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RADIOISOTOPIC SPACE POWER - PROSPECTS AND LIMITATIONS

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RADIOISOTOPIC SPACE POWER PROSPECTS AND LIMITATIONS

INTRODUCTION

Although it was about sixty years ago that the Curies first reported the self-heating phenomenon from their study of radium, it was only five years ago that this unique property of radioisotopes was demonstrated as a feasible source of power. The device which accomplished this was called SNAP-3 and contained about one-half gram of polonium to produce about three watts of useful electricity. The heat to electricity conversion was achieved by means of special thermocouples. Since mid-1961 at least four radioisotopic powered satellites have been operated in orbit for use as navigational aids. About the same number of similar devices has been demonstrated on land and sea to operate remote unmanned instruments for weather reporting and aids to navigation. The satellites have been powered with plutonium-238; the earth bound devices have used strontium-90 as the source of power.

Although there are over a thousand known radioisotopes and a variety of techniques by which they can be produced, the candidates that can be practically considered for application number only about a dozen; however, these few candidates differ so widely in characteristics that with an adequate understanding of their engineering properties logical applications can be conceived for use in a variety of missions. In this study, the basis for selection of radioisotopes for power applications is reviewed along with the engineering properties that establish them as practical materials.

The principal features of certain radioisotopes which make them especially attractive as power sources are: (1) A long useful live - with some, this

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is far longer than can be matched by associated electronic equipment; (2) Reliability - although the power output declines with time, this rate is readily and precisely predictable with absolute certainty; and (3) Compactness - small volumes of many radioisotopes generate large amounts of heat - many watts per cubic centimeter.

Although radioisotopes appear to have outstanding properties which will assure their widespread use, factors of limited availability and cost make it quite certain that their uses will be very specialized for applications requiring only modest amounts of continuous power generally in the range of less than a few hundred watts. For many applications, when comparisons are made on the basis of weight, reliability, cost and useful lifetime, radioisotopes have no competitors.

COMPARISONS OF POWER SOURCES

If we compare the complete spectrum of space power uses ranging from a few watts powering a tiny satellite to a few megawatts for electric propulsion systems to be used on manned interplanetary flights, we must then compare the complete spectrum of power systems. We must compare chemical combustion, fuel cells, batteries, solar radiation, nuclear reactor and radioisotopic systems. General criteria for evaluating and selecting a power system is suggested by Bo-natowicz, Guentert and Klann[1] of NASA. It includes the following: (1) mass; (2) ease of integration into the complete vehicle system; (3) compatibility with the space environment; (4) life and reliability; (5) hazard to human life; (6) cost, and (7) availability or status of technology.

It becomes evident quite early in the comparison that radioisotopic power plants surpass all competition in those space systems which require a few hundred watts for duration of one to five years.

In comparison with conventionally fueled (fuel plus oxidizer) devices, the weight economics are extremely favorable as illustrated in the following example:

Basis: A power source of 100 net electrical watts continuous. Operation for a period of five years. A thermal to electrical efficiency of 5% for a typical thermoelectric device.

Radioisotope	Kerosene and Oxygen
Specific power of Strontium-90 at five years = 0.80 watts/gram	1 lb. Kerosene @ 20,000 BTU/lb requires 4.25 lbs. of oxygen (with 20% excess).
2,000 watts = required thermal output at five years.	20,000 BTU = 5.89 KWH_t
$\frac{2,000}{80}$ = 2500 grams of Sr-90 required. = 5.5 lbs.	at 5% conversion = 0.293 KWH_e
Radioisotopic Fuel (Sr-90) requirement is thus about 6	100 watts for 5 years = 4380 KWH_e $\frac{4380}{(.293)(2000)}$ = 7.48 tons of Kerosene plus 31.8 tons of Oxygen.

The above comparison may be regarded as too conservative in view of inefficiency of the "combustion thermopile." However, even if the most optimistic view is taken for combustion (thermal to electrical efficiency = 75%) in

recently developed fuel cells, at least a half ton of kerosene and over two tons of oxygen would still be required. The comparison of the system weights is not of consequence after the above fuel comparison.

The above sample is typical for the most available radioisotopes; similar support exists for several of the others, some of which have other properties more favorable than the candidate selected for the example, particularly in power density and type of radiation.

For power requirements of much shorter duration, chemical systems and solar cells have certain advantages. This is primarily because of the cost of radioisotopes. As the power requirements increase for long duration systems, nuclear reactors are obviously favored because of the limited availability of radioisotopes. While solar collection systems may be comparable in cost and weight, when one considers the problem of reliability and orientation of huge collectors and radiators, the simplicity of the radioisotopic system is favorable.

The principal factors which make radioisotopes attractive for power production are: (1) Compactness: because of the power density (watts/cc), isotopic heat sources are very small. This size factor adds very much to the simplicity of the heat producing part of the system. (2) Reliability: they provide a continuous, though declining source of heat which cannot be changed in rate by any practical means. There is absolute certainty of thermal output and lifetimes. (3) Long useful life: although different isotopes have different but fixed half lives, some of the more available ones possess half lives so long that power flattening need not be provided for and furthermore, the life far exceeds the expected reliabile life times of the associated equipment for

power conversion and power utilization. (4) The above three characteristics assure relatively light weight for the power source and system.

Because of the compactness and simplicity of the isotopic heat sources, they can be made to perform with assurance of safety. New designs are adequate to provide a high degree of safety during launch and operations and re-entry.

RADIOSIOTOPE CONSIDERATIONS

Although a chart of the nuclides shows many candidate radioisotopic heat sources (over one-hundred), the practical limitation of availability in the kilogram quantities required eliminates nearly ninety per cent of these candidates. Many have been detected only in the residues from accelerator experiments which use massive ions as projectiles or special target materials. Such techniques cannot be regarded as production processes. Other candidates are producible but only as members of a family of isotopes of a common element. To be useful, most of these would have to be separated or concentrated by isotopic separation processes. Such processes do not exist and are unlikely to exist in the foreseeable future for highly radioactive materials in useful amounts. There are also a few more candidates whose manufacturing process would be so fantastically costly that they could not be considered as practical heat sources. Common physical and chemical properties alone eliminate some other candidates; for example, elements which exist as stable gases have densities so low as to make them unsuitable.

With the restraints as mentioned above, only about a dozen radioisotopes appear to have any realistic prospects as practical heat sources. These are listed in Table I with their important characteristics. Inspection shows a difference in properties of this rather small group of candidates. This

CHARACTERISTICS OF RADIOISOTOPIC HEAT SOURCES

Isotope	Co-60	Sr-90	Cs-137	Ce-144	Pm-147	Tm-170	Tl 204	Po-210	Th-228	U-232	Pu-238	Am 241	Cm 242	Cm-244
Watts/Gm (Pure) (#)	17 4	0))	0 42	25 6	0 33	15 6	0)7	141	170	4 4	0 56	0 11	120	2 8
Half-Life Years	5 3	28	30	0 78	2 7	0 35	4	0 38	1 9	74	89	458	0 45	18
Estimated Isotopic Purity %	10	50	35	18	95	7 5[a]	20[b]	95	95	85	80	90	90	90
Compound Form	Metal	$SrTiO_3$	Glass	CeO_2	Pm_2O_3	Tm_2O_3	Tl_2O_3	Metal	ThO_2	UO_2	PuO_2	Metal	Cm_2O_3	Cm_2O_3
Active Isotope in Compd %	10	24	16	15	82	6 57	17 7	95	83	75	70	90	82	82
Watts/Gm Compd	1 7	0 23	0 067	3 8	0 27	1 03	0 12	134	141	3 3	0 39	0 1	98	2 3
Density of Compd Gm/Cm^3	8 9	4 6	3 2	6 4	6 6	7 7	9)	9 3	9	10	10	11 7	11 75	11 75
Power Density Watts/Cm^3 Compd	15 5	1 0)	0 215	24 5	1 8	7 9	1)8	1210	1270	33	3 9	1 17	1150	27
Volume for 2 KW of Heat Cm^3	129	1840	9300	80	1120	253	1850	1 65	1 58	61	513	1710	1 74	74
Availability Annual KW_t 1967-	Avail	Avail 67 KW	Avail 48 KW	Avail 800 KW	Avail 11 KW	Poten Avail	Poten Avail	Avail	Poten Avail	Poten Avail	Limited Avail	Limited Prod	Poten Avail	Poten Avail
Type of Radiation (Major)	$\gamma\beta$	β(c)	$\beta\gamma$(c)	$\beta\gamma$(c)	β	β	β	α	$\alpha\gamma$	$\alpha\gamma$	α	α	αn	αn
Shielding Required	Heavy	Heavy	Heavy	Heavy	Minor	Minor	Minor	Minor	Heavy	Heavy	Minor	Minor	Minor(d)	Minor (d)
Biological Hazard MPC, $\mu c/Cm^3$	3×10^{-9}	3×10^{-10}	5×10^{-9}	2×10^{-9}	2×10^{-8}	10^{-8}	9×10^{-9}	2×10^{-9}	2×10^{-12}	9×10^{-12}	7×10^{-13}	2×10^{-12}	4×10^{-11}	3×10^{-12}
Est Cost $/Gm (Pure)	570	18	9	23	30	156	67	26 500[**]	6600	1540	500	200	2000	1000[c]
Est Cost $/Watt	33	19	21	1 00	)1	10	100	188	40	350	894	1820	17	357
Curies/Gm (Pure)	1130	142	87	3180	914	6000	428	4500	4100(e)	114(e)	17	3 25	3310	84
Curies/Watt	65	150	207	124	2770	385	640	32	24	26	30	30	28	30
Min Cost $/$KWH_e$ (for ( )year mission)	36(3)	5 60(10)	5 8(10)	5 60(1)	143(3)	130(0 35)	114( )	2300(0 42)	89(2)	95(10)	228(10)	415(10)	180(0 42)	124(10)
Spont Fission Half-Life Years	-	-	-	-	-	-	-	-	-	8×10^{13}	$4\ 9 \times 10^{10}$	$1\ 4 \times 10^{13}$	$7\ 2 \times 10^{6}$	$1\ 4 \times 10^{7}$

#Includes contributions from daughters at equilibrium (thermal watts)

[*]From proposed Hanford Isotope Plant KW_t thermal kilowatts
[**] From AEC data also Nucleonics March 1963 Table I page 63 (projected costs)
[***] At terminal or lowest specific power (watts/gm) at 5% thermal to electrical conversion efficiency
For Comparison power from chemical batteries (specifically flashlight batteries) is calculated to cost $100/$KWH_e$

(a) Tm 170 at this concentration is expected on Tm-169 irradiation without need for isotopic separation
(b) Tl-204 at this concentration is probable only with isotopic separation or irradiation at very high flux
(c) Penetrating bremsstrahlung
(d) Except for shielding against neutrons
α - alpha
β beta
γ - gamma
n neutron
e alpha disintegration curies including daughters at equilibrium

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Hanford Laboratories General Electric Company
Richland Washington 12/16/63

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diverse distribution of properties, when viewed from the standpoint of the requirements of a particular radioisotopic heat source use or mission, invariably imposes further restraints to limit the selection. For example, missions which have as their objective an accurate detection and measurement of a wide spectrum of radiation in space, would certainly avoid use of a radioisotopic heat source characterized by being a profuse gamma or bremsstrahlung emitter for which an impractical amount of shielding would be necessary to bring the local radiation significantly below background. Although it is fortunate that there is a wide diversity in properties of candidates, the final choice of a particular one is in most cases limited by such factors as mentioned above, to a single or at most a very few choices. Similarly, the half life of a selected isotope must be approximately as long as the expected useful life of the mission; otherwise, an excessive variation in power output would be introduced.

A discussion of the important characteristics follows.

Half-Life

Half-life is perhaps the most important factor in the evaluation and selection for a radioisotopic heat source since it establishes the time for which such a material is capable of being useful. Half-life is also generally closely related to specific power - thermal watts per gram. Long lived materials will have low specific power while shorter lived ones will have higher specific power. For practical purposes, materials with half-lives of less than one-hundred days would be severely limited in their use in competition with even conventional fuels. Complex production recovery processes and delivery operations consume too large a fraction of the useful life of the short lived materials.

Specific Power and Power Density

Although specific power is among the most important properties, practical considerations require its incorporation into the property called power density which takes into account the purity of the isotope, the composition of the compound form in which it is to be used, and the attainable density of this compound. This figure, power density or thermal watts per cubic centimeter, thus establishes the limit on how much heat can be produced in a given volume of a device from each potential candidate. Some of these materials, however, have such high power densities that dilution will be required to assure a volume with enough outer surface area to permit release of the heat which is evolved.

Type of Radiation

Radioisotopic heat sources in the course of their decay may emit radiation as alpha, beta, and neutron particles, and as gamma rays. Alpha and low energy beta particles are easily shielded; in fact, are to a major extent absorbed in the mass of the isotope. However, both can give rise to other radiations: neutrons from collision of alpha particles with lighter elements (carbon, boron, oxygen, fluorine, etc.) and bremsstrahlung (X-rays) from the slowing down of energetic beta particles. Neutrons are also emitted by some candidates through spontaneous fission which also gives rise to fission products. These fission products emit energy as they decay to their stable states. To avoid undesired shielding, the preferred radioisotopes would be pure alpha emitters with very long spontaneous fission half-lives and pure beta emitters with rather low beta energy. Such choices would avoid neutrons, gamma rays and energetic bremsstrahlung. An inspection of Table I shows that such choices are extremely limited.

Biological Hazard

Although all radioisotopes are regarded as biologically hazardous materials, there is a wide range of variation in their toxicities. For the probable candidates, this range from the least to the most hazardous differs by a factor of about 100,000. Biological considerations should be considered, but no longer represent the limiting factors in selecting energy sources.

Availability

Certainly availability is a significant factor in the evaluation of any isotope. Practical isotope separations processes for highly radioactive materials do not exist today; thus, those isotopes which would require such processing cannot be considered as available.

Similarly, materials which involve processes requiring irradiation with multigram quantities of protons, alpha or other heavy ions must be regarded as outside the scope of today's practical technology. Radioisotopes must, therefore, be at hand as by-products of fission or must be economically producible by neutron irradiation of available target materials accompanied by feasible separations processes. The latter requirement involves chemical rather than physical or isotopic separations.

Cost

Cost will be an important factor in selection of isotopes and also in consideration of competitive power sources - batteries, solar cells, fuel cells, etc. Only recently have representative cost figures become available. Since the government today is the only producer and only small amounts of isotopes have been produced for research purposes, the costs available today are not particularly representative of what they may be when produced in larger

quantities by commercial companies for a profit. Even so, indicated costs for some of these materials appear to be highly attractive when compared with conventional alternatives.

DESIGN CONSIDERATIONS

Radioisotopic space power systems could employ either the dynamic turbo-generator power generation equipment or static conversion devices. The latter is generally considered the most appropriate, and thermoelectric and thermionic devices are generally a part of radioisotopic power system designs in order to optimize the mechanical simplicity and thus the reliability of the system.

According to Carpenter[2], present radioisotopic power systems display a power to weight ratio of one watt per pound, and he estimates that within the next few years, two to three watts per pound would be achieved. NASA has now asked for proposals to develop a system that has a specific power of two watts per pound.

The design criteria for a radioisotopic space power system is about the same as previously defined for a space power system in general. The design criteria for the radioisotopic source are:

1. The isotopic source should be of minimum size and weight.
2. The half-life should be so that power flattening requirements are a minimum.
3. Shielding should be minor.
4. Cost should be low.
5. The isotopic form must be chemically compatible with its containment material.

6. Mission safety requirements must be accommodated in the selection of isotope form, containment, and handling.

Although on a preliminary view of power densities, one might conclude that the alpha emitters are overwhelmingly favored by the easily shielded and absorbed energy of the massive alpha particles, practical considerations require that void space must be provided with such sources to contain securely the accumulating helium gas which is the end product of alpha particles. In practice, the void space is usually made equal to the volume of the isotopic material. Such provisions are not required with beta emitters. The significance of this situation may be appreciated by the following comparison:

Bases: A capsule of inside dimension 15 cm long and 3 cm in diameter, a wall thickness of 0.3 cm for an alpha emitter, $Pu^{238}O_2$, and 0.15 for a beta emitter, $(Pm_2{}^{147}O_3)$.

Assume the void volume is equal to the volume of the PuO_2.

Compare: The maximum heat output of each capsule and the gross power density of the capsule (watt/cc of total volume).

Inside dimensions of both capsules = 15 cm x 3 cm = 106 ccm

Outside dimensions of $Pu^{238}O_2$ capsule = 15.6 cm x 3.6 cm = 158.8 ccm

Outside dimensions of $Pm_2{}^{147}O_3$ capsule = 15.3 x 3.3 cm = 130.8 ccm

For $Pu^{238}O_2$ Case:

Inside volume is 106 cm but in view of void space requirement only 53 ccm of this volume can be occupied by the isotope compound

53 x 3.9 watts/ccm (power density of $Pu^{238}O_2$)

Heat output of capsule = 206.8 watts = 1.3 watts per ccm of total capsule volume (external).

For the $Pm_2{}^{147}O_3$ Case:

Inside volume is 106 ccm with no need for void space allowance.

106 x 1.8 watts/ccm (power density of $Pm_2{}^{147}O_3$)

Heat output of capsule = 190.8 watts - 1.46 watts/ccm of total capsule volume (external).

This comparison shows that promethium oxide in the encapsulated form may have a significantly higher practical power density than does plutonium-238 oxide. This fact is not apparent from a cursory inspection of radioisotope properties (Table I) but comes to light when the materials are considered from the standpoint of practical engineering design.

For smaller capsules, the comparison, as made above, would be even more divergent. This situation should be taken into account when comparing any of the alpha emitters with the beta emitters.

A similar situation exists in the case of the isotopes of very high power densities such as Po-210. In such materials it is unlikely that the pure isotope could be handled, fabricated or even used without some dilution. The heat output from even small volumes of the pure materials is so high that extraordinary means are needed to prevent melting and volatilization of the isotopes as well as the encapsulating materials. Thus, from a practical standpoint, designs could probably employ Po-210, Cm-242 or Th-228 only with substantial dilution and thus at more modest power densities.

A comparison of shielding requirements is shown in Table II. Based on these data, Pm-147 and Pu-238 require much less shielding than the other isotopes.

TABLE II

COMPARATIVE SHIELDING REQUIREMENTS[3]
FOR TYPICAL RADIOISOTOPIC POWER SOURCES

Basic: 1000 Watt Source

Source	Inches of Lead Required for 10 mr/hr at 1 meter
Sr-90	6.1
Cs-137	5.4
Ce-144	10.3
Pm-147	1.1 (a)
Pu-238	1 (b)

(a) Pm with two years of aging.

(b) Without shielding the dose rate is less than 10 mr/hr at 1 meter.

In comparing the radioisotopes listed in Table I against the design criteria, we see that Po-210, Th-228, and Cm-242 excel in criteria number 1 because of their high specific power; however, they have some other shortcomings such as cost and half-life for Po-210, cost, half-life and shielding for Cm-242 and heavy shielding for Th-228. The isotopes Sr-90, Cs-137, U-232, Pu-238, Am-241, and Cm-244 have advantages of long half lives for long flat power curves. From the standpoint of minor shielding requirements, Pm-147, Tm-170, Tl-204, Po-210, Pu-238 and Am-241 are excellent.

The more abundant fission products will always be produced at the lowest cost; however, some of the irradiated isotopes such as Po-210 will come down in cost after they are in production.

Compatibility with the container leads us into the problem of materials considerations.

MATERIALS CONSIDERATIONS

The keys to higher specific power for radioisotopic space power systems is higher source temperature and better utilization of the heat generated by the source. Each of these depend upon an increased knowledge of materials on the part of the design engineer and on the development of materials that will meet the requirements. Higher specific heat sources are available so that the problem lies in developing containment materials, structural materials, and electrical energy conversion materials that will allow the use of a higher temperature source and allow dissipation of heat at a higher temperature. The dissipation of heat at a higher temperature allows for smaller size radiators, thus lower weight in the over-all power producing system.

FIGURE I

Thermal Efficiency of System

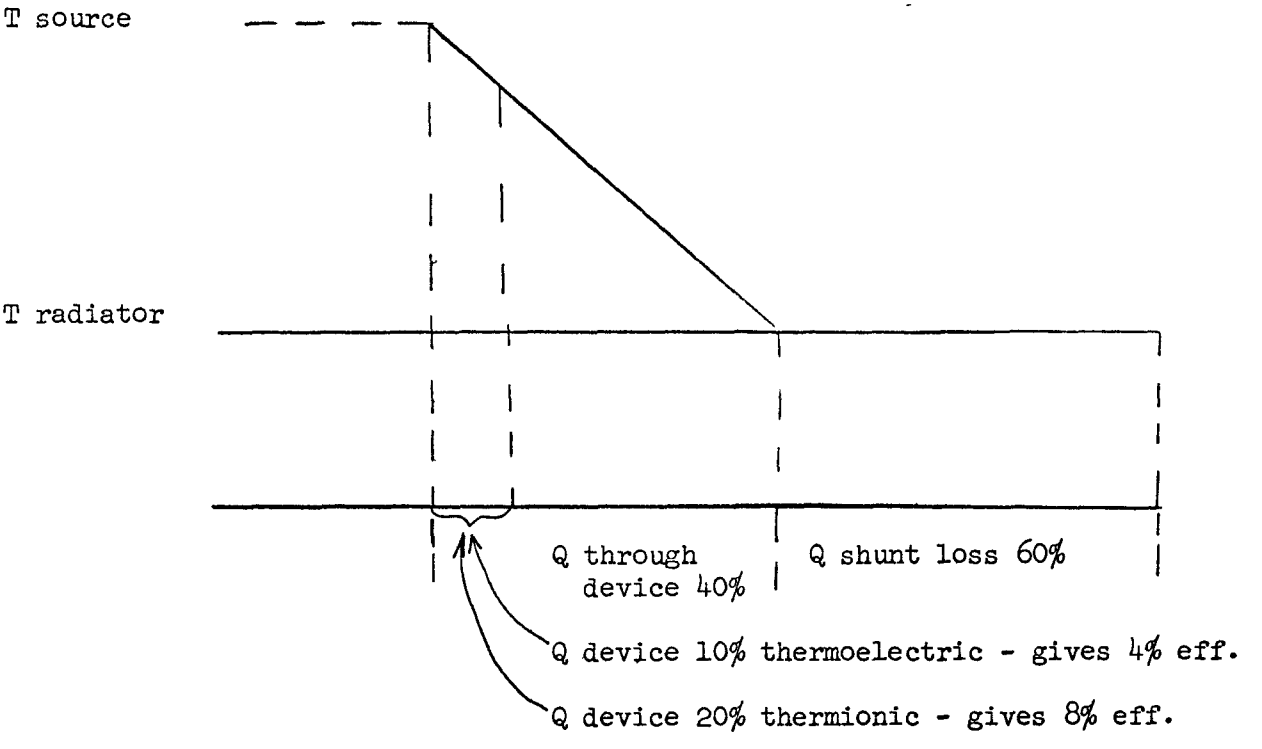

Figure I is a plot of the thermal efficiency of a system. On the left we plot the temperature of the source and the temperature of the radiator. The distances along the bottom are the Q representing the heat dissipation through the device and the Q for the shunt loss or the loss of heat by-passing the device.

In most systems as now designed, the Q through the device will not be more than about 40%. With a 10% conversion efficiency of a thermoelectric device, this gives us about 4% over-all conversion of isotopic heat to electricity. With a 20% Q conversion in a thermionic device, we obtain about 8% over-all efficiency from thermal to electrical energy. If the T (temperature) of the source is increased and the T of the radiator is increased with no change in the ratio or the length of the Q's, the thermal efficiency of the system would remain the same, but the size of the radiator could be smaller. This, however, does place a requirement for higher temperature materials to produce the same quantity of electricity. There is a possibility that if we increase the temperature of the source and maintain a constant temperature in the radiator, that we could put two devices in series in the Q through the device such that we are generating power in both devices and getting a higher conversion percentage of the Q through devices. For example, if we add a thermionic device that operated at a temperature from 2300°K to 1400°K and a thermoelectric device in series which operated from 1200°K to 600°K, we could recover 30% of the net Q through the device. This would perhaps make our over-all system 12% efficient. We can also increase the efficiency by decreasing the shunt loss. This again would depend on improved design and application of better insulation materials.

If we design for higher temperatures of the source, this will create increased problems of compatibility of the source material with the containment material. The nature of this compatibility will depend on whether the source material is in the solid or molten state. It will also depend on whether the source material is in the metallic form or a compound form.

Very little is known about many of the power isotopes either in the pure state or their compounds. Most of the physical property data that is available for isotopic materials is listed in Table III. Much of this data is estimated or not very accurate. The lack of data is noted by the great number of blanks in the Table. Programs should be conducted in the very near future to obtain these physical and chemical properties and provide these properties to the engineering designer. Experiments to determine the compatibility of many of these power isotopes with candidate containment materials at higher temperatures must also be conducted. Because of the tremendous emphasis on safety, higher temperature compounds of the power isotopes must be evaluated for hazards involved in launch pad fires and various types of mission abort and re-entry conditions. The actual power isotopes should be used in these studies since it has been found that radioisotopes have different physical and chemical reactions with their environment than the stable isotopes of the same element.

SAFETY

The hazardous nature of radioisotopes requires that any device be provided with near absolute safeguards to prevent the uncontrolled release of these materials to the environment. For terrestrial uses, there must be certainty that the heat of radioactive decay can be dissipated, otherwise temperatures

TABLE III

PHYSICAL PROPERTIES OF ISOTOPIC HEAT SOURCES

Compound	Co-Metal	SrO	$SrTiO_3$	CeO_2	Cs Glass Borosilicate
Atomic Structure	HCP	Cubic		Cubic	
Melting Point °C	1495	2430	1900	2680	1275
Boiling Point °C	2900			3800	
Density - Theoretical gr/cc	8.8	4.7	5.11	7.3	3.1
Specific Heat cal/gr/°C	(20°C) .099	(750°C) .128		(20°C).086	
Thermal Conductivity cal/sq cm/cm/sec/°C	(20°C) .165		(20°C) .0173	(1000°C).0073	(2000°C).0025
Heat of Fusion cal/gr	58.4				
Coeff. Thermal Expansion to 1000°C in/in/°C	13.8×10^{-6}		1.1×10^{-5}	9.6×10^{-6}	1.5×10^{-5}
Vapor Pressure					
1000°C		1.6×10^{-19} Atm.			
1500°C		1.6×10^{-10} Atm.		10^{-7} Atm.	3.5 mg/cm^2/hr*
2000°C		1.5×10^{-7} Atm.			
2500°C		4.8×10^{-4} Atm.		10^{-3} Atm.	*Evaporation Rate

Sources of Data 5,6,7,8,9,10,11

TABLE III

(CONTINUED)

Compound	Pm_2O_3	Tm-Metal	Tl_2O_3	Po-Metal	ThO_2	UO_2	PuO_2
Atomic Structure		HCP	HEX	Cubic & Rhom.	FCC	Cubic	FCC
Melting Point °C	2350	1550	7.7	254	3200	2750	2300
Boiling Point °C		2127	875	962			
Density - Theoretical gr/cc	7.3	9.3	10.2	9.4	10.0	10.9	11.5
Specific Heat cal/gr/°C	(20°C).094				(20°C).058		
Thermal Conductivity cal/sq cm/cm/sec/°C	(150°C).006				(20°C).02	(700°C).02	(700°C) .0065
Heat of Fusion cal/gr		26.04	7.66		17.41		
Coeff. Thermal Expansion to 1000°C	10.8×10^{-6}			2.35×10^{-5}	12.5×10^{-6}	5.0×10^{-6}	9.7×10^{-6}
Vapor Pressure				$\text{Log } P_{mm} = 7.2345 - \frac{5377.8}{T}$			
1000°C							
1500°C					$10^{-7.4}$ Atmos.		4.37×10^{-9} Atmos.
2000°C					10^{-4} Atmos.		
2500°C							

*Estimated

TABLE III

(CONTINUED)

Compound	Am-Metal	Cm_2O_3
Atomic Structure	HEX	Cubic
Melting Point °C	1100+	1500
Boiling Point °C	2460	
Density - Theoretical gr/cc	11.9	10.7
Specific Heat cal/gr/°C		
Thermal Conductivity cal/sq cm/cm/sec/°C		
Heat of Fusion cal/gr		
Coeff. Thermal Expansion to 1000°C		
Vapor Pressure	$\text{Log } P_{mm} = 7.02 - 11,300/T$	
1000°C		
1500°C		
2000°C		
2500°C		

will increase to the point of melting and eventual destruction of the heat source capsule and release of the radioisotope to the surroundings. Ordinary operations such as transportation of these materials requires that the shipment withstand any credible accident of prolonged fire, high speed impact against an immovable barrier, and prolonged burial in collision debris, landslide and water. Corrosion by such common agents as humid air, fuels and sea water is an important consideration. For use in space devices, there are even more problems regarding safety such as fire and explosion on the launch pad, prelaunch assembly and disassemble in case of a "scrubbed" flight, post launch and pre-orbit abort and finally re-entry, intact or dispersed.

These problems of safety are met by engineering solutions involving materials, designs, statistical appraisal of risks of credible accidents and incidents, and operating or handling procedures.

FUTURE PROSPECTS

It is certain that the unique heat (power) producing properties of radioisotopes will find increasingly practical applications for the operation of unmanned instrumentation in remote areas on the earth, on or under the sea and in space. More devices may be used as navigational aids and to report universal weather conditions and to observe storm patterns and progress via satellites. The output of such devices may be used by all nations who choose to provide their own reception facilities.

There are, of course, many other applications including seismic observations, military reconnaissance and defensive monitoring undersea, on land and in space.

Conceivably, all of these uses would require more than the available radioisotope resources. This is readily realized when the near future availability of these materials is appraised. Among the fission products alone, the combined prospective annual output for the long lived ones (strontium-90, cesium-137 and promethium-147) is equivalent to slightly over one-hundred kilowatts of thermal power.(4) If the conversion to electrical energy is to be done via conventional thermoelectric devices, the thermal to electrical efficiency is about 5%. Thus, the annual output of electricity is conceivably only about 5 kw from the prospective supply of fission product radioisotopes. Therefore, even though a single device such as weather monitoring satellite may require only about one-hundred electrical watts continuously, the annual number of such devices may thus be limited by the supply of radioisotopic "fuel". Since such a use would be most suitable for those isotopes which require a minimum of shielding (such as promethium-147 or plutonium-238 - the least plentiful ones), further supply limitations are thus imposed. Fortunately for this supply picture, the cost of satellites and their placement in orbits apart from the cost of the power supply is so great that only a very few of such important devices would be expected to be launched in any given year. This, however, is not expected to be the situation with earth based devices where conceivably hundreds of units may be justified. Present prospects for radioisotope supplies are limited but certainly adequate for the immediate future. As the civilian nuclear power economy grows, additional supply of fission product radioisotopes will be provided. Also, the supply of those radioisotopes produced by intentional or concurrent irradiation of special target elements will also increase. Plutonium-238 (via special neptunium-237 irradiations)

and curium-244 from reactors based on plutonium recycle will certainly have increasing availability. If the demand exceeds the supply of these costly materials, efforts can be initiated to produce others including cobalt-60, thallium-204, uranium-232 americium-241, and plutonium-238 via curium-242. All of these could, of course, be employed today but until a market consumes all of the present more readily available ones, little incentive exists to produce these alternate candidates. At the present time, all demands can be met by existing capacity for producing Sr-90, Cs-137, Ce-144, Pm-147, Pu-238, and Po-210. Furthermore, the processing of the fission products could be readily expanded to the production levels indicated on Table I, Item 10. With that as a first step, little likelihood exists for extension into a production campaign for most of the other candidates in the very near future. Off in the more distant future, however, there lies the prospect of more economical neutron bombardment facilities and practical and economical isotope separations facilities.

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