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Potentialities of Radioisotope Propulsion for Space Probes

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The application of radioisotope engines to space probes is investigated, with emphasis given to design concepts, operating constraints, and performance. Direct heating engines, which incorporate cooling schemes to reject radioisotope energy during engine-off periods, are considered. The performance of these engines is limited by isotope availability, power density, and half-life. Large-scale production of the high-power-density isotopes (Cm-242, Po-210, and Nb-95) is necessary to allow engine designs of a few pounds thrust and reasonable performance. Payloads delivered from Earth orbit by radioisotope and radioisotope-augmented chemical stages for various flyby missions are compared with high-performance chemical systems. A radioisotope engine of 10-lb thrust and 800-sec specific impulse, fueled with a high-power-density isotope, outperforms chemical systems for some of the missions studied. Increasing the specific impulse of radioisotope engines by the use of fluidized beds or molten cores results in considerable payload advantage over chemical systems.

Nomenclature

g = gravitational constant, ft/sec/sec
I_{sp} = specific impulse, sec
P = power, kw; or pressure, psia
p = isotope power density, kw/lb
t = time, sec or days
$t_{1/2}$ = isotope half-life, sec
T = thrust, lb
W = weight, lb
ΔV = velocity increment, fps

Subscripts

c = chamber conditions
e = nozzle-exit conditions
F = fuel or propellant
Ft = fuel or propellant at any time t
I = isotope or isotope compound
i = conditions at time of initiation of thrust
o = initial conditions at time of engine fueling
PL = payload
s = engine structures
sh = shielding
t = any time after initiation of thrust
T = tank

Introduction

Chemical and nuclear-fission energies have received much consideration for propulsion applications. Another source of energy, i.e., that derived from radioactive decay, has received little attention. Because of anticipated increased production of isotopes and their already successful application to power systems, renewed interest in radioisotope propulsion has been stimulated.[1,2] This paper discusses radioisotope propulsion and examines its potential applications to space probes.

Although the radioisotope engine is simple in principle (propellant flows through a core and is heated), unique problems limit its practical use. The continuous release of energy imposes constraints on engine design and operation. Isotope availability, power density, and radiation are other important parameters that limit engine design.

This discussion considers missions in which Atlas-Centaur-type payloads are injected from Earth orbit to their destination. A 10-lb-thrust radioisotope unit of 800-sec specific impulse, used alone or in combination with a chemical unit (radioisotope-augmented system), supplies initial velocity requirements. The payload weights obtainable with this engine for escape, and Mars, Jupiter, and solar flyby missions,

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are compared to those possible with high-performance chemical systems.

In general, systems using radioisotope engines outperform chemical systems, but in many cases the payload advantages are marginal. Considerable payload advantage is realized with radioisotope engines of advanced core design. The prospect for engine designs of the fluidized-bed and molten-core types is given some consideration.

Engine Design Concepts

Radioisotope engines of the direct-heating type consist of a heat-producing core with channels through which the propellant flows. These designs are similar to solid-core nuclear reactors, but are simpler because they involve no criticality or nucleonic control problems. The core can be flat plates, a solid piece with channels, or any other geometric arrangement consistent with isotope canning schemes and heat transfer. In designs for high-temperature operation, the isotope fuel can be imbedded and clad with a refractory such as tungsten.

Advanced engine designs using fluidized beds or a molten core also are conceptually possible with radioisotope heat sources. Such designs have been proposed for fission reactors.[3–5] These engines would consist of granular particles or molten radioisotope material contained within a chamber by rotation. The propellant would flow through the particles or bubble through the liquid to be heated. Another way of heating the propellant in molten cores is by flowing it through the channel formed by rotation of the liquid. This concept, called the "molten channel" engine, has the advantage of eliminating splashing of the core. By choosing an isotope material of high melting point, high propellant temperatures are possible. The fortuitous potential availability of Nb-95 having a high-power density and the possibility of its large-scale recovery from isotope processing plants make advanced designs promising. This isotope is a refractory metal of high melting point and also forms NbC of even higher melting point. Many technical problems must be solved, however, before engines using Nb-95 can be developed.

Engine Cooling Schemes

The uncontrolled release of energy from radioisotopes imposes some constraint on engine design and operation. Continuous core cooling is necessary from the time the engine is manufactured until the end of the engine's useful life. Although this problem might appear difficult, some solutions are foreseen, at least at moderate power levels.

For example, an engine to be used for injecting a payload from orbit into a planetary mission might be cooled as follows. During production and transportation and before launch, the engine is cooled by circulating a fluid through the core using techniques similar to those being developed for power sources. During launch and initial flight, the engine is cooled by diverting small amounts of booster propellants (perhaps boiloff) through the isotope core. During injection, the engine is thrusting and is cooled by the propellant. At the end of injection, the system has acquired the required

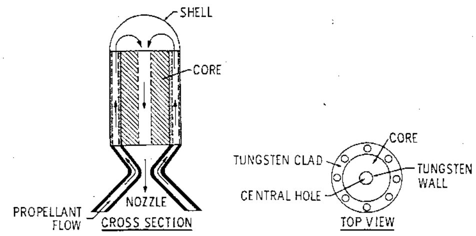

Fig. 1 Self-cooled engine.

velocity, and the propulsion unit can be scrapped, converted into a power cycle, or made self-cooled for future use.

Major design variations result from the cooling scheme employed during the post-injection period, if it is desired to keep the engine for further use either for power or propulsion. At least four design schemes may be used for cooling the engine: 1) passive cooling, 2) expandable core, 3) combined propulsion and power, and 4) movable thermal insulator designs.

Designs of the passive-cooling type are self-cooled by limiting the dimensions so as to avoid large temperature differences within the engine. The energy generated is radiated away during engine-off periods. Figure 1 shows one example of a simple design of this type in which the diameter is limited. It consists of a radioisotope core clad on the outside with a thick layer of tungsten. The core consists of particles of radioisotope compound imbedded in tungsten. Regenerative cooling is used; propellant flows through the nozzle walls, through the tungsten clad, and, finally, through the core. During operation, radiation loss at the outer wall is minimized since the propellant cools the outer surface. During engine-off periods, no propellant flows through the system; the energy produced is conducted to the outside and radiated at the surface. Because the diameter of each unit is limited, the size (thrust) also is limited, and it is necessary to use many units to produce high thrusts. Also, size-limited engines must be fueled with alpha emitters, which have a low range. Otherwise, a large fraction of the energy escapes as subnuclear radiation.

Table 1 lists some maximum core temperatures calculated for various diameters and power densities, assuming the core is a 30% (by volume) isotope compound and an infinitely long cylinder. If the isotope power density is low, the engine will be self-cooled at a tolerable maximum temperature for fairly large core diameters; but if the power density is high, only small core diameters are possible. Engine cooling might be enhanced somewhat by adding radiation fins or louvers.

Figure 2 shows an example of an expandable-core design that is cooled by expanding the core into a radiator during engine-off periods. The bottom of the chamber is detached and pulled away from the main chamber, expanding the telescoping fuel plates outside the chamber. When the core is folded, the chamber bottom seals to the upper chamber to prevent propellant loss. The propellant flows through the

Table 1 Maximum inner-wall temperature (°F) in radioisotope cores

Core diam, in.	Core power density, Btu/lb-sec				
	0.01	0.10	1.0	10.0	100
0.25	598	1012	1837	3264	7150
0.50	765	1413	2516	5167	...
1.0	1012	1834	3449	8944	...
2.0	1247	2364	5184	...	...
4.0	1557	3196	9752	...	...

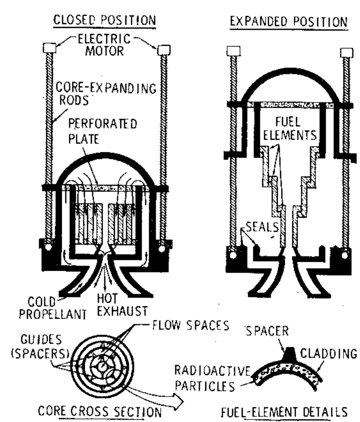

Fig. 2 Expandable-core engine.

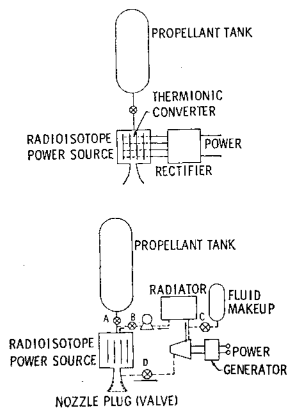

Fig. 3 Combined radioisotope propulsion and power units.

nozzle walls, around the outer shell, and through the fuel plates. At the lower left-hand side, a cross section of the core flow spaces is shown. The flow must be maintained when the fuel plates are folded. The size (power) of this reactor is limited only by the integrity of the design and, in principle, can be large. The mode of expanding the core can be varied, but, from a purely mechanical point of view, a telescoping type seems preferable. Details of the fuel element are shown at the lower right. If a gamma-emitting isotope is used to fuel the engine, absorption of the energy within the reactor can be enhanced by using thick fuel elements and chamber walls.

Figure 3 shows designs in which the propulsion engine is combined with a power cycle. The system can be operated either as a propulsion or a power unit. The extra benefit of producing electrical power (and perhaps also thermal control) from the isotope is obtained, and the unit is available for additional intermittent thrusting after injection. In the design shown at the bottom of Fig. 3, a fluid power cycle is used. To operate as a power unit, valve A and the nozzle plug are closed and valves B and D are opened. The working fluid for the power cycle flows through the reactor, expands through a turbine, flows through a radiator, and is pumped back to the reactor to complete the cycle. Fluid lost from the power cycle is resupplied from the makeup tank. At the top in Fig. 3, a design is shown which combines a thermionic power cycle with a propulsion unit. Its main advantages are that it has no moving parts, and that the power and propulsion cycles can be operated either concurrently or separately.

The movable thermal insulator design uses a movable thermal insulator to control the flow of heat (Fig. 4). The thermal insulator is mechanically removed from around the engine, thereby either insulating or exposing the engine for radiation cooling. Figure 4 illustrates the operation when used with an advanced molten-core engine. In the closed (operating) position, the core becomes hot enough to melt. During cooling periods, the insulator is removed from the engine, and the heat produced radiates to space, cooling the core enough to solidify it. The engine must be properly sized to be self-cooled when the insulator is removed.

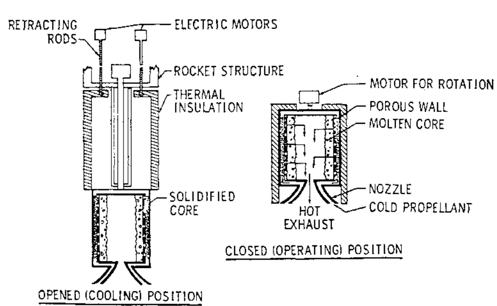

Fig. 4 Engine cooled by movable thermal insulator.

Engine Characteristics

The weight of nonshielded radioisotope engines depends on the isotope power density. Low-power-density isotopes will necessitate considerable isotope investment; this results in large chamber and engine weights. The actual weight also depends somewhat on the design; however, preliminary studies of simple designs of the clad-type engines indicate that the engine inert weight (all weight except isotope investment) is about 20 to 30 times the isotope investment. Thus, lightweight engines are possible if high-power-density isotopes (such as Po-210, Cm-242, and Nb-95) are used. Typical weight for an engine of the type shown in Fig. 1, fueled with Po-210 and designed for 0.25 lb of thrust, is about 2 lb. An engine of the type shown in Fig. 2, fueled with Nb-95 and designed for 10 lb of thrust, will weigh about 200 lb. If nuclear shielding is used, the latter engine will weigh considerably more than 200 lb.

The operating temperature of radioisotope engines of the solid-core type is dictated by the cladding evaporation rate. At high temperatures, this might be considerable even for elements clad with tungsten, if long-duration thrust is anticipated.[6] Below 4000°F, however, several months of continuous thrust are possible without excessive cladding loss. An outlet propellant temperature of around 3900°F is a reasonable operating level; it yields a specific impulse of around 800 sec at 14.7 psia. The thermal efficiency of these engines will be about 70 to 90%, depending on the design.

By using radioisotope engines of the fluidized-bed or molten-core types, much higher specific impulses are possible. The specific impulse of fluidized-bed systems is limited by the melting point of the core material. The specific impulse of molten-core engines is limited by evaporation of the core, as is the case with molten-core fission nuclear engines.[7] Figure 5 shows the specific impulse potential for engines fueled with Nb and NbC. These calculations are based on equations from Ref. 8 and assume ideal, adiabatic expansion to vacuum under frozen-flow conditions. The molecular weight used in the equations is an average for the exhaust. Vapor-pressure data for the core materials were taken from Refs. 9 and 10, and data for hydrogen were taken from Ref. 11. The specific impulse increases with temperature, reaching a maximum around 1100 to 1400 sec, and then decreases sharply. The maximum for uranium metal, which is plotted for comparison, occurs at about 860 sec. The behavior of specific impulse is the result of core evaporation, which greatly increases the exhaust molecular weight as the temperature increases. In practice, it is necessary to operate at specific impulses of 10 to 20% below the maximum to avoid excessive fuel loss. Thus, the operating specific impulse for Nb or NbC is around 1200 sec.

Isotope Availability

Isotope availability is the major obstacle at present to the use of isotopes for propulsion applications. Engines with even a few pounds of thrust necessitate the investment of many kilowatts of isotope power; no isotope will be produced

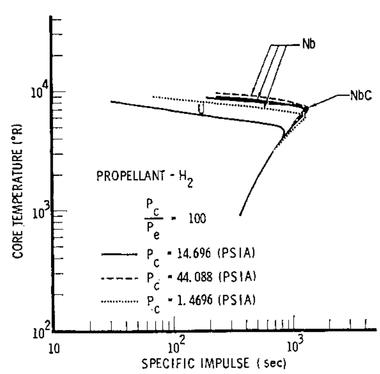

Fig. 5 Specific impulse of molten-core radioisotope propulsion engines.

Table 2 List of useful isotopes

Isotope	Decay product	Type	Half-life, days	Power density, kw/lb	Potential production 1970, kw, thermal
Cm-242	Alpha, neutrons	Reactor-produced	156	44.5	9.5
Po-210	Alpha	Reactor-produced	138	60.7	1000
Ce-144	Beta, gamma	Fission product	285	1.72	1330
Nb-95[a]	94.2% gamma	Fission product	35	85.5	500–1000
Y-91[a]	99.5% beta	Fission product	59	8.6	500–1000
Sr-89[a]	99% beta	Fission product	50.4	2.8	500–1000
Zr-95[a] and Nb-95	...	Fission product	...	5.1	1000

[a] Data on short-lived isotopes were obtained from C. A. Rohrmann.

for some time to come in these quantities. By 1970, production (if it materializes) of some long-lived isotopes (half-life greater than 130 days) will be sufficient to allow design of engines with a few pounds of thrust. Designers of larger engines must look to increased production of these isotopes or to the recovery of short-lived (half-life of 30 to 60 days) fission products. These isotopes will be present in large quantities in the waste streams of fuel processing plants. Little information is available on process recovery, but C. A. Rohrmann[12] suggests that there is good prospect of recovering several hundred kilowatts per year of some short-lived isotopes (Nb-95, Zr-95, Y-91, and Sr-89). An advantage of using short-lived fission products is that all production can be used for propulsion purposes. Because their half-life is short, it is doubtful that they would find much use in power systems. In contrast, long-lived isotopes will find their main use in power systems, and probably only a small percentage of the production could be diverted to propulsion.

Table 2 lists some data for a few of the useful isotopes. Other data for these and other isotopes may be found in the literature.[13,14] The first four are relatively long-lived isotopes, whose production has been considered. The last four are short-lived fission products previously not considered. Of particular interest for propulsion use is Nb-95, an isotope that occurs in the Class II group of fission products, has a high-power density, and decays primarily by gamma radiation.[12]

The power densities for the short-lived isotopes were calculated assuming a process with a fairly relaxed schedule in which the normal cooling of the stream is allowed.[12] Better power densities are possible if the process time is shortened; however, because knowledge of the process is preliminary, these values will be assumed to be representative.

Engine Performance

Effects of Isotope Half-Life

Radioisotope power decays with time, and the performance of engines fueled with short-lived isotopes can change considerably over a period of a few days. An isotope decays exponentially with a characteristic decay constant, called half-life. Because power density and thrust are proportional to the decay rate, they also decay correspondingly. Thus, if an engine is initially fueled with P_o kilowatts of isotope power, after time t the power will be:

$$P = P_o e^{-0.693t/t_{1/2}} \tag{1}$$

Table 3 Decay of Niobium-95

Time, days	Power, kw	Thrust (I_{sp} = 800 sec), lb	Power density, kw/lb
0	500	28	85
35	250	14	43
70	125	7.2	21.2
100	70	4.0	11.7

The rapid degradation of power for the short-lived isotopes necessitates a rigid schedule of procedures from engine loading to launch. As illustrated in Table 3 for Nb-95, if the time period from isotope loading to launching of the vehicle is greater than about 40 days, serious losses in performance can be incurred.

The thrust-to-weight ratio during flight will depend not only on the fuel exhausted but also on the decay of thrust. It is given by

$$(T/W)_t = [T_i e^{-0.693t/t_{1/2}}/(W_i - W_{Ft})] \tag{2}$$

Substituting for W_{Ft}, the weight of fuel exhausted, Eq. (2) becomes:

$$\left(\frac{T}{W}\right)_t = \frac{\left(\dfrac{T_i}{W_i}\right) e^{-0.693t/t_{1/2}}}{1 - \left(\dfrac{1}{0.693}\right)\left(\dfrac{t_{1/2}}{I\mathrm{sp}}\right)\left(\dfrac{T_i}{W_i}\right)(1 - e^{-0.693t/t_{1/2}})} \tag{3}$$

Figure 6 shows typical time variations of thrust and thrust-to-weight ratio for 9000-lb Atlas-Centaur payloads accelerated from Earth orbit. The engines under consideration have an initial thrust of 10 lb and a specific impulse of 800 sec. The decrease of thrust over a few days is small, amounting to a few percent. The thrust-to-weight ratios remain fairly constant for 3 to 4 days after initiation of thrust, but increase rapidly thereafter.

Note that the thrust-to-weight ratio varies less rapidly for isotopes of shorter half-life. This arises because of the compensating effects that the decay of thrust and the fuel exhausted have on the thrust-to-weight ratio.

Velocity Requirements

The thrust levels of radioisotope engines are expected to be low. These are limited by isotope availability, but even if isotopes were available in unlimited quantities, manufacturing difficulties would limit thrust levels to manageable values. For example, the design of an engine with 100 lb of thrust would involve the investment of some 2 Mw of power; this power must be removed during manufacture and prior to launch. It is obvious that cooling such large engines would be difficult. The exact limit of manufacturing capabilities is not known at present, but it is doubtful that designs with large quantities of power will be undertaken. Another reason why engines will probably not be designed with thrusts greater

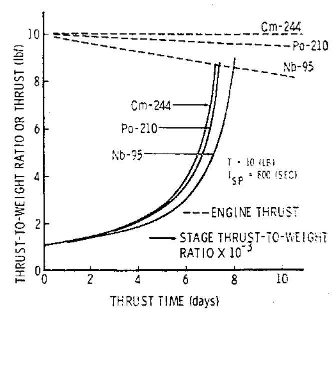

Fig. 6 Variation of system thrust and thrust-to-weight ratio.

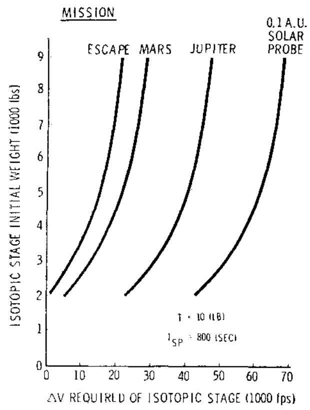

Fig. 7 Velocity requirements for various missions.

than a few pounds has to do with isotope power density. As shown below, the performance (for the type of mission considered) maximizes at a thrust of 10 to 50 lb. Attempts to design engines of higher thrust result in considerable performance loss.

The low thrust levels and large system weights (considering Atlas-Centaur-type payload weights) will limit radioisotope propulsion to low accelerations (about $10^{-3}g$). A consequence will be higher velocity requirements near a gravitational field. To overcome gravitational losses, it might be desirable to thrust with high acceleration near the gravitational field and to operate the radioisotope engine away from the field. An example would be a chemical system that thrusts initially from orbit, augmented by a radioisotope engine that supplies additional velocity requirements.

Figure 7 shows velocity requirements (for a typical launch period in 1969) for escape and various flyby missions for both pure radioisotope and radioisotope-augmented chemical systems. Atlas-Centaur payloads (9000 lb) initially in a 100-naut-mile Earth orbit are accelerated to their destination. The abscissa represents the velocity required of the isotope stage to complete the mission. In the radioisotope-augmented systems, some fraction of the initial 9000 lb in orbit is used for the chemical stage, the remainder becomes the radioisotope stage initial weight. Thus, an initial isotope stage weight of 2000 lb implies that 7000 lb of the 9000-lb Atlas-Centaur payload is used as a chemical stage.

The chemical stage is assumed to have a performance comparable to the Centaur (specific impulse of 426 sec). The radioisotope engine used is of 10-lb thrust and of 800-sec specific impulse. No coasting is assumed following termination of chemical thrust because calculations show no advantage to this operation. No gravitation losses have been assumed beyond escape; if further losses are incurred, the ΔV's will be somewhat higher. However, it is seen that ΔV requirements for the radioisotopes system are twice those of impulsive systems in many missions.

Payload Capabilities

The total gross weight of an isotope system is given by:

$$W_i = W_F + W_T + W_I + W_s + W_{sh} + W_{PL} \qquad (4)$$

As an approximation, the tankage weight will be assumed to be 10% of the fuel required, and the engine structure weight will be assumed to be 20 times the isotope investment. The shielding weight can be considerable, especially for gamma-emitting isotopes.[2] In the present work, it is assumed that, by proper configuration of the spacecraft, taking advantage of the distance and structural shadow shields, negligible shielding will be needed to protect critical components. For this condition, Eq. (4) becomes

$$W_i = 1.1\ W_F + 21\ W_I + W_{PL} \qquad (5)$$

The fuel necessary is given by

$$W_F = W_i(1 - e^{-\Delta V/gI_{sp}}) \qquad (6)$$

and the isotope investment by

$$W_i = P_i/p_i = 0.0218\ I_{sp}\ T_i/p_i \qquad (7)$$

Substituting Eqs. (7) and (6) into Eq. (5), and solving for payload weight, the result is

$$W_{PL} = W_i(1.1e^{-\Delta V/gI_{sp}} - 0.10) - 0.458\ I_{sp}T_i/p_i \qquad (8)$$

Figures 8 and 9 show payloads vs isotope power density for Mars and Jupiter missions. Similar results were obtained for the other missions studied. The payload levels off and is insensitive to power density above some minimum power density that is dependent on the mission. This occurs above the power density at which the radioisotope engine weight is insignificant. Since the payload drops off sharply at low-power-density-levels, it is necessary to use radioisotopes of high-power density, limiting the useful isotopes to Cm-242, Po-210, and Nb-95. Another interesting result obtained is that in the near-Earth missions (i.e., escape and Mars), it is better to thrust radioisotopically from orbit all the way; whereas in far-Earth missions (i.e., Jupiter and solar), it is better to use a radioisotope-augmented chemical system. The engine thrust time in all cases is reasonable and amounts

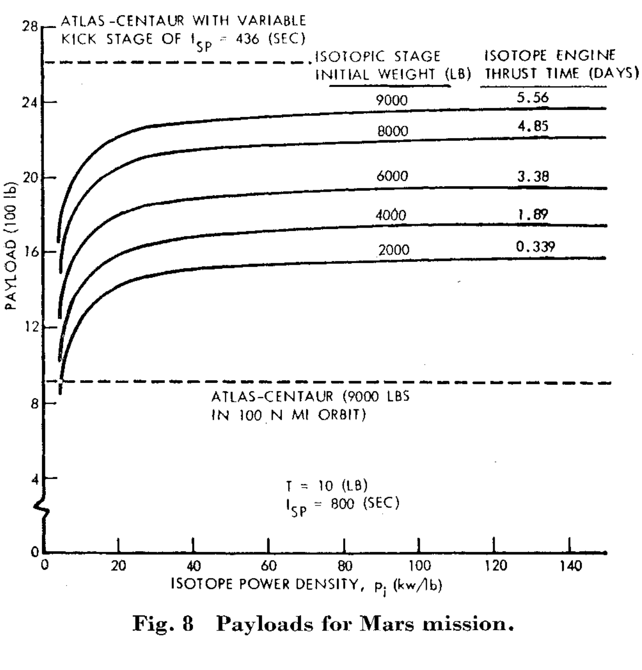

Fig. 8 Payloads for Mars mission.

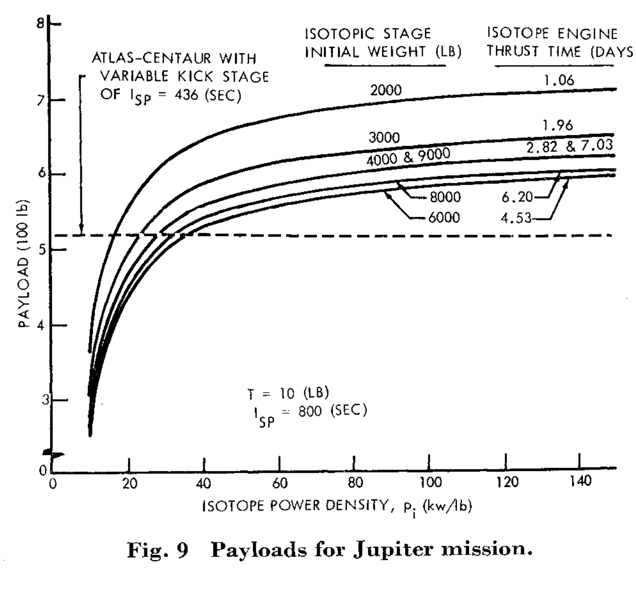

Fig. 9 Payloads for Jupiter mission.

to a few days at the most. For comparison purposes, Fig. 10 illustrates the payload advantages obtainable for a Mars mission with a molten-core engine. Considerable payload advantages also are realized for the other missions, especially the Jupiter and solar flybys.

The payloads obtained with radioisotope engines are compared to those obtained from an Atlas-Centaur (9000 lb in a 100-naut-mile orbit) and an Atlas-Centaur system supplemented by a high-performance kick stage. A summary of paylods obtainable from these various systems is shown in Fig. 11. For all missions studied, the radioisotope systems better the payload obtained from an Atlas-Centaur. The molten-core radioisotope system ($I_{sp} = 1200$ sec) shows considerable payload advantage over all chemical systems, including the ones using a kick stage. The solid-core radioisotope system ($I_{sp} = 800$ sec) betters the payloads obtained with a chemical kick stage for all missions except to Mars. (The payload advantage is marginal for the escape mission.) For the more ambitious Jupiter and solar missions considerable gains are realized from radioisotope engines. Martinez and Jortner[1] also have shown that the performance of isotope engines (Poodle type) atop Titan II and Centaur stages becomes better for ambitious missions. In fact, the solar mission cannot be performed with Atlas-Centaur-type chemical systems, even using a kick stage. Better payloads can be obtained by further chemical staging or by using nuclear fission reactors. However, it is perhaps unfair to compare radioisotope engines on this basis. In many missions, isotope electrical power is a necessity, and it might be advantageous to attempt isotope propulsion in combined propulsion-power units; such systems also might be more reliable than systems with many stages. The isotope engine is simpler than fission reactors, and development time is much shorter because full-scale electrical simulation is possible.

Typical effects of varying engine thrust level are shown in Fig. 12. Payloads for an escape mission are plotted vs engine thrust, with isotope power density as the parameter. As thrust is decreased, the payloads converge because the engine weight is negligible even for low-power-density systems. As thrust is increased, the payload increases to a maximum characteristic of the power density and mission and decreases sharply beyond this range. This behavior is the result of competition between increasing system acceleration and engine weight. For the available high-power-density isotopes, which have power ranges from 20 to 80 kw/lb, the maximum occurs in the 5- to 50-lb-thrust range. Attempts to design engines of much higher thrust will result in payload losses, unless isotopes are found with higher power densities. This was cited previously as one factor that would limit radioisotope engine thrust. Note again that, at about 10 lb of thrust, the payload is insensitive to the power density, if the latter is greater than 30 kw/lb. If the thrust level is below 1 lb, the long thrust time will probably make the engines unreliable.

The black dots in Fig. 12 represent the approximate performance expected from the isotopes indicated (based on published power density and availability data). A probable design point is shown which assumes that only one or two engines will be built per year, and that 10% of the long-lived isotopes and 100% of the short-lived fission fragments could be made available for propulsion. A 10% value for long-

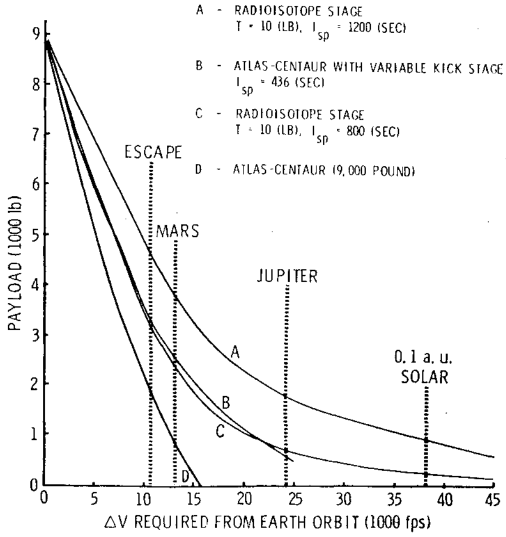

Fig. 11 Comparison of payloads for chemical and radioisotope propulsion systems (mission starts at a 100-naut-mile Earth orbit).

lived isotopes was assumed because their primary application will be in power systems. The Nb-95 isotope falls near the maximum. This fact and the possibility of greater availability are reasons why further consideration should be given to fueling of engines with Nb-95. If production were increased for Cm-242 or Po-210, comparable performance to Nb-95 would be obtained. The Nb-95 isotope has a power density of about 85 kw/lb at the time of loading; however, the power density decays to about 40 kw/lb (the value shown) during manufacturing and prelaunch, if about 40 days are assumed for these operations.

Figure 13 shows a probable mission plan for a 10-lb-thrust unit fueled with Nb-95. About 40 days are allowed for fuel preparation, engine loading, and preparation. During this time, the power decays from about 500 to 220 kw. The unit is launched, and it thrusts for a few days to give the desired velocity requirements. At the end of thrusting, the unit is discarded, integrated with a power unit, or made self-cooled for future use. If the engine is kept during coast, which might be several hundred days, its power can be used for thermal control during the trip and for data transmission. If more power is needed, a small amount of some long-half-life isotope (for example, Cm-244) could be added initially to supplement the long-time needs.

Conclusions

The direct-heated radioisotope engine concept is simple in design; it consists of a core through which the propellant flows and is heated. Although the uninterrupted release of energy by isotopes creates a heat problem, engine cooling does not appear insurmountable for reasonable power levels.

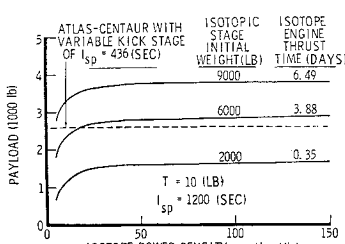

Fig. 10 Payloads for Mars mission (molten-core).

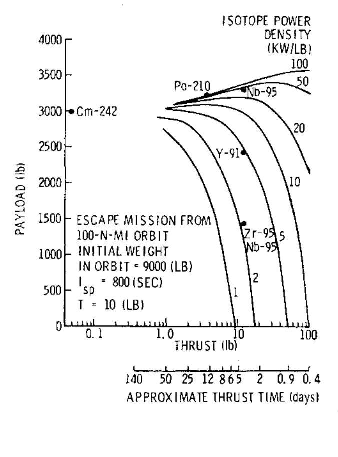

Fig. 12 Effects of thrust level on engine performance.

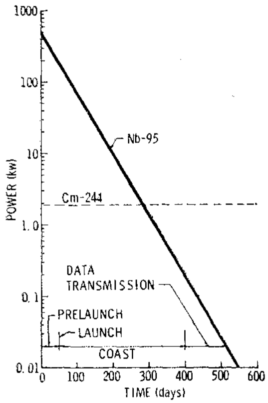

Fig. 13 Mission plan for radioisotope-propelled system.

Suggested design concepts include self-cooled reactors, reactors with expandable cores, combined propulsion and power units, and reactors with removable thermal insulators.

Major isotope-engine limitations are power density, availability, and half-life. To be useful for propulsion, an isotope must have a high-power density, be available in large quantities, and have a half-life at least long enough to allow manufacturing of the engine without major deterioration of power. In the 10-lb-thrust class, power densities greater than 30 kw/lb are desirable. Availability must be at least close to 1 Mw/yr, if one or two engines of the 10-lb class are to be built.

Only three isotopes, Po-210, Cm-242, and Nb-95, have the desired power density, but these must be produced in large quantities to allow designs of the 10-lb-thrust class. Po-210 and Cm-242 are produced by reactor operations. Nb-95 is a fission product that will be present in the waste stream of fuel-processing plants. Large-scale production of Nb-95 for propulsion applications probably can be inexpensive and simple, and it merits a more detailed analysis. The isotope half-life will have a bearing on production, mission planning, and use of the isotope (decay of power). Nb-95 has a half-life of 35 days which might make processing difficult.

In all flyby missions studied (except the Mars mission), the solid-core radioisotope propulsion system, by itself or in a radioisotope-augmented chemical system, outperforms pure chemical systems. In general, these units show better performance as the mission becomes more ambitious. A unit with 10 lb of thrust and 800 sec of specific impulse yields considerably better payloads than Atlas-Centaur chemical systems, and has significant payload advantages over chemical systems using a kick stage. Further advantage probably can be realized if the isotope unit also is used for power, especially because this type of power might be required for some of the missions considered.

A major limitation of radioisotope engines is their low acceleration levels and the accompanying losses near a gravitational field. This results in increased velocity requirements and serious performance losses. Two ways of improving this situation are to increase the engine thrust level, or to increase the engine's specific impulse. Of the two, the former appears to be out of the question (for the foreseeable future) because it would involve increased isotope production by at least an order of magnitude. The latter is possible, at least conceptually, with advanced radioisotope engines. Advanced radioisotope core designs of the fluidized-bed or molten-core types can produce higher specific impulses, and much higher payload advantages can be obtained.

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