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RADIOISOTOPIC HEAT SOURCES

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By

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PREFACE TO REVISED EDITION

In the short time since this document was issued February 1, 1963, related studies have been completed. Although these studies do not change the general content or conclusions of the original document, some significant data on certain of the isotopes have changed. The most important changes are in the half-life and specific power of promethium. The new data were obtained from experimental determinations and from the results of a study of the economics of fission product recovery and encapsulation at Hanford.⁽²⁷⁾ The latter study provides the most representative cost figures available today. Furthermore, new projected costs for Po^{210} , Pu^{238} , Cm^{242} , and Cm^{244} have been published by others. Since demand for the original document has exhausted the supply of extra copies, the latest data have been included in this revision. The data included are now current with the most realistic technology that has been developed since the first issue of this document.

Table VI (page 52) has been added because of its usefulness in general comparisons of candidate radioisotopic heat sources including those of longer as well as shorter half-lives than those which were selected originally. The costs shown for Am^{241} and Cm^{242} are the author's own predictions for conditions of future power reactor production with plutonium recycle. The costs of electricity for specified mission lifetimes may be of special interest to certain readers especially when it is realized that power from such ordinary useful sources such as flashlight batteries costs about \$100 per kilowatt hour.

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RADIOISOTOPIC HEAT SOURCES

INTRODUCTION

Although nearly 60 years ago the Curies first observed that radioactivity (in radium) resulted in the liberation of heat, it is only in the last few years that vigorous application of radioisotopes as practical heat sources for electrical conversion has been considered. With over a thousand known radioisotopes,⁽¹⁾ the problem of logically selecting the most likely heat source candidates may at first seem formidable. The great variety of techniques available for the production of radioisotopes (thermal and fast fission of certain elements, neutron irradiation of various stable or long-lived isotopes, accelerator processes, and recovery of certain rare elements and special isotopes from minerals) makes the problem seem even more complicated. It is to be expected, however, that there are a few criteria which can be applied to simplify and provide firm bases for the selection of a few outstanding candidates.

Only two radioisotopes are in actual use as heat sources, strontium-90 and plutonium-238.^(2, 3) Two others, cesium-137⁽²⁾ and curium-242⁽⁴⁾ are committed for use. The objective of this study is to review the properties of candidate materials, outline the characteristics which determine the feasibility of the production and use of a candidate, identify isotopes which fit the needed characteristics, and thus, hopefully expand the list of candidate isotopes. A further objective is to provide data that clearly show those isotopes which justify most intensive consideration for production or further research and development for use as heat sources.

SUMMARY

There are about 50 radioisotopes with half-lives of one to one hundred years. These represent about 40 elements and comprise essentially all isotopes which are considered most useful as heat sources. Nine are fission products. The others either occur in nature, have been detected in residues from accelerator experiments, or may be produced by neutron irradiation. However, if reasonable restraints are used as bases for

selection of these materials, the list of suitable candidates is reduced to eight. These eight are: cobalt-60, strontium-90, cesium-137, promethium-147, thorium-228, uranium-232, plutonium-238, and curium-244, with properties listed in Table I. Expansion of this list in the near future is not anticipated.

Aside from the half-life criterion, the most significant restraint which limits the selection is the need for a realistic production process. Economical use of other than thermal reactor neutron irradiation processes which are necessary for the production of certain of these materials does not appear to be attainable soon. Furthermore, the requirement for an isotopic separation process for either target or product also excludes a large number of otherwise attractive materials. Prospects for the development of economical isotope separations processes for intensely radioactive isotopes at a multigram level within the next decade are not encouraging.

The wide variation in properties which are significant for heat source uses complicates the problem of logical selection. Those materials finding use today are those which either are at hand or are obtainable by fairly straightforward, though costly, methods.

This study indicates that, in comparison with plutonium-238, promethium-147 should be receiving more attention. These two are the only candidates on hand with which shielding is a minor problem. Also, uranium-232 (and its daughter, thorium-228) continues to show outstanding characteristics. For the presently available materials, strontium-90 and cesium-137 appear to be the least expensive on a cost per watt basis. In some applications, cobalt-60 may also be justified economically.

Although curium-244 can be considered to be available today via special irradiation of plutonium, it may be expected to be obtainable as a byproduct from the processing of highly exposed plutonium, which has been recycled as a fuel in thermal reactors. At that time its cost on a heat basis should be significantly less than that of plutonium-238.

TABLE I

CHARACTERISTICS OF ATTRACTIVE RADIOISOTOPIC HEAT SOURCES

	Cobalt-60	Strontium-90	Cesium-137	Promethium-147	Thorium-228	Uranium-232	Plutonium-238	Curium-244
Specific Power watts/kg	17.4	0.95	0.42	0.33	170	4.4	0.56	2.8
Half Life years	5.3	28	30	2.7	1.9	74	83	17.6
Isotopic Purity %	10	50	35	95	95	85	80	30
Compound Form	Metal	SrTiO ₃	Glass	Pm ₂ O ₃	ThO ₂	UO ₂	PuO ₂	Cm ₂ O ₃
Density of Compound g/cc	8.9	4.6 ^(a)	3.2 ^(b)	6.6 ^(c)	9 ^(c)	10 ^(c)	10 ^(c)	11.75 ^(d)
Active Isotope in Compound %	10	24	16	82	83	75	70	82
Specific Power of Compound watts/kg	1.7	0.23	0.067	0.27	141	3.3	0.33	2.3
Power Density watts/cc of Compound	15.5	1.05	0.215	1.8	1270	33	3.9	27
Volume for 2 kw Heat cc	123	1840	9300	1120	1.6	61.2	513	74
Availability	Producible Now	F P** 5.8%FY	F P** 6.0%FY	F P** 2.6%FY	Potentially Available	Potentially Available	Limited Available	Potentially Available
Shielding Requirement	Heavy	Heavy	Heavy	Minor	Heavy	Heavy	Minor	Minor ^(j)
Biological Hazard***	3 x 10 ⁻⁹	3 x 10 ⁻¹⁰	5 x 10 ⁻⁹	2 x 10 ⁻⁸	2 x 10 ⁻¹²	9 x 10 ⁻¹²	7 x 10 ⁻¹³	3 x 10 ⁻¹²
Estimated Cost \$/watt ^(e)	33	19 ^(h)	21 ^(h)	91 ^(h)	40	350 ^(f)	814	357
Estimated Cost \$/gram*	570	18 ^(h)	9 ^(h)	30 ^(h)	6600	1540 ^(f)	500 ^(g)	1000 ^(g)
Curies per gram*	1130	142	87	972	4100 ^(g)	114 ^(g)	17	84
Curies per watt*	65	149	209	2770	24 ^(g)	26 ^(g)	30	33

* For pure isotope (plus contributions of daughters at equilibrium (thermal watts))

** These fission products exist in large amounts in reactor fuel processing wastes and are assumed to be available for recovery

*** U.S. Department of Commerce National Bureau of Standards Handbook 69 Most limiting MPC 168 hrs/wk air µc/cc

(a) Charles F. Crompton Isotopic Heat and Power 1962 Nuclear Congress Preprint Paper #84 page 9 (Adjusted to 90% theoretical density)

(b) Cs-137 fueled Generator RRC Cs-0100 Royal Research Corporation page 65

(c) Estimated at 30% of theoretical density

(d) Reference 6 page 70

(e) Basis Cobalt-60 at \$0.50/curie cesium-137 and strontium-90^(h) promethium-147^(h) uranium-232 at \$1000/g thorium-228 at \$6600/g plutonium-238 Nuclonics April 1961 (Reference 6)

(f) Includes cost of thorium-228 needed to achieve 4.4 watt/g initially otherwise uranium-232 cost/watt is \$230

(g) Sum of alpha curies of isotope plus daughters at equilibrium

(h) Cost numbers based on the proposed Hanford Isotope Production Plant HW 77770 July 1 1963 (27)

(i) Nuclonics March 1963 Isotope Costs and Availability by H. L. Davis page 63

(j) Except for neutrons from spontaneous fission

DISCUSSION

Review of Characteristics

1. Half-Life

Half-life is perhaps the most important factor in the evaluation of radioisotopes for use as heat sources, since it establishes the time during which a device which uses the radioisotope may function. In addition, within limits, it is closely related to specific thermal power. For practical heat source uses, consideration is limited to those isotopes having half-lives of not less than about one year or more than one hundred years.

In setting the minimum half-life at one year for acceptable heat source candidates, a number of isotopes, some of which have high specific power, have been excluded: 285-day cerium-144, 163-day curium-242, 138-day polonium-210, and several less familiar ones. Except for use in very special missions where high costs and excessive gamma activity can be tolerated materials such as polonium-210 and cerium-144 could be justifiably replaced by other isotopes or by chemical and solar batteries. With the exception of curium-242, it is not appropriate to include materials with such marginal advantages in a list of candidate isotopes. At the other end of the scale, at about the 100-year half-life limit, the specific power is generally low. There are, however, only a few isotopes of possible interest (argon-39, polonium-209, gadolinium-148, americium-241) excluded by this requirement. Argon-39 is an inert gas. There are no apparent practical production processes for polonium-209 and gadolinium-148. When plutonium assumes a major place as a power reactor fuel, americium-241 may be recovered as a byproduct in significant quantities from the decay of plutonium-241 during storage. Americium-241 has a half-life of 458 years and a specific power of about 0.1 watt per gram. It appears to be the only isotope with a half-life of a few hundred years which has any possibility for use as a heat source. Isotopes of longer half-lives have even lower specific powers. Although the specific power of americium-241 is low, its compounds would be expected to have high specific gravity and, thus, perhaps an acceptable power density (about 1 watt per cubic

centimeter). However, the present price of this isotope (\$1500 per gram), its low specific power, and the lack of definite prospects for its large scale production does not justify its inclusion in the present list of candidate materials.

Although the advantages of long-lived isotopes are obvious in assuring long operating periods with only a gradual decline in power output, there are two limits to such advantages: (1) technical obsolescence of a long-lived device and the instrumentation powered by it; and (2) the inability to match usable isotope life with the reliability or durability of the complex electronic equipment, the use of which is supported by the radioisotopic power source. So far, no reliability data on the actual devices in use have been noted.* It is possible then that if a choice were available, materials with half-lives in the range of 5 to 10 years may be preferred over those materials available for use now.

Figures 1 and 2 show the change in thermal heat output with time from an initial gram of each of several isotopes. These two figures cover short-lived and relatively long-lived materials. Some isotopes in addition to those listed in Table I are shown in Figure 1. In view of the large difference in the time scale shown on these two figures, one of the representative short-lived candidates, promethium-147, is also shown in Figure 2 to emphasize the very great difference in the rate of decline of heat output between the long-lived and representative short-lived candidates.

2. Radioactivity (Curies/Gram)

Radioisotopes are commonly described in terms of their activity, curies per gram. Although this value alone does not contribute to the description with regard to heat output, it is a factor which when combined with other descriptive properties can lead to the calculation of the heat output or specific thermal power (watts/gram).

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* The TRANSIT IV-B navigational satellite launched about 2 years ago and which was powered by about 100 grams of plutonium-238 is no longer operating, although the similarly powered TRANSIT IV-A is still operating after over 2 years in orbit.

3. Curies/Watt

The expression curies/watt is also a value used to describe the properties of an isotope. This value provides information on the energy of the particular emission. This value combined with curies/gram establishes the value for the specific thermal power (watts per gram).

4. Specific Thermal Power (Watts/Gram)

The specific power, watts/gram (heat output), when considered along with half-life, is obviously one of the most important values since it describes the quality of an isotope as a heat producer. It is generally high for short half-life materials and low for long half-life materials.

5. Power Density (Watts/Cubic Centimeter)

The preceding expressions define the heat producing properties of an isotope; however, in order to provide information on the isotope in the compound form in which it may be used, the power density value is needed. This value takes into account the concentration of the specific isotope in the final compound form in which it is to be used, the specific power, and also the density of the compound. This value then is the watts per cubic centimeter of the final product as it is encapsulated and used as a heat source.

6. Type of Radiation

Ideally, a selected heat source would emit either no gamma radiation or would emit radiation of sufficiently low energy that the encapsulating material would provide the necessary shielding. This condition exists with only three of the eight, attractive, candidate isotopes (promethium-147, plutonium 238, and curium-244). Although strontium-90 is a pure beta emitter, its daughter, yttrium-90, emits energetic gamma as well as beta particles which are of sufficiently high energy to require heavy shielding. Thus, many isotopes by themselves also show little or no gamma activity; however, these materials may be part of a complex decay chain, some one or more members of which are intense gamma emitters. This is the case with uranium-232 (and thorium-238) which has in its decay chain

thallium-208, which is a short-lived isotope of extremely energetic gamma activity. In addition, both strontium-90 and promethium-147 are associated with relatively short-lived companion isotopes (strontium-89, an energetic beta emitter and promethium-148, a gamma emitter) either of which may be reduced to much less significant concentrations by prolonged aging. This is of particular importance with promethium-147 for which, in contrast with strontium-90, the bremsstrahlung problem is not expected to be significant.*

7. Availability or Fission Yield

Certainly availability is a significant factor in the evaluation of any isotope. For fission products, a high fission yield is an adequate indication of availability. For other isotopes, the availability of the target elements and the feasibility of the production process must be considered. Isotope separations processes for highly radioactive materials do not exist today. Thus, these isotopes which would require such processing are regarded as unavailable. Also, processes which require irradiation with multigram quantities of protons or alpha particles must be regarded as outside of today's technology.

8. Biological Factors

Although all radioisotopes must be regarded as very hazardous materials, the fate and effects of isotopes in biological systems may be a significant factor in a choice among the most attractive materials. Elements such as strontium and plutonium are readily deposited in living tissues (bone, for example) and are relatively difficult to expel. Cesium and promethium, on the other hand, are not as readily retained in living tissues. The most limiting condition may be used for comparisons. The "Maximum Permissible Concentrations in Air" for continuous exposure from "Handbook 69"⁽⁵⁾ is the limiting condition taken here as the basis for comparing the biological factors in radioisotope utilization.

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* This does not mean that promethium-147 is without bremsstrahlung. Secondary radiation will exist but it will be of sufficiently low energy that self absorption, design of the capsule, and mass of normal structural material in the device will provide adequate shielding without need for special additional barrier material.

9. Costs

Firm estimates of cost are not available; however, there are some references which provide indications or expectations of cost^(6, 7, 27) for a few radioisotopes. Present published prices for radioisotopes are not representative of the costs attainable when a market justifying large-scale production is finally established. As the market develops, costs will be substantially reduced, even below the most recently published prices for large shipments of cesium-137 and strontium-90. In earlier studies, these two isotopes were expected to be at about the same price per curie. Recent advances in processing technology which are reflected in the most recent announcements of reduced prices⁽⁸⁾ indicate a spread in these prices favoring cesium-137 (50 cents per curie for cesium-137 in 100,000 curie amounts and 75 cents per curie for strontium-90 in 30,000 curie amounts). The estimated costs shown in Table I have been derived from a number of sources and are expected to be substantially different from estimates obtained after more intensive future studies of proposed large scale integrated production processes have been made.⁽²⁷⁾

Criteria for Selection

Heat source uses comprise those applications where the heat of radioactive decay is converted to electricity for the operation of remote and unmanned instrumentation. Although the energy requirements for many such practical devices are small (less than 100 watts), the diversity and magnitude of these unique applications is expected to be sufficiently great to support substantial radioisotope production efforts. With such efforts in mind, it is important to know the limitations and characteristics of all reasonably attractive candidates so that early efforts at their production can be firmly scoped and directed. As a primary limitation, it was concluded early in this study that little likelihood existed for expecting substantial routine heat source uses for isotopes having half-lives of less than one year. Where such materials have advantages, it would be expected that special production would be utilized. In this review, the isotopes

were surveyed, and all having half-lives of over one year and less than 100 years were identified and listed in Table II. Concurrently, a list of factors of importance to the choice of a candidate isotope was established. Table II lists a total of 51 candidate isotopes of 40 elements.* However, when the qualifying criteria are applied, this list shrinks to only eight isotopes; three of these (strontium-90, cesium-137, and promethium-147) are fission products. One, cobalt-60, can be readily produced in suitable concentration by irradiation of a common, inexpensive, monoisotopic element, cobalt-59. The remaining ones, uranium-232, plutonium-238, and curium-244 are produced by neutron irradiation of special and costly target materials. One (thorium-228) is obtained as the decay product of uranium-232.

The characteristics which determine the practicality of an isotope for use as a heat source may be listed under two headings: (a) those characteristics which relate to its utility as a heat source, and (b) those characteristics which relate to the feasibility of production in practical amounts (many grams to a few kilograms). A listing of these factors which are subsequently discussed is made as follows:

- a. Characteristics which assure the utility of an isotope as a heat source:
  - 1.** A half-life in the range of 1 to 100 years.
  - 2.** A material which can exist in high concentration as a stable, inert solid at the operating temperatures (usually many hundreds of degrees centigrade).
  3. A heat output greater than 0.1 watt/gram of pure isotope.
- b. Characteristics which assure the future, practical, and economical production of multigram quantities of the isotope:
  - 1.** Isotopic separations processes are not required for either target or product.
  - 2.** The target material must not be rare, too costly, or practically unobtainable.

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* The two charts of Reference (1) were used in this selection; an isotope was not included in Table II if its indicated half-life was outside of the 1 to 100 year range on either chart.

** These criteria are the major ones.

- 3.* Sufficient information must be at hand to define a realistic production process.
- 4.* If the product is a fission product, the fission yield must be greater than 0.1%.
5. The thermal neutron cross section of the product shall not exceed about 1500 barns.
6. The thermal neutron cross section of the target shall not be less than about two barns.
7. There shall be no more than two steps of neutron irradiation and three steps of chemical processing in the production scheme.
8. The isotope as delivered for heat source preparation shall not cost more than about \$2000 per initial watt manufactured on more than a prototype scale.

In addition to the discussion of half-life as covered earlier (see pages 7 and 8), the complexity of radioisotope processing and the extremely specialized nature of some of the most attractive applications have a significant bearing on the establishment of a realistic half-life limit in the lower range. For the upper limit of about 100 years these factors are, of course, not so critical. Large-scale radiochemical processing, in general, is done in a highly deliberate and organized fashion. Although time may be an important factor, it is subordinate to safety and process economy (high yield of valuable materials). It is not realistic to anticipate short processing times which would be necessary with relatively short-lived isotopes. The unique uses of radioisotopic heat sources in orbiting satellites and space probes, as well as installation in remote and relatively inaccessible areas of the world, such as polar regions, all involve scheduling problems which are influenced by (1) seasons of the year for shipments to polar regions involving prolonged ocean voyages (assuming air shipment is not feasible), (2) astronomical factors involving optimum positions of the earth, moon, and planets, and (3) local weather conditions

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*These criteria are the major ones.

which may severely hamper otherwise precisely scheduled launchings. It is reasonable that under normal conditions a time period in the range of one-third to one-half year should be allowed for processing and delivery of a heat source powered device. Short-lived materials—those with half-lives of less than one year—would lose a large fraction of their activity in the processing and delivery period. These factors coupled with allowances for launch and shipment to point of productive use further impair the utility of short-lived materials. The minimum half-life of one year has, therefore, been assumed as a reasonable criterion for selection.

The need for materials which can be maintained in the form of stable, inert solids at high temperatures makes impractical the use of isotopes such as krypton-85 and argon-42 which are inert gases. This requirement also probably rules out the use of tritium, since the high temperature stability of tritides (analogous to hydrides) is questionable.

Materials which generate less than about 0.1 watt/gram appear to be at such a disadvantage in comparison with available isotopes of much higher heat generating capabilities that they should be dropped from consideration (samarium-151, for example, 90 year half-life, less than 0.01 watt/gram).

If an isotope separations process is necessary for the production of either or both the target for irradiation or the product of irradiation, such techniques are not considered practical for near-future application; the products which are producible by such means are excluded as candidate heat sources and are listed in Table III. This restriction may be revised as isotope separation techniques are greatly improved. However, economical isotope separations processes applicable to multigram production of the intensely radioactive isotopes as represented by heat source candidates are not now realizable. It should be noted that without isotope separation, some of the more obvious and useful isotopes such as strontium-90 and cesium-137 cannot be obtained free of substantial inert isotope contamination. However, the active isotopic content of such mixtures is generally high enough to provide a source of adequate power density without need or justification for complex isotope separations processes.

Isotopes which can be made only from very rare elements or which are rare members of known decay chains should also not be considered (lead-210, radium-228, and actinium-227) for economic reasons.

Another class of radioisotopes which was eliminated includes those for which no practical production process is apparent; generally, these have been identified in trace amounts via accelerator experiments where materials are irradiated with particles other than neutrons, for example, p, n and α , n reactions, to produce sodium-22, bismuth-207, polonium-208, neptunium-235, etc. These types of isotopes are listed in Table IV.

Isotopes with fission yields of less than 0.1% were excluded because of the probable high cost of recovering sufficient material for practical use as heat sources.

If the thermal neutron cross section of the isotope produced is high (above about 1500 barns) or if the target cross section is low (below about two barns), such materials should be eliminated from consideration. For the high cross-section materials, the possibility of efficient neutron economy and realization of the desired isotope in high yield are not likely. Europium-152 and 155 are examples. Similarly, for low cross-section target materials, the quantity and processing of such materials make economic recovery unlikely. Polonium-210 from bismuth-209 is an example in which probably tons of bismuth are required to be irradiated to yield a very few grams of polonium.

Materials which require many steps of neutron irradiation and chemical processing for isolation are also avoided (californium-250, californium-252, and einsteinium-254, for example) because of the expectation of extremely high costs per gram for such materials.

The matter of cost as a basis for appraisal of the practical use of an isotope, although certainly an ultimate factor, is not readily established. Some estimates have been made.^(6, 7) On the basis of estimates reported by others⁽⁶⁾ for the most likely candidates, plutonium-238 is shown to have a very high cost per watt of heat. Furthermore, this cost (\$1600 per

watt) is for projected future production. It is concluded that present costs are higher. Using plutonium-238 as a basis, it is reasonable to use \$2000 per watt of thermal energy as the maximum in selecting candidate materials producible on a multigram or more than prototype scale.

The isotopes which were excluded because of the various reasons discussed above are listed in Table V.

There are, of course, other characteristics of radioisotopes which are not essential to their use or production, but which may be factors in the choice of an isotope for a particular use. For example, although all radioisotopes are regarded as hazardous, they differ widely in their biological properties. Strontium and plutonium are especially hazardous because of their tendency to lodge in bone tissue. Promethium and cesium, on the other hand, do not exhibit such biological retention. The latter should therefore be favored for use in near-earth satellites, while strontium would be less favored. The type of radiation emitted by the isotope is another factor which may determine the preferred manner for use of an isotope. Those which are essentially pure alpha emitters, such as plutonium-238 and curium-244, or low energy, pure beta emitters, such as promethium-147, require the least shielding: a significant advantage where manual handling and minimum weight are of interest.

Some characteristics may appear to have been omitted; however, it is felt that those enumerated above, in most cases, adequately cover the situation. For example, for those isotopes which may be produced by irradiation of target materials, the number of neutrons consumed in the process may be regarded as a factor which should be listed. For the purpose of this compilation, such factors are assumed to be a part of the cost, and therefore, need not be listed separately.

When fast reactors and plutonium "burners" become significant factors in the power reactor field, the changes in the yields of the fission products may indicate more or less emphasis on some isotopes, including

those which result as byproducts. For example, plutonium fission yields far more ruthenium-106 than does uranium-235 fission.⁽⁹⁾ Also, the long-lived curium-244 may eventually be available in substantial quantities from thermal reactors in which high exposure plutonium (high plutonium-242 content) is being consumed.

EVALUATION OF CANDIDATE ISOTOPES

The list of eight candidate isotopes resulted from consideration of realistically usable half-lives and the practicality of the production processes. These two criteria were the controlling ones. Although heat output would appear to be most important, it is of less importance in selection, especially, in view of these two more critical bases. In general, the most suitable fission products have low specific power, and the other isotopes which must be produced by neutron irradiation of special target materials usually have high specific power. The heat producing properties become much more significant and impressive when the density of the compound form in which the isotope may be ultimately used and the isotopic purity which can be attained are taken into account. These striking differences are shown in the values for power density (watts per cubic centimeter) and the volume needed for a given heat output in Table I. In this table, the volume of the compound needed to provide two kilowatts of heat is shown. Two kilowatts were chosen because at a realizable conversion efficiency of 5%⁽¹⁰⁾ (thermal to electrical energy) 100 watts of electrical energy could be produced. One hundred watts is in the range needed for a practical communications satellite.⁽¹¹⁾

Fission Products

Fission products are of special interest because they exist in the wastes from nuclear reactor fuel processing and are thus available for recovery in substantial quantities. The particular fission products of interest, in addition to having acceptable half-lives, are also produced in relatively high yield in the fission process.

1. Strontium-90

Strontium-90 which has a half-life of 28 years exists in reactor fuel processing wastes along with other strontium isotopes, including strontium-86 and strontium-88 (which are stable) and strontium-89 (which has a half-life of 50 days and is an emitter of very hard beta energy). As recovered, the mixture of strontium isotopes should contain about 50% strontium-90. In addition to the energetic gamma activity from yttrium-90, the intense, high energy, beta activity of strontium-89 and also yttrium-90, results in high energy bremsstrahlung for which heavy shielding is required. Unless the strontium has aged sufficiently, the 50-day strontium-89 contributes a substantial fraction of heat from the strontium isotope mixture. Some degree of aging is thus advisable in order to provide a heat source with minor contribution from strontium-89; otherwise, the source will show a rapid decline in heat output characteristic of the short-lived strontium-89. The specific power of strontium-90 is 0.95 watts per gram. The power density of strontium titanate is about 1.05 watts per cubic centimeter.

Although all radioisotopes are hazardous and have very low maximum permissible concentrations (MPC), strontium-90 has a far larger MPC than any of the alpha emitters; however, among the fission products and cobalt-60 heat source candidates, its MPC is substantially smaller (more hazardous). In contrast with this latter feature, the form in which it is proposed to fix the strontium (strontium titanate) is perhaps the most ideal for any radioisotope. This compound is extremely stable chemically and is very resistant to solution in fresh and sea water.

A factor which has been of some concern, but about which there is little information, relates to the ultimate stability of a radioisotope compound in the course of its changing into different elemental forms (change in valence state) throughout radioactive decay. In other words, as strontium-90 decays through yttrium-90 to zirconium-90, there may be significant alterations in the titanate compound, which could result in intolerable

changes in volume, thermal conductivity, or chemical inertness of the encapsulated material. It is likely that such changes may be observed only after prolonged use or experience with the compound—at least only after an appreciable fraction of the half-life. At the present time, large quantities of strontium-90 in the form of the titanate have been in prototype use for less than 2 years.

2. Cesium-137

Cesium-137 comprises about one-third of the cesium isotopes in reactor fuel processing wastes. The other isotopes are stable cesium-133, 2.3 year half-life cesium-134, and slightly active, 2 million year half-life cesium-135. Thus, for practical purposes, cesium-135 can also be considered to be stable. The specific power for cesium-137 is 0.42 watts/gram. The power density of cesium "glass" is about 0.22 watts per cubic centimeter. Although cesium-137 is a beta emitter, its 2.6 minute daughter, barium-137, is the source of fairly energetic gamma activity. Cesium-137 requires slightly less shielding than strontium-90 because of the higher energy of some of the gamma bremsstrahlung from the strontium-90 decay chain. In the value for specific power (watts per gram of cesium-137, Table I) about one-third is from beta energy and two-thirds is from the gamma energy from barium-137 decay. It is concluded that the energy of the gamma activity is low enough (in contrast with cobalt-60) to assure that most of it will be absorbed and will produce heat in the mass of the compound and encapsulating material. Biologically, cesium-137 is far less hazardous than strontium-90. The fission yield is high but the isotopic purity, low density of the compound form, borosilicate glass,⁽¹²⁾ and principally, the low content of cesium-137 in this compound form result in a heat source of rather low power density—about one-fifth that of strontium titanate.

3. Promethium-147

Although promethium-147 has not received the same attention as strontium-90 and cesium-137, its properties justify more critical and favorable review. In the fission process, it is the only isotope of promethium realized in appreciable yield. Although its yield is only about half that of either strontium-90 or cesium-137, it must still be regarded as having a reasonably high yield and should, therefore, be regarded as a fairly available material. Its higher atomic weight reduces the apparent disadvantage of fission yield in comparison with strontium-90. Since it has only one step in its decay scheme to "stable" (10^{11} year) samarium-147, it may be regarded as a pure beta emitter. The energy of the beta emission is relatively low; therefore, the bremsstrahlung will have low energy which should be easily shielded with a minimum of mass. However, in the irradiation process, energetic, gamma emitting, 42-day promethium-148 is formed by neutron capture in promethium-147; this contaminating isotope though present in very small concentrations is sufficient to mask the pure beta activity advantage of promethium-147. When recovered from fuel of only moderate age (less than a year), promethium has enough gamma energy from promethium-148 such that shielding to achieve equivalent exposures is essentially the same as for strontium-90 and cesium-137—several inches of lead. On such a basis, promethium shows no significant advantage over these more prevalent isotopes. Recently it has been noted that some gamma radiation can also be expected from the trace amounts of promethium-146 which is also present. Promethium-146 has a half-life of about 1.9 year which approximates that of promethium-147. It has been concluded, however, that the amount of promethium-146 is not sufficient to add seriously to the shielding problem⁽¹³⁾ even with well aged promethium. For promethium-148 with its half-life of 42 days, aging for about one promethium-147 half-life is sufficient to reduce the total shielding requirements to about that which would be expected for shielding bremsstrahlung from this beta emitter—a fraction of an inch of lead. This is regarded as a minor shielding requirement and is expected to be met

by the mass of the usual encapsulating material. This aging step would, however, further reduce the apparent yield of this type of material. To achieve the highest power densities, the daughter products accumulated during this aging step would also have to be separated.

Promethium has a shorter half-life than nearly all of the other attractive heat source isotopes, but this 2.7 -year figure is considered long enough for a number of useful missions. Its specific power is 0.33 watts per gram; the power density of the oxide is expected to be about 1.8 watts per cubic centimeter.

Although its cost is expected to be higher than either strontium-90 or cesium-137, this should not be sufficient to impair consideration for use; particularly, if it is recognized to be the only competitor for the very expensive plutonium-238 and curium-244 with their minimum shielding requirements. Present costs are expected to be higher than strontium-90 and cesium-137 because of lower yield and somewhat increased processing complexity. However, chromatographic ion exchange technology already has been successfully demonstrated at Hanford for the recovery of several thousand curies of pure promethium. With the acknowledged high cost and limited availability of heat sources which require minor shielding, such as plutonium-238 and curium-244, aged promethium-147 justifies more objective consideration; especially, since in the form of well-aged processing wastes, large amounts of this desirable type of promethium-147 already are at hand. In the light of Hanford experience, the reported projected costs for promethium⁽⁶⁾ are not regarded as representative of what costs may be attained, particularly if such production is integrated with large scale recovery of other isotopes such as strontium-90, cesium-137, and cerium-144.⁽²⁷⁾

Biologically, promethium-147 is far less hazardous than any of the heat source isotopes which have been considered.

As a heat source, if power density is an important consideration, promethium-147 in the oxide form is a superior choice since it is about twice as good as strontium-90 in the titanate form, and nine times as good

as cesium-137 in the form of the borosilicate glass. In addition, it should be noted that when both are compared in the oxide form, promethium-147 still has about one-half the power density of plutonium-238. If its low biological hazard could be taken into account, such that a less chemically stable form like the metal could also be used, some advantages in thermal conductivity and heat source fabrication may also be realized.

Although recovery of promethium-147 from fuel processing wastes appears to be a practical route for which no alternate needs to be considered, it is of interest to note that promethium-147 could be produced by neutron irradiation of neodymium. Although neodymium is next to cerium as the most abundant of the so-called rare earths, the several neodymium isotopes complicate such an application. For reasonable neutron economy, neodymium isotopically enriched in neodymium-146 (17% of natural neodymium) would probably be necessary. There is, therefore, little basis for considering other than reactor fuel processing wastes as the source of promethium-147.

The advantageous properties of promethium are summarized as follows:

Although in comparison with other fission products, promethium is somewhat deficient in half-life and fission yield, it has some other very favorable characteristics. Although the fission yield appears as less than half that of strontium-90 and cesium-137, on a weight basis the promethium-147 yield is still over two-thirds of that of strontium-90. Also on a weight basis, the heat output (specific power) for promethium-147 is still about 80% of that for cesium-137. However, the total heat from available promethium-147 is only about one-quarter for that of strontium-90 in normally aged fuel; for fuel aged for about one promethium-147 half-life, the heat available from promethium-147 would be about one-eighth of that from strontium-90. These deficiencies are, however, fairly well compensated by the isotopic purity, essentially 100% promethium-147, and the high density expected for Pm_2O_3 such that its power density is essentially double that of $\text{Sr}^{90}\text{TiO}_3$. In addition, the biological hazard of promethium-147 is the lowest among heat source isotopes. For aged material.

promethium-147 is the only heat source candidate with which the shielding requirement is low and comparable with plutonium-238 and curium-244. The cost, although higher per watt than strontium-90, is expected to be far less than that of either plutonium-238 and curium-244. Furthermore, plutonium-238 in the oxide form has a power density which is only about twice that of Pm_2O_3 .

Isotopes Producing by Neutron Irradiation of Special Target Materials

Although it appears most convenient to recover desirable materials from wastes (strontium-90, cesium-137, and promethium-147) such recovery has problems of dilution, low isotopic purity, limited choice of properties, and costs which are expected to be quite high. This review, therefore, also shows in Table I, four attractive isotopes (cobalt-60, uranium-232, plutonium-238, and curium-244) which may be produced by neutron irradiation of special target materials, and a fifth (thorium-228) which could be separated as a decay product of one of these four (uranium-232). Of these, only one is in production as a heat source today (plutonium-238). The production of such materials is associated, of course, with a number of new and costly operations, such as the preparation of special target materials, target fabrication, irradiation, and chemical processing. However, in contrast with recovery of available isotopes from large volumes of wastes, these processes based on special irradiation may be involved with relatively small volumes in materials and in processes. Probably most significant, however, are the unique qualities of the isotopes which may only be obtained in this way.

1. Cobalt-60

Cobalt-60 is produced in substantial quantities today for use as a gamma source. In portable radiographic devices, it has largely replaced radium. Its half-life is fairly long, 5.3 years; it is of lower biological toxicity than most other candidate materials (strontium-90 and all the alpha emitters). Its production today is at rather low specific power; however, except for cost, there is no reason to expect that higher levels could not be obtained routinely. The fact that the inactive normal cobalt can be

encapsulated and then irradiated to the required activity without further processing is a distinct advantage specific to this isotope. Although a cost far below today's actual figure of several dollars per curie was used in Table I, the low figure of \$0.50 per curie does show the level at which it is competitive with most of the other candidates. The characteristics of its radiation are unfortunate for the present purposes because of the major component of hard gamma energy which must be absorbed to yield appreciable heat. This is unique to this isotope and requires a special design for the heat generator apart from also requiring heavy shielding. For those applications where weight is an important consideration, cobalt-60 is, therefore, at a disadvantage. Furthermore, its intense and energetic gamma activity inhibits its use as a typical or representative heat source for use in demonstration devices. Although today's prices for material of high specific activity put cobalt-60 in the class with the more costly radioisotopic heat sources, it is very simple to produce and is available to day without need for further investment in processing or encapsulation facilities. Like all isotopes which have a substantial portion of their heat in a gamma component or in hard bremsstrahlung, an appreciable part of this energy is not recoverable because the penetrating radiation cannot be completely absorbed and converted to heat only in that section of the device in contact with the thermoelectric elements. The specific power of cobalt-60 is high, 17.4 watts per gram, but the concentrations which can be practically attained would limit the heat output to about 10% of that figure. Even so, for metal, a power density of 15.5 watts per cubic centimeter appears achievable.

2. Plutonium-238

Plutonium-238 is produced by the irradiation of neptunium-237*. The latter isotope is recovered from irradiated uranium processing streams. Neptunium-237 is formed in very small quantities by two processes: in one, an $n, 2n$ reaction on uranium-238 produces uranium-237 which rapidly

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* It is interesting to recall that plutonium (plutonium-238) formed in this way was the route which lead to the discovery of this element in 1940 by Seaborg and co-workers.

decays to neptunium-237; in the other, neutron capture in uranium-235 produces uranium-236 (of long half-life and low cross section) which, in turn, captures a neutron to produce uranium-237 (6.7 day half-life) which decays to neptunium-237 (very long half-life). Neptunium-237 is offered from AEC stocks at \$500 per gram.⁽¹⁴⁾ On the assumption that this is a representative figure, the indicated projected cost of plutonium-238, \$1600 per thermal watt⁽⁶⁾ or \$880 per gram does not appear out of line. The total cycle for plutonium-238 production involves recovery and purification of neptunium-237, fabrication of neptunium-237 into target elements, irradiation of the target elements to convert some of the neptunium-237 to plutonium-238, and chemical processing for the recovery and purification of the plutonium-238 and unconverted neptunium-237.⁽¹⁵⁾

Plutonium-238 has the longest half-life (89.6 years) of any of the radioisotopes which have promise as heat sources. Its specific power is only moderate, 0.56 watts per gram, but its high density, particularly as the metal, puts it near the top of the attractive heat source isotopes on hand today. Its extremely weak gamma components allow its use without special shielding. Among those on hand today, it is the only radioisotope with which shielding is not a problem. However, its limited availability,⁽¹⁶⁾ extremely high biological hazard, and high cost per watt as listed in Table I, are factors unfavorable to plans for widespread use. Although the purity obtainable is quite high, it still can be expected to be contaminated with other plutonium isotopes, which would be regarded as diluents (unless it is produced by americium-241 irradiation and curium-242 decay, in which case, it should be of greater purity). In view of its chemical reactivity as a metal, the oxide form has been used as the basis for comparison in Table I. For plutonium-238, as with all alpha emitters, allowance must be made in the design of the capsule for the accumulation of gaseous helium. Helium is the end-product of alpha particles. Unless adequate space is provided, such accumulations will result in high pressures. A lesser problem also common among some of the high atomic weight alpha emitters is that of the neutron and resulting gamma activity derived from

spontaneous fission. Fortunately, the spontaneous fission half-lives are long and thus afford relatively minor fluxes which can be accommodated in the design of the device. The spontaneous fission half-life of plutonium-238 is 4×10^{10} years. ⁽¹⁷⁾

3. Uranium-232 (and Its Daughter Thorium-228)

The technology, process, and economic feasibility of the production of uranium-232 and its daughter thorium-228 have been covered in earlier documents. ^(7, 18) Like the successive irradiations of uranium-235, uranium-236, and neptunium-237 to produce plutonium-238, the process for uranium-232 involves irradiation of thorium-230, the rather long-lived isotope of thorium formed in uranium ores via the alpha decay of uranium-238. Sources of thorium sufficiently high in the thorium-230 isotope to assure economical uranium-232 manufacture without need for isotopic separation have been located. ⁽⁷⁾ Production of a gram of uranium-232 via the irradiation of protactinium-231 was accomplished last year at the Oak Ridge National Laboratory. ⁽¹⁹⁾ Uranium-232 is characterized by its high specific power (4.4 watts per gram) and very high power density (33 watts per cubic centimeter in the form of the dioxide). These high power values result from the unique decay of uranium-232 which, in contrast with other radioisotopes, consists of a long chain of energetic alpha emitters including a fairly high yield of its reasonably long-lived daughter, thorium-228, as shown in Figure 3. In this chain the thallium-208 is the source of intense and energetic gamma activity. This makes the shielding requirement per watt of thermal energy almost identical with that for cerium-144. ⁽¹⁸⁾ Another peculiarity of uranium-232 relates to the effect of its first decay product, its daughter thorium-228. This daughter is the longest-lived member in the decay chain. Thus, uranium-232 does not reach its maximum specific power until saturation with the growing in of the daughter takes place. For pure uranium-232, this is not reached fully until about 8 years after separation. If, however, a stock of uranium-232 is at hand from which thorium-228 can be "milked" and this thorium-228 then used to "activate" the uranium-232, near maximum heat output of uranium-232 can

be achieved at once and retained near maximum for over thirty years with very small amounts of thorium-228 being required (see Figure 4). This is indeed a unique characteristic and one which may be extremely useful in applications which require a very long period of nearly uniform heat evolution. This characteristic is specific to uranium-232 "activated" in this way and is probably not duplicated by any other isotope or combination. The spontaneous fission half-life for uranium-232 is long, 8×10^{13} years.

Since there are no efforts toward the recovery of the necessary raw material, thorium-230, from the uranium industry, uranium-232 can be regarded as only potentially available. Its biological hazard factor is somewhat more favorable than plutonium-238 but still appreciably more hazardous than most other candidates of Table I. Its cost will be high but still much less than plutonium-238 and possibly compensated for by its high specific power and power density, and also by the possibilities of the unique flattening of the power-life curve over nearly one-half of its very long half-life (Figure 4). Substantial lowering of cost may be possible by thorium-230-thorium-232 irradiation to produce special benefits in commercial power reactors as described in Reference (7).

With a production effort on uranium-232 and a stock of such material at hand, thorium-228 could also be routinely recovered. From heat output and half-life standpoints, thorium-228 has no equal (170 watts per gram, 1.9 year half-life). This is particularly impressive when the power density is noted, 1270 watts per cubic centimeter. Even at the high estimated cost per gram, the large thermal yield is sufficient to make this energy source competitive with the cheapest candidates as shown in Table I. No spontaneous fission half-life is shown for thorium-228.⁽¹⁷⁾ It is interesting to note the magnitude of this heat release by the following comparison: Ten grams of thorium-228 over one half-life will release heat equivalent to the burning of about two and a half tons of coal. Such burning would also require about 35 tons of air!

Figure 5 illustrates a means of producing uranium-232 and thorium-228.

4. Curium-244

Curium-244 has a very desirable half-life of 17.6 years. It is an alpha emitter with radiation characteristics very similar in composition and energy to those of plutonium-238. Shielding should therefore also be minor; however, the spontaneous fission half-life is much shorter than plutonium-238, 1.4×10^7 years. Its specific power is calculated to be 2.8 watts per gram. The power density for the oxide should then be about 27 watts per cubic centimeter. Like other alpha emitters, the biological hazard is severe. The material is only slightly less hazardous than plutonium-238. It is produced by successive neutron captures in plutonium and finally in americium-243. It is unique in that in this whole irradiation chain it has the smallest neutron capture cross section. Thus, when plutonium is exposed to prolonged irradiation, one of the products* reaching highest concentration in the residues is curium-244. In addition, this minimum cross section should assure material of good purity since the adjacent isotopes have very high cross sections. The current "Transuranium Program" is providing data on this buildup of curium-244.⁽²⁰⁾ In this program, several kilograms of plutonium are being irradiated to produce ultimately a few hundred milligrams of californium-252. In view of the conveniently low cross section of curium-244, it provides a sort of stopping place or plateau on the route to californium-252. At this point where a large fraction of the plutonium has disappeared, the residual plutonium is essentially pure plutonium-242 with relatively high concentrations of americium-243 and curium-244. These are to be separated and are then to be converted to the californium-252 via a few more years of irradiation. An estimate of the composition of a portion of the residues at the conclusion of the first prolonged irradiation of plutonium for the "Transuranium Program" has been reported to be as follows:⁽²¹⁾ total plutonium: about 5 grams, of which 95% is plutonium-242; americium-243: about 1 gram; and curium-244: about 3 grams. Originally, about 90 grams of plutonium were exposed to

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*Exclusive of fission products.

irradiation to produce these amounts of residues. Other additional fissionable material, of course, was required to "drive" the irradiation to this high burnup. It is concluded that on a watt of product (curium-244) basis today, this means is probably an economical method of producing curium-244 for use as a heat source in comparison with present or projected costs for plutonium-238. This is fairly certain to be the case, if a low value, such as \$8.00 per gram, is used for the cost of plutonium-239. However, when plutonium is used routinely in power reactors to provide a significant fraction of the fuel, substantial curium-244 production may be realized by relatively simple treatments in the course of the normal fuel recovery process. Curium-244 should then be much cheaper than projected plutonium-238 costs. This possibility, it should be emphasized, represents a situation that will exist only in the somewhat indefinite future. Curium-244 is, therefore, regarded as a heat source of limited availability for today's or near-future large scale use. The Transuranium Program has, however, produced a few hundred grams of curium-244⁽²⁰⁾ and this exists today as spent fuel elements which are to be processed in mid-1963. But the curium-244, recovered at that time, is scheduled for the californium-252 production effort and is thus probably unavailable for heat source uses.

Comments on Other Isotopes

Although the bases used in this study establish the rather limited choice of radioisotopic heat sources to the few shown in Table I, a number of others which are marginal from the standpoints of production feasibility, properties, and cost, justify some comments; some of these have also been listed in the other tables and are discussed below:

1. Tritium (H-3)

Tritium has a suitable half-life (12.3 years), a very weak beta activity and a specific power of about 0.5 watts per gram. It may also be

available in pure form. All these are fairly desirable properties. Although in its most stable forms it is liquid or gaseous, the solid compounds equivalent to normal hydrides may be sufficiently stable for heat source applications. Compared with other radioisotopes, its biological hazard is very small. Essentially, the only reason for not considering it is the estimated cost per watt. Its production process involves the use of not less than one neutron per atom of tritium. With a minimum cost of neutrons estimated at \$4000 per gram^(7, page 25) and with one gram of these neutrons represented in three grams of tritium which yield a total of about 1.4 watts of heat, the minimum cost of heat from this source would be not less than \$2650 per watt. This figure is thus felt to be noncompetitively high and well beyond the arbitrary limit set in this study (item 8, page 14). This cost, however, may not be too high for other than heat source uses which can take advantage of tritium's unique properties; phosphors, for example.

2. Krypton-85

Krypton-85 has a suitable half-life (10.4 years). Its specific power is about 0.7 watts per gram, mostly from beta but with some fairly energetic gamma derived from less than 1% of the beta decays. Its fission yield is only about 0.3%. It should be recoverable along with stable krypton isotopes such that without isotopic enrichment, it would comprise only about 7.5% of the krypton mixture. Unless stable compounds such as have recently been produced with xenon⁽²²⁾ can be made, the power density (watts per cubic centimeter) would be extremely low in comparison with other radioisotopes commonly available as dense solids. It is concluded that its existence as an inert gas is sufficient reason to omit it from among the heat source candidates. However, its application for other uses, special phosphors, is already underway.⁽²³⁾

3. Ruthenium-106

Next to xenon, ruthenium is the fission product produced in highest yield. It comprises a mixture of at least seven isotopes of which ruthenium-106 has a half-life of 1 year. Three of the other isotopes are stable. The specific power from ruthenium-106 is fairly high, 31 watts per gram (Table II).

However, the fission yield of ruthenium-106 (from uranium-235) is the smallest of the ruthenium isotopes (0.38%), such that the isotopic purity of ruthenium-106 in the mixture with its stable relatives is only about 3.4%. The yield of ruthenium-106 in plutonium fission is, however, substantially greater (about 4.5%). Thus, the purity would also appear to be much greater under conditions of plutonium fission: possibly as high as 20% (instead of 3.4% from uranium-235 fission).⁽²⁴⁾ In power reactors operating on low enrichment uranium, ruthenium-106 would result from both plutonium and uranium-235 fission; the isotopic purity of the ruthenium-106 would then lie between 3.4% and 20%, possibly near 12%. The specific power from ruthenium containing such concentrations of the 106 isotope would still be appreciable, possibly 3.7 watts per gram. The power density for ruthenium metal would then be nearly 47 watts per cubic centimeter.

The biological hazard for ruthenium-106 is also relatively low, about the same as for cobalt-60. Although ruthenium-106 is a beta emitter, its daughter, rhodium-106 emits a number of high energy gammas. Shielding would therefore have to be heavy. The chemistry of ruthenium is complex because of the various valence states. Since it is a noble metal, once obtained, it should be readily maintained in a stable form as the metal. However, because of its isotopic dilution, marginal half-life of barely 1 year, probable processing complexity, low fission yield from uranium-235, and lack of distinctive advantageous characteristics, it is not included in the list of most attractive candidates. However, under today's conditions of availability, it perhaps should be receiving as much attention as cerium-144.

4. Cerium-144

Because its half-life is less than 1 year (285 days), cerium-144 has not been included as one of the attractive candidates. However, its high fission yield (6.0% from uranium-235) and high specific power (21.5 watts per gram) may appear to make it outstanding. The extremely energetic gamma activity of its daughter praseodymium-144 and its dilution

with stable cerium isotopes are distinct disadvantages. On the basis of the ratio of gamma energy per watt of total energy, cerium-144 and uranium-232(thorium-228) are almost identical. Because of the fairly short half-life of cerium-144, its concentration with relation to the stable cerium-140 and 142 will vary significantly depending on the age of the material since formation in the fission process. However, there does not appear to be the aging problem for 33-day cerium-141 in cerium-144 as there is for strontium-89 in strontium-90.

Initially, the concentration of cerium-144 (exclusive of cerium-141) obtainable from uranium-235 fission would be about 32.5%; however, with the prolonged exposure of fuel and subsequent aging before processing, lower concentration must be assumed. Furthermore, the yield from plutonium fission is somewhat less (27%). For the realistic situation then, it is concluded that it is unlikely that the isotopic purity of cerium-144 will exceed about 18%. Even at such dilutions, the power density of the oxide at 90% of theoretical density is about 21 watts per cubic centimeter. The biological hazard of cerium-144 is relatively low being about the same as for cobalt-60 and cesium-137. Because of both its very high specific power and high fission yield, cerium-144 is potentially the cheapest heat source (on a watt basis). However, the short half-life and energetic gamma activity detract very severely from these apparent advantages.

5. Thallium-204

Thallium-204 has very desirable properties as a radioisotopic heat source. The specific power is about 1.2 watts per gram, essentially all from beta decay. Shielding for bremsstrahlung should be only moderate. The power density for thallium monoxide (at 10 grams per cubic centimeter) would be about 10 watts per cubic centimeter. The biological hazard is slightly less than for cesium-137, cobalt-60, and cerium-144. The cross section and availability of the element favor the formation of thallium-204. However, to achieve the indicated power density, isotopic separation of thallium-204 from the thallium-203 target material would be required.

Such processing for efficient recovery of kilogram quantities of active thallium-204 is not expected for the near future. For this reason, thallium-204 is not considered as a likely heat source.

6. Polonium-210

Polonium-210, a very rare element occurring in the decay chain of uranium-238, and also producible by the irradiation of bismuth was the first radioisotope used to demonstrate the "SNAP III", a prototype power device, early in 1959. Its specific power is a very high 140 watts per gram. However, its half-life is only 138 days. It is an alpha emitter with negligible gamma activity such that essentially no shielding is needed. Compared with other alpha emitters its biological hazard is low. It can be prepared with high purity. A few years ago when liquid metal fueled power reactors using bismuth as the heat transfer medium were being considered, there were expectations that substantial quantities of polonium would be available as an economical byproduct. These reactor plans were abandoned. Practical production of polonium thus can only proceed via the costly irradiation and processing of enormous quantities of bismuth (see comment, page 16 of this report) which would make polonium an uncompetitive heat source. Calculations from the indicated projected costs per curie⁽²⁵⁾ for polonium-210 result in a figure of \$90,000 per gram (\$640 per watt) for this isotope. The very short half-life and this unfavorable economic situation place this isotope outside of the attractive ones covered here. (See alternate cost figures shown in Table VI.)

7. Curium-242

For some of the investigations on the moon, curium-242 has been proposed as the radioisotopic power source for the necessary, remote, unmanned monitoring and instrumentation.⁽²⁶⁾ A reason given for the use of this material is that since curium-242 and its daughter, plutonium-238 are man-made elements, their existence as contaminants in the lunar geography would not interfere with precise analytical efforts to determine lunar compositions. Curium-242 has a half-life of 163 days. Its specific

power is about 120 watts per gram and the power density for Cm_2O_3 should be about 1170 watts per cubic centimeter. It is essentially a pure alpha emitter and thus requires minimum shielding. Its spontaneous fission half-life is 7.2×10^6 years, about half that of curium-244. As with other alpha emitters, its biological hazard is much higher than fission products or cobalt-60. It is made by neutron irradiation of americium-241, which is only available as a decay product of rare plutonium-241. Fifteen hundred dollars per gram is the price today for americium-241. In spite of the high cost of the raw material and other costs of irradiation and chemical processing, the high specific power may lead to fairly reasonable costs, of about \$170 per initial watt. Calculation from data in Reference (25) indicate a cost of \$20,000 per gram (\$6 per curie). The short half-life limits its utility and is the reason for not including it among the most promising isotopes in this study. (Note alternate costs in Table VI.)

CONCLUSIONS

Of the large number of radioisotopes possibly suitable as heat sources, only a few appear to be practically and economically available. For those with half-lives comfortably over a year, only eight appear to be obtainable in the foreseeable future. All must be regarded as very hazardous materials which require special and costly means for preparation and handling.

The fission products, strontium-90, cesium-137, and promethium-147, have special appeal because they exist in fairly large quantities in wastes from reactor fuel processing. Dilution with relatively enormous volumes of other elements and salts in these wastes makes for costly isolation and purification of these materials.

Among those isotopes producible by irradiation of special target materials (cobalt-60, uranium-232, plutonium-238, and curium-244) cobalt-60, though easy to produce, requires a special design for the heat source generator because much of its emitted energy is penetrating gamma radiation. This is not the case to the same degree with any other of the favored isotopes. Cobalt-60 appears, therefore, to be rather limited in its prospects for use.

Plutonium-238 is today perhaps most generally favored as a heat source because of its long half-life and the fact that it can be used with essentially no special shielding. However, its projected high cost, scarcity, and unfavorable biological hazard encourages the search for a competitive material. It is probable that for many uses the very long half-life of plutonium-238 cannot be justified as a strong point in its favor.

It is expected that whenever plutonium assumes a significant place as a recycled fuel in thermal reactors for power production, curium-244 can then become available at costs substantially below that for plutonium-238. Curium-244 has five times the specific power of plutonium-238 and appears to be just as easy to handle with regard to encapsulation and shielding. Its half-life, although shorter than plutonium-238, is sufficiently long to assure its efficient use in consideration of the probable life of other vital components in the power generator.

Promethium-147, although probably on the "short end" of the half-life scale, can be considered realistically for some uses as a substitute for plutonium-238, particularly if aged promethium-147 can be produced. Energy, cost, low shielding requirements, and minimum biological hazard are all factors which are favorable to promethium-147.

Although the factors of availability, gamma activity, and biological characteristics are unfavorable, the strong points for uranium-232 (and thorium-228) are extremely high power densities, relatively low expected costs, and unusually long-life at nearly constant heat output. The relatively short-life of thorium-228 (1.9 years) is a disadvantage in comparison with the other isotopes of Table I, except for promethium-147.

This study strongly indicates that promethium-147 should be receiving more serious attention as a heat source, particularly, if utility of plutonium-238 may be impaired by availability, biological hazard, and cost considerations.

On a cost per watt basis, strontium-90, cesium-137, and thorium-228 appear to be competitive. Cobalt-60 is competitive only if a cost far below today's prices is assumed. The extremely high cost of plutonium-238 emphasizes consideration of aged promethium-147 as a competitive material where extremely long half-life is not essential. Curium-244 appears to have very good possibilities on a cost per watt basis especially under future situations when plutonium is being recycled as a fuel in power reactors.

TABLE II

LISTING OF ISOTOPES WITH HALF-LIVES OF 1 TO 100 YEARS

Isotope	Half-Life Years	Watts per Gram	Isotope Separation Required		Fission Yield (if FP)%	Production Feasibility			Comments
			for Target	for Product		High	Mod	Low	
Tritium (Hydrogen-3)	12.3	0.47	Yes	No	---	X			Already produced on a large scale. V*
Sodium-22	2.6	25.4	No	No	---			X	**No known practical production process. IV
Argon-42	3.5	---	No	Yes	---			X	A noble gas, requires two neutron captures on argon-40; argon-41 has short half-life and very low cross section. V
Iron-55	2.7	---	Yes	Yes	---			X	Iron-54 has low cross section. III
Cobalt-60	5.3	17.4	No	No	---	X			Well known production technology; but without isotope separation would obtain much lower heat output. I
Krypton-85 ^f	10.4	0.71	---	Yes	0.3	X			Well known technology but is a noble gas. V
Strontium-90 ^f	28	0.95	---	No	5.9	X			Well known technology excellent availability. I
Niobium-93	12	---			---			X	** IV
Rhodium-101	5	---			---			X	** IV

* Indicates other tables in which this isotope is included.

** Detected in accelerator experiments. No known process by which multigram production could be achieved economically.

f = fission product

TABLE II (contd)

Isotope	Half-Life Years	Watts per Gram	Isotope Separation Required		Fission Yield (if FP)%	Production Feasibility			Comments
			for Target	for Product		High	Mod	Low	
Ruthenium-106 ^f	1	31	---	Yes	0.38	X			Difficult technology; marginal half-life, highly diluted by stable isotopes. V*
Silver-108	5	---	Yes	Yes	---			X	III
Cadmium-109	1.3	---	Yes	Yes	---			X	Cadmium-108 isotope concentration very low in natural cadmium (0.88%). V
Cadmium-113 ^m ^f	14	0.35	---	Yes	0.012			X	Very low fission yield. III, V
Tin-121	5	---	Yes	Yes	---			X	Very low cross section for tin-120. V
Antimony-125 ^f	2.7	2.9	Yes	No	0.036			X	Very low fission yield. Isotope separation required if tin-124 used as target. Tin- 124 has very low cross section. III
Cesium-134 ^f	2.1	6.8	No	Yes				X	Cross section higher than that of target. Isotopic separation of product required. III
Cesium-137 ^f	30	0.46	---	No	6.0	X			Well known and simple technology. I

* Indicates other tables in which this isotope is included.

** Detected in accelerator experiments. No known process by which multigram production could be achieved economically.

f = fission product

TABLE II (contd)

Isotope	Half-Life Years	Watts per Gram	Isotope Separation Required		Fission Yield (if FP)%	Production Feasibility			Comments
			for Target	for Product		High	Mod	Low	
Barium-133	7.5	---	Yes	Yes	---			X	Low cross section and very low concentration for barium-132. V*
Promethium-144	1.1	---	---	---	---			X	** IV
Promethium-145	18	---	---	---	---			X	** IV
Promethium-146	2	4.6	---	---	---			X	** IV
Promethium-147 ^f	2.7	0.33	---	No	2.6	X			Fairly well known technology, good availability. I
Samarium-151 ^f	90	---	---	Yes	0.45			X	Low heat potential, low energy beta, and gamma. V
Europium-152	13	0.79	Yes	Yes	---			X	Very high cross section for europium-152. V
Europium-154	16	0.76	Yes	Yes	---			X	Very high cross section for europium-154. V
Europium-155 ^f	1.7	0.91	Yes	Yes	0.03			X	Very low fission yield. Also very high cross section. V
Terbium-157	30	---	---	---	---			X	** IV
Gadolinium-162	1	---	---	---	---			X	V
Holmium-166	30	---	No	Yes	---		X		III
Thulium-171	1.9	0.27	Yes	No	---		X		Low energy. Target erbium-170 is a rare element. V

* Indicates other tables in which this isotope is included.

** Detected in accelerator experiments. No known process by which multigram production could be achieved economically.

f = fission product

TABLE II (contd)

Isotope	Half-Life Years	Watts per Gram	Isotope Separation Required		Fission Yield (if FP)%	Production Feasibility			Comments
			for Target	for Product		High	Mod	Low	
Lutetium-173	1.4	---	---	---	---			X	** IV*
Hafnium-172	5	---	---	---	---			X	** IV
Tantalum-179	1.6	---	---	---	---			X	** IV
Osmium-194	2	---	Yes	Yes	---			X	Very rare target isotope of low cross section. V
Thallium-204	3.9	1.2	No	Yes	---			X	III
Lead-210	21	0.29	---	---	---			X	Very rare natural isotope. V
Bismuth-207	30	---	---	---	---			X	** IV
Polonium-208	2.9	17.8	---	---	---			X	** IV
Radium-228	6.7	---	---	---	---			X	Very rare natural isotope. V
Actinium-227	21		No	No	---			X	Very rare natural isotope. V
Thorium-228	1.9	170	No	No	---	X			From uranium-232. I
Uranium-232	74	4.4	No	No	---	X			Good possibilities via irradi- ation of thorium-230. I
Neptunium-235	1.1	---	---	---	---			X	** IV
Plutonium-236	2.9	19.2	---	Yes	---			X	V
Plutonium-238	89	0.56	No	No	---	X			Already produced on substantial scale. I

* Indicates other tables in which this isotope is included

** Detected in accelerator experiments. No known process by which multigram production could be achieved economically.

TABLE II (contd)

<u>Isotope</u>	<u>Half- Life Years</u>	<u>Watts per Gram</u>	<u>Isotope Separation Required</u>		<u>Fission Yield (if FP)%</u>	<u>Production Feasibility</u>			<u>Comments</u>
			<u>for Target</u>	<u>for Product</u>		<u>High</u>	<u>Mod</u>	<u>Low</u>	
Plutonium-241	13	---	No	Yes	---			X	V*
Curium-243	32	1.4	No	Yes	---			X	V
Curium-244	18	2.8	No	No	---	X			From thermal reactors which burn plutonium. I
Californium-250	10	5.1	No	No	---			X	Multistep irradiation. V
Californium-252	2.6	4.6	No	No	---			X	Multistep irradiation. V
Einsteinium-254	1.3	---	No	No	---			X	Multistep irradiation. V

-----
 * Indicates other tables in which this isotope is included.

TABLE III

ATTRACTIVE ISOTOPES REQUIRING
ISOTOPE SEPARATION PROCESSES

<u>Isotope</u>	<u>Half-Life</u> <u>Years</u>	<u>Cross Section</u>		<u>Watts/</u> <u>Gram</u>
		<u>Target</u>	<u>Product</u>	
Iron-55	2.7	2.5	---	---
Silver-108	5	40	---	---
Cadmium-113 ^m	14	---	---	0.35
Antimony-125*	2.7	0.2	---	2.9
Cesium-134	2.1	31	134	6.8
Holmium-166	30	64	---	---
Thallium-204	3.9	11	---	1.2

-----
 *Also a fission product (but mixed with stable isotopes).

TABLE IV

ISOTOPES FOR WHICH NO PRACTICAL PRODUCTION
PROCESS IS APPARENT

<u>Isotope</u>	<u>Half-Life Years</u>	<u>Type of Radiation</u>
Sodium-22	2.6	Beta / Gamma
Niobium-93	12	Weak Gamma, internal trans.
Rhodium-101	5	Weak Gamma, internal trans.
Promethium-144	1.1	Gamma
Promethium-145	18	Beta
Promethium-146	2	Beta, Gamma
Terbium-157	30	---
Lutetium-173	1.4	Beta, Gamma
Hafnium-172	5	Beta, Gamma
Tantalum-179	1.6	Beta, Gamma
Bismuth-207	30	Beta, Gamma
Polonium-208	2.9	Alpha, Gamma
Neptunium-235	1.1	Alpha

TABLE V
OTHER POTENTIAL HEAT-SOURCE ISOTOPES WITH UNFAVORABLE
PROPERTIES AND ECONOMICS
OR UNFEASIBLE PRODUCTION CAPABILITY

<u>Isotope</u>	<u>Half-Life Years</u>	<u>Reason for not Considering</u>
Tritium (Hydrogen-3)	12.3	Too costly per watt (minimum of \$2650 for neutrons alone).
Argon-42	3.5	Argon-41 (from argon-40) has a half-life so short (1.8 hours) that retention for sufficient time to assure a high yield of argon-42 is unlikely. Argon is an inert gas.
Krypton-85 ^f	10.4	Krypton is an inert gas.
Ruthenium-106 ^f	1	The chemistry of this rare metal is known to be extremely complex. Half-life is of borderline utility. It is diluted to major extent by inactive isotopes from either uranium-235 or plutonium-239 fission.
Cadmium-109	1.3	Requires isotope separation for both target and product. The cadmium-108 concentration in natural cadmium is very low (0.88%).
Cadmium-113 ^m ^f	14	Fission product of very low fission yield (0.012%) but fast fission of uranium-235 would increase yield by a factor of about 100. Uranium-235 is not the best fuel in fast reactors.
Tin-121	5	Requires isotopic separation for both product and target. In addition, tin-120 (target) has a very low cross section (0.001 / 0.1 barn).
Barium-133	7.5	Requires isotopic separation. In addition, concentration of barium-132 in natural barium is very low (0.097%); the cross section of this target is low (3.0 barns).
Samarium-151 ^f	80	Requires isotopic separation. In addition, the energy of both beta and gamma emission is extremely low. Specific power would therefore also be very low. Furthermore, the cross section of samarium-151 is extremely high (12,000 barns).
Europium-152	13	Requires isotopic separation. Europium-152 has a very high cross section (5,000 barns).

-----
f = fission product

TABLE V (contd)

<u>Isotope</u>	<u>Half-Life Years</u>	<u>Reason for not Considering</u>
Europium-154	16	Requires isotopic separation. Europium-154 has high cross section (1400 barns).
Europium-155 ^f	1.7	Isotope separation would be required. As a fission product, the yield is extremely low (0.03%). In addition, the cross section is extremely high (13,000 barns).
Gadolinium-162	1	Isotope separation would be required for target which also has extremely low cross section.
Thulium-171	1.9	Isotope separation required for rare target erbium-170; same for thulium-171 via thulium-169 route.
Osmium-194	2	Isotope separation would be required. Target element, osmium-192, is extremely rare; it has a low cross section (1.5 barns). In addition, the intermediate target, osmium-193 has a short life (31 hours).
Lead-210	21	Very rare natural isotope (from uranium decay-0.005 gram per ton).
Radium-228	6.7	Very rare natural isotope (from thorium-232 decay-0.00043 grams radium-228 per ton thorium-232).
Actinium-227	21	Very rare and costly target isotope, radium-226.
Plutonium-236	2.9	Isotopic separation required on product.
Plutonium-241	13	Isotopic separation required.
Curium-243	32	Isotopic separation required on product.
Californium-250	10	All require multistep irradiation and processing.
Californium-252	2.6	
Einsteinium-254	1.3	

FIGURE 1

Thermal Watts Output per Initial Gram Versus Time
Short-Lived Radioisotopic Heat Sources

FIGURE 2

Thermal Watts Output per Initial Gram Versus Time
Long-Lived Radioisotopic Heat Sources

* 7.7 GRAMS Th-228 PER YEAR FROM STORAGE
OF ONE Kg U-232

FIGURE 3
Radioactive Decay of Uranium-232

FIGURE 4
Heat Output from Uranium-232

FIGURE 5
Uranium-232 and Thorium-228 Production

TABLE VI

CHARACTERISTICS OF RADIOISOTOPIC HEAT SOURCES

Isotope	Co-60	Sr-90	Cs-137	Ce-144	Pm-147	Po-210	Th-228	U-232	Pu-238	Am-241	Cm-242	Cm-244
Watts/Gm (Pure)	17.4	0.95	0.42	25.6	0.33	141	170	4.4	0.56	0.11	120	2.8
Half-Life, Years	5.3	28	30	0.78	2.7	0.38	1.9	74	89	438	0.43	18
Estimated Isotopic Purity, %	10	50	35	18	95	95	95	85	80	90	90	90
Compound Form	Metal	SrTiO ₃	Glass	CeO ₂	Pm ₂ O ₃	Metal	ThO ₂	UO ₂	PuO ₂	Metal	Cm ₂ O ₃	Cm ₂ O ₃
Active Isotope in Comp'd, %	10	24	16	15	82	95	83	75	70	30	82	82
Watts/Gm Comp'd	1.7	0.23	0.067	3.8	0.27	134	141	3.3	0.39	0.1	98	2.3
Density of Comp'd, Gm/Cm ³	8.9	4.6	3.2	6.4	6.6	9.3	9	10	10	11.7	11.75	11.75
Power Density, Watts/Cm ³ Comp'd	15.5	1.05	0.215	24.5	1.8	1210	1270	33	3.9	1.17	1150	27
Volume for 2 KW of Heat, Cm ³	129	1840	9300	80	1120	1.65	1.58	61	513	1710	1.74	74
Availability Annual KW _t , 1967-*	Prod Today	F.P. F.Y. 5.8% 67 KW	F.P. F.Y. 6.0% 48 KW	F.P. F.Y. 5.6% 800 KW	F.P. F.Y. 2.6% 11 KW	Prod Today	Poten. Avail.	Poten. Avail.	Limited Prod	Limited Prod	Poten. Avail	Poten. Avail
Shielding Required	Heavy	Heavy	Heavy	Heavy	Minor	Minor	Heavy	Heavy	Minor	Minor	Minor	Minor
Biological Hazard, MPC, cc/Cm ³	3x10 ⁻⁹	3x10 ⁻¹⁰	5x10 ⁻⁹	2x10 ⁻⁹	2x10 ⁻⁸	2x10 ⁻⁹	2x10 ⁻¹²	9x10 ⁻¹²	7x10 ⁻¹³	2x10 ⁻¹²	4x10 ⁻¹¹	3x10 ⁻¹²
Est. Cost, \$/Gm (Pure)	570	18*	9*	23*	30*	26,500**	6600	1540	500**	200	2000	1000**
Est. Cost, \$/Watt	33	19*	21*	1.00*	91*	188	40	350	894	1820	17	357
Curies/Gm (Pure)	1130	142	87	3180	914	4500	4100	114	17	3.25	3310	84
Curies/Watt	65	150	207	124	2770	32	24	26	30	30	28	30
Min Cost, \$/KWH _e *** (for 1-year mission)	36(3)	5.60(10)	5.8(10)	5.60(1)	143(3)	2300(0.42)	89(2)	95(10)	228(10)	415(10)	180(0.42)	124(10)
Spont Fission Half-life, Years	-	-	-	-	-	-	-	8x10 ¹³	4.9x10 ¹⁰	1.4x10 ¹³	7.2x10 ⁶	1.4x10 ⁷

* From proposed Hanford Isotope Plant

** 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.

REFERENCES

1. Chart of the Nuclides, Knolls Atomic Power Laboratory, operated by the General Electric Co. under direction of Naval Reactors, U.S. Atomic Energy Commission Sixth Edition Revised to December 1961, and Chart of the Nuclides, Second Edition, prepared at the Institute of Radiochemistry, Nuclear Research Centre Karlsruhe, published by Gersbach & Sohn Verlag, Munchen 34, Barer Strasse 32, literature revised to July 1961.
2. "AEC Isotope Unit Sponsoring Major Development Effort in Power Supplies; Lamont to Use Cesium-137 Device", Nucleonics, Vol. 19, No. 9: 26. September, 1961.
3. "Radioisotopes at Work: Inside the Arctic Circle", Nucleonics, Vol. 19, No. 8: 25. August, 1961.
4. "Space Nucleonics", Nucleonics, Vol. 19, No. 8: 32. August, 1961.
5. "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure", U. S. Department of Commerce, National Bureau of Standards Handbook 69, Superintendent of Documents, Washington, D. C. June 5, 1959.
6. Harvey, D. G. and J. G. Morse, "Radionuclide Power for Space Missions", Nucleonics, Vol. 19: 70. (Table I) April, 1961.
7. Rohrmann, C. A. Special Radioisotopes for Power: Availability and Applications for Thorium-230 (Ionium) from Uranium Ore Mills, HW-71319 REV, Table I, page 13. October 16, 1961.
8. Nucleonics Week, Vol. 3, No. 14. April 5, 1962.
9. "Handbook of Nuclear Technology", reprinted by Nucleonics: 236-243. Fission-Product Yields from U, Th, and Pu, by Seymour Katcoff, McGraw-Hill, New York, N. Y. 1960.
10. Crompton, Charles, E. "Isotopic Heat and Power", 1962 Nuclear Congress Preprint, Paper #84, page 2, published by Engineers Joint Council, N. Y.
11. "Symposium on Nuclear Power for Communications Satellites", Atomic Industrial Forum, Inc., N. Y. Summary of Discussions, Washington, D. C., September 14, 1961. Page 5, Item b.
12. Royal Research Corporation, Cs-137 Fueled Generator, RRC-Cs-0100, page 65.
13. Private Communication from H. H. Van Tuyl, Senior Scientist, Hanford Laboratories.
14. Atomic Industry Reporter, March 7, 1962, page 8:74.
15. The Forum Memo to Members, November 1962, page 14.
16. Nucleonics Week, Vol. 3, No. 10, March 8, 1962, page 1, third paragraph.

17. Sullivan, W. H. "Trilinear Chart of Nuclides", USAEC, January, 1957.
18. Rohrmann, C. A. Ionium-Uranium-232, and Thorium-228 Properties, Applications and Availability, HW-66600, Chart II. August 1, 1960.
19. Oak Ridge National Laboratory, Status and Progress Report, page 26, ORNL-3351. August, 1962.
20. Burch, W. D., et al. "Production of the Transuranium Elements", Transactions of the American Nuclear Society, Vol. 5, No. 1:14-15. June, 1962.
21. Bradley, J. G. to R. L. Moore. "Recovery of Am-243", Private Communication. Hanford Laboratories, February 9, 1962.
22. Chernick, C. L., et al. "Fluorine Compounds of Xenon and Radon", Science, Vol. 138:136-138. October 12, 1962.
23. Nucleonics Week, Vol. 3, No. 32:4. August 9, 1962.
24. Katcoff, S. "Fission-Product Yields from Neutron-Induced Fission", Nucleonics, Vol. 18, No. 11: 201-208. November, 1960.
25. "Present and Potential Annual Availability of Isotopic Power Fuel", Division of Isotopic Development USAEC, Table IV. April, 1962.
26. Nucleonics Week, Vol. 2:4. February 16, 1961.
27. Rohrmann, C. A., et al. "The Hanford Isotopes Production Plant Engineering Study," HW-77770. July 1963.

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