IV. ISOTOPES AND ISOTOPE THERMOELECTRIC GENERATORS

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INTRODUCTION

Isotope power systems are particularly attractive for missions in which relative freedom from environment, long life, and compactness are desirable. The properties of isotopes of interest to space, thermoelectric conversion, thermoelectric generators, and two NASA missions which illustrate this attractiveness are discussed briefly herein.

Isotope heat sources produce heat by stopping the alpha, beta, or gamma particles emitted by suitable radioactive nuclides. This heat can be used with many of the various power conversion cycles, which are discussed in detail in papers V, VIII, and IX. Because of availability, cost, and safety problems, isotope power will generally be limited to applications of a few kilowatts or less. Some of these problems are discussed in more detail in this paper.

ISOTOPIC POWER

Advantages and Disadvantages

Some of the principal advantages and disadvantages of isotopic power are as follows:

Advantages	Disadvantages
Can be used in any environment	Safety requirements
No power storage requirement	Availability
Flexible in operation	Possible costs
Long operational use	Unfamiliarity to users
Compact	Possible interference with experiments
Heat available to maintain equipment thermal balance	
Highly reliable	

Isotopes need no power storage system, and excess heat is available, if needed, to maintain equipment thermal balance and for thermal life support systems. However, isotopes can pose

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severe spacecraft integration problems because of the heat and radiation produced. Because of the potential usefulness of isotopes, NASA is considering an increasing variety of advanced missions, both manned and unmanned, since it is convinced that these problems will be solved. Such missions, in which isotopes are expected to play an important role in providing needed power, are Voyager, Manned Orbital Research Laboratories, Jupiter Flyby, and others. The AEC, which has the primary responsibility for providing the isotopes and developing the isotope sources, is conducting a vigorous program to increase availability, reduce costs, and provide needed information regarding fuel forms and heat sources.

Isotopic Power for Space Use

The beta-emitting isotopes, which have been considered for space use, are listed in table IV-1(a). They are cobalt 60 (Co^{60}), strontium 90 (Sr^{90}), promethium 147 (Pm^{147}), and thulium 170 (Tm^{170}). Beta emitters are usually easier to obtain than alpha emitters and hence could be more plentiful and less expensive. However, most of them have high shielding penalties that complicate spacecraft handling and safety problems. All of them have high bare-dose rates, as shown in table IV-1(a), and shielding is required. Promethium 147 is the best beta emitter with respect to shielding, and its 2.7-year half-life is attractive for many missions. Although unavailable at present for space power use, Pm^{147} will become available after 1970 from the Isochem purification plant being constructed at Hanford, Washington. Its capacity will be about 10 thermal kilowatts of aged Pm^{147} per year. The low shielded dose rate from Pm^{147} depends on the impurity content of Pm^{146} and Pm^{148}, as shown in figure IV-1. After about 700 days, the dominant radiation from Pm^{147} comes from the Pm^{146} impurity content. If Pm^{147} is appreciably contaminated with these active impurities, the dose rate will be higher than the bare and shielded levels of 100 roentgens per hour and 1 milliroentgen per hour, respectively, and in that case more shielding may be required.

The advantage of the alpha emitters over the beta emitters is that they generally require less shielding and can be more easily handled. The alpha emitters of principal interest are given in table IV-1(b). These include the short-half-life polonium 210 (Po^{210}) and curium 242 (Cm^{242}) and the longer half-life curium 244 (Cm^{244}) and plutonium 238 (Pu^{238}). Of all the isotopes, Pu^{238} is accompanied by the least external radiation, thus simplifying its handling and integration problems. Its half-life of 86 years makes Pu^{238} suitable for long-lived missions, and it can be stockpiled for later use with little loss from decay. It is, therefore, the isotope of choice for many missions, and all space flights with isotope generators to date have used Pu^{238}. All these isotopes have fuel forms that have high melting points, which make them suitable for consideration for higher temperature and more efficient conversion systems like thermionic or Brayton conversion cycles.

While shielding of isotope generators may be a disadvantage, most spacecraft will face radiation from other causes in space, and in many cases shielding will be required. The radiation levels that can be expected from the Van Allen belts, solar flare protons, and galactic cosmic rays are given in table IV-2. Radiation levels of thousands of rads per hour from primary electrons in the Van Allen belts can be virtually eliminated by a shield equivalent to 10 grams per

square centimeter. However, an appreciable fraction of the bremsstrahlung radiation remains. Other radiations except the high-energy galactic cosmic rays can be considerably reduced by shielding. Thus, some shielding will probably be aboard many spacecraft, and the most efficient design should take advantage of this to reduce any special isotope generator shield requirements, especially for manned missions.

ISOTOPIC-POWER GENERATORS

A considerable number of isotopic-power generators ranging from a few milliwatts to about 60 watts have been built. All of them have been built by the AEC. Table IV-3 gives the space units and, for completeness, the terrestrial units that have been built or are under development to date. The AEC has assigned odd numbers to its isotope Systems for Nuclear Auxiliary Power (SNAP) and even numbers to its reactor systems, such as SNAP-8 and SNAP-10A. Five generators of the SNAP-3 and 9 types have been launched into space. One of them, a SNAP-3 unit launched in June 1961, is still operating on isotope thermoelectric power, sending back telemetry signals through the isotope-powered circuit. This is the longest lived satellite operating in orbit since Vanguard I ceased. All these units were fueled with Pu^{238} and all of them used lead telluride thermoelectric conversion modules.

These early model generators experienced some power degradation in space because of various problems, such as leakage and increased contact resistance at the hot junction. Current designs incorporate many technical improvements, such as reduction in number of seals, improved thermoelectric materials, and better thermal and mechanical designs, which are expected to reduce degradation to within about 5 percent of initial power.

SNAP-19 and SNAP-27 are being developed for NASA missions. SNAP-19 will be flown on Nimbus B in late 1967, and SNAP-27 will be launched on the first Apollo mission before 1970.

One generator, SNAP-13, is a thermionic demonstration device. It was fueled with Cm^{242} at the Oak Ridge National Laboratory and operated for about 43 hours when a leak developed in the converter, and the test was terminated. Technology efforts are underway both at AEC and NASA to improve performance and life of isotope thermionic generators. One of the principal problems is the development of a suitable high-temperature heat capsule. The advantage, of course, is potential higher efficiency.

The SNAP-29 generator, whose development has been recently initiated by the AEC to meet the Department of Defense requirements is also under study by the Marshall Space Flight Center as a possible power supply to extend the usefulness of the Instrument Unit aboard the Saturn V launch vehicle. Under consideration are applications for a potential orbital workshop under the Apollo application program. In these applications, one or more generators could be used to satisfy increasing power needs. Many other studies are underway concerning isotope generators for future missions, including Voyager lander, Jupiter flyby, and galactic and solar probes. Obviously, long life and reliable operation of these generators must be achieved if they are to satisfy future mission requirements. For these space missions, the alpha emitters, particularly Pu^{238}, are desirable to minimize weight, shielding, and integration problems. On the other hand, the terrestrial units generally employ the less expensive and more abundant beta emitters, particularly Sr^{90}, since heavy shielding, of the order of tons, can be tolerated. In

both cases, however, the generators employ similar thermoelectric elements, and therefore the tests of these terrestrial generators contribute to the development of the long life and reliability so important to space thermoelectric power units.

Figure of Merit

One measure of thermoelectric material performance is the figure of merit. The figure of merit for lead telluride materials is shown as a function of temperature in figure IV-2. Similar data for silicon-germanium alloys are shown in figure IV-3. While many semiconductor materials have been examined during extensive research over the past 10 years, these two materials have been found to be most generally suitable for space power use. The figure of merit of a thermoelectric material is given by the equation $Z = S^2/\rho K$, where S is the Seebeck coefficient, ρ is the electrical resistivity, and K is the thermal conductivity. The figure of merit depends on the inherent properties of the materials and is very sensitive to impurities and temperature. As can be seen from the figures, lead telluride has a higher figure of merit at low temperatures, and silicon-germanium alloys have a higher value than lead telluride only when the temperature exceeds about 1000° K. Similar relations have been found for both n and p materials. This sensitivity to impurities is undoubtedly one of the reasons for some of the degradation noted in lead telluride thermoelectrics. Better quality control and improved bonding techniques will improve this condition. The good low-temperature performance of lead telluride is the principal reason it has been used in all space isotope power generators thus far. It will be necessary to qualify a fuel capsule for higher temperatures in order to obtain equal performance from silicon-germanium. On the other hand, lead telluride is brittle, oxidizes easily, and is volatile at 1000° K.

Heat Pipes Combined with Thermionic Converters

In addition to thermoelectric conversion, an interesting technology effort to improve conversion efficiency in low-power generators is the combination of heat pipes with thermionic converters. The heat pipe is an excellent thermal control device that can transfer heat from the isotope heat source to the cathode of a converter. In tests at the Radio Corporation of America (RCA), a heat pipe of TZM molybdenum alloy, which used lithium as a working fluid, successfully completed a 1000-hour life and compatibility test. It was also demonstrated that the heat fluxes could be concentrated up to a ratio of over 9.3 to 1. This limit existed because the heat-sink area of the heat-removal section of the heat pipe, which was progressively decreased while maintaining the input area constant, could not be reduced further.

Figure IV-4 shows a combination of the heat pipe with a thermionic diode. This equipment was used to determine the conversion efficiency of the heat pipe - diode combination, which was found to agree closely with the calculated value (14.5 percent).

A test setup combining the heat pipe, the thermionic converter, and a power flattening device

is shown in figure IV-5(a). This setup operated very well. Figure IV-5(b) shows the same test equipped with meters to demonstrate the constant diode output, automatically maintained by the power flattening device, although the input power, simulating the decay of an isotope, may be greatly reduced. In this experiment the power input was reduced from an initial 12 to 4 kilowatts, that is, a decrease of a factor of 3. As the heat is reduced, the hot length of the heat pipe is reduced, but the temperature of the diode emitter and hence the output of the diode remain essentially constant (from the 87 W shown in fig. IV-6 to 85 W). These tests suggest the practicality of using relatively low power density isotopes such as Pu^{238} for driving thermionic converters and of using short half-lived isotopes such as Po^{210} for missions of 2 or 3 half-life durations.

MISSIONS USING ISOTOPIC THERMOELECTRIC GENERATORS

The remainder of this paper discusses briefly two NASA missions that will use isotopic thermoelectric generators and the availability and cost of the isotopes that may be used for future space missions.

Nimbus B

The first mission is Nimbus B illustrated in figure IV-6. Two SNAP-19 generators will be aboard this spacecraft, each producing 25 to 30 watts to supplement the 185 to 200 watts of power produced by the two large solar paddles shown in the figure. Nimbus B is in reality designed for solar power, and the two SNAP-19 units are retrofitted to the Nimbus sensory ring. It is therefore not an optimum design, but it will nearly double the useful power aboard the satellite since about 120 watts are needed to keep the satellite operating in its high-noon sun-oriented mode. SNAP-19 also can be considered an important Nimbus B experiment that will provide useful experience and guidance for followup isotope powered missions. Figure IV-7 is a cutaway drawing of the SNAP-19 generator. A Pu^{238} fuel capsule, located in the center, provides heat to the lead telluride thermoelectric element hot junctions through the graphite heat-accumulator block. Rows of thermoelectric elements surround the fuel capsule and are interconnected, in much the same manner as solar cells, to provide extremely high reliability. Heat is rejected to space through the radiator fins. SNAP-19 is an improved generator design. It has fewer seals and leakage paths than either SNAP-3 or SNAP-9 and uses improved thermoelectric materials.

The SNAP-19 is shown in figure IV-8 while undergoing tests on the Nimbus spacecraft. Mechanical, mass, and electrical checkouts are underway in preparation for a late 1967 launch. The remaining schedule for the generators is as follows:

Event	Scheduled date
Development started	January 1964
Fueled-prototype qualification completed	October 1966
Electrically heated prototype made available	October 1966
Safety evaluation report submitted	December 1966
Fueled flight model qualified	January 1967
Fueled flight model backup made available	April 1967

In the next few months the fuel prototype system will be qualified. A total of seven power systems are in the program; each consists of two generators for a total of 14. Two sets of fuel capsules for ground checkout and flight use are provided. The first fueled model will be shipped and qualified about the beginning of 1967. A fueled flight backup system will become available about 3 months later. The important point is that the thermoelectric isotope power units can be used in flight programs in which tight schedules have to be met.

Apollo Lunar Surface Experiment Package

The second NASA isotope-powered mission is shown in figure IV-9. The SNAP-27 generator, which is under development by the AEC for the Apollo Lunar Surface Experiment Package (ALSEP), will provide power for a number of scientific experiments that will be left on the surface of the moon by the Apollo astronauts. This generator is the first one to be used by NASA where isotope power was specifically intended for the spacecraft application, rather than retrofitted to a solar power design, as in the case of Nimbus B.

Consequently, SNAP-27 is more efficient, and it produces more power for less weight. The generator is designed to be fueled on the lunar surface. The astronaut will take the single fuel capsule out of a special cask located on the Lunar Excursion Module (LEM) and insert it into the generator with the aid of a special lightweight tool. The fuel cask is located externally to the LEM and the fuel capsule is not part of the generator when it is aboard the spacecraft. This arrangement, which was decided upon after a complete detailed analysis of the entire system from the beginning to the end of the mission, minimizes the thermal problem within the shroud during the launch and parking orbital phases of the mission.

Figure IV-10 illustrates the SNAP-27 generator. Like SNAP-19, it uses Pu^{238} in a central fuel element. This design employs improved lead telluride elements and a lightweight beryllium radiator. It weighs 46 pounds, including the cask and handling tool, and produces 56 watts of power.

Some of the characteristics of this generator, which is designed to operate on the lunar surface for 1 year after 2 years storage on earth, are as follows:

Power (end of life), W	56
Voltage, V	14
Efficiency, percent	4
Diameter (over fins), in.	15.7
Length, in.	18.1
Temperature (maximum lunar day), ^{o}F:	
Fuel clad	1390
Hot junction	1100
Cold junction	525

AVAILABILITY AND COSTS OF ISOTOPES

Civilian Sources

The availability of isotopes, their production, and their cost are discussed briefly in this section.

Figure IV-11 shows the potential production of isotopes from civilian power only, not from AEC sources. It is very encouraging and significant to note the large upsurge in the introduction of civilian nuclear power in the past 2 years. In a 1962 report to the President, the Commission estimated that there would be 40,000 megawatts of electrical power installed in the United States by 1980. Further study resulted in an interim estimate given by the AEC at the Third Geneva Conference on Peaceful Uses of Atomic Energy in the range of 60 000 to 90 000 megawatts by 1980. Recent AEC estimates indicate an even larger potential, perhaps as much as 110,000 megawatts of electricity by 1980. As a matter of fact, the majority of large new powerplants that have been ordered in the United States during the past year have been nuclear. The important point of this discussion is that as the civilian nuclear industry increases, the potential for recovery of isotopes also increases. If proper steps are taken, approximately 1 thermal kilowatt of Pu^{238}, the isotope of choice, can be obtained for every 1000 megawatts of installed thermal power in the industry. It should be emphasized that the amounts of isotopes shown in figure IV-12 represent merely amounts potentially available from civilian industry. Proper incentives will have to be offerred to ensure their becoming truly available. As is shown in figure IV-11, more than 500 thermal kilowatts annually of Sr^{90} might become available by 1980. For Pu^{238}, unfortunately, only minor amounts can probably become available until the late 1970's when about 100 thermal kilowatts might be produced annually. Promethium 147 production is low since much of that produced is destroyed by radioactive decay or by neutron absorption in the reactor. The figure indicates that curium 244 has a good production potential.

Atomic Energy Commission Sources

The second good source of needed isotopes is the AEC. The commission can respond to varying requirements through the management of its vast reactor and separation facilities.

Figure IV-12 shows how the isotope of choice, Pu^{238}, can be obtained. The key to Pu^{238} production is Np^{237}, a relatively stable isotope that has a half-life of about 2 million years. Neptunium 237 is obtained chiefly by two reactions. The first is the (n,γ) reaction on U^{235}, producing U^{236}, which is further irradiated to produce U^{237}, which decays rapidly to Np^{237} by beta emission. Yields of U^{237} are very low since U^{236} has a very small absorption cross section. The fuel is therefore recycled several times and upgraded when necessary to improve the yield of U^{237}. Since Np^{237} is different chemically and has a very long half-life, it can be separated and stored or irradiated in a special reactor to produce Pu^{238}. The other reaction is the $(n, 2n)$ reaction on U^{238} to produce U^{237}. The engire process requires about 7 years. The fuel must be irradiated and reirradiated to build up the U^{236} content because of the small cross section until a reasonable yield of Np^{237} is obtained.

Furthermore, only about 10 to 20 percent of the Np^{237} can be converted to Pu^{238} per reactor cycle. Attempts to increase the yield by increasing the flux or the irradiation time are not practical, since the Np^{238} and Pu^{238} already formed have high fission and neutron absorption cross sections, respectively, and are readily burned out.

Thus, the production of Pu^{238} involves many variables that have to be considered if good yields at low cost are to be obtained. In short, the production of Pu^{238} is a very complex subject. The amounts obtained depend upon the amount of fuel consumption, its enrichment, the fast- to thermal-neutron flux ratio, the times of irradiation, and many other factors. The yields of products and the costs will change accordingly. In addition, there may be competing demands on the reactors for other purposes, thus reducing their optimum Np^{237} yields. To specify in advance just what will become available in any given year is therefore extremely difficult. However, since it takes about 7 years to complete a Pu^{238} production cycle, the amounts of isotopes that will ultimately be needed must be anticipated so that proper steps can be taken by the AEC to ensure that a sufficient amount of Pu^{238} will be available from civilian industries and their own reactor facilities.

Since Np^{237} is the key to Pu^{238} availability, the amounts of Np^{237} that might be produced in various types of civilian power reactors, both operating and proposed, should be estimated. Table IV-4 gives the amounts of Np^{237} that could be produced in a sodium-graphite reactor (Hallam), pressurized-water reactor (Yankee), boiling-water reactor (Dresden), heavy-water-cooled reactor (Douglas Point), gas-cooled reactor (Hinkley Point), and several advanced reactor designs. At low enrichments, most of the Np^{237} is produced by the (n, 2n) reaction on U^{238} rather than by neutron absorption in U^{235}. The yield of Np^{237} increases rapidly with burnup so that the economy of the fuel cycle itself will greatly influence results. Obviously, some incentives to industry must be given if the Np^{237} in these reactors is to be recovered. It has been estimated that a credit value for Np^{237} of about 150 dollars per gram would be equivalent to a reduction in fuel cost of about 0.3 to 0.4 mill per kilowatt hour.

Figure IV-13 gives the possible AEC production of Pu^{238} for space use. The AEC probably could produce for space purposes between now and 1980 an amount ranging from somewhat over 200 thermal kilowatts to perhaps more than 400 thermal kilowatts. The key problem is that in the critical time period of the mid 1970's very little Pu^{238} will be available from civilian power; thus, the AEC reactors will be the primary sources. If a manned orbiting research laboratory were selected at this time period, only approximately 100 to 200 thermal kilowatts would be available. It is therefore most important that we design with care to get a highly efficient conversion system to utilize the isotopes that might be available in that period.

Figure IV-14 summarizes the possible cumulative availability of Pu^{238} for space use. The curve represents only possible civilian production. The AEC has been requested to provide a total of 500 thermal kilowatts by 1980. This production of Pu^{238} would be from their own sources or from a combination of their own and civilian sources. Obviously the AEC may have demands on plutonium other than NASA, such as those used for medical applications (heart pacers and heart pumps) and for military generators. By 1980, 800 thermal kilowatts could be available for NASA if the proper steps are taken. Again the difficulty is in the mid 1970's when civilian sources will be negligible and AEC sources will be dominant. Obviously the AEC could be producing material earlier, as was indicated in figure IV-13.

The estimated cost of the isotopes is as follows:

Radioisotope	Cost per thermal watt, dollars
Strontium 90	24
Promethium 147	93
Thulium 170	20 to 25
Polonium 210	30 to 40
Plutonium 238	500
Curium 244	700

Strontium 90 and thulium 170 are relatively inexpensive. Promethium 147 will cost about 93 dollars per thermal watt. But, in general, the long-half-life alpha emitters, Pu^{238} and Cm^{244}, are quite expensive. The short-half-life isotopes, such as Pm^{147}, Tm^{170}, and Po^{210}, are relatively inexpensive. Therefore, strong economic motivation exists for using either Pu^{238} very efficiently or the beta emitters if possible. The interest of NASA in the advantages of isotopes for future missions led to a comprehensive study last year at the Lewis Research Center on the selection of isotopes for NASA use. This study was the basis for the guidance given to AEC by NASA in March 1965. This guidance, summarized in table IV-5, was related to both availability of isotopes and additional technology efforts required to determine more adequately their usefulness in a wide variety of both manned and unmanned applications.

NASA asked the AEC for a minimum of 500 thermal kilowatts of Pu^{238} and also asked them to determine methods of producing more than 500 thermal kilowatts at low costs. NASA also agreed to support the current efforts of AEC on Cm^{244}, which is to produce 4.5 kilograms of Cm^{244} and to determine its properties and its suitability for space use. Requirements for Po^{210} were deferred pending mission selection because it appears Po^{210} apparently can be produced within a lead time that is shorter than the mission lead time. The short-half-life isotopes cannot be stored. Plutonium 238, on the other hand, can be stored since it has an 86-year half-life. It can be stored even more efficiently at less cost as Np^{237} since the Np^{237} has a 2-million-year half-life, which prevents any loss by decay.

Because appreciable amounts of all other isotopes are lost by radioactive decay, their production becomes rather mission dependent, and the timely scheduling of missions becomes very important in maintaining an adequate supply of short-lived isotopes. The AEC is also being supported by NASA in their current effort on Pm^{147}, which is to make available 10 thermal kilowatts per year. The use of Pm^{147} is very attractive provided, as discussed earlier, that it can be made free from highly radioactive contaminants. At present, Sr^{90} is not being considered for space use. It is, however, a highly attractive isotope for terrestrial applications, but NASA does not have any present interest in it until the AEC can demonstrate that Sr^{90} can be handled safely and that it does not unduly complicate spacecraft integration and launching procedures. In the area of technology, the AEC was asked to look into problems of high-temperature fuel forms, which will be needed if some of the higher temperature conversion systems, discussed in

papers V, VIII, and IX are to be used.

The AEC was also requested to determine the criticality limits of some of the alpha emitters, to investigate the safety problems of large heat sources because kilowatts of isotope power are being considered for manned missions, to define safety criteria, and to supply more information on the basic properties of the various fuel forms, such as thermal conductivity, vapor pressure, compatibility, radiation spectra, etc. NASA has given this guidance to the AEC because it is convinced that the advantages are so overwhelming that it is worth attempting to solve some of the problems that have been discussed.

In conclusion, isotopes will be available in sufficient quantities to be considered for many future space missions. The extent of their future use will be dependent on the programs now underway to improve performance and availability, to define properties, and to provide acceptable fuel capsules.

TABLE IV-1. - CHARACTERISTICS OF ISOTOPES

FOR POWER PRODUCTION

(a) Beta emitters

Isotope	Half-life	Compound	Compound power, W/g	Dose rate, mR/hr[a]	
				Bare	3-cm of uranium
Cobalt 60	5.27 yr	Metal	[b]3.0	3×10^{8}	6×10^{6}
Strontium 90	28 yr	$SrTiO_3$	.2	6×10^{6}	1×10^{4}
Promethium 147[c]	2.67 yr	Pm_2O_3	.3	1×10^{5}	1.0
Thulium 170	127 days	Tm_2O_3	1.75	4×10^{6}	50

(b) Alpha emitters

Polonium 210	138 days	Metal matrix	17.6	760	1.8
Plutonium 238	86 yr	PuO_2	.35	5	.03
Curium 242	163 days	Cm_2O_3 in metal matrix	15.5	280	2
Curium 244	18.4 yr	Cm_2O_3	2.5	600	32

[a]At 1 m from 5-thermal-kW source.

[b]200 Ci/g metal.

[c]Aged, 1 half-life.

TABLE IV-2. - RADIATION LEVELS IN SPACE

Radiation	Radiation level, rad/hr	
	Bare	10 g/cm^2 shield
Van Allen belts:		
Electrons	10^3 to 10^5	~0
Bremsstrahlung	1 to 100	1 to 30
Protons	10 to 100	1 to 10
Solar flare protons	10 to 100	1 to 10
Galactic cosmic rays	$\sim10^{-3}$	$\sim10^{-3}$

TABLE IV-3. - ISOTOPIC POWER UNITS

SNAP	Power, W	Use	Fuel	Design life, yr	Status
Space applications					
3	2.7	Department of Defense navigation satellite	Plutonium 238	5	In orbit
9A	25	Department of Defense navigation satellite	Plutonium 238	5	In orbit
11	25	Surveyor	Curium 242	.25	Tested
13	12.5	Thermionic demonstration	Curium 242	.25	Tested
19	30	Nimbus B	Plutonium 238	5	Under development
27	50	Apollo Lunar Surface Experiment Package	Plutonium 238	1	Under development
29	500	Department of Defense application	Polonium 210	.25	Under development
Terrestrial applications					
Sentry	5	Weather station	Strontium 90	2	In use
7A	10	Light buoy	↓	10	↓
7B	60	Land light		10	
7C	10	Weather station		10	
7D	60	Boat weather station		10	
7E	7	Sonar		10	
7F	60	Navigation aid		10	Tested
15A	.001	Department of Defense applications	Plutonium 238	5	Tested
21	10	Advanced undersea	Strontium 90	5	Under development
23	60	Advanced terrestrial	Strontium 90	5	Under development

TABLE IV-4. - PRODUCTION OF NEPTUNIUM 237

IN SPECIFIC REACTORS

Reactor	Thermal power, MW	Initial enrichment, percent	Neptunium 237 production, kg/yr
Hallam	240	3.60	0.8
Yankee	485	3.40	1.4
Dresden	626	1.50	2.3
Douglas Point	693	.71	1.8
Hinkley Point	954	.71	2.5
Oak Ridge National Laboratory GCR-3	1908	3.00	4.7
Saline water reactor	8300	.71	24.0

TABLE IV-5. - GUIDANCE GIVEN TO ATOMIC ENERGY COMMISSION BY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

[March 1965.]

Isotope	Availability	Technology
Plutonium 238	500 thermal kW by 1980	Develop high-temperature fuel forms; determine criticality limits; investigate large heat sources; define safety requirements; determine properties.
Curium 244	Support current efforts (3 to 4 kg)	
Polonium 210	Deferred pending mission requirements	
Promethium 147	Support current effort (10 thermal kW/yr)	
Strontium 90	No present interest	

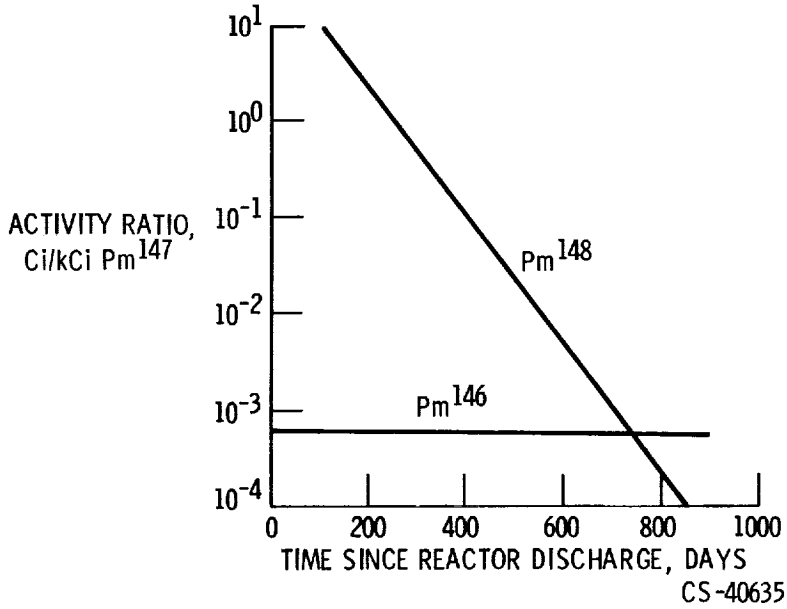


Figure IV-1. - Decay of promethium 146 and promethium 148 impurities relative to promethium 147. (From ORNL-64-709.)

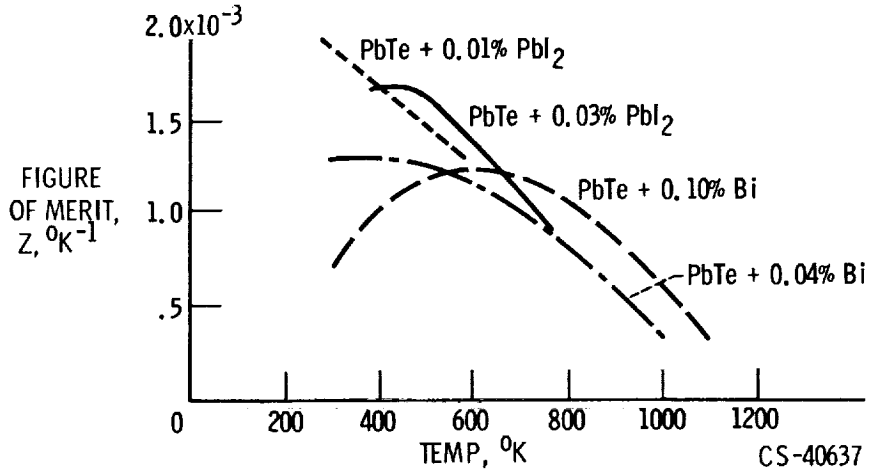


Figure IV-2. - Figure of merit of n-type lead telluride.

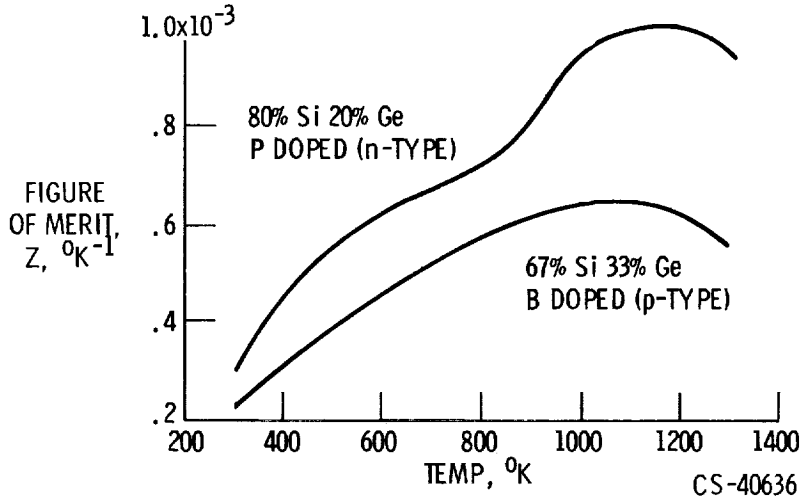


Figure IV-3. - Figure of merit of optimum silicon-germanium alloys.

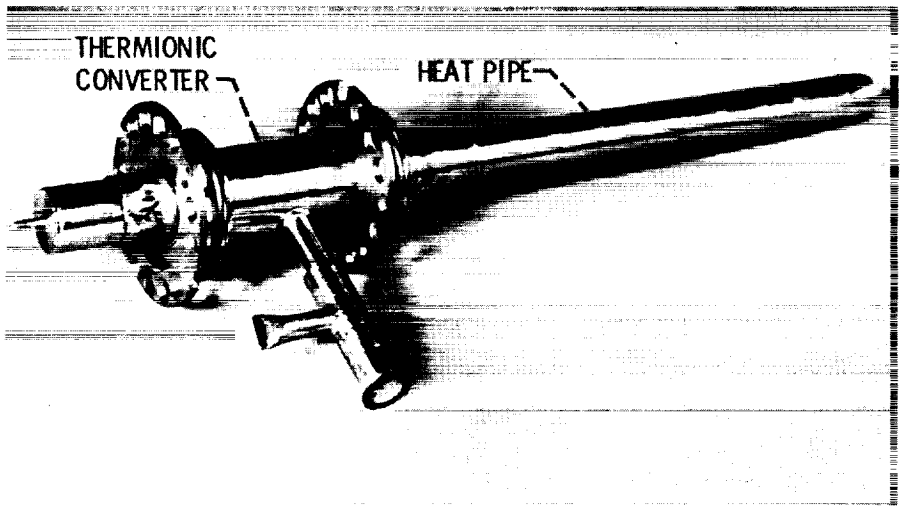
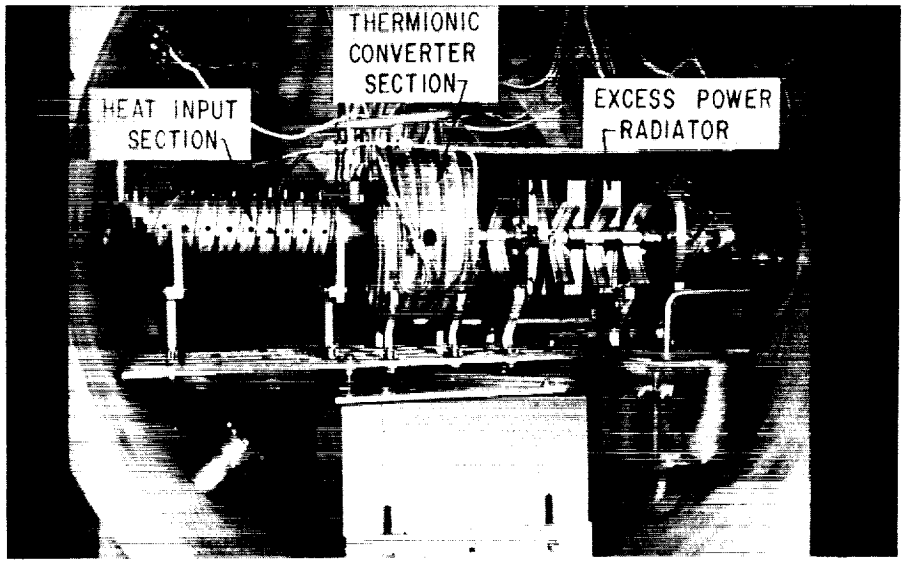
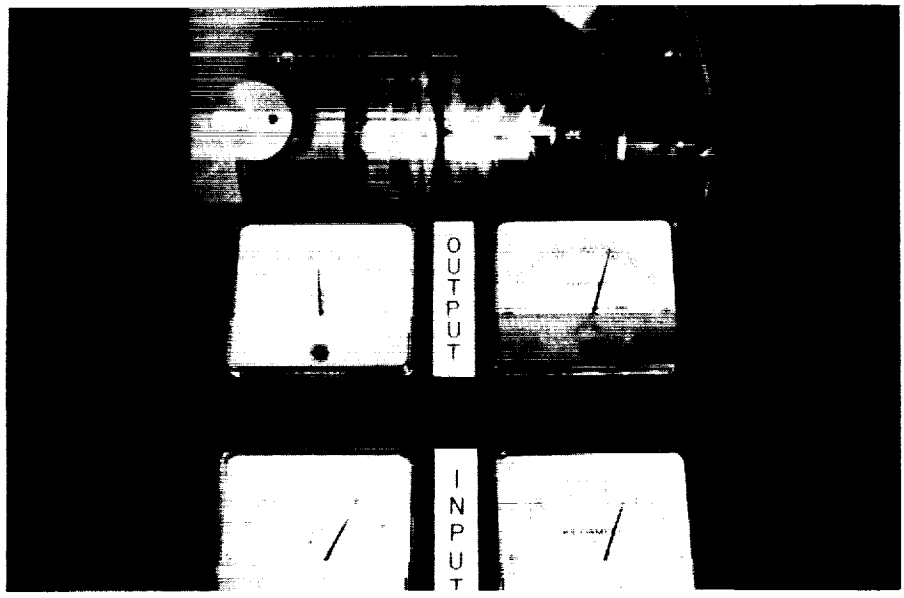


Figure IV-4. - Thermionic heat-pipe experiment. Heat pipe material, TZM molybdenum alloy; working fluid, lithium; test temperature, 1500° C; thermionic converter, molybdenum; area, 50 square centimeters; measured efficiency, 14 percent; power output, 175 watts.



CS-40582

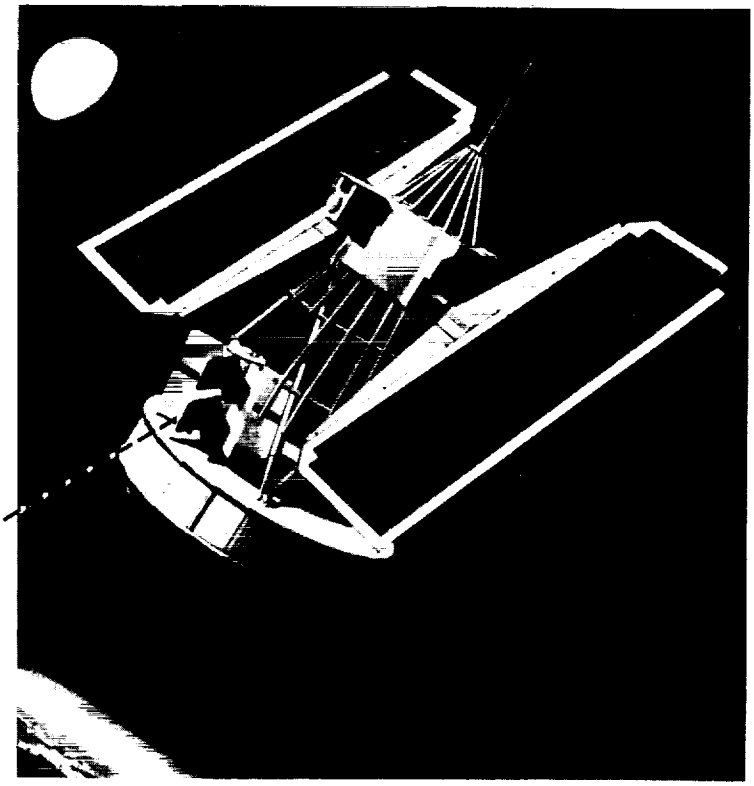
(a) System not operating.



CS-40583

(b) System operating.

Figure IV-5. - Thermionic heat-pipe experiment.



CS-40584

Figure IV-6. - Nimbus B.

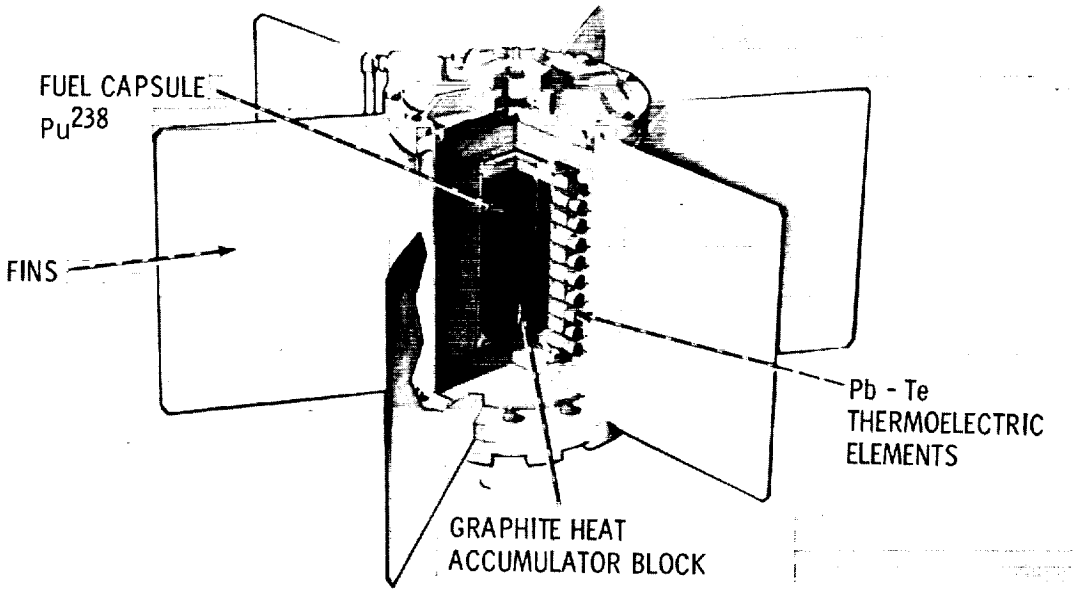
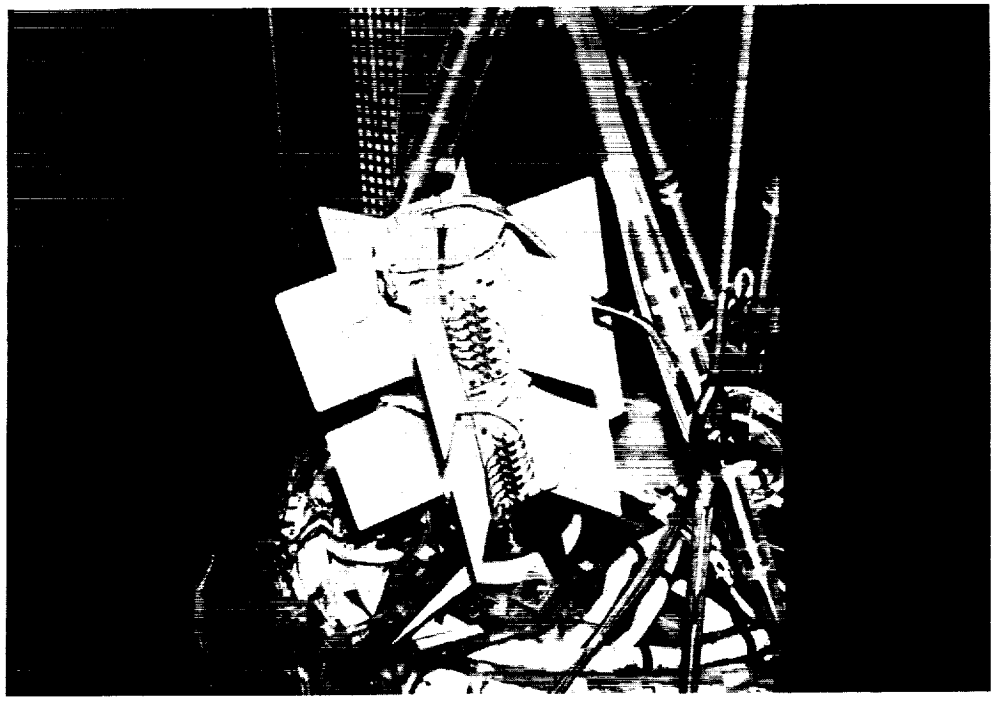
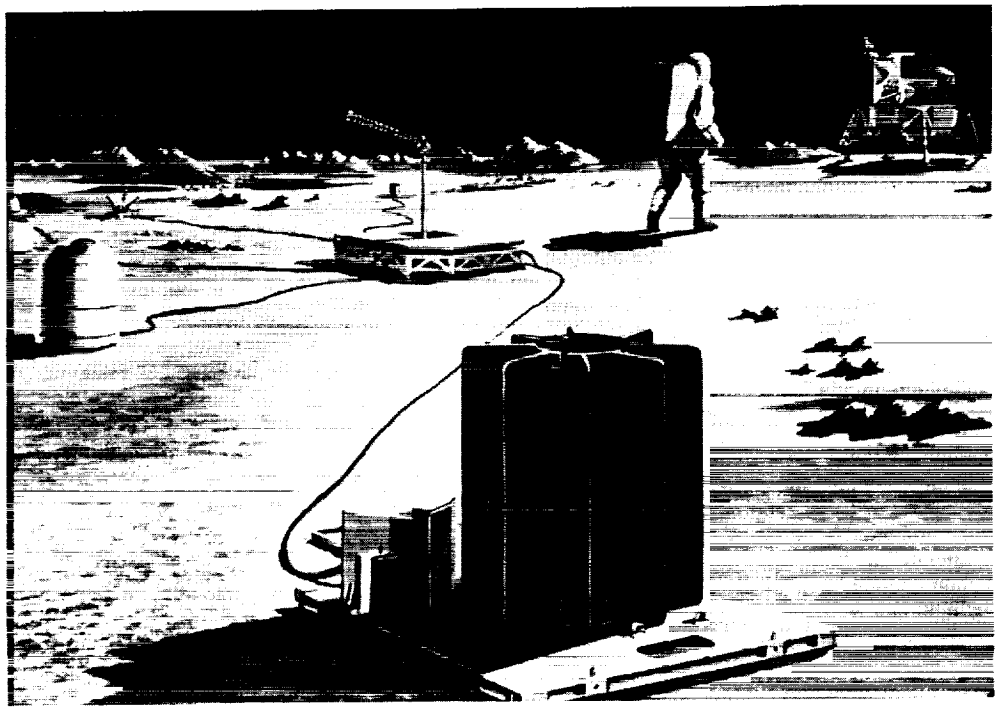


Figure IV-7. - SNAP-19 generator. Weight, 30 pounds; power output, 30 watts.



CS-40340

Figure IV-8. - SNAP-19 generator on Nimbus B.



CS-40341

Figure IV-9. - Apollo Lunar Surface Experiment Package (ALSEP) with SNAP-27 generator.

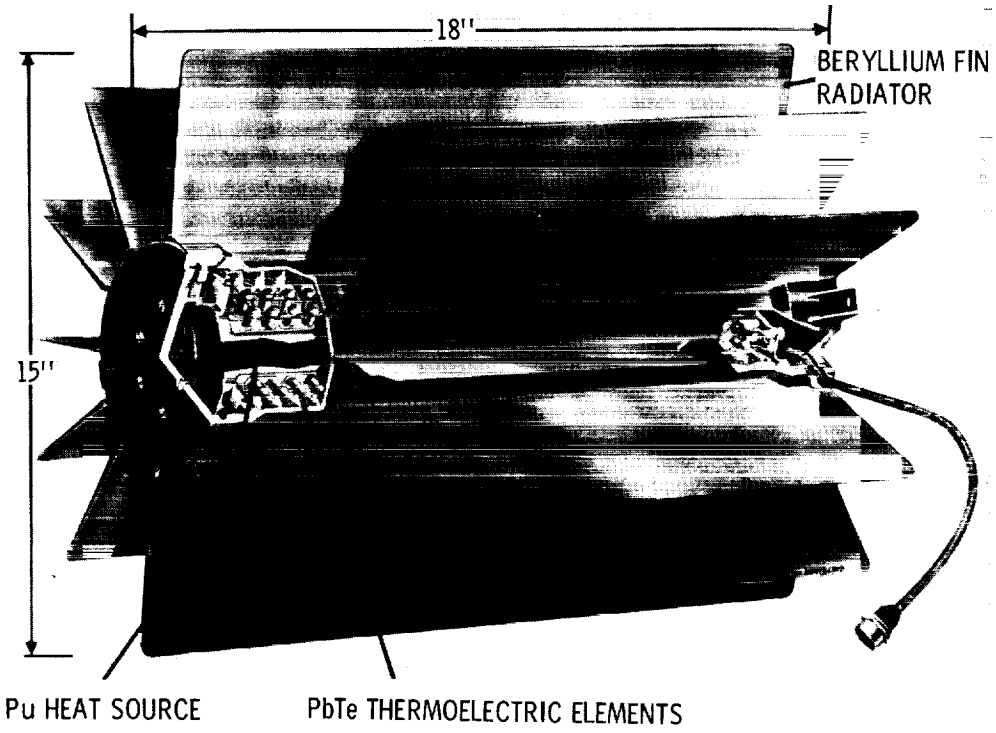


Figure IV-10. - SNAP-27 generator. Weight, 46 pounds; power, 56 watts.

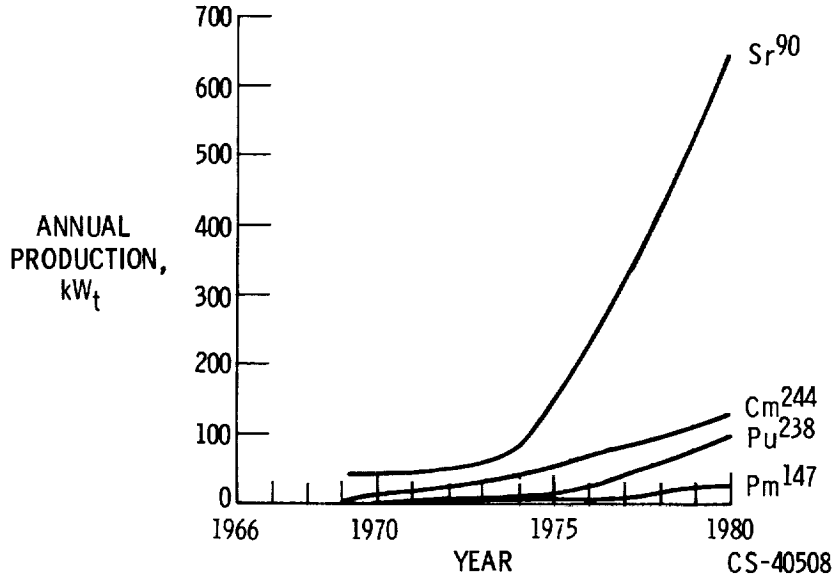


Figure IV-11. - Potential production of isotopes based on projected installed civilian power.

NUCLEAR PROCESS

$$\left.\begin{matrix} U^{238}\ (n,2n) \\ U^{235}\ (n,\gamma)\ U^{236}\ (n,\gamma) \end{matrix}\right\} U^{237} \xrightarrow[6.7d]{\beta,\gamma} Np^{237}$$

$$Np^{237}\ (n,\gamma)\ Np^{238} \xrightarrow[2.1d]{\beta,\gamma} Pu^{238}$$

FACILITIES FLOWSHEET

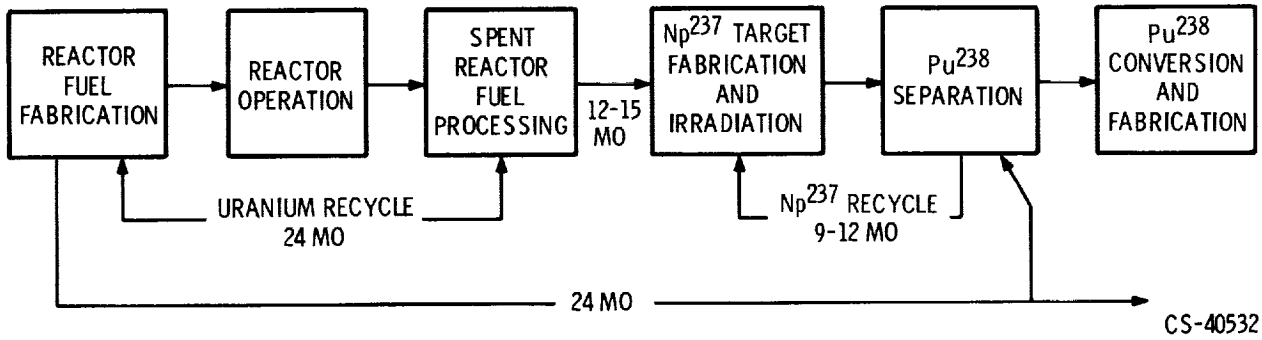


Figure IV-12. - Production of plutonium 238.

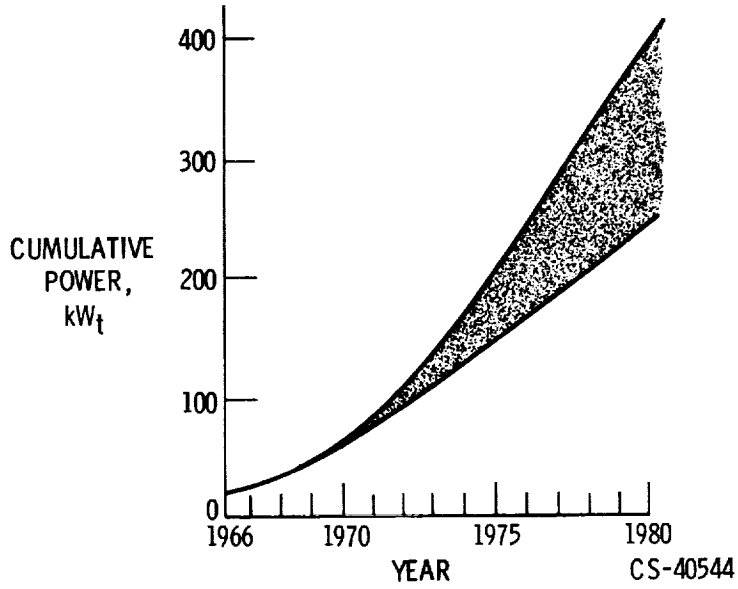


Figure IV-13. - Possible production of plutonium 238 by Atomic Energy Commission.

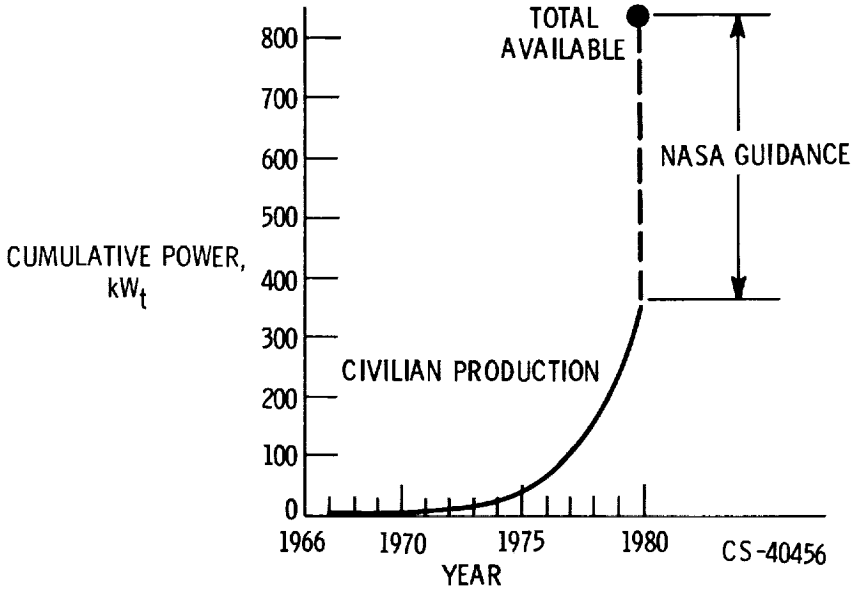


Figure IV-14. - Cumulative availability of plutonium 238.