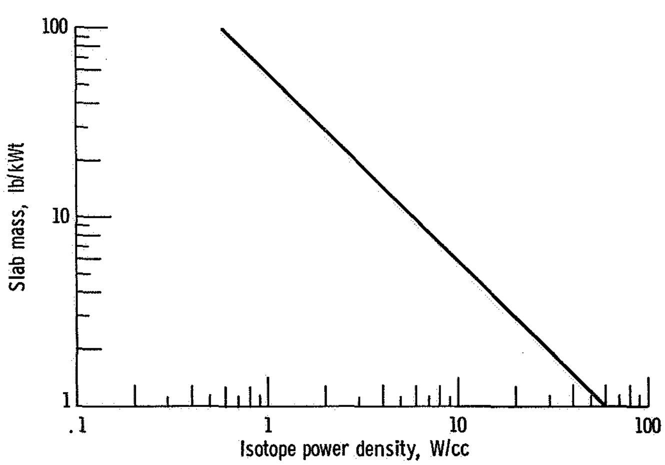

Figure 3. - Effect of power density on slab area.

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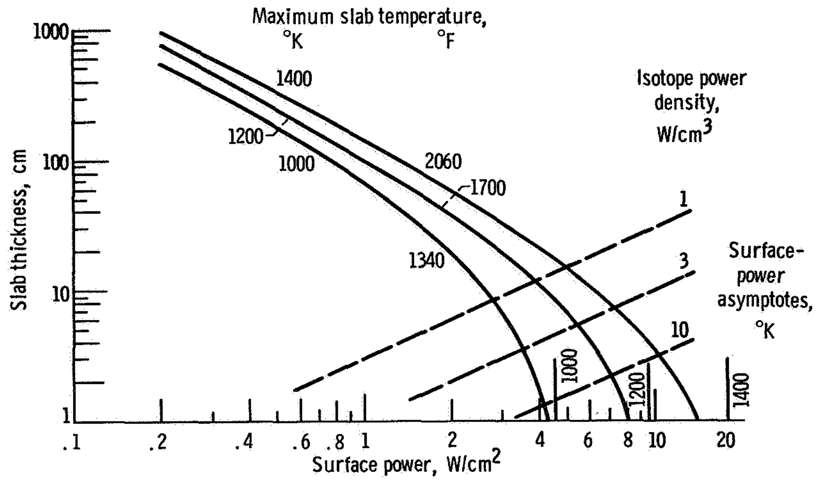

Figure 4. - Slab geometry and temperature.

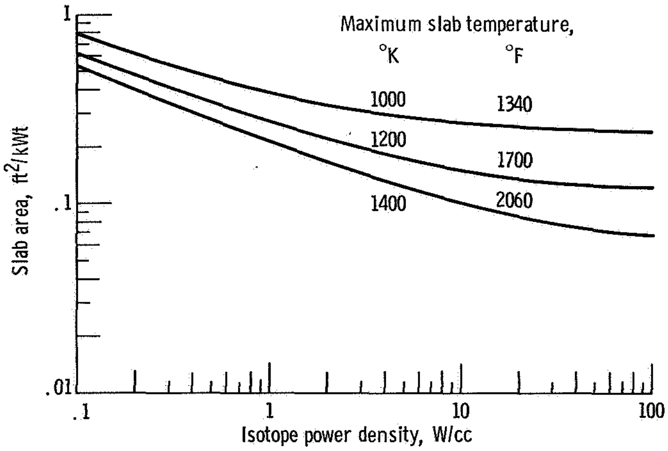

Figure 5. - Effect of power density on slab area.

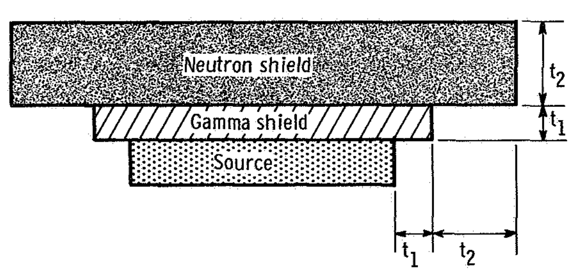

Figure 6. - Shield geometry.