Radioisotope Propulsion

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Propulsion devices, powered with isotopes whose large-scale production is anticipated, are evaluated from the point of view of design concepts and performance limitations. Direct-heating devices, in which the propellant is heated in a radioisotope core, and direct-momentum devices, in which escaping particles impart thrust, are considered. Since direct-heating devices must reject excess heat during "off" periods, self-cooled designs or designs integrated with power units are suggested. These devices are limited in thrust by isotope availability. The maximum operating temperature for long-period operation must be maintained below 4000°F (I_{sp} = 800–1000 sec) to avoid excessive fuel clad evaporation. Component weights (radiation shields, structures, and isotope investment), thrust, and operating temperature limit engine thrust-to-weight ratio to 10^{-2} to 10^{-4}. Probable applications may be in orbit changes and satellite control. Direct momentum devices are limited to low thrusts and low thrust-to-weight ratios by particle self-absorption, particle isotropy, radiation hazards, and charge neutralization. Their application to propulsion is very limited.

Nomenclature

A = area of radioactive surface, cm² or ft²
a = constant
E = particle kinetic energy, Mev
I_{sp} = specific impulse, lbf-sec/lbm
L = dimensionless thickness of radioactive layer
l = thickness of radioactive material, cm
M = atomic weight of radioactive material, g/g-mole
m = mass of emitted particle, g
N = Avogadro's number, 6.023×10^{23} particles/g-mole
n = number of particles
n_t = target nuclei particle density, number/cm³
r = range of particle, cm
R = range multiplied by material density, mg/cm²
S = particles emitted, particles/sec-cm²-unit steradian
T = thrust, lbf, or temperature, °F
t = time, sec
v = particle velocity, cm/sec
$\bar{v}_x$ = average particle velocity at $x = 0$
W = initial mass of engine, lbm or g
X = dimensionless distance, x/r
x = distance, cm
ϕ = flux of particles, number/cm²-sec
θ = angle between x direction and radius, rad
λ = radioactive decay constant, sec⁻¹
ρ = density of radioactive material, g/cm³
σ = cross section, b
ϵ = emissivity

Subscripts

f = fission fragments or fission
g = gas layer
0 = initial value
p = protons or hydrogen ions
s = solid layer
v = unit volume
x = x component at $x = 0$
α = alpha particles

Introduction

RADIOISOTOPE power sources possess three attractive characteristics: simplicity, long power life, and good performance capability. These characteristics can be advantageous in some propulsion applications, such as orbit changes and satellite control. Recently, some interest has been shown in this type of propulsion.[1] Radioisotopes can be used for propulsion in 1) systems in which the propellant is heated in an isotope core, and 2) systems in which the emitted particles exert thrust directly. Their use has been limited by their availability, but within the past few years, developments in the isotope power field have created a need for large quantities of some isotopes. Production of these isotopes is expected to soar, and quantity availability at reasonable costs is anticipated.[2]

Performance of isotope engines is limited by isotope properties and design constraints. The continuous and uncontrolled release of energy is a major problem. Although this release implies heat rejection by radiation to space during no-thrust periods, the system could be designed both as a thrustor and radiator, or it could be integrated with an isotope power unit. Other properties of isotopes—power density, half-life, and radiation hazards—limit the engine thrust-to-weight ratios.[3] In this paper conceptual designs of direct-heating and direct-momentum devices are discussed; such factors as isotope properties, availability, and design constraints which limit engine performance are described.

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Direct-Heating Devices

Conceptual Designs

Isotope propulsion engines using direct heating consist basically of an isotope-bearing core enclosed in a pressure shell, a nozzle, and a heat rejection mechanism. The propellant is heated as it flows through channels in the core and is exhausted through the nozzle to produce thrust. During "engine-off" periods, the energy released by the radioisotopes can be rejected either by a radiator, an auxiliary fluid and pumping equipment, or by direct radiation cooling of the engine itself (self-cooling).

The self-cooled engine shown in Fig. 1 is folded into a compact core during thrust, and the hinged plates are extended to a radiator during "off" periods. In this manner, the core serves the dual purpose of heat source and radiator. Figure 2 indicates that required radiator areas are within design possibilities at temperature levels and thrusts of interest. Figure 3 shows a design that is sized to be self-cooled and does not involve a moving core: heat is rejected during engine-off periods by radiation at the outer wall surface. This simpler design is useful only when the flow of heat is sufficient to maintain the core at a tolerable temperature. Calculations show that tolerable temperatures are possible for low powers and small diameters (less than ¾ in.).[3] During thrust, radiation to space is minimized by the flow of cold

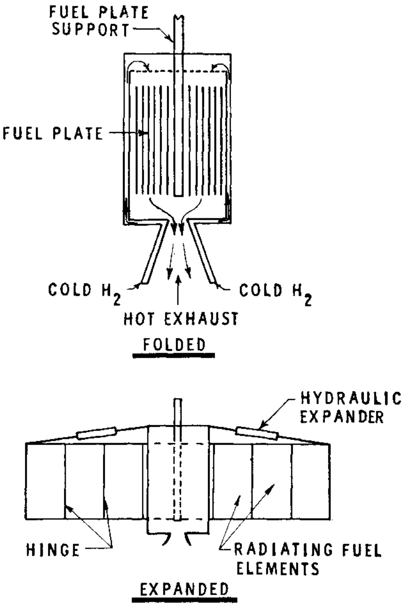


Fig. 1 Radioisotope engine with expanding - folding core.

propellant through the annular space between walls. The insert in Fig. 3 shows one (of many) possible fuel element designs in which the radioactive material, probably in the oxide form, is imbedded in tungsten refractory and clad with tungsten sheet. The cladding thickness is dictated by the operating time and temperature (total evaporation).

Another intriguing design, shown in Fig. 4, utilizes an existing isotope power unit, or part thereof, for propulsion. During engine-off periods, the unit produces power for electrical requirements, thus taking advantage of the continuous energy release and, at the same time, reducing heat rejection and shielding equipment weights. The thrusting is matched intermittently with electrical needs; obviously, such designs must be integrated into the over-all power cycle of the system.

Isotope Availability and Cost Limitations

The availability of a given isotope in the near future depends on its commercial production. Factors that will determine commercial production are isotope half-life, ease of production, economics, and probable applications. Based on these and other factors, there appear to be only 12 power-source candidates in the half-life range of 100 days to 2000 years.[4–6] On the other hand, isotopes with half-lives less than 100 days have received very little attention. In this range are found many fission fragments; for example, fission fragments of Class II, which release a large fraction of the total energy.[7] It might be possible to find propulsion applications for these isotopes either as a gross mixture or as individual isotopes. Further study on their production and applications is thus warranted.

Table 1 summarizes the properties of nine isotopes for which projected production capacity for 1970 varies from 10 to 1300 thermal kw/yr.[2, 8] As one might expect, cost is generally inversely related to production capacity. Availabilities of these isotopes for propulsion are quite nebulous at the moment. Obviously, it would help if increased production of some of them could be justified for this application. On the assumption that 10% of the total isotope production capacity in 1970 could be used for propulsion, Fig. 5 shows estimates of thrust limitations for the various isotopes. Only two, Ce-144 and Tm-170, could give thrusts greater than 1 lb; the rest will be limited (by availability) to thrusts of a fraction of a pound. If, however, production figures are increased, or if the propulsion unit is combined with a power unit, the available thrusts can be increased severalfold.

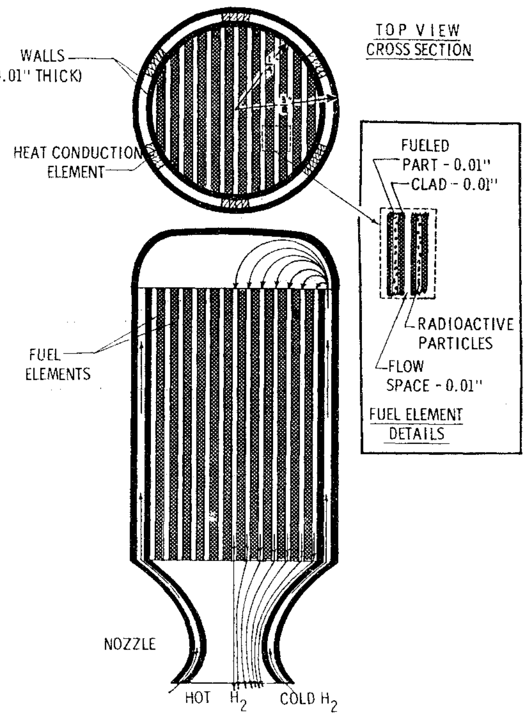


Fig. 3 Self-cooling radioisotope engine.

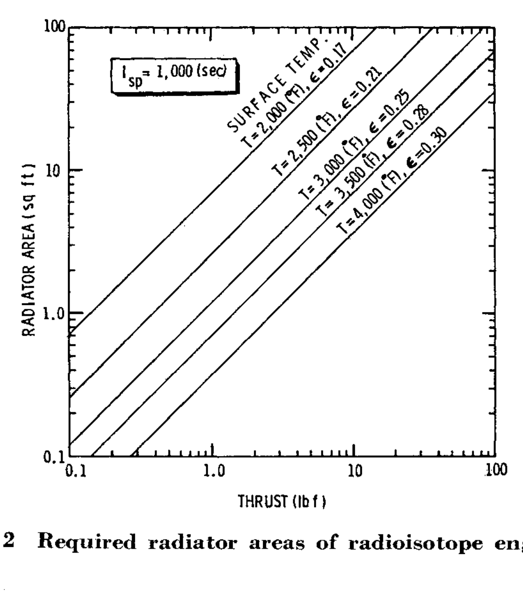


Fig. 2 Required radiator areas of radioisotope engines.

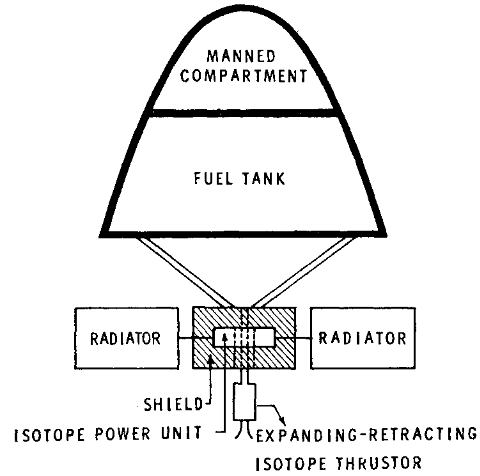


Fig. 4 Propulsion engine integrated with isotope power unit.

Table 1 List of useful isotopes[a]

Isotope	Chem. form	Decay prod.	Half-life, yr	M.p., °C	Density, g/cm³	Specific thermal power, w/g,[b]	Useful mission life, yr	Prod'n. cap'y. 1970, Kw_t/yr	Proj. fuel cost, $/$w_t$
Pu-238	metal	α	90	...	10.0	0.48 (0.39)	10	25.8	1040
Cm-244	Cm_2O_3	α, n	18	2000	11.8	2.3	10	129	435
Cm-242	Cm_2O_3	α, n	0.44	2000	11.8	120 (98)	0.5	9.5	165
Po-210	metal	α	0.38	...	9.3	140 (134)	0.5	14	190
Sr-90	$SrTiO_3$	β	28	...	5.1	0.20	10	157	77
Cs-137	glass	β, γ	27	...	3.2	0.07	10	110	104
Pm-147	Pm_2O_3	β	2.6	2300	6.6	0.18 (0.27)	2.5	25	485
Ce-144	CeO_2	β, γ	0.78	2680	6.4	2.3 (3.8)	1.0	1330	5
Tm-170	Tm_2O_3	β, γ	0.35	...	8.7	1.75	0.5	1000	40

[a] Data taken from Refs. 2, 4, 5, and 8.
[b] Numbers in parenthesis are from Ref. 5.

The total isotope investment for a given thrust level, which depends largely on the isotope power density, varies widely, e.g., a thrust of 1 lb requires 0.2 kg of Cm-242 oxide or 100 kg of $SrTiO_3$ (Fig. 6). The isotope investment can be decreased by using the isotope in pure metallic form or by increasing the active isotopes in the compound, but this leads to increased production complexity and cost. The data of Figs. 5 and 6 assume 100% efficiency. In actual practice, engines will have efficiencies in the order 80–90%, based on results for resistojets and solid-core nuclear reactors, which are comparable. In actual designs, the efficiency must be accounted for, and thrusts and isotope investments must be computed accordingly.

Costs of isotope propulsion units are dictated by availability, ease of production, and investment. Many isotopes, especially those requiring neutron irradiation in a reactor, are produced by costly radiation schemes. These costs are further augmented by complicated chemical separation schemes.[4] Projected *propulsion costs in millions of dollars per pound of thrust* are:

Pu-238	22.6	Cs-137	2.3
Pm-147	10.6	Sr-90	1.7
Cm-244	9.5	Tm-170	0.9
Po-210	4.2	Ce-144	0.1
	Cm-242	3.6	

The final economics will depend, among other things, on production and on the mission, but Ce-144 is by far the cheapest, and Pu-238 will probably be ruled out.

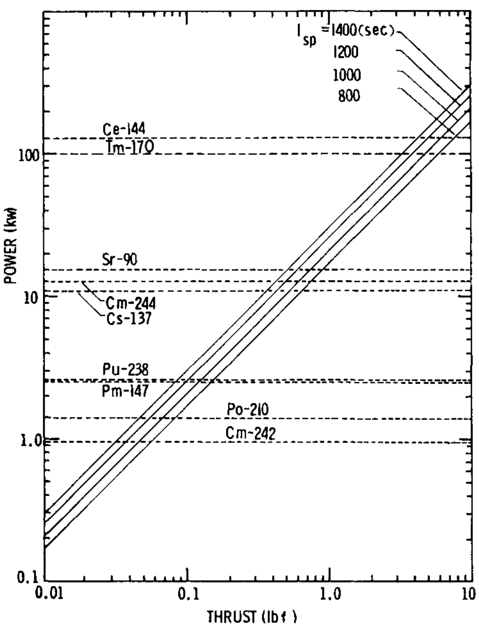


Fig. 5 Isotope availability; based on 10% of the 1970 production.[2]

Radiation Hazards and Shielding

Radiation hazards for radioisotope propulsion must be considered during production, launch, and flight. Hazards associated with production of isotopes and launch of vehicles are under scrutiny in relation to power sources. It is expected that essentially the same procedures will apply to propulsion systems. Shielding to man-rate a space system or to protect sensitive instrumentation results in extra weight, which affects engine performance. Permissible dosage limits for instruments, however, are approximately 10^7 rad total dose, and the performance degradation will be much less than for man-rated systems. Shielding seldom can be specified until vehicle design and mission are known, since it depends on the isotope employed, geometrical arrangement, and permissible dosage limits. In many missions, shielding will be required to protect against solar flares, and this might reduce or eliminate isotope shielding.

Dimensions and weights of shadow shields required to reduce the dose of a 10-kw source of given dimensions to 25 rad/yr of gamma rays or 25 rem/yr of neutrons are given in Table 2 for the various isotopes. These results were obtained using The Boeing Company shielding computer code, which employs a ray theory model with build-up.[9] Cross-sectional data was inputed from National Bureau of Standards and Oak Ridge National Laboratory sources. The dose is computed for a particular arrangement, which might be typical of propulsion systems in which the dose plane is 10 ft from the nearest source surface. Since the attenuation is large, the shielding required is very insensitive

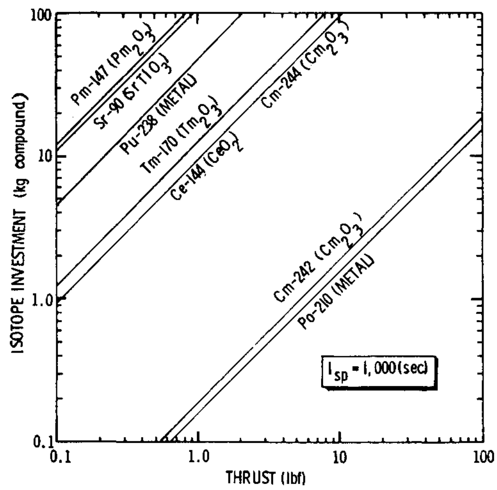
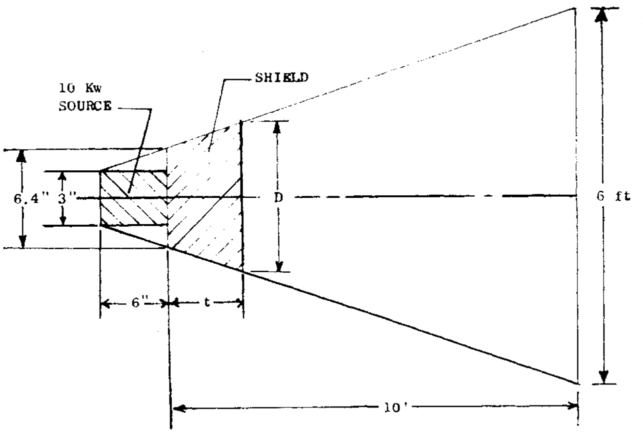


Fig. 6 Isotope investment; based on isotope compound as commonly available.

Table 2 Shielding requirements to limit γ dose to 25 (rad/yr) and neutron dose to 25 (rem/yr)



Isotope	Shield	D, in.	t, in.	Volume, in.^{3}	Shield weight, lbm
Ce-144	Pb	11.5	9	595	244
Sr-90	Pb	10.5	7.25	406	166
Cs-137	Pb	10	6.2	330	135
Cm-244	LiH	19.4	23	3270	96
Tm-170	Pb	8.3	3.3	154	63
Cm-242	LiH	13.8	13	1090	32
Po-210	Pb	7.2	1.4	51	21
Pu-238	LiH	7.5	1.9	74	2
Pm-147	Pb	6.4	0.1	3.3	1.4

to power level. Thus power levels one or two orders higher necessitate increases in the shielding thickness of only a small percentage to obtain the same dose. Since no absorption in the source is assumed, the computed weights will tend to be conservative. Weights are greatest for the gamma-emitting fission fragments, such as Sr-90, Cs-137, and Ce-144, and smallest for pure beta emitters, such as Pm-147; for some of the alpha emitters, weights are dominated by neutron emission resulting from spontaneous fission. Lithium hydride is used for neutron shielding and also to shield the low-level bremsstrahlung of these isotopes. Cm-244, which decays by spontaneous fission with a half-life of 1.4×10^7 yr and has low power density, requires heavy neutron shielding. Cm-242 has an even shorter fission half-life but, since its power density is much higher, neutron shielding is not so severe. Pu-238, with a long fission half-life, and Po-210, which does not undergo fission, require little or no neutron shielding, but Po-210 requires some lead shielding because of low-level gamma emission.

Engine Performance

The maximum specific impulse is, to a large extent, determined by the integrity of the material used to clad the fuel elements. In most applications, this must be designed to operate for long periods, perhaps months, and the total integrated evaporation of the cladding will determine the useful fuel life. In Fig. 7, the evaporation rate of tungsten (the best metallic refractory) is plotted as a function of temperature.[10, 11] The thickness evaporated can be considerable for continuous operation above 4000°F over long periods (0.01 in. for six months at 4400°F). To keep long-time evaporation to tolerable levels, the maximum temperature must be held below 4000°F, which limits I_{sp} to the range of 800 to 1000 sec, depending on the chamber pressure.

The engine T/W ratio, which is inherently low for isotopes, is limited by thrust availability, isotope investment, structure weights, shielding weights, and operating temperature. Figure 8 shows "isotope T/W ratio," defined here as the maximum T/W possible for the isotopic compound (excludes structure and cladding weights) at a given I_{sp}, vs power density. Most isotopes possess very low T/W even on this optimistic basis. Since it depends strongly on power density, isotope T/W is higher for the short half-life alpha-emitters Po-210 and Cm-242, the only ones which could possibly produce $T/W > 1.0$. Sr-90, Pm-147, Pu-238, and Cs-137 will have inherently low engine ratios, which may make them noncompetitive with other isotopes or other means of propulsion.

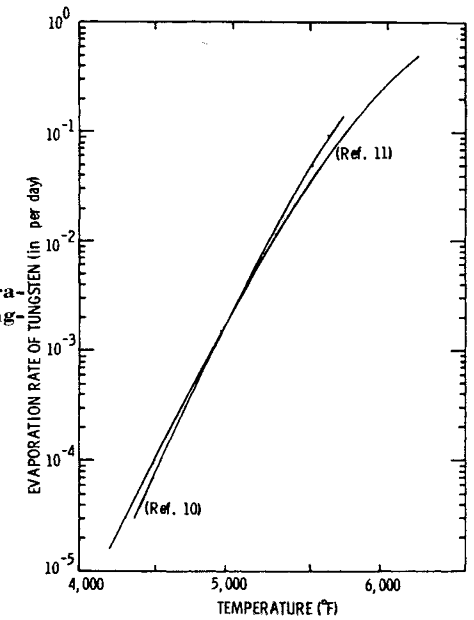


Fig. 7 Evaporation rate of tungsten.

Table 3 shows T/W ratios for shielded and unshielded 10-kw engines fueled with various isotopes. For the shielded designs, the shielding weights are taken from Table 2. Isotope investment is computed from the power density at I_{sp} = 800 sec. Structure weights are assumed to be 20 times the isotope investment; this is perhaps a typical ratio for a 1-yr mission life based on considerations of cladding thicknesses, chamber weights, and auxiliary equipment used. Structure weight contributes a sizeable fraction of the over-all weight for all isotopes except Cm-242 and Po-210. Shielded engine T/W's range from about 10^{-4} to 10^{-2}. Unshielded engine

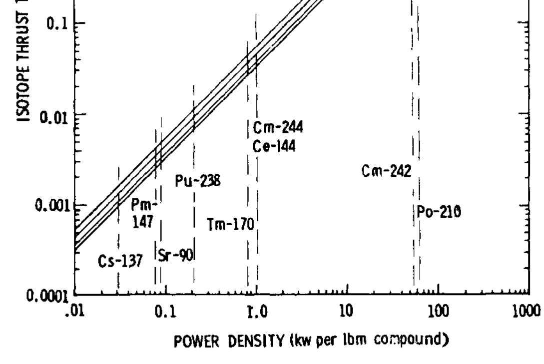


Fig. 8 Isotope T/W ratios; based on isotope compounds as commonly available.

Table 3 Engine thrust-to-weight ratios: power—10 kw thermal; thrust—0.573 lbf at 800 sec I_{sp} and 100% efficiency

Isotope	Isotope investment, lbm	Structure weight, lbm	Shielded engine, T/W	Unshielded engine, T/W
Pu-238	46	920	0.0006	0.0006
Cm-244	9.6	192	0.00193	0.00285
Cm-242	0.185	3.70	0.016	0.148
Po-210	0.16	3.20	0.0235	0.17
Sr-90	110	2200	0.000231	0.000248
Cs-137	315	6300	0.000085	0.0000865
Pm-147	123	2460	0.000222	0.000222
Ce-144	9.6	192	0.00128	0.00284
Tm-170	12.6	252	0.00175	0.00216

T/W's are improved significantly only for the high power density isotopes, Cm-242 and Po-210, for which shielding weight is predominant. The advantages of integrating propulsion units and power units as a means of decreasing shielding and structure weights is again obvious.

Example of Specific Design

A typical engine based on the nonexpandable core with dimensions as shown in Fig. 2 is designed to heat hydrogen at 14.7 psia to 3900°F (vacuum I_{sp} = 860 sec) and to thrust for three months with an initial thrust level of 0.0166 lbf. The initial thrust will decrease because of the decay of the Cm_2O_3 isotope to half the initial value after about 160 days. The core section is made of twelve parallel plates spaced 0.01-in. inside a cylindrical shell of 0.5-in. diameter. The over-all diameter is held to 0.75 in. to permit radiation cooling during engine-off periods at a maximum temperature of about 4000°F within the core.[12] Each plate consists of a fueled part 0.01-in. thick and an outer cladding of 0.01-in. of tungsten, 1% of which will evaporate in three months.

The required power at 100% efficiency (0.311 kw) is supplied by 2.6 g of Cm_2O_3 (using Cm-242 for its high power density), which leads to a core length of about 0.75 in. when the composition of the fueled part of the element is 37% Cm_2O_3 by volume. In actual practice, the efficiency of the engine will be about 85% which requires a 15% increase in isotope and a corresponding increase in core length or isotope composition. Rough heat-transfer calculations indicate that this path length is also sufficient for heat-transfer purposes, since heat transfer at low Reynolds numbers takes place very rapidly.[13] The engine (unshielded) weighs about 0.1 lb and has a T/W of about 0.15; if enough shadow shielding is included to man-rate it, the T/W is reduced to about 0.016.

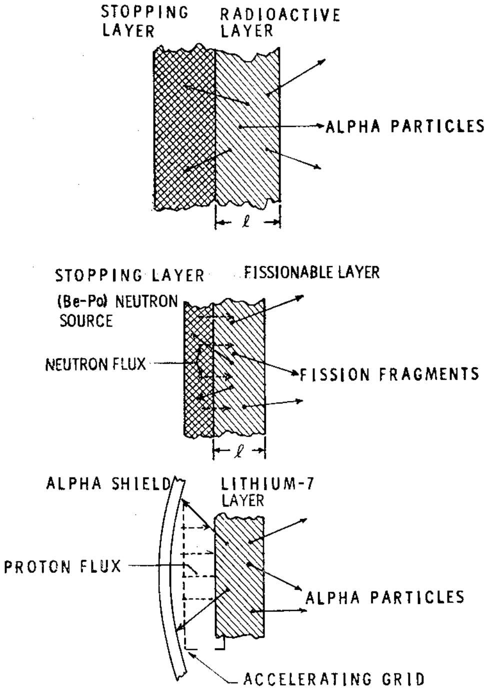


Fig. 9 Direct-momentum devices.

Probable Applications

The acceleration of radioisotope-powered vehicles will be low—10^{-3} g's or less. (After 1970, production of isotopes with reasonable power densities will increase, and this limitation may be relaxed somewhat.) Consequently, isotope devices are not attractive as primary propulsion systems for escape missions or ambitious orbit transfers. (The mass ratio for escape from a 300-naut-mile orbit is about 0.40 for radioisotope systems, compared to 0.50 for the chemical system H_2—O_2.) Their most probable applications are believed to include small orbit changes, satellite control, and satellite maintenance, where low-thrust, long-period thrusting is required and they could advantageously replace chemical or gas systems in many cases. Systems such as Manned Orbital Research Laboratory (MORL), Orbiting Space Station (OSS), and other advanced space laboratory concepts are examples.

Direct-Momentum Devices

Design Concepts

Direct-momentum radioisotope propulsion devices, which utilize energetic particles escaping from a surface to impart thrust, produce I_{sp}'s in the extremely high range of 10^5 to 10^6 sec. Three such schemes are depicted in Fig. 9. The first scheme consists of an alpha-emitting radioisotope layer of thickness l "painted" on an inert stopping layer.[14] Particles decay in the isotope layer isotropically: those moving to the left are stopped in the inert layer and impart no momentum on the system; some of those moving to the right escape and impart thrust on the system. The second concept (the induced-reaction type) consists of a layer of fissionable material bombarded continuously by a neutron flux that induces fissions in the layer. The beryllium-polonium neutron source also acts as a stopper for fission fragments directed toward the left. It is possible that the higher mass of the fission fragments will make this device superior to the alpha particle devices described above. The third concept[15] utilizes reactions produced in a Li-7 target by the reaction

$${}_1H^1 + {}_3Li^7 = {}_2He^4 + {}_2He^4 + 17.28 \text{ Mev}$$

Protons are accelerated electrostatically to a few hundred kev into the lithium surface to produce reactions. The idea is to trade protons (hydrogen ions) at lower energy for the higher-mass helium atoms at higher energy and thus to obtain thrust augmentation. Since the hydrogen ion accelerator could be an ion engine, the device, if workable, could be called an ion engine amplifier.

Analysis of Direct-Momentum Devices

Short and Sabin[14] have made an analysis of an alpha-emitting direct-momentum device that takes into account the self-absorption and isotropy of the emitted particles. Essentially, the same kind of analysis also applies to systems of the inducted-reaction type. The thrust per unit area is given by

$$\frac{T}{A} = 4\pi m v_\alpha r_\alpha S \int_0^L \frac{\bar{v}_x}{v} \, dX \tag{1}$$

where

$$\frac{\bar{v}_x}{v} = \frac{1}{2}\int_0^{\theta = \text{arc cos}X} \left(1 - \frac{X}{\cos\theta}\right)^{a/2} \cos\theta \sin\theta \, d\theta \qquad (2)$$

Here, S, the number of particles emitted per unit time per unit volume per unit solid angle, is given by the following equations for the processes described in Fig. 9: for constant emission rate of alpha particles,

$$S = \frac{(dn_v/dt)}{4\pi} = \frac{\lambda \rho N}{4\pi M} \qquad (3a)$$

For induced fission fragment reactions,

$$S = \frac{2\phi_0(1 - e^{-n_t\sigma_f l})}{4\pi l} \qquad (3b)$$

and for induced reactions in Li-7,

$$S = \frac{2\phi_{op}(1 - e^{-n_t\sigma l})}{4\pi l} \qquad (3c)$$

Equation 2 can be integrated by expanding $[1 - (X/\cos\theta)]^{a/2}$ using the binomial theorem. The value of the constant a is determined from the slope of the range-energy curves, assuming the relationship $E = R^a$. Range-energy curves have been computed for pure metallic layers from available data[16] for the various particles of interest. The values of the constants a's computed from these curves are tabulated below.

Particle	a
Alphas in Th-228, Cm-242, and Cm-244	0.635
Alphas in Li-7	0.618
Fission fragments in U-235	0.331

On expanding the function $[1 - (X/\cos\theta)]^{a/2}$ for these values of a's, the values of $\bar{v}_x/v$ are approximated by the following functions: for alpha particles in Th-228, Cm-242, Cm-244, and Li-7,

$$\bar{v}_x/v_\alpha = \tfrac{1}{4}(1 - X) \qquad (4a)$$

and for fission fragments in U-235,

$$\bar{v}_x/v_f = \tfrac{1}{4}(1 - X^2) - 0.166X(1 - X) \qquad (4b)$$

Equation (1) can now be integrated immediately to the following: for alpha particles in Th-228, Cm-242, Cm-244, and Li-7,

$$T/A = \pi m_\alpha v_\alpha r_\alpha SL[1 - (L/2)] \qquad (5)$$

and for fission fragments in U-235,

$$T/A = \pi m_f v_f r_f SL(1 - 0.082L - 0.278L^2) \qquad (6)$$

Figure 10 shows that, for the various processes of interest, T/A increases with L at a decreasing rate, leveling off at $L = 1$ where the maximum occurs. The equations as integrated are applicable only over the range $0 \leq L \leq 1$; at $L = 1$ the layer thickness equals the particle range, and further increase in layer thickness does not change T/A because particles generated at larger thicknesses do not escape from the surface.

Of the alpha-emitting isotopes, Th-228, which emits five α particles in rapid succession,[14] yields the highest T/A ($\sim 10^{-5}$ lbf/ft^2). The newer α emitter Cm-242 is about one-half as effective as Th-228, and Cm-244 is several orders of magnitude below these. The engine T/W, assuming enough beryllium backing is used to stop all α particles emitted in one direction, is of the order of 10^{-4} for Th-228 and Cm-242 and 10^{-5} for Cm-244. Because of the inherently low T/W and the accompanying problems of radiation hazards and charge neutralization, it is doubtful that these systems will find applications in propulsion.

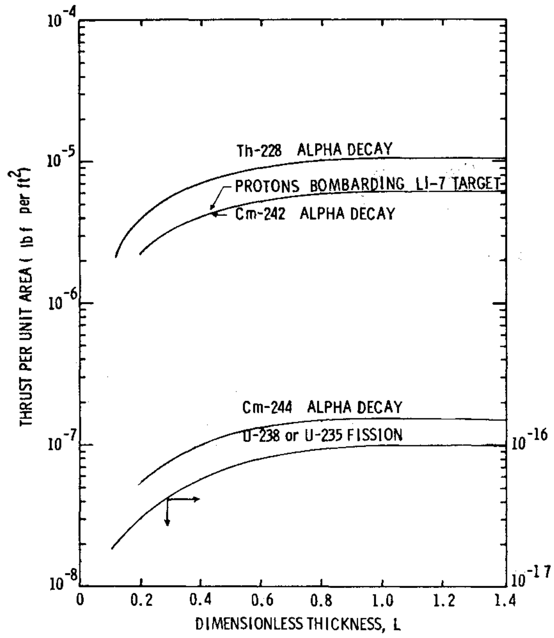


Fig. 10 Thrust per unit area for direct-momentum devices.

For the fission fragment concept, T/A can be calculated for a typical case of a beryllium-polonium source, which gives a neutron flux of 10^5 sec^{-1} cm^{-2}, with an average energy per neutron of about 5 Mev[17] and a U-235 fission cross section of approximately 1 b.[18] These figures give $T/A \simeq 10^{-16}$ lbf/ft^2, and $T/W \approx 10^{-14}$, which are of no practical interest for propulsion. Even with impractically large increases in neutron flux and cross section, low performance is obtained.

The ion amplifier is also unattractive because of low cross sections. For an optimistic proton flux of 10^{17}/sec^{-1}-cm^{-2} with an energy of 0.5 Mev and a cross section of the order of 0.01 b, T/A obtained from the Li-7 target is about 10^{-5} lbf/ft^2. However, the T/A that would be obtained from the protons if they were not stopped is of the order of 0.35 lbf/ft^2. Thus, despite the fact that the induced α particles have an average energy of 8.63 Mev, a de-amplification, rather than an amplification, results. This concept would amplify, if the cross section were increased, by a factor of 10^4 to 10^5. (Similar conclusions were reached by Barrett[15] using a slightly different approach.) Such a cross section would indeed be anomalous and would also be of great interest in the fusion field.

Finally, consider the advantages of replacing the solid reactive layers of Fig. 9 with gaseous reaction layers to utilize the fact that particles travel a longer distance in gas. The ratio of the thrusts obtained is $T_g/T_s = r_g S_s / r_s S_s = R_g/R_s$. Since the R's in milligrams per square centimeter for both solid and gas (being of the same element of equal Z) are equal, the result is $T_g = T_s$. Thus, no gain in thrust would be obtained even by using a pure gas layer without containment walls (but the gas layer would, in fact, require solid walls for containment).

Conclusions

Two basic design concepts are considered as a means of solving the heat rejection problem for radioisotope propulsion systems during engine-off periods. In the first, the engine is self-cooled by radiation, either directly from the wall surfaces (applicable to low powers and small diameters) or by expanding the core into a radiator, and in the second, a propulsion unit is integrated with a power unit, so that the two operate alternatively with common heat rejection and shielding equipment.

Engine thrust is limited by isotope availability. On the basis of 10% of the 1970 production capacity, only Ce-144 and Tm-170 will be available in sufficient quantities to allow designs of over 1-lb thrust. Projected costs for 1970 vary widely, from about 0.1×10^6 \$/lb thrust for Ce-144 to over 20×10^6 \$/lb thrust for Pu-238, with most other isotopes falling in the 1×10^6 to 10×10^6 \$/lbf range.

Radiation hazards will limit propulsion devices, primarily because of the effects of shielding weight on engine performance. The γ-emitting fission fragments require heavy shields to man-rate them. Some α emitters require large lithium hydride shields to stop neutron radiation from spontaneous fission. The smallest shields are required by pure β emitters (Pm-147), and nonfissioning α emitters (Pu-238).

Engine T/W is limited by engine weight and engine integrity. Because engine life must be preserved for long periods of time, the temperature must be maintained below 4000°F to reduce evaporation of the fuel-cladding material. This limits I_{sp} to 800 to 1000 sec. Many isotopes are inherently limited to low T/W because of their power density; only Cm-242 and Po-210 are capable of idealized "isotope T/W ratios" greater than 1. The over-all engine T/W, which depends on shielding weight, structure weight, and isotope investment, ranges from 10^{-2} to 10^{-4}.

Direct-momentum devices may consist of a radioactive layer painted on a surface or a reactive layer on which nuclear reactions are induced by particle bombardment. Momentum is imparted on the system by the escaping decay particles. These devices are limited by particle self-absorption and isotropy to thrust of 10^{-5} lbf/ft^2, and their T/W ratio to below 10^{-4}. Because of these low values and other associated problems, their practical value to propulsion is very limited.

Basically, the main limitation of direct-momentum isotope devices results from the fact that the atoms do not decay fast enough to produce useful thrusts or, if they decay fast, they do not last long enough to be of any use to propulsion. Two hypothetical schemes to which nuclear scientists might turn their long-range thinking are 1) a scheme by which a short half-life isotope can be produced continuously and in quantity aboard a spaceship (it might be recognized that devices of the induced-reaction type considered in the foregoing and also fusion devices are, in reality, schemes attempting to utilize this principle), and 2) a method by which the emission or fragmentation rate of a given radioactive isotope can be artificially increased for short periods for propulsion. The latter idea seems particularly farfetched, but the advantages that could (theoretically) accrue from such a scheme are tremendous. For example, a 10^6-lb booster producing 1.5×10^6 lbf thrust for 200 sec with H_2 at 5000°K (a vacuum I_{sp} of 1750 sec at 440 psia) would require a mere 5 lb of Cm-242, if its half-life could be reduced (temporarily) enough, so that all the Cm-242 "burns" within the chamber.

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