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RADIOISOTOPE POWER SUBSYSTEMS FOR SPACE APPLICATIONS

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Introduction

Many future space power requirements in the low power regime (watts to a few kilowatts), with durations of a few months to years, are potentially satisfied by utilization of radioisotope power subsystems. The isotope power subsystems of today, essentially first generation devices, do not provide a direct basis for extrapolation to future performance capabilities. Many development problems must be solved before isotope power subsystems realize their full potential.

The currently operational isotope powered "SNAP" units for space application are characterized by high specific weight (1 watt/lb), low power output (≤25 watts), low heat source temperature (~1000°F), and low conversion efficiency (≤5%).[1] Future capabilities promise 10 to 20 watts/lb, 2000°C heat source operation, and conversion efficiencies approaching 20%. This paper examines the technical advancements necessary to attain these performance capabilities.

Summary

The radioisotope power subsystem is potentially an excellent space power subsystem. The radioisotope (thermoelectric) power subsystems of today, SNAP 3, SNAP 9A, SNAP 11, are characterized by high specific weight (1 watt/lb), low operating temperature (~1000°F), and low conversion efficiency (~5%). The radioisotope (thermionic) SNAP 13 operates at 7% generator efficiency (3.1 watt/lb).

The major constraints that will ultimately limit the utility of isotope power subsystems are (1) isotope availability and (2) radiation hazard problems.

As power requirements and capabilities increase to the .5-10 KWe range, isotope economy becomes a stringent necessity, demanding high thermal-electrical conversion efficiency.

Radiation hazard problems are of equal importance in considering application of isotope power subsystems. The problem is that of effectively designing a "safe" subsystem and still retaining favorable weight and volume characteristics. The most serious safety problems occur between the time of launch and insertion in orbit and re-entry upon completion of the mission.

This study includes a survey of the current technologies of energy converters, isotopic fuel form and cladding material compatibility, and launch and operational safety requirements.

Converter device performance is presented parametrically, with tabulated data on current laboratory and/or hardware development devices.

Thermoelectric generator efficiency (3-5%) appears to be insufficient to warrant consideration for power applications over a few hundred watts.

Thermionic devices become attractive efficiency-wise as operating temperatures approach 1500°C. Containment and isotopic fuel form technology have not reached this temperature to date but current development programs, designed to establish this high temperature compatibility in the near future, make the application of thermionic-isotope subsystems attractive from weight and volume considerations.

The Rankine (inorganic and liquid metal working fluids) and Brayton (inert gas working fluids) thermodynamic cycles were studied. The Brayton cycle was judged unattractive due to high subsystem weight. The Rankine biphenyl subsystem appears to be the most attractive power conversion scheme for power levels of 1.5 KW or greater.

A comparison of Rankine biphenyl and high temperature thermionic subsystems indicated the latter has more potential for space application, due to lower converter and radiator weight.

Data on isotope availability and cost is presented, and various isotope suitability for each conversion device is discussed.

Cladding material properties are discussed and related to launch handling and operational hazards problems. Considerations of ablative versus intact re-entry of the isotopic sources are reviewed, and intact re-entry is found to be more suitable, since trends towards high temperature fuel forms make the ablative approach impractical.

The Isotope Heat Source Design Considerations

The selection of a particular isotope for heat source application is dependent on many considerations. These considerations include isotope power density, half life, melting temperature, shielding requirements, cost and availability, and cladding (container) material compatibility. It may be categorically stated that a perfect isotope heat source does not exist for space applications. However, several isotopes do provide favorable heat source characteristics.

The candidate isotope must possess a reasonably high power density in order to provide usable heat fluxes to the conversion devices. Generally, isotopes providing high heat fluxes are most desirable, although not necessary for some conversion schemes.

The half life of the candidate isotope should offer a reasonably flat power-time profile, consistent with mission duration requirements. This allows utilization of a minimum amount of isotope, lowering cost and reducing shielding and safety problems. Matching mission duration with isotope half life is not always possible, however, and in some cases, not advisable.

Current safety requirements dictate that the isotope fuel must not operate in the molten state due to its characteristically high vapor pressure, creating a biological hazard in the event of rupture of the isotope container. However, it is imperative that space power subsystems operate at as high a temperature as possible so that radiator requirements are minimal. Since most of the pure isotope melting temperatures are low it is necessary to alloy the basic isotope or provide heat paths to insure solid phase operation. Alloying reduces the power density but generally increases the thermal conductivity of the source, thereby allowing higher temperature operation.

Many of the isotope candidates providing favorable thermal characteristics require extensive radiation shielding for manned application, ground handling, or electronics payload protection. The shielding weight is assigned to the power subsystem and may severely restrict the use of a particular isotope.

Availability and cost of the heat source isotopes appear to be the most serious limitation to their widespread application. Creation of greater demand may improve availability and cost, but the production capability of some candidates is seriously limited.

It is desirable that the candidate isotopes be available readily, with short production lead times. Ideally, the cost per thermal watt should be low. However, for many applications a high cost isotope with other favorable characteristics may provide more utility system-wise than a low cost candidate.

Data on the critical mass of some of the trans-uranium isotopes is not available. The potential hazard of spontaneous fission due to neutron emission during isotope decay must be recognized. Critical mass calculations of the trans-uranium high temperature fuel compounds may show the necessity of adding a neutron poisoning material to the fuel form to guarantee non criticality. This addition would reduce the effective power density of the isotopes.

The canister, or isotope cladding material, must possess high strength and favorable thermal properties at high temperature. The canister material must also be compatible with the fuel at all operating temperatures. The choice of cladding materials is limited at temperatures greater than 1800°C but investigations currently being conducted by the Atomic Energy Commission indicate cladding compatibility is possible at these and even higher temperatures. The canister material should also be capable of containing gases evolved during decay, unless a method of gas venting is provided. Total containment or venting is a necessity, since gas diffusing through the canister material may enhance thermal losses in the canister insulating material.

Isotope Power Subsystem Components

Heat Source Isotope Selection

The Atomic Energy Commission has published data on some fourteen heat source isotopes[2]. Obviously not all the candidate isotopes can be produced in large quantities. Table I lists the characteristics of several of the more "popular" heat source candidates. Gamma emitters have not been considered here, since the attenuation material required to generate the working heat and provide biological safety results in extremely heavy canister-shield weight.

TABLE I HEAT SOURCE ISOTOPES CHARACTERISTICS

ISOTOPE	DECAY MODE	POWER DENSITY W/CC	WATT/G COMPOUND	HALF LIFE (YEARS)	MAXIMUM OPERATING TEMP (°C)	SHIELDING REQUIRED	CLADDING MATERIAL	1967 AVAILABILITY (KW$_t$/YR)	1967 COST (\$/W$_t$)
POLONIUM 210	α	800	134	.38	2000	MINOR	W	70	4500
PLUTONIUM 238	α	4.9	.39	86.4	2600	MINOR	W, TA	24	894
CURIUM 242	α	1150	98	.45	2200	NEUTRON	NB, TA, W		17
CURIUM 244	α	27	2.3	18.0	2200	NEUTRON	NB, TA, W		357
STRONTIUM 90	β	1.5	.23	28	2400	HEAVY β, X	TA, W	67	19-90
CERIUM 144	β	40	3.8	.78	2400	HEAVY β, γ, X	W, TA	800	1.0
PROMETHIUM-147	β	2.36	.27	2.7	2300	MINOR	TA, W	11	91
THULIUM 170	β	7.9	1.03	.35	1950	MINOR			10

The power densities and maximum operating temperature are for compound forms of the isotopes. Generally these fuel forms are classified; the data presented in Table I should therefore be considered representative rather than specific. The power densities listed assume no void volume for the alpha emitters. The maximum operating temperature does not necessarily correspond to the power density value, since little data on thermal conductivity at these high temperatures is available. It may be necessary to provide heat paths or alloy the isotope with a material of high thermal conductivity to insure solid phase operation. This procedure would effectively dilute the power density. The maximum operating temperature given in Table I is generally within a few degrees of the compound fuel's melting temperature. Further physical properties data, including thermal conductivity, coefficient of thermal expansion, and modulus of elasticity is rather sketchy at these high temperatures.

The alpha emitters are characterized by limited availability, high cost, minimal shielding, and favorable heat source characteristics. Pressure buildup due to helium gas production during decay must be considered. The current safety requirement to contain the gas within the canister for several half lives necessitates incorporation of large void volumes in the fuel, reducing the power density by as much as an order of magnitude. This power density reduction may be overcome in future designs by venting the helium.

The beta emitters are obtained from reactor fission waste products. Consequently, the betas are less expensive and more readily available than the alphas.

Table II summarizes future production capabilities for polonium 210, plutonium 238, curium 244, and strontium 90.[3] Availability and costs are given for present production and potential production rates.

TABLE II FUTURE PRODUCTION CAPABILITIES FOR PO_{210}, PU_{238}, CU_{244}, SR_{90}

ISOTOPE	1972 PRODUCTION		1980 PRODUCTION	
	PRESENT RATE	POTENTIAL	PRESENT RATE	POTENTIAL
POLONIUM-210 α EMITTER		115-141 KW_T/YR \$10-18/W_T		9400 KW_T/YR \$10/W_T
PLUTONIUM-238 α EMITTER	93 KW_T CUM'L. \$815/W_T	200 KW_T CUM'L \$3025/W_T	215 KW_T CUM'L \$535/W_T	~200 KW_T/YR 1370 KW_T CUL'M \$875/W_T
CURIUM-244 α EMITTER	35 KW_T CUM'L \$1340/W_T	915 KW_T CUM'L \$985/W_T	54 KW_T CUM'L \$1100/W_T	~350 KW_T/YR 3940 KW_T CUM'L. \$480/W_T
STRONTIUM-90 β EMITTER	519 KW_T CUM'L. \$50/W_T	575 KW_T CUM'L \$80/W	1500 KW_T CUM'L. \$50/W_T	150-700 KW_T/YR ~2000 KW_T \$80/W_T

Excluding their currently high cost, the alpha emitters are extremely attractive for in-space heat sources due to their low toxicity, minimal shielding, and high power density.

The beta emitters are generally less attractive than the alphas due to their higher toxicity and shielding requirements. Nonetheless, the betas are still suitable for conversion devices requiring only low power fluxes.

In general, the isotope fuel and cladding compatibility technologies are rapidly approaching reliable operation at 2000°C. As future applications requirements are made known, the specific isotope-materials capabilities and limitations will determine the heat source configuration. The point of importance is the direction the research efforts are taking...high temperature, high density fuel forms and cladding material compatibility at these temperatures.

Isotope Cladding Materials - In selecting a cladding material for the radioisotope fuel, several requirements must be satisfied. The canister material must be compatible with the fuel at elevated temperatures and be capable of operating in air at these temperatures without corrosion. Further, the cladding material must possess high mechanical strength, good ductility and excellent dimensional stability at room temperature and high temperature. The canister must also provide high thermal and stability at the operating temperatures of the heat source.

The requirement of satisfying the above conditions at temperatures above 1200-1500°C severely restricts the choice of cladding materials of the pure elements, only tungsten, tantalum, molybdenum, niobium, and rhenium have sufficiently high melting or sublimation temperatures to permit their consideration. The metallic carbides of niobium, tantalum, zirconium, and titanium offer promise as high temperature isotope canisters.

The behavior of these refractory metals at room temperature is poor because of their mechanical properties in this range. Fabrication of the metal cladding elements is difficult. Cladding of the heat source must usually be done by hot cell operations, using a diffusion bonding technique.

The second major weakness of refractory metals is their lack of oxidation resistance at elevated temperatures, necessitating a protective coating. Several coating systems have been developed for sheet refractory metals involving the formation of a metallic diffusion alloy with the metal which is subsequently oxidized to form a metal bonded-metal modified oxide.

For low temperature (1000 to 1500°C) applications, the refractory metal claddings can be used most satisfactorily. For higher temperature operation, the carbides of the refractory metals offer much promise. The carbides all appear to have good thermal characteristics above 1900°C. The main disadvantage of the carbides is their poor mechanical properties at any temperature. The carbides are brittle at most temperatures and their fabrication into cladding elements is difficult.

Little is known about the compatibility of the carbides with the isotope sources. Generally they should be compatible with the isotope's carbide form, but incompatible with the oxide.

A combination of a refractory metal and a ceramic which would possess the high temperature capabilities of a ceramic and the thermal and mechanical properties of the refractory metal would be a highly desirable cladding material. Ceramics reinforced with refractory metal sheet, wire and fibers are now under development.[4] These materials could be of considerable utility as cladding and structural materials at 2000°C or greater.

Table 3 summarizes the cladding materials high temperature properties.[4]

TABLE III PHYSICAL PROPERTIES OF ISOTOPE CLADDING MATERIALS

ELEMENT	MELTING POINT (°C)	TENSILE STRENGTH @ 1100°C (psi)	THERMAL SHOCK RESISTANCE	THERMAL CONDUCTIVITY (BTU/HR/FT/°F	OXIDATION RESISTANCE @ HIGH TEMP.
TUNGSTEN	3380	60,000- 140,000	GOOD	96.6	POOR
TANTALUM	3060	50,000- 70,000	GOOD	31.5	POOR
TA-10%W	3560	110,000	GOOD	31	POOR
MOLYBDENUM	2600	30,000- 60,000	GOOD	84.5	POOR
NIOBIUM	2400	30,000	GOOD	16	POOR
RHENIUM	3160	90,000- 130,000	GOOD		POOR
NB C	3860		GOOD AT HIGH TEMP.	8.2	POOR
TAC	3850	2,000- 4,000	GOOD AT HIGH TEMP.	13	POOR
ZR C	3280	14,000	GOOD AT HIGH TEMP.	12	POOR
TIC	3150		GOOD AT HIGHTEMP.	10	POOR

Power Conversion Devices

Radioisotope-Brayton Power Conversion

There has been a great deal of experience gained in the development of Brayton cycle subsystems and components due to the development of the turbo-jet engine. The closed Brayton cycle permits use of relatively simple and reliable turbomachinery.

The closed Brayton cycle offers the designer the advantage of being able to choose the optimum working fluid to meet some specified criterion (i.e. maximum cycle efficiency, minimum radiator area, minimum subsystem weight, etc.). Generally, for high powered reactor systems a compromise is made between the criterion of minimum radiator area and minimum subsystem weight. Due to the limited availability of radioisotopes, radioisotope power systems will generally perform in the lower power areas (.1-10 KW) with the requirement of maintaining high efficiencies to reduce the isotope shielding requirements and inventory. Therefore the criterion for selecting a working fluid will probably be a compromise between maximum cycle efficiency and minimum radiator area. It is thought that minimization of weight will not be a high priority item because of operation in lower power levels where weight is not as stringent a limitation as in the higher power ranges of reactor systems. The Brayton cycle, operating at relatively low heat rejection temperatures, must trade efficiency for practical radiator area, in order to be utilized for space power subsystems.

The cycle efficiency of a Brayton cycle space power subsystem is highly dependent on the type of working fluid and especially the efficiencies of the turbine and compressor. The choice of a working fluid is then a compromise between fluids having good heat transfer and cycle characteristics and fluids that will give high turbine and compressor efficiencies.

Generally, monatomic gases will give approximately 5% greater turbine and compressor efficiencies than diatomic gases. This immediately narrows the spectrum of choice to the inert gases. Inert gases offer another attractive feature, that of being non-reactive with the metal containment devices in a high temperature environment. The problem remains to identify that inert gas that is a compromise between:

1. Fluids having good heat transfer characteristics to facilitate small lightweight heat exchangers and recuperators.

2. Fluids having properties that result in efficient turbines and compressors.

To illustrate the effect of these components on the cycle, a schematic diagram of a typical Brayton cycle as applied to a radioisotope power subsystem is shown in figure 1.

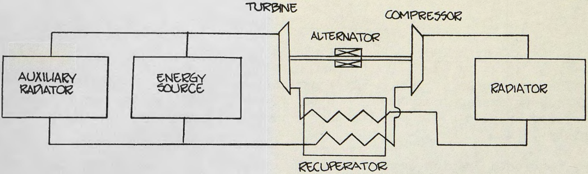

FIGURE 1 SCHEMATIC DIAGRAM OF ISOTOPE BRAYTON SPACE POWER SUBSYSTEM

From the standpoint of the cycle and heat transfer properties of the gas, the following properties are desired:

1. High specific heat working fluids
2. High working pressure

Efficient turbines and compressors require:

1. Low specific heat working fluids
2. Pressures that result in proper specific speed and Reynolds number.

The light inert gases such as helium have the highest specific heat and are best from the heat transfer and cycle standpoint while the heavier inert gases such as Zenon have good characteristics from the turbine efficiency standpoint. To meet the criterion of minimum system weight, an inert gas with an atomic weight of approximately 40 is optimum. This corresponds to argon. However, in radioisotope systems, efficiency is more important that light weight and the choice is the heavier inert gases with their lower corresponding specific heats, results in higher system efficiency and weight. Krypton allows a reasonable compromise between efficiency and weight for application to radioisotope power systems because of its molecular weight and thermal conductivity.

Under certain conditions a recuperator can be used to improve the cycle efficiency of the Brayton cycle. The recuperator is merely a device for recovering heat from the turbine outlet gas to the compressor outlet and thereby increasing the cycle efficiency as shown in figure 2.

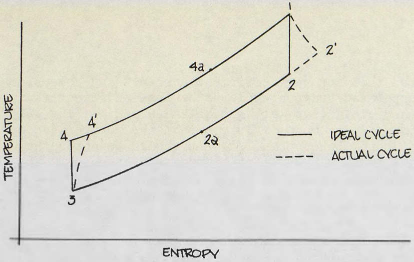

FIGURE 2 TEMPERATURE-ENTROPY DIAGRAM FOR THE BRAYTON CYCLE

where: 1-2 - isentropic expansion through turbine

2-2a - heat rejection in recuperator

2a-3 - constant pressure heat rejection in radiator

3-4 - isentropic compression in compressor

4-4a - constant pressure heat addition from energy source

Instead of radiating heat from 2' to 2a, this heat is pumped into the working fluid as it comes out of the compressor from 4' to 4a. Heat addition then occurs from 4a to 1 in the recuperated Brayton cycle while in a typical unrecuperated Brayton cycle, heat would be added from 4' to 1.

The results of a cycle analysis of both the recuperated and unrecuperated Brayton cycle is presented in figure 3.

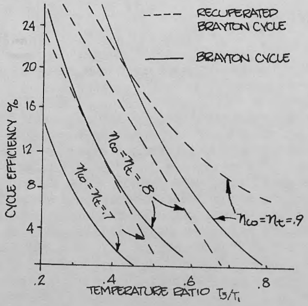

FIGURE 3 BRAYTON CYCLE MAXIMUM EFFICIENCY

It should be noted that for very efficient turbines and compressors it is possible for the recuperated Brayton cycle to be less efficient than the unrecuperated Brayton cycle. (i.e. at $N_t = N_{co} = .9$ and $T_3/T_1 = .425$ the unrecuperated Brayton cycle is more efficient than the recuperated cycle). This results from T_2' being lower than T_4'. It should be noted that the efficiency numbers are the maximum powerplant thermal efficiencies. The alternator and bearing losses have been neglected and would probably drop the cycle efficiency by another four or five percent to give the overall efficiency.

Radioisotope-Rankine Subsystems

The performance of the Rankine cycle radioisotope power subsystem may be predicted by analyzing the performance of the cycle, working fluid, turbogenerating unit, and auxiliary components.

A simplified schematic diagram of direct cycle (steady state) operation is shown in Figure 4. The working fluid is pumped through an isotope heat exchanger and vaporized (4-5-1). The saturated vapor is then expanded through the turbine (1-2), producing rotational shaft power. The fluid exits the turbine and is condensed in the radiator (2-3). The turbine drives the generator unit, and the generator power output is conditioned for application requirements.

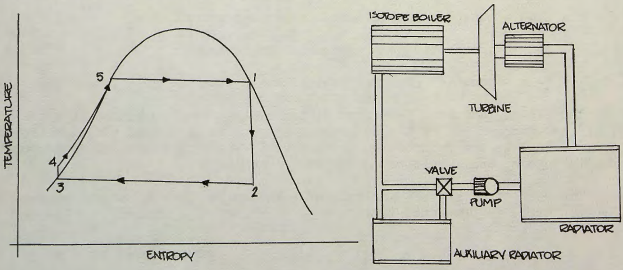

FIGURE4 SCHEMATIC DIAGRAM OF RANKINE SPACE POWER SUBSYSTEM

Determination of Cycle Efficiency - Two distinct types of working fluids may be utilized, each of which has certain advantages.[5] Type "a" fluids are those for which fluid performance may be determined directly from thermodynamic properties. Type "b" fluids are those requiring individual analysis of their thermodynamic properties to determine fluid performance. The fluid type classification is determined by the fluid's temperature-entropy diagram for both types of fluids. Type "a" fluids include water, ammonia, mercury, rubidium, sodium, potassium, and cesium. An analysis of subsystem capabilities using mercury working fluid was performed. The type "b" fluids include diphenyl (biphenyl), freons, Dowtherm "A", aluminum bromide and hydrocarbons. Biphenyl subsystem performance was analyzed; similar performance results are attainable with Dowtherm "A".

The fluid efficiency of the type "a" fluids may be determined by comparative analysis of the fluid properties (vapor quality, latent heat of vaporization, and specific heat).[5] The fluid efficiency of the type "b" fluids can only be determined from individual analysis of their temperature-entropy properties.[5]

The Rankine cycle for biphenyl working fluid is shown in the temperature-entropy diagram in figure 5.

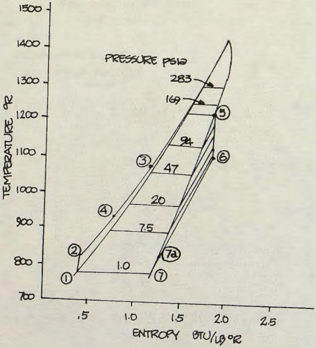

FIGURE 5 TEMPERATURE-ENTROPY DIAGRAM FOR BIPHENYL

The use of a regenerator will yield increased cycle efficiency. The regenerator cycle is from 6-7a and 2-3. The cycle characteristics (heat input, temperature) must be maintained with time for optimum performance. If a short half life isotope is used, power flattening, or constant thermal input, must be maintained to achieve optimum conversion performance. An auxiliary radiator, as shown in figure 6 will accomplish this requirement.

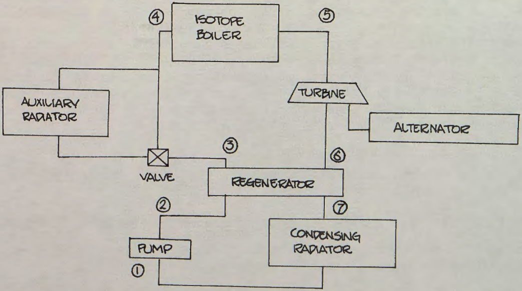

FIGURE 6 SCHEMATIC DIAGRAM OF ISOTOPE RANKINE BIPHENYL POWER SUBSYSTEM

The results of a cycle analysis using the previously presented methods are presented in figure 7.

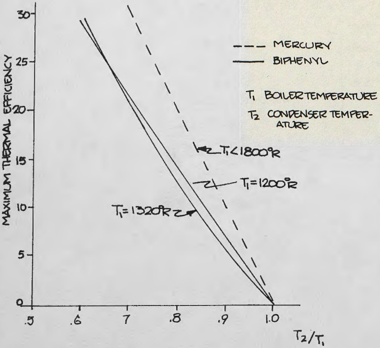

FIGURE 7 MAXIMUM THERMAL EFFICIENCY OF RANKINE CYCLE SUBSYSTEMS

Turbine Performance - The turbine efficiency will be an important factor in choosing the most suitable working fluid. The product of turbine, carnot, and fluid efficiency closely approximates the overall system efficiency. Because of the negative slope of the temperature-entropy characteristic of biphenyl, the vapor is essentially dry and supersonic flow in the turbine can be tolerated. The formation of liquid droplets within the turbine can have disastrous effects on the turbine blades. Therefore, the mercury system must either expand through a number of stages and keep the fluid flow in the turbine well below the sonic level, or use interstage superheating to insure that the quality of the vapor does not drop below 100%. The saturated vapor of biphenyl also has a higher specific heat (.3 BTU/#°F) whereas mercury is very low (.025 BTU/#°F). This infers that mercury requires very large pressure drops to extract sufficient energy in order to maintain the cycle efficiency. This leads to the conclusion that the biphenyl system will have a much higher turbine efficiency. The mercury system will require 2-3 stages and result in only moderate overall efficiencies.

In the low power regime the high mass flow rate of the biphenyl system is an added factor in the resulting high turbine efficiency. Mercury at low power levels suffers from very small sized turbines.

Table IV indicates the performance of presently available turbines.

TABLE IV CURRENT RANKINE CYCLE TURBINE PERFORMANCE

APPLICATION	NUMBER OF STAGES	POWER OUTPUT KWe	ADIABATIC HEAD, Δh_{ad} BTU/LB	TURBINE EFFICIENCY %	WORKING FLUID	TURBINE ROTATIONAL SPEED RPM	MASS FLOW RATE LB/MIN	TURBINE INLET TEMPERATURE °R
SNAP II	2	3.47	47	46	MERCURY	40,000	14.25	1595
SNAP I	3	.65	50	40	MERCURY	40,000	1.86	1760
SUNDSTRAND CRU	1	1.65	61.5	65	BIPHENYL	24,000	2.3	1210
SNAP VIII	4	35	23	63	MERCURY	12,000	153	1710

Biphenyl has a high vapor pressure at moderate temperature. While mercury requires a turbine inlet temperature of at least 1400°R, the biphenyl system only requires about 1200°R. The critical temperature for biphenyl is 1420°R and this establishes an upper limit on turbine inlet temperature for this working fluid.

Alternator Efficiency - Generally, alternators with efficiencies of about 85% are considered state of the art.

Using the data on cycle efficiencies presented in figure 7 along with alternator and turbine efficiency data presented above, reasonable estimates of system efficiencies for the rankine biphenyl and mercury subsystems can be made. It should be kept in mind when using figure 7 that the theoretical optimum temperature ratio for minimum radiator weight is $T_1/T_2 = .75$. The efficiency of the system can be increased by going to lower temperature ratios but not without having to accept large radiator areas and weights. Practically speaking, temperature ratios of .7 are realistic.

Thermoelectric Subsystem

The energy conversion of thermoelectric generators is completely static and therefore offers an intrinsically high reliability. Thermoelectric generators have been under active development for the past ten years. A sophisticated technology exists for lead-telluride and silicon-germanium alloys. Recently Monsanto Research Corporation has developed a high temperature thermoelectric element, MCC-50 and MCC-60, that are capable of performing in the 1200°C range at 3 to 4% conversion efficiency.

Unfortunately the efficiency of the thermoelectric system (5-7%) is so low that its candidacy for high power level radioisotope power conversion is doubtful due to the correspondingly large isotope inventory requirement.

A schematic diagram of a typical thermoelectric device is shown in figure 8.

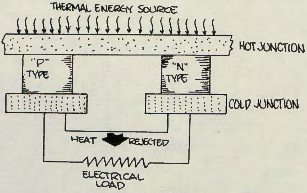

FIGURE 8 SCHEMATIC DIAGRAM OF THERMOELECTRIC CONVERTER

The efficiency of a thermoelectric element may be considered to be the product of the carnot efficiency and thermoelectric materials efficiency.

$$\eta = \eta_{\text{carnot}} \cdot \eta_{\text{material}}$$

The materials efficiency can be directly related to the familiar figure of merit for a thermoelectric element. The figure of merit is a complex function of temperature and the purity of the semiconductor material.

The performance of a number of thermoelectric materials is given in table V at their typical operating temperatures.

TABLE V THERMOELECTRIC PERFORMANCE CALCULATIONS

"N" TYPE MATERIALS				"P" TYPE MATERIALS			
MATERIAL	HOT JUNC. TEMPERATURE °C	MATERIAL EFFICIENCY*	GENERATOR EFFICIENCY+	MATERIAL	HOT JUNC. TEMPERATURE °C	MATERIAL EFFICIENCY*	GENERATOR EFFICIENCY+
PbTe + .3% Na	600	11.9	6	PbTe + PbI_2	600	14.2	7.0
LiMn + TeSe	1027	10.5	5.2	GeSi	1000	13.1	6.6
GeSi	1000	7.7	3.8	InAs + P	867	12.1	6.0
MCC 50	1200	4.7	2.34	MCC 60	1200	4.66	2.34

* BASED ON "FIGURE OF MERIT"
\+ ASSUMES CARNOT EFFICIENCY = .5

An interesting aspect in the development of the high temperature thermoelectric material is the possibility of segmenting a number of thermoelectric materials to obtain higher hot junction temperatures. That is using several different thermoelectric elements in thermal series with a common heat source. This would allow higher carnot efficiencies resulting in higher overall system efficiencies. Of course by increasing the carnot efficiency, the system weight rises due to the increase in radiator area required to dissipate the rejected heat. Obviously weight can readily be traded for efficiency once the desired system characteristics are defined.

Table VI is a summary of the thermoelectric SNAP units that are presently available or under development.

TABLE VI CURRENT THERMOELECTRIC SNAP UNITS

APPLICATION	POWER WATTS	WEIGHT LBS	ISOTOPE	DESIGN LIFE
SNAP 9A	25	27	PU 238	5 YRS
SNAP 11	25	30	CM 242	90 DAYS
SNAP 17	25	28	SR 90	5 YRS

Thermionic Conversion

The thermionic converter is a static, high temperature device, converting thermal energy directly to electrical energy. Thermionic conversion is accomplished most efficiently at high temperature (1200-2000°C). Conversion efficiencies of 5 and 20% respectively are attainable in this temperature regime.[8] The SNAP 13 thermionic generator, a curium 242 12.5 watt unit, has demonstrated 6.5% efficiency at 1465°C for 6400 hours using an electrical heat source. The current SNAP 13 program goals call for increased overall efficiency, 8.7%, (12.1 diode efficiency) at an output power of 20 watts. Current performance capabilities utilizing SNAP 13 technology are given in Table VII.

TABLE VII CURRENT ISOTOPE THERMIONIC SUBSYSTEM PERFORMANCE CAPABILITIES

EMITTER TEMPERATURE........ 1465°C
EMITTER DIAMETER.............. 1.4 IN.
POWER OUTPUT..................... 50 WATTS
  CURRENT............ 83.5 AMPS
  VOLTAGE .... .6 VOLTS
THERMAL INPUT POWER........... 419 WATTS
LOSSES
  ELECTRON COOLING.......... 220 WATTS
  RADIATION LOSS (CATHODE).. 81 WATTS
  THERMAL SHIELD LOSS....... 35 WATTS
  EDGE LOSS, THERMAL SHIELD... 27 WATTS

DIODE EFFICIENCY....................14.3%
OVERALL CONVERSION EFFICIENCY.....12.0%
ESTIMATED TOTAL WEIGHT, INCLUDING:
  THERMIONIC CONVERTER
  CM242 HEAT SOURCE
  REENTRY CAPSULE .... 5 LBS.

Thermionic subsystems of the above type permit modularization to obtain high power levels; the weight of the module will vary linearly with the number of units.

A significant disadvantage of the thermionic system is its low voltage high current output. Power conditioning for this type of power presents numerous problems. There has been much recent progress in this area. RCA has developed a power conditioning unit specifically designed for thermionics which utilizes tunnel diodes as active elements. Minneapolis-Honeywell has also developed a transistorized power conditioning unit for this purpose. Generally, these power conditioning units are 85 per cent efficient with specific weights as low as 25 lbs/KWe.

Table VII indicates that the electron cooling term contains more than half the total input power. By simply controlling the electrical load resistance this electron cooling power can be varied. Thus the diode acts as a thermal shutter for purposes of temperature control.

Conclusions

Isotope Heat Source

The availability of isotope heat source material is currently limited. Future power requirements can be met by the Atomic Energy Commission if early identification of these requirements are made known (see Table II). The number of candidate isotopes to be produced will be limited, by economic necessity.

Current heat source development programs offer optimistic results for high temperature, high power flux containment, while meeting current safety requirements. Many fuel manufacturing and cladding compatibility problems do exist, but the high application potential warrants their solution. Since high temperature fuel forms and high power outputs are desirable, intact re-entry is more practical than the ablative approach. Re-entry capsule containing the heat source and converter can be used as the subsystem radiator, operating at low temperature but offering total impact integrity and very low weight. (See Table VII).

Power Conversion Devices

Current isotope power subsystems are characteristically low in efficiency and high in weight. Advancing converter and heat source technology promise to reduce isotope inventory requirements and low overall subsystem weight considerably. High efficiency, low specific weight and volume, and long life are the primary requirements to be satisfied by the conversion scheme.

Accurate subsystem weight and volume predictions are difficult without specific requirements and consistent assumptions. A survey of proposed dynamic cycle isotope power subsystems is presented in Tables VIII to indicate trends and relative merits of these concepts. Table IX shows the trends and relative merits of the static converters. The potential of each candidate isotope-converter subsystem is outlined in the following paragraphs.

Brayton Cycle - From considerations of efficiency the recuperated Brayton Cycle is ideal for isotope powered applications. Operating temperature and power density requirements are currently within the state of the art for many heat source candidate technologies. Efficiencies of up to 20% are attainable. Brayton subsystem weight and radiator area requirements offset the attractive efficiency. (See Table X).

Rankine Cycle - The Biphenyl working fluid cycle provides higher efficiency than the Rankine-mercury and is competitive with the Brayton cycle for power outputs below 5 kilowatts. Operational biphenyl units have demonstrated 1700 hours operation. The temperature and power flux requirements are within the current state of the art of isotope heat source technologies.

TABLE VIII RADIOISOTOPE DYNAMIC CONVERTER PARAMETRIC PERFORMANCE

CYCLE and WORKING FLUID	POWER OUTPUT KWe	CYCLE EFFICIENCY %	SPECIFIC WEIGHT LB/KWe	DURATION	TURBINE INLET TEMPERATURE	T_2/T_1	TURBINE EFFICIENCY %	PROPOSED BY
RANKINE/BIPHENYL	1.5	17.5	195 incl. redundant *	14-120 DAYS	1210°R	.62	65	SUNDSTRAND
RANKINE/DOW "A"	1.5	17	160 incl. redundant *	14-120 DAYS				SUNDSTRAND
RANKINE/HG	1.7	9.9	300 incl redundant *	120 DAYS	1650°R	.63	55	ATOMICS INT'L
RANKINE/HG	3.0	15-16	120 *	120 DAYS				TRW
RANKINE/HG	4.0	15-16	~300 incl.* redundant	90 DAYS +				ATOMICS INT'L
BRAYTON/ARGON	1.5	15-18	365 *	30-60 DAYS	2000°R	.3	85 ...78 COMP...	GARRETT
BRAYTON/KRYPTON	.5	14	304 *	18 MO.	2000°R	.28		GARRETT
BRAYTON/ARGON	5.0		235 incl* redundant		2000°R	.26		GARRETT

*UNSHIELDED

ASSUMPTIONS
1. Specific Weights Exclude Isotope Heat Source
2. Redundant Components Include Turbine, Generator, Power Conditioning and Control

T_2 = Compressor or Pump Inlet Temperature
T_1 = Turbine Inlet Temperature

Data From References 8, 9, 10, and 11.

Thermoelectrics - The radioisotope thermoelectric subsystems provide essentially "on the shelf" technology for power levels less than 100 watts. In the kilowatt regimes, thermoelectric conversion becomes economically impractical due to its low conversion efficiency and high subsystem weight. Thermal series designs are possible, bolstering efficiency, but creating the necessity for large radiator areas.

Thermionics - The radioisotope thermionic subsystems appear to be applicable to a very broad range of power levels due to its high conversion efficiency and inherent light weight. The proven lifetimes of these devices approach one year. Radiator requirements are minimal, and specific weights of 100 lb/KWe or less are foreseeable.

TABLE IX RADIOISOTOPE STATIC CONVERTER PARAMETRIC PERFORMANCE

PARAMETER	THERMOELECTRICS	THERMIONICS
TEMPERATURE REGIME	HOT JUNCTION - TO 1400°C MAX EFFICIENCY 600-900°C	HOT JUNCTION - TO 2000°C MAX EFFICIENCY ≥ 2000°C
EFFICIENCY	DEVICE - TO 14% GENERATOR - TO 6%	DEVICE - TO 20% GENERATOR 15 TO 20%
SPECIFIC WEIGHT	250-300 LB/KW	50-200 LB/KW
SPECIFIC VOLUME	~ 3 CU FT/KW	~ 1 CU FT/KW
RADIATOR SIZE	10 FT^2/KW @ 1000°K	< 1 FT^2/KW @ $T_H \geq 1500$°K

Figure 9 shows the temperature regime of the various conceptual subsystems with their corresponding efficiency potential. Figure 10 shows the probable specific weight regimes for the isotope subsystems at the 1.5 kilowatt level.

In summary, the future utility and versatility of isotope power subsystems is dependent on the advent of high temperature fuel form and converter technology. Evolution of compact (1 ft^3/kw) light weight ($\leq$ 100#/kw) units is foreseeable, if current development efforts are successful.

Thermionic subsystems appear to have the highest potential payoff. While competitive with the Brayton cycle efficiency, the thermionic subsystem will not be penalized with the large radiator area of the Brayton cycle.

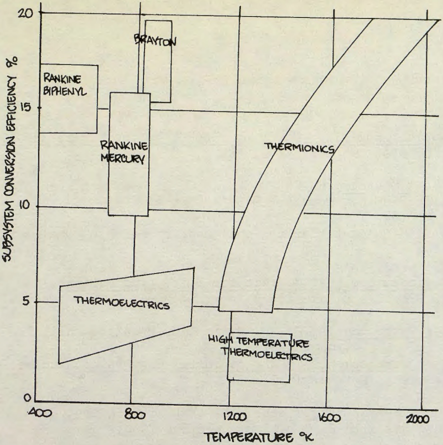

FIGURE 9 TEMPERATURE-EFFICIENCY REGIME OF CONCEPTUAL ISOTOPE POWER SUBSYSTEMS

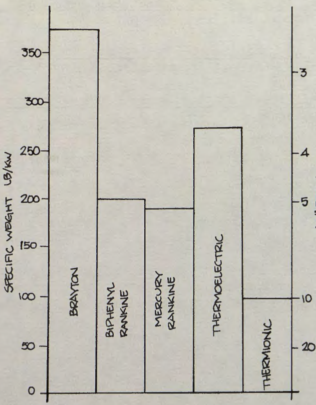

FIGURE 10 SPECIFIC WEIGHT REGIME OF CONCEPTUAL ISOTOPE POWER SUBSYSTEMS

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