Economic Feasibility of Strontium-90 Fueled Heaters for Use in Cold Regions

by
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February 1978

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SUMMARY

The objectives of this study are to conceptually design and obtain cost estimates for various radioisotope fueled heating systems for use in potential cold regions applications, and to determine the economic feasibility of radioisotope fueled heaters by comparing them to fuel oil systems. The applications have been identified and grouped, according to thermal output: 1) 1 kWt septic tank heaters, well-head heaters, heaters to assist operation of sewage lagoons, and 2) 7 or 12 kWt potable water system heaters. Potentially economic locations for these heaters are in remote Alaskan communities of 50 to 200 residents, where fuel oil prices and reliability requirements are high.

The advantages of radioisotope energy systems are: refueling only every five to ten years, low maintenance requirements, and high reliability. These systems consist of a radioisotope heat source, radiation shielding, and heat transfer and energy converting devices. Their safety has been demonstrated in the past in powering both remote weather stations and navigational aid systems.

Strontium-90 is the radioisotope heat source used in the heater conceptual designs and is presently available from the Hanford Waste Encapsulation and Storage Facility (operated for the Department of Energy by Rockwell International, Hanford Operations) through the Isotope Sales Division at Oak Ridge National Laboratory, Oak Ridge, Tennessee. The heat generating material is contained in a double-walled stainless steel capsule which is approximately 20 in. long and 2.6 in. in diameter. The heat generation rate is about 1 kWt per capsule.

Two basic conceptual heat designs were considered: a heat source and radiation shielding with no external heat transfer equipment, and a heat source and radiation shielding with external heat transfer equipment. Costs for both conceptual designs were estimated for heater sizes of 1 kWt, 7 kWt, and 12 kWt. The major costs were for the heat source and equipment. One capsule (1 kWt) is equivalent to 150,000 curies of strontium-90 (^{90}Sr). The present government price for this encapsulated ^{90}Sr is 10¢/curie fob

Hanford, Washington; thus, one capsule would cost \$15,000. The costs for 7 kWt, or 7 capsules, would be \$105,000 and for 12 kWt, or 12 capsules, \$180,000. The approximate costs are summarized below based on system size. Fuel oil system costs, based on \$1.50/gal fuel oil, are also given for comparison. Total capital cost for the radioisotope systems includes equipment, transportation and isotope fuel. Design, development, and licensing costs are not included. Annual cost includes both a pro-rated annual capital cost and operating costs.

System Size	Total Capital Cost, 1976 \$		Total Annual Cost, 1976 \$	
	Radioisotope System	Fuel Oil System	Radioisotope System	Fuel Oil System
1 kWt	50,000	4,000-10,000	8,000	2,000-6000
7 kWt	170,000-180,000	10,000	30,000-40,000	11,000
12 kWt	260,000-310,000	10,000	40,000-50,000	11,000

Radioisotope heaters are much more expensive than fuel oil systems. To assist in cost analysis, the costs can be reduced to overall equivalent fuel oil price, i.e., the price of fuel oil that would make radioisotope systems compete equally with fuel oil systems. These are summarized below. Isotope fuel costs have been factored out to show their contribution.

Radioisotope System Size	Equivalent Fuel Oil Price, \$/gal	
	Overall Costs	Radioisotope Fuel
1 kWt	7-16	6-8
7 kWt	11-12	9
12 kWt	12-15	11

A representative fuel oil price for remote locations in 1976 can be taken as \$1.50/gal; thus, fuel oil prices must increase dramatically before radioisotope systems can be economically competitive. If a 10% inflation rate of fuel oil prices over 10 years is assumed (10 years was taken as both radioisotope and fuel oil system life), the average effective fuel oil price would be \$2.50/gal, which is still much less than the lowest radioisotope system overall cost in equivalent fuel oil price of \$7/gal.

As shown above, the radioisotope fuel costs contribute 50% or more to the overall cost. Thus, an effective method to make a substantial reduction in radioisotope system cost would be to lower the strontium price from 10¢/curie. To make the radioisotope system economically competitive with \$1.50/gal fuel oil, the price would need to be lowered to 0¢/curie. Since the primary reason for encapsulating the strontium-90 is for nuclear waste management and not for providing radioisotope heat sources, a price reduction may not be entirely out of the question, but this must be decided by various government agencies who are in charge of the strontium, and by potential user agencies or potential user private groups. A primary consideration for the potential user is that the present supply of strontium-90 is limited to about 800 capsules; a future supply for system refueling may be available only at a price greater than 10¢/curie.

In conclusion, radioisotope heaters will not be economically competitive with fuel oil systems unless one or more of the following situations occur:

- the price of strontium-90 is reduced below 10¢/curie,
- fuel oil prices increase significantly, or
- for a particular application, the reliability or adaptability of a fuel oil system is unacceptable and a radioisotope system is satisfactory.

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ECONOMIC FEASIBILITY OF STRONTIUM-90 FUELED HEATERS FOR USE IN COLD REGIONS

1.0 INTRODUCTION

During the fission process in nuclear reactor operation, radioisotopes, termed fission products, are generated in the reactor fuel. After use in the reactor, the fuel can be reprocessed to recover uranium and plutonium for recycling into fresh nuclear fuel. The remaining fission products and fuel cladding are described as "nuclear waste" since with present technology they cannot be reused in nuclear fuel. However, due to radioactive decay, certain waste fission products have shown potential as heat and irradiation sources; these products could be termed "potential energy resources." The use of radioisotopes as energy sources is considered to be demonstrated technology. Radioisotope heat sources have been used in the past to power such systems as remote weather and navigation aid stations.^(1,2,3) Irradiation sources have been used to sterilize food⁽⁴⁾ and are currently being studied as a method of sewage treatment.⁽⁵⁾

One radioisotope heat source that is presently available from the Department of Energy (DOE) is strontium-90 (^{90}Sr). This radioisotope is being produced in encapsulated form, and each capsule generates approximately 1 kWt. The Division of Advanced Systems and Materials Production of DOE is conducting programs to identify, develop, and demonstrate beneficial applications of waste fission products. Since radioisotope powered systems are highly reliable, require little maintenance, and have long periods between refueling, potential markets for radioisotope systems are remote cold regions, where such qualities in energy systems are highly desirable.

Pacific Northwest Laboratory recently completed a study for DOE to identify potential cold regions applications.⁽³⁾ One promising application was the use of ^{90}Sr capsules in heating sewage and potable water systems which serve about 50 to 200 people in a remote community.

The objectives of the present study were to:

- describe the use of radioisotope heat sources,
- conceptually design radioisotope heaters for septic tank and water storage tank applications,
- estimate costs of both radioisotope and fuel oil heaters,
- compare the costs of these two types of systems, and
- make conclusions on the economic feasibility of the radioisotope heaters.

2.0 RADIOISOTOPE ENERGY SYSTEMS

Radioisotope energy systems are powered by the energy released from the decay of a radioisotope. These systems may be designed to provide heat or convert heat to electricity.

2.1 RADIOISOTOPE HEAT SOURCES

The principal advantages of using radioisotope heat sources are their high reliability, low maintenance requirements, and long periods between refueling. These advantages compete against the relatively high costs of recovering the radioisotope fuel from the other waste fission products, of encapsulating the fuel material in a metal container, of providing shielding against radiation, and of other factors principally related to the radioactive characteristics of the fuel material.

Due primarily to their radioactivity, radioisotopes can be hazardous. These potential hazards are controlled by the use of external shielding (e.g., lead) to reduce radiation exposure and by providing barriers (e.g., a metal container) against ingestion or inhalation of the radioisotopic material. Since the type of radiation emitted is dependent on the radioisotope, the precautions required may vary significantly. For example, the shielding required for alpha radiation can be provided by a sheet of paper, but for gamma radiation, several feet of concrete or 6 in. of lead may be needed.

The mixture of waste fission products contained in spent nuclear reactor fuel produces all types of radiation; thus, during separation of a specific radioisotope for use as a heat source, the facility must have thick concrete walls and must be built to withstand earthquakes and other natural disasters. Control and maintenance must be done remotely and require special equipment. Once separated, the radioisotope is placed in a high quality metal capsule. The capsule is welded and leak tested. Any radioactive material adhering to the outer walls of the capsule is removed before the capsule is placed in a radioisotope power system. During transport of the fuel capsules either to a power system already on location or in a power

system being moved to location, radiation shielding must be provided, which can be bulky and heavy. Also, additional weight for structural support may be required to protect the fuel material from entry into the environment in case the transport vehicle is involved in an accident. The above operations and precautions present no technical difficulties; they have been perfected over the past 30 years. However, the elaborate facilities, materials, and operations needed for the radioisotope fuel do significantly increase the costs of these systems.

2.2 LICENSING REQUIREMENTS

Since there are potential hazards in using radioactive material, Nuclear Regulatory Commission (NRC) requirements must be met and licenses obtained in order to use a radioisotope powered system. Regulatory Guide 6.3, "Design, Construction, and Use of Radioisotopic Power Generators for Certain Land and Sea Applications"⁽⁶⁾ has been issued, which recommends with several additions the International Atomic Energy Agency's Safety Series No. 33.⁽⁷⁾ The tests required for the fuel capsule are outlined below:

- a drop test from 9 m
- a percussion test
- thermal test - heated to 800°C (or maximum operating temperatures if higher) for 30 minutes
- thermal shock test
- external pressure test - 10^8 ^{newtons} ~~neutrons~~/m² (1.45×10^4 psia)
- leakage test - 10^{-8} (STP) cm³/sec
- other tests (e.g., corrosion, creep, irradiation) may be specified.

The fuel capsule housing, which is an integral part of the power system, must be tested in a similar manner. If the housing contains the radiation shielding, this shielding must remain intact after each test. If the fuel capsule is transported in a heavy-walled container (transport cask) and placed in the capsule housing on site, the cask must be tested and approved.

Licensing and a safety assessment report must be completed for the NRC before the heaters can be installed. A license application must designate the radioisotope fuel, intended purpose of device, name and radiation training of individual users of the power systems, radiation experience, radiation detection instruments, facility installation, handling equipment, radiation protection program, and disposal of waste. A safety assessment report requires descriptions of the fuel, fuel capsule, power system, proposed application, accident and hazard analysis, maintenance, responsibility, test program, and ultimate disposal. The length and detail of these reports would be greater for a prototype system than for a design that has been previously used.

Transport of radioisotopes is regulated by the Department of Transportation and the Nuclear Regulatory Commission. The radioisotopes must be transported in approved containers. For the quantities of material discussed here, the common name for the container is "transport cask;" the required shielding and structural protection make up a device that would weigh hundreds of pounds. The cask can be part of the energy system, which is usually the case with radioisotope thermoelectric generators, or it can be separate. In the later case, the heat source would be transported to the site, removed from the cask, and inserted into the energy system. The type of cask and the requirements that must be met depend on the transportation mode: rail, sea, truck, or aircraft. Radioisotopes have been transported safely for many years; the design and use of approved shipping casks present no technical difficulties.

2.3 SYSTEM DESCRIPTIONS

In general, radioisotope power systems have three common characteristics:

- 1) a heat source consisting of a radioisotope material enclosed in a metal capsule (heat is generated by the radioactive decay of the isotope);
- 2) shielding to reduce the external radiation from the heat source; and
- 3) additional heat transfer and energy converting devices to achieve the desired output: electric, mechanical, or heat.

The most common type of radioisotope power system that has been developed and used to date is the radioisotope thermoelectric generator (RTG). The RTG is based on the thermoelectric principle that when two dissimilar metals are joined together and heated at the junction, an electrical voltage difference exists between the two free ends. An RTG has a radioisotope source which heats the metal junctions, resulting in an electrical generator that has no moving parts. Energy conversion efficiency of RTGs is approximately 5%. Since the rate of energy production decays with time, the system must be periodically refueled or replaced. The length of time between these operations depends on the specific radioisotope used and on the energy requirements; for strontium-90, a 10-year period can be used as a guideline.

Many RTGs have been built and demonstrated successfully, primarily as remote weather stations and as navigation aids. For example, an RTG has powered a weather station on Fairway Rock in the Bering Strait for over ten years. (See References 1, 2, 3 for more detailed information on other RTG demonstrations.) The Alaskan Region Office, Federal Aviation Administration, installed five RTGs in September 1977 to power aircraft navigation aid systems located in the Lake Clark Pass area between Bristol Bay and Kenai; propane fueled thermoelectric generators were not adequately reliable.

Another type of system which has received increased attention recently due to its higher efficiency (~15%) involves a radioisotope source heating a working fluid which drives a dynamic electrical generating system. Examples are the Rankine, Brayton, and Sterling Cycle Systems. These systems have not been developed and demonstrated as extensively as RTGs. The dynamic system requires additional operating experience to demonstrate its reliability; the high reliability of the radioisotope heat source is already known from RTG technology.

In the present application of radioisotopes used to heat liquid, the heat source technology (e.g., encapsulating the fuel material and providing radiation shielding) is established technology. However, further experimental work may be needed to determine heat transfer characteristics.

3.0 COLD REGION RADIOISOTOPE HEATERS

Remote cold regions have high fuel oil costs and high system reliability requirements. This has led to the identification of potential applications of radioisotope fueled heaters for sewage and potable water systems.

3.1 STRONTIUM-90 HEAT SOURCE

The heat source that is presently available for these heaters is a strontium fluoride (SrF_2) capsule currently being produced at the Hanford Waste Encapsulation and Storage Facility (WESF), operated for DOE by Rockwell International, Rockwell Hanford Operations. The capsules contain ^{90}Sr , which undergoes radioactive decay and in turn, generates heat. The diagram of the SrF_2 capsule is shown in Figure 1.⁽⁸⁾ This capsule has double containment. The figure also describes the cesium chloride (CsCl) capsule, another WESF product that is less suitable as a heat source.^(a) These materials were produced during national defense programs and are being encapsulated for nuclear waste management; presently the capsules are stored in water basins that provide cooling and shielding.

Each SrF_2 capsule contains about 150,000 curies of ^{90}Sr (mostly beta decay energy), which generate approximately 1 kWt. As the ^{90}Sr decays it decreases with time. The half-life of ^{90}Sr is 29 years. Half-life is defined as the time required for a sample of a particular radioisotope to decay to only half the original number of atoms of that radioisotope. For example, a sample of pure ^{90}Sr would be 50% ^{90}Sr and 50% ^{90}Zr after 29 years (the heat generation rate would drop to approximately 0.9 kWt and 0.8 kWt after 5 and 10 years, respectively).

The Federal Government is presently making its inventory of ^{90}Sr available through the Isotope Sales Division at Oak Ridge National Laboratory, Oak Ridge, Tennessee, at a price of 10¢/Ci;⁽⁹⁾ thus, a WESF capsule

(a) The CsCl capsule generates about 0.3 kWt, primarily from gamma decay energy. Since the ^{137}Cs gamma radiation penetrates further than the ^{90}Sr beta radiation and the Cs capsule heat load is about 1/3 the Sr capsule heat load, the Cs source has more potential in radiation applications.^(4,5)

WASTE ENCAPSULATION AND STORAGE FACILITY CAPSULE

	Strontium Fluoride Capsule	Cesium Chloride Capsule
Inner Capsule:		
Material	Hastelloy C-276 or 316-L stainless steel	316-L stainless steel
Wall Thickness	0.205 cm	0.241 cm
Outside Diameter	5.72 cm	5.72 cm
Total Length	48.89 cm	50.10 cm
Total Cap Thickness	1.02 cm	1.02 cm
Outer Capsule:		
Material	316-L stainless steel	316-L stainless steel
Wall Thickness	0.277 cm	0.277 cm
Outside Diameter	6.67 cm	6.67 cm
Total Length	51.05 cm	52.77 cm
Total Cap Thickness	1.02 cm	1.02 cm
Density	2.76 - 2.97 g/cm ³	2.47 g/cm ³
Quantity of Radioisotope	48 - 49 wt% ⁹⁰ Sr	48 - 49 wt% ¹³⁷ Cs
Impurities	4 - 6 wt%	4 - 6 wt%
Heat Generation	1 kW	300 watts
Radioactivity	150,000 Ci ⁹⁰ Sr	70,000 Ci ¹³⁷ Cs

FIGURE 1. WESF Strontium Fluoride and Cesium Chloride Capsule Characteristics

would cost \$15,000, excluding incremental handling and shipping charges. There are presently about 200 SrF_2 capsules on hand. Total production is planned for about 800 capsules.

3.2 POTENTIAL APPLICATIONS

Potential applications for radioisotope fueled heaters were identified during discussions with Public Health Service and Environmental Protection Agency staff, who are responsible for designing, building, and maintaining sewage treatment and potable water systems in remote Alaskan communities.

The severe climate and relatively high cost of fuel are the motivating factors for the consideration of radioisotope heaters. These heaters may be economically competitive with other systems because of:

- 1) high reliability since in extreme cold the failure of a fuel oil system can cause significant damage to equipment;
- 2) special applications where a radioisotope heater may have reduced capital cost, such as heating an underground septic tank; and
- 3) a periodic refueling requirement of approximately 10 yr.

The problems associated with sewage treatment are caused by low temperatures inhibiting sewage digestion. Tile fields in septic tank systems may need replacement in one or two years because of plugging from solids. The addition of heat to the tank would assist the anaerobic digestion of solids. Heating lagoons would also be beneficial; however, to keep a lagoon from freezing would be extremely costly without insulating the free surface. Keeping small surface areas and transfer structures ice-free might be practical. The Public Health Service roughly estimated that they could use 100 to 200 1-kWt heaters. Additional applications by others could at least double these numbers. The Federal Aviation Administration has similar sewage treatment problems at some of their remote installations. In general, heating both septic tanks and lagoon systems is considered technically feasible in areas with little or no permafrost.

Heat requirements for potable water systems are about 100 times greater than for sewage treatment systems, and could be more important in terms of creating a market for radioisotope systems. In many cases, storage tanks are needed for constant potable water supply and must be heated during the winter. The heat requirements vary from month to month. Table 1 gives heat requirements for a 200,000 gal water storage tank located above ground on pilings (a requirement in permafrost areas) and insulated with 4 in. of urethane foam. A radioisotope fueled heater could supply either the total heat requirement or a portion of the requirement (with the remainder supplied by a fuel oil system). Both alternatives will be considered. Another potential use for radioisotope heaters would be to heat a water well, allowing year-round pumping; this system would be similar to the 1 kWt heaters discussed above.

TABLE 1. Heat Requirements for a 200,000 Gal Water Storage Tank^(a)

Month	Average Air Temp., °F	Heat Requirements	
		Btu/hr	kWt
Jan	-60	40,000	11.7
Feb	-50	38,000	11.1
Mar	-30	34,500	10.1
Apr	-10	30,700	9.0
May	+10	27,200	8.0
June	+20	25,400	7.4
July-Sept	+40 or more	none	none
Oct	+10	27,200	8.0
Nov	-10	30,700	9.0
Dec	-30	34,500	10.1
Average/Mo		29,000	8.5

Basis: 200 people using 50 gal/person/day

Water inlet temp. = 33°F, Outlet (Static) = 40°F

4 in. of urethane foam ($K = 0.11 \frac{\text{Btu}}{\text{hrft}^2\text{°F/in.}}$)

Tank dimensions = 12 ft high, 27 ft radius

^(a) This information was provided by L. P. Wallace, Senior Sanitary Engineer, U.S. Public Health Service, Anchorage, Alaska, November 1976.

Conceptual designs have been developed for the following radioisotope heater systems:

- 1) 1 kWt self-contained (one WESF capsule) heater which is licensed as a transport cask. No external heat transfer equipment is provided. It is expected that a heater this size could be used to heat a 10,000 gal septic tank which serves a community of about 100 people, lagoon systems, or potable water wells (to allow year-round pumping).
- 2) 1 kWt heater which has external heat transfer equipment to enhance heat distribution. The heat source will be transported in a cask, removed from the cask, and inserted into the system. The cask will be reused for fueling other systems. The potential applications are the same as those above.
- 3) 12 kWt heater without external heat transfer equipment for a 200,000 gallon potable water tank. This will replace an equivalent size fuel oil system.
- 4) 12 kWt heater with external heat transfer equipment for a potable water tank. The system will be completely built before being fueled with the heat generating capsules.
- 5) 7 kWt heater without external heat transfer equipment for a potable water tank. Additional peak loads to 12 kWt will be supplied by a back-up 5 kWt fuel oil system.
- 6) 7 kWt heater with external heat transfer equipment for a potable water tank. A 5 kWt fuel oil system for additional peak loads will also be needed.

4.0 ECONOMICS

The primary economic factors for radioisotope heaters are transportation costs, capital costs for fuel and equipment, installation costs, and minor operating costs. For fuel oil systems the cost factors are for installation, equipment, transportation, fuel oil, and maintenance. By comparing total costs for both systems (on capital and annual cost bases), the economic feasibility of each radioisotope system can be determined.

4.1 TRANSPORTATION OF RADIOISOTOPE FUEL

For many years radioactive materials have been safely shipped by truck, train, ship, and aircraft. A number of special transportation containers or casks have been designed and used. A review was made of available shipping casks to determine if one existed which could be used to transport a ^{90}Sr WESF capsule by air since this would be the primary method of transport for remote cold region locations. To transport one ^{90}Sr capsule, the container would require shielding equivalent to approximately 7 in. of lead (4 in. of uranium) and a 3 x 24 in. cavity. No existing casks met the requirements for air (several are available for other transport modes). Recent NRC regulations for licensing air transport casks involve stringent fire and drop tests; thus, it is likely an additional cask would need to be designed and fabricated.

Depending on the design of the heater: 1) the transport cask could be part of the heating system, or 2) the heat sources could be removed from the cask and inserted into the heater system in the field. The first alternative involves less handling of the heat sources when the heater is fueled and refueled, but the capital investment of the heater increases due to the cost of the transport cask. The cask in the second alternative could be used many times to deliver and recover heat sources, and concrete could be used as the heater system shielding.^(a) However, a secondary heat

^(a) Concrete thickness of 3 ft is approximately equivalent to 0.7 in. of lead shielding. Concrete and other materials such as iron are unsuitable as cask shielding for air transport since cask size and weight would be greatly increased. Size and weight are important when considering air transportation charges.

transfer system may be needed because of the low thermal conductivity and thickness (about 3 ft) of concrete. Costs will be estimated for both cask alternatives.

The logistics of transport have alternatives also. It may be more economical to transport three capsules from Hanford to Alaska, then distribute them to three different sites, rather than make a separate delivery for each capsule. A cask containing six or seven capsules could potentially reduce transport costs. Table 2 presents the cask sizes, weights, and costs for lead and uranium shielding. Cost estimates are based on \$4.20/lb for lead and \$12.60/lb for uranium casks (updated from Ref 10). Lead shielding thickness is 7 in. and uranium thickness is 4 in. One in. of stainless steel shell has been included. A stand and cooling fins would add about 250 lb. Uranium has the advantage of being a more effective shielding material than lead, and cask size and weight is reduced for the same cavity size; however, it is more expensive than lead. For a prototype cask, the costs would be much higher for design, safety analysis, and testing.^(a)

The transport costs, which can be significant in remote locations, will be based on the following:

- the community is located 260 miles from a major city, such as Fairbanks;
- transport is by fixed wing aircraft; and
- there is either a device in the community or one on the same flight as the cask to handle the cask on the ground.

(a) A range of \$50,000 to \$100,000 for the design, safety analysis, and testing of a prototype cask has been estimated. These are one-time costs for a specific design. Since it is assumed one cask design would be used to construct many casks or that one cask would be reused many times, these costs would be distributed to all the systems. For 100 systems, the additional cost would be only \$500 to \$1,000. These costs are included in this study in a cask use charge for those situations where one cask is used many times. For the cases where many casks are built from one design (cask as part of heater system), these costs are minor and have not been included. It is recommended that in future analyses if it is known that the number of applications of the cask will be much less than 100, these costs should be included by adding them to those listed in Table 2.

TABLE 2. Transport Casks

<u>No. of Capsules</u>	<u>Shielding Material</u>	<u>Cavity Dimensions, in.</u>	<u>Overall Dimensions, in.</u>	<u>Weight, lbs.</u>	<u>Cost, 1976\$</u>
1	Lead	3x24	19x40	4500	20,000
1	Uranium	3x24	13x34	2600	33,000
3	Lead	6x24	22x40	5800	25,000
3	Uranium	6x24	16x34	3700	47,000
7	Lead	9x24	25x40	7200	30,000
7	Uranium	9x24	19x34	4800	60,000

Once the transport cask is loaded, it must be shipped from Hanford to Fairbanks, then from Fairbanks to the application site. The cask must be returned to Hanford if it is to be reused. Table 3 summarizes estimated transportation charges for two alternatives: 1) the cask is part of the heater system, and 2) the cask is reused to fuel many heater systems.

TABLE 3. Costs to Transport Radioisotopes

<u>No. of Capsules</u>	<u>Shielding Material</u>	<u>Cask Wt., lbs</u>	<u>Transport Hanford to Fairbanks, 1976\$</u>	<u>Transport Fairbanks to Site, 1976\$</u>	<u>Total Transport Costs-Cask Part of Heater, 1976\$</u>	<u>Total Transport Costs-Cask Reused, 1976\$</u>
1	Pb	4500	800	900	5200	6800
1	U	2600	500	900	4600	5600
3	Pb	5800	1000	900	5600	7600
3	U	3700	700	900	5000	6400
7	Pb	7200	1300	900	6200	8800
7	U	4800	900	900	5400	7200

Basis: C-46 Aircraft - 12,000 lb payload, \$3/air mile plus 5% tax and \$100 loading fee

Truck freight Hanford to Fairbanks ~ \$16/100 lbs.

Costs are for truck transport to Fairbanks. Air transport costs are based on a C-46 aircraft. It has the advantage of a 12,000 lb payload which allows the crew and materials needed for cask unloading to be transported in the same flight as the cask. It is assumed that ground transport for the cask would be available at the site or could be carried in the C-46.^(a)

4.2 RADIOISOTOPE HEATERS

Potential applications for radioisotope heaters in cold regions are primarily in heating septic tanks, lagoon systems and potable water systems. The thermal output required for septic tanks, lagoon transfer structures, and water wells is 1 kWt; for a community water tank, 12 kWt are required. Thus, in this study we are concerned with 1 kWt and 12 kWt radioisotope systems, as well as a 12 kWt combination radioisotope (7 kWt)/fuel oil (5 kWt) system.

The cost estimates for these systems are based on conceptual designs and not on detailed heat transfer analyses. If these radioisotope systems show economic potential, detailed design and cost analysis will be justified. An overall contingency of 20% is used to account for the absence of detailed design. Detailed design and development costs for the radioisotope systems have been assumed to be one-time costs that would be distributed among many systems and have not been included in the capital cost estimates. Annual capital costs are based on 10% interest over 10 yr, pro-rating these costs over the 10-yr period.^(b)

(a) For the uranium cask which weighs 2600 lb, a Twin Otter aircraft (maximum payload 3100 lb) might be used, but the charges would be about the same as for the C-46. If ground transportation is not available at the site or the C-46 cannot carry it, a Hercules aircraft could be used but at a significant cost increase (45,000 lb payload at about \$8.50/air mile).

(b) The annual capital cost has been calculated by multiplying the total capital cost by a "capital-recovery factor" (0.163). The capital-recovery factor is the inverse of the "discrete uniform-series present-worth factors."

4.2.1 1 kWt Heaters

The first radioisotope heater concept is for a 1 kWt heater that has no external heat transfer equipment; thus, it is essentially a transport cask. Potential applications are for heating septic tanks, lagoon transfer structures, and water wells. Capital costs are for the transport cask, radioisotope fuel, and cask transportation. Operating costs are assumed to be minimal; an inspection each year is probably necessary. This could be done in conjunction with other duties so the costs are distributed. Based on four hours of inspection at \$25/hr and a distributed living and transportation expense of \$400/trip, total yearly operating costs are estimated to be about \$500. The cask has lead shielding since the capital cost for a lead cask (\$20,000) is less than for a uranium cask (Table 2). The radioisotope fuel costs are \$15,000. Total transport costs are estimated at \$5200 (Table 3). Table 4 summarizes the costs for this heater concept.

TABLE 4. Preliminary Cost Estimate for 1 kWt Strontium-90 Heater, No External Heat Transfer Equipment

<u>Item</u>	<u>Cost, 1976\$</u>
Transport Cask (4500 lb lead cask as part of heater)	<u>\$20,000</u>
Equipment Cost Total	\$20,000
Transportation Cost	5,200
Total	
Radioisotope Fuel (1 ⁹⁰ Sr Capsule @ \$15,000)	\$15,000
Heater Emplacement and Recovery (2 workers, 8 hr @ R50/hr)	<u>800</u>
Radioisotope Fuel Cost Total	<u>15,800</u>
Capital Cost Subtotal	\$41,000
Contingency 20%	8,200
Total Capital Cost	<u>\$49,200</u>
Annual Capital Cost (10% interest over 10 yrs)	\$ 8,000
Annual Operating Cost (one inspection per year)	<u>500</u>
Total Annual Costs	<u>\$8,500</u>

The second concept is for a 1 kWt heater that has external heat transfer devices to distribute the heat. A preliminary cost estimate for this system is given in Table 5. The radiation shielding is provided by concrete and the transport cask is reused to fuel many other systems; the objective is to reduce capital costs. A conceptual design of this concept for heating a septic tank is shown in Figure 2.

TABLE 5. Preliminary Cost Estimate for 1 kWt Strontium-90 Heater,
External Heat Transfer Equipment

<u>Item</u>	<u>Cost, 1976\$</u>	
Concrete for Shielding (9 yd ³ @ \$600/yd ³)	\$5,400	
2-in. Stainless Steel Pipe (100 ft @ \$40/ft)	4,000	
4-in. Stainless Steel Pipe (20 ft @ \$50/ft)	1,000	
Stainless Steel Shell (300 lb @ \$3/lb)	900	
Installation Crew (2 workers - 5 days @ \$50/hr)	<u>4,000</u>	
Equipment Costs Total		\$15,300
Equipment Transportation from Hanford (1,500 lbs)	\$1,000	
Installation Crew Transportation (Return to Fairbanks)	400	
Cask Use Charge (Cost of 1 cask @ \$100,000 distributed between 100 systems)	1,000	
Radioisotope Transport (Delivery and Return)	<u>5,600</u>	
Transportation Costs Total		8,000
Radioisotope Fuel (1 ⁹⁰ Sr Capsule @ \$15,000)	\$15,000	
Radioisotope Fuel Handling (2 workers - 8 hr @ \$50/hr)	<u>800</u>	
Radioisotope Fuel Total		<u>15,800</u>
Capital Cost Subtotal		\$39,100
Contingency 20%		<u>7,800</u>
Total Capital Costs		<u>\$46,900</u>
Annual Capital Cost (10% interest over 10 yrs)		\$ 7,600
Annual Operating Cost (one inspection per yr)		<u>500</u>
Total Annual Costs		<u>\$ 8,100</u>

FIGURE 2. Septic Tank Heater - 1 kw

The cost estimates in Tables 4 and 5 show that the 1 kWt heater with external heat transfer equipment may have a slight cost advantage over the heater without external equipment. However, the difference in total annual cost of \$8500 to \$8100 is not significant, due to the uncertainty of the estimates.

4.2.2 12 kWt Heaters

The cost estimate for a 12 kWt heater that has no external heat transfer equipment is presented in Table 6. This concept is for two large lead transport casks placed under a 200,000 gal water storage tank. Insulation is added around the lower edge of the tank enclosing the transport casks; thus, heat transfers from the casks up into the water tank. Pilings, a platform, and insulation are needed under the casks to prevent thawing of permafrost. During the warmer months the insulation could be removed or a vent system could be provided to remove excess heat. The total annual cost for this system is estimated at about \$52,000 per year (over half is the cost of the radioisotopes).

TABLE 6. Preliminary Cost Estimate for a 12 kWt Strontium-90 Water Heater, No External Heat Transfer Equipment

<u>Item</u>	<u>Cost, 1976\$</u>
Transport Casks (2 lead casks, 7200 lbs each)	\$60,000
Housing for Heater (Structure, Insulation, etc. @ \$100/ft ² , 50 ft ²)	<u>5,000</u>
Equipment Cost Total	\$65,000
Transport Costs Total	12,400
Isotope Fuel (12 ⁹⁰ Sr Capsules @ \$15,000 ea)	\$180,000
Heater Emplacement and Recovery (2 workers, 16 hrs @ \$50/hr)	<u>1,600</u>
Isotope Fuel Cost Total	<u>181,600</u>
Capital Cost Subtotal	\$259,000
Contingency 20%	<u>51,800</u>
Total Capital Cost	<u>\$310,800</u>
Annual Capital Cost (10% interest over 10 yrs)	\$50,700
Annual Operating Cost (One inspection per yr plus manual control of heat)	<u>1,000</u>
Total Annual Costs	<u>\$51,700</u>

A 12 kWt water tank heater with heat transfer equipment is shown in Figure 3. The primary components are concrete shielding (about 3 ft thick), the secondary barrier (stainless steel pipe) between the capsule and water, and piping for water transport. There is an air gap between the capsule and secondary barrier, with a drain at the bottom of the gap; thus, if a leak develops in the barrier, any water that might contact the capsule would flow out of the system. This water would become contaminated with strontium-90 only if the double capsule walls, the primary barriers, were breached. Therefore, this design ensures that no strontium-90 could enter the potable water system. This concept assumes natural circulation of the water. The capsules are transported in a cask, then loaded into the system. The preliminary cost estimate for this heater concept is given in Table 7. Several modes of capsules transport were considered: 1 capsule per cask, 3 capsules per cask, and 7 capsules per cask. The costs of these various options can be compared by referring to Table 3; the reuse of the 7 capsule cask is the most cost-effective.

In comparing the two types of 12 kWt heaters, once again the system with the external heat transfer equipment has a lower annual cost estimate (\$44,000) than the system consisting of two lead transport casks (\$52,000). This is primarily due to the higher estimated cost of the transport casks compared to the concrete shielded heat transfer system. However, several assumptions have been made for the latter system which, if varied, could significantly increase costs. The costs of concrete are based on four times Hanford costs, assuming it is fabricated in the field. Pipe costs have been estimated based on Hanford costs plus field labor and transportation since piping could be pre-fabricated then assembled on location.

4.2.3 12 kWt Combination Radioisotope/Fuel Oil Systems

The last two concepts are water tank heaters consisting of a 7 kWt isotope heater with a secondary 5 kWt fuel oil system to supply additional power during winter peak loads (the 5 kWt system costs are developed in the following section). The radioisotope heater with no external heat transfer equipment is compared to one with external heat transfer equipment. The

FIGURE 3. Water Storage Heater - 12 kWt

TABLE 7. Preliminary Cost Estimate for a 12 kWt Strontium-90
Water Heater, External Heat Transfer Equipment

<u>Item</u>	<u>Cost, 1976\$</u>
Concrete for Shielding (13 yd ³ @ \$600 yd ³)	\$8,000
Stainless Steel (Secondary barriers, cavity lines, etc. fabricated at Hanford)	5,000
2-in. Stainless Steel (50 ft @ \$50/ft) Pipe	2,500
Installation Crew (3 workers - 5 days @ \$50/hr)	<u>6,000</u>
Equipment Costs Total	\$ 21,500
Equipment Transportation from Hanford (about 2,000 lb)	\$1,000
Installation Crew Transportation (Return to Fairbanks)	400
Cask Use Charge (Cost of Cask @ \$150,000 Distributed between 100 systems)	1,500
Radioisotope Transport (Delivery and Return)	<u>14,400</u>
Transportation Costs Total	17,300
Radioisotope Fuel (12 ⁹⁰ Sr Capsules @ \$15,000 ea)	\$180,000
Radioisotope Fuel Handling (2 workers-24 hr @ \$50/hr)	<u>2,400</u>
Radioisotope Fuel Total	<u>182,400</u>
Capital Cost Subtotal	\$221,200
Contingency 20%	<u>44,200</u>
Total Capital Costs	<u>\$265,400</u>
Annual Capital Cost (10% interest over 10 yr)	\$43,300
Annual Operating Costs (one inspection per yr)	<u>500</u>
Total Annual Costs	<u>\$43,800</u>

costs for the 7 kWt radioisotope portion of these combination systems are presented in Tables 8 and 9, respectively. The annual costs are somewhat higher for the self-contained heater (\$29,000 compared to \$27,000), as in the previous cases.

TABLE 8. Preliminary Cost Estimate for a 7 kWt Strontium-90 Water Heater, No External Heat Transfer Equipment

<u>Item</u>	<u>Cost, 1976/\$</u>
Transport Cask (1 lead cask, 7200 lb)	\$30,000
Housing for Heater	<u>3,000</u>
Equipment Cost Total	\$33,000
Transportation Cost Total	6,200
Radioisotope Fuel (7 ⁹⁰ Sr Capsules @ \$15,000 ea)	\$105,000
Heater Emplacement and Recovery (2 workers - 12 hr @ \$50/hr)	<u>1,200</u>
Radioisotope Fuel Cost Total	<u>\$106,200</u>
Capital Cost Subtotal	145,400
Contingency 20%	<u>29,100</u>
Total Capital Cost	<u>\$174,500</u>
Annual Capital Cost (10% interest over 10 yr)	\$28,400
Annual Operating Cost	1,000
Total Annual Cost	<u>\$29,400</u>

TABLE 9. Preliminary Cost Estimate for a 7 kWt Strontium-90
Water Heater, External Heat Transfer Equipment

<u>Item</u>	<u>Cost, 1976\$</u>
Concrete for Shielding (11 yd ³ @ \$600/yd ³)	\$6,600
Stainless Steel (Secondary barriers, cavity liner, etc. fabricated at Hanford)	4,000
2-in. Stainless Steel Pipe (50 ft @ \$50/ft)	2,500
Installation Crew (3 workers-5 days @ \$50/hr)	<u>6,000</u>
Equipment Cost Total	\$19,100
Equipment Transportation from Hanford (about 7,000 lb)	\$1,000
Installation Crew Transportation (Return to Fairbanks)	400
Cask Use Charge (Cost of cask @ \$150,000 distributed between 100 systems)	1,500
Radioisotope Transport (Delivery and Return)	<u>7,200</u>
Transportation Costs Total	10,100
Radioisotope Fuel (7 ⁹⁰ Sr Capsules @ \$15,000 ea)	\$105,000
Radioisotope Fuel Handling (2 workers - 16 hr @ \$50/hr)	<u>1,600</u>
Radioisotope Fuel Total	<u>106,600</u>
Capital Cost Subtotal	\$135,800
Contingency 20%	<u>27,200</u>
Total Capital Costs	<u>\$163,000</u>
Annual Capital Costs (10% interest over 10 yr)	\$26,600
Annual Operating Costs (One inspection per yr)	<u>500</u>
Total Annual Costs	<u>\$27,100</u>

Two basic radioisotope systems have been discussed: self-contained units (transport casks) and concrete shielded power units with external heat transfer equipment. The latter systems appear to be slightly less costly than the self-contained units, at least from the cost estimate assumptions used here. However, the self-contained units have several advantages which could make them more economical: 1) licensing could be simpler since an air transport cask would probably be designed to withstand more severe conditions than would be required for a radioisotope heater, and 2) handling of capsules at the site would be minimized (they remain in the transport cask). An advantage of the units with external heat transfer equipment is that in certain applications they distribute heat more efficiently and economically.

4.3 FUEL OIL SYSTEMS^(a)

The smallest fuel oil boiler available in Anchorage, Alaska, has a maximum output of 23 kWt (80,000 BTU/hr) and consumes about 1 gal fuel oil/hr. The cost estimates for fuel oil heaters located in remote Alaskan communities are based on this boiler. Four modes of operation are considered:

- 1) heating a potable water tank (200,000 gal), maximum requirement during the coldest weather is 12 kWt;
- 2) heating a potable water tank in conjunction with a 7 kWt radio-isotope heater, maximum output is 5 kWt;
- 3) heating a septic tank or other equipment that has continuous heat requirement (1 kWt); and
- 4) heating both a potable water tank and a septic tank, maximum output is 13 kWt.

Since 13 kWt is the maximum output needed, the 23 kWt boiler is underutilized by at least 10 kWt.

^(a) The costs for fuel oil systems have been extrapolated from information supplied by engineers who have experience with these types of systems: L. P. Wallace, Senior Sanitary Engineer, U.S. Public Health Service, Alaska Area Native Health Service, Anchorage Alaska, and B. H. Reid, Research Engineer, Environmental Protection Agency, Artic Environmental Research Laboratory, College, Alaska, November 1976.

4.3.1 12 kWt Heaters

One method of heating a potable water tank is to operate the 23 kWt capacity boiler at a 12 kWt level. The fuel oil consumption is 3200 gal/yr, based on heat load information in Table 1 (Section 3.2) with slight additions for heating the boiler building. Table 10 outlines the estimated cost of this system. Total capital cost is \$9700 and the total annual cost, including fuel oil at \$1.50/gal, is \$10,300.

TABLE 10. Cost Estimate for a 12 kWt Fuel Oil Water Tank Heater

Item	Cost, 1976\$
Boiler	\$1,000
Heat Exchanger	300
Piping	200
Electrical	100
Installation	<u>1,000</u>
Boiler Equipment Costs Subtotal	\$2,600
Building	\$4,500
Site Preparation	100
Electrical	200
Miscellaneous	<u>200</u>
Building Cost Subtotal	<u>\$5,000</u>
Equipment Cost Total	\$7,600
Transportation Cost Total	<u>1,200</u>
Capital Cost Subtotal	8,800
Contingency 10%	<u>900</u>
Total Capital Cost	<u><u>\$9,700</u></u>
Annual Capital Cost (10% interest over 10 yrs)	\$1,600
Annual Labor	1,800
Annual Inspection and Repairs	1,600
Electricity	500
Fuel Oil @ \$1.50 (3200 gal)	<u>4,800</u>
Total Annual Cost	<u><u>\$10,300</u></u>

An alternative to using a 12 kWt system produced solely by fuel oil is to supplement the fuel oil heater with a radioisotope heater. A 5 kWt fuel oil heater in conjunction with a 7 kWt radioisotope heater was considered as such an alternative. For a 5 kWt fuel oil system, the capital cost is the same as the 12 kWt system, \$9700 (both systems use the 23 kWt boiler). Annual operating costs would be reduced, since 5 kWt (needed only in coldest periods, see Table 1) would only use 800 gal of fuel oil a year. The savings of \$3600 would result in a total annual cost of \$6700/yr. Costs of a 7 kWt radioisotope system have to be included in this alternative, and significantly effect the estimate (Tables 8 and 9).

4.3.2 1 kWt Heaters

It is estimated that only 1 kWt of power is required to heat the septic tank.^(a) This can be accomplished in two ways: 1) by running the 23 kWt boiler periodically, having the same effect as a 1 kWt heater running continuously, or 2) by using the same boiler as the water tank heater by increasing the output from 12 kWt to 13 kWt.

The first option is the least efficient and the most expensive. Such an option would only be considered if the septic tank is isolated and no other heat sources are feasible. The total capital cost would again be \$9700. The fuel oil requirement would be 400 gal/yr, saving \$4200/yr from the 12 kWt fuel costs. Total annual costs for this system would be \$6100.

The second option for heating a septic tank is far more cost effective than the first, but is dependent on a community having the need for both 12 kWt and 1 kWt heaters. It involves piping steam from a boiler house to a heat exchanger in the septic tank. In this case, costs for the 13 kWt system (12 kWt for water heater + 1 kWt for the septic tank) are distributed to the 1 kWt system by a factor of 1/13 (excluding costs for additional piping, heat exchanger and fuel oil). Assuming a distance of 50 ft between the boiler house and the septic tank, the capital cost for the 1 kWt

^(a) Other equipment such as lagoon transfer structures and water wells could also use 1 kWt for more efficient operation. A septic tank is used here only as an example.

portion of the system is \$3800 (including two separate pipes at \$25/ft and a heat exchanger at \$500). The fuel oil consumption is about 480 gal/yr since some heat is lost during transport through the pipes. Thus, the total annual cost is \$1600/yr.

If full use could be made of the 23kWt capacity boiler, costs could be distributed in all the systems, making each more cost effective. One possible additional application is the heating of homes; however most dwellings are located more than 50 ft from the boiler, so it is probably more cost effective to have separate home heaters. In this study, it will be assumed that the 5 and 12 kWt fuel oil systems do not have distributed costs; a 1 kWt system would more likely have distributed costs.

4.4 ECONOMIC COMPARISONS

When comparing radioisotope and fuel oil systems, the reliability of the radioisotope systems can offer significant cost savings. This is one of the prime motivating factors for the Federal Aviation Administration's interest in using radioisotope thermoelectric generators to power remote aircraft navigational aid systems. The reliability of fuel oil systems varies with complexity of the system and the conditions of system failure. One rough estimate was that one or two systems must be replaced each year out of a total of 60 to 70 systems. The freezing and subsequent destruction of equipment, and accidental damage during attempts to restart or repair systems are reasons for system replacement. To account for this reliability, a factor of 2/60 (0.033) will be added to the annual capital cost of each fuel oil system. Thus, 60 systems are charged for the 2 systems that fail each year. The annual cost is \$300 for each 12 and 5 kWt system and from \$100 to \$300 for a 1 kWt system.

Table 11 summarizes the costs for both radioisotope and fuel oil systems. In every case, the capital investment required for radioisotope systems is high when compared to the fuel oil system. However, since the radioisotope systems do not consume fuel oil, which is an operating cost, it is more appropriate to compare the two types of systems based on total annual cost,

TABLE 11. Comparison Between Total Capital and Annual Costs of Radioisotope and Fuel Oil Heaters

Strontium-90 Radioisotope Systems			Fuel Oil Systems			Potential Applications
Description	Total Annual Cost, 1976\$	Total Annual Cost, 1976\$	Description	Total Capital Cost, 1976\$	Total Annual Cost, 1976\$	
1 kWt Self-Contained Heater	49,200	8,500	1 kWt Fuel Oil System	3,800 - 9,700	1,700 - 6,400	Heaters for Septic Tanks, Well Heads, Lagoon Transfer Structures
1 kWt Heater with External Heat Transfer Equipment	46,800	8,100	1 kWt Fuel Oil System	3,800 - 9,700	1,700 - 6,400	
12 kWt Self-Contained Heater	310,000	51,700	12 kWt Fuel Oil System	9,700	10,600	
12 kWt Heater with External Heat Transfer Equipment	260,900	43,000	12 kWt Fuel Oil System	9,700	10,600	Heaters for Potable Water Storage Tanks, 200,000 gal
7 kWt Self-Contained Heater with a 5 kWt Back-up Fuel Oil System	184,200	36,400	12 kWt Fuel Oil System	9,700	10,600	
7 kWt Heater with External Heat Transfer Equipment and a 5 kWt Back-up Fuel Oil System	168,700	33,400	12 kWt Fuel Oil System	9,700	10,600	

which includes both annual capital and operating charges. Again the radioisotope systems are more costly, but the ratios are lower. Apparently, there is a slight advantage of a 7 kWt radioisotope heater combined with a 5 kWt fuel oil system over a 12 kWt radioisotope heater. The combination system has annual costs 3 to 4 times higher than a 12 kWt fuel oil system; the 12 kWt radioisotope system's annual costs are 4 to 5 times higher.

For the 1 kWt heater, the radioisotope systems appear to approach the upper annual cost range of the fuel oil systems. However, it must be noted that this upper range is for a 23 kWt boiler totally dedicated to delivering 1 kWt. This could only occur: 1) if there were no other 23 kWt fuel oil boilers in the community which could supply 1 kWt so that a separate boiler was required, or 2) if piping costs to span the distance between an existing 23 kWt boiler and the 1 kWt were large enough to justify a separate system (approximate limit on piping distance is 600 ft, not including energy loss for transport of steam and condensate).

One cost that has not been included for the radioisotope systems is for licensing - completing a license application and safety assessment report. For the first prototype system the costs would be significant, but for additional applications of the same system the costs would be reduced since much of the information contained in the first safety assessment would apply to the additional applications (see Section 2.2). It is estimated that these licensing activities would cost \$2,000 to \$5,000 per application. These costs would be somewhat offset by fuel oil system design costs which are also not included. The fuel oil system costs could run about the same order of magnitude as the isotope system licensing costs. Thus, the impact of not including these costs on the results in Table 11 is minor. Radioisotope system development costs are also not included. These are assumed to be a one-time cost distributed among many systems.

The results in Table 11 are based on a fuel oil price of \$1.50/gal. Since these prices depend on location and are increasing at a potentially higher rate than equipment and other costs, radioisotope systems could become more economically competitive in the future. One method of

analyzing various costs is to consider the costs on the basis of an equivalent fuel oil price:

- equating annual radioisotope system and fuel oil costs;
- factoring out the annual fuel oil quantity requirement; and
- dividing by the requirement.

The following equation further describes this method. For radioisotope system costs to equal fuel oil system costs:

$$\text{Annual Cost of Radioisotope System} = \text{Annual Cost of Fuel Oil System}$$

$$\left. \begin{array}{l} \text{(Annual Capital Cost + Annual} \\ \text{Operating Cost) Radioisotope} \\ \text{System} \end{array} \right\} = \left\{ \begin{array}{l} \text{(Annual Capital Cost + Annual} \\ \text{Operating Cost) Fuel Oil} \\ \text{System} \end{array} \right.$$

$$\left. \begin{array}{l} \text{Annual Equipment Cost (EC}_R\text{) +} \\ \text{Annual Transportation Costs (TC}_R\text{) +} \\ \text{Annual Radioisotope Fuel Costs} \\ \text{(RFC}_R\text{) +} \\ \text{Annual Operating Costs (OC}_R\text{)} \end{array} \right\} = \left\{ \begin{array}{l} \text{Annual Capital Cost (CC}_{FO}\text{) +} \\ \text{Annual Operating Costs (OC}_{FO}\text{)} \\ \text{(not including fuel oil) +} \\ \text{[Annual Fuel Oil Quantity (FOQ}_{FO}\text{) x} \\ \text{Price of Fuel Oil (\$/gal)]} \end{array} \right.$$

$$EC_R + TC_R + RFC_R + OC_R = CC_{FO} + OC_{FO} + (FOQ_{FO} \times \$/\text{gal})$$

Rearranging:

$$\text{Overall Equivalent Fuel Oil Price for Economical Radioisotope Systems, } = \frac{EC_R + TC_R + RFC_R + OC_R - CC_{FO} - OC_{FO}}{FOQ_{FO}} \text{ } \$/\text{gal}$$

Thus, overall equivalent fuel oil price is the price of fuel oil that would make radioisotope systems economically competitive with fuel oil systems; any fuel oil price higher than this value indicates that radioisotope systems are more cost effective. The right side of the above equation allows various costs to be factored out in terms of equivalent fuel oil price.

Table 12 gives equivalent fuel oil prices for each alternative radioisotope system. Contingency has been distributed among the various costs. On this basis, the price of fuel oil which presently can vary from \$1.00 to \$2.00/gal (\$1.50 gal seems to be a representative value in remote communities) would have to increase to at least \$7.00/gal or as high as \$16.00/gal for radioisotope heaters to compete economically with fuel oil systems. Based on 10% inflation each year for 10 yr and an initial fuel oil price of \$1.50/gal, the effective average fuel oil price over the full 10 yr is \$2.40/gal. Thus, radioisotope systems are not economical.

About one-half the major costs for the 1 kWt radioisotope systems are for equipment. Equipment costs in Table 12 are based on a 10-yr life. If the equipment life could be extended to 20 yr (10% interest over 20 yr), the annual costs would be reduced. The most likely application would be the self-contained unit which could possibly be returned, refueled, and used as a heater for another 10 yr. If this occurred, equipment costs would be reduced to between \$5.84 and \$7.57/gal and overall equivalent fuel oil price would decrease to a range of \$13.54 to \$5.14/gal. These costs are still much too high for economic application. The 20-yr evaluation could be applied to the other self-contained 12 kWt and 7kWt systems, but the cost reduction would be less since the equipment costs make up a smaller fraction of the total. Another problem with 20-yr systems is that a reasonably priced supply of heat generating material to refuel the heaters after 10 yr is not certain at this time.

The other major cost factor to consider in radioisotope systems is fuel based on 10¢/curie, which is the official Federal Government price.⁽⁹⁾ The question arises: if capsules of strontium are produced for nuclear waste management reasons and if they are not used beneficially because the price is too high, why not supply these capsules at no cost and at least gain some benefit by saving fuel oil? If this were to occur, the overall equivalent fuel oil price of the 1 kWt heaters could drop below \$2.40/gal (or even \$1.50/gal) for certain applications, where the distance from the existing 23 kWt system is large or a 23 kWt boiler is totally dedicated to a 1 kWt requirement. Also, the overall costs for a 12 kWt radioisotope

TABLE 12. Comparison Between Radioisotope and Fuel Oil Heaters Based on Equivalent Fuel Oil Price

Isotope System Description	Radioisotope System Annual Costs, \$/gal				Fuel Oil System Annual Costs, \$/gal		Overall Equivalent Fuel Oil Price, \$/gal ^(b)	Potential Applications
	Equipment	Transportation	Radioisotope Fuel ^(c)	Operating	Capital	Operating ^(a)		
1 kWt Self-Contained Heater	8.13-10.54	2.08-2.70	6.46-8.38	1.04-1.35	1.25-4.32	0.63-10.54	15.63-8.11	Heaters for Septic Tanks, Well Heads, Lagoon Transfer Structures
1 kWt Heater with External Heat Transfer Equipment	6.25- 8.11	3.13-4.05	6.46-8.38	1.04-1.35	1.25-4.32	0.63-10.54	15.00-7.04	
12 kWt Self-Container Heater	3.97	0.75	11.13	0.31	0.50	1.22	14.44	Heaters for Potable Water Storage Tanks - 200,000 gal
12 kWt Heater with External Heat Transfer Equipment	1.31	1.06	11.16	0.16	0.50	1.22	11.97	
7 kWt Self-Contained Heater with 5 kWt Back-up Fuel Oil System	2.96	0.50	8.63	2.04	0.67	1.63	11.33	
7 kWt Heater with External Heat Transfer Equipment with 5 kWt Back-up Fuel Oil System	2.21	0.82	8.71	1.83	0.67	1.63	11.28	

(a) Excluding fuel oil costs

(b) Overall Equivalent Fuel Oil Price = Radioisotope System Annual Cost - Fuel Oil System Annual Cost

(c) Based on 10¢/Ci ⁹⁰Sr

heater with external heat transfer equipment combined with a 5 kWt back-up fuel oil system could decrease to about \$2.50/gal. However advantageous a strontium price reduction to zero appears, the following factors should be considered:

- 1) the present supply of Hanford's Waste Encapsulation and Storage Facility (WESF) strontium-90 capsules is limited. Current projections are for a maximum of 800 capsules which would supply about 67 12-kWt or 800 1-kWt radioisotope heaters;
- 2) a portion of the presently available strontium capsules would be needed for more cost effective applications which, in general, would be specialty uses where other types of systems are unsatisfactory from a reliability standpoint, e.g., space applications, navigation aids such as aircraft or submarine, and communications systems;
- 3) one of the objectives of current nuclear waste programs is to develop large scale applications which would economically justify private industry to construct and operate a nuclear waste fission recovery plant. If private industry were to recover strontium on a large scale, it is likely that prices would be higher than 10¢/curie. Therefore, once the zero cost strontium supply is consumed, radioisotope fuel resupply costs for existing heaters and initial fuel costs for the new radioisotope heaters would increase even above the costs presented in Tables 11 and 12.

The likelihood of a strontium price reduction is uncertain at this time. This decision must be made by various government agencies which are in charge of the radioisotopes and potential user agencies or potential private users.

5.0 CONCLUSIONS

The use of strontium-90 heat sources to fuel cold region radioisotope heaters does not appear to be an economically feasible venture, at least based on a price of 10¢/curie. Various factors which would make radioisotope heaters more economically competitive are:

- 1) a price reduction to below 10¢/curie,
- 2) a dramatic increase in fuel oil prices, and
- 3) a decision that fuel oil system reliability or adaptability is not satisfactory and radioisotope systems would be satisfactory.

It is recommended that these heaters not be considered further unless at least one of the preceding factors occurs. The costs of radioisotope heaters are so high that it would probably take a combination of these factors to make cold regions radioisotope heaters economically feasible.

REFERENCES

1. W. R. Corliss and D. G. Hawey, Radioisotopic Power Generation. Prentice-Hall, Inc., Englewood, NJ, 1964.
2. R. P. Cope and T. P. Fleming, "U.S. Navy Radioisotope Power Generator Program." Isotopes and Radiation Technology 9(3):323-329, 1972.
3. L. D. Perrigo, Cold Regions Isotope Applications. BNWL-1935, Battelle, Pacific Northwest Laboratories, Richland, WA, 99352, April 1976.
4. International Atomic Energy Agency and the Food and Agriculture Organization of the United Nations, Radiation Preservation of Food, Proceedings of a Symposium held in Bombay, November 13-17, 1972, International Atomic Energy Agency, Vienna, 1973.
5. W. C. Remini, E. J. Wahlquist, and H. D. Sivinski, Beneficial of Waste Nuclear Isotopes - 137 Cesium Irradiation Treatment of Municipal Sludge and Compost, ERDA 77-17, National Technical Information Service, U.S. Department of Commerce, Springfield, VA, January 5, 1977.
6. U.S. Nuclear Regulatory Commission, Office of Standards Development, Regulatory Guide 6.3 - Design, Construction, and Use of Radioisotope Power Generators for Certain Land and Sea Applications, National Technical Information Service, Springfield, VA 22161.
7. International Atomic Energy Agency, Safety Series No. 33 - Guide to the Safe Design, Construction, and Use of Radioisotope Power Generators for Certain Land and Sea Applications, UNIPUB, New York, NY 10016, 1970.
8. R. R. Jackson, "Hanford Waste Encapsulation: Strontium and Cesium." Nuclear Technology 32(1):10-15, January 1977.
9. 34 Federal Register 16034, August 9, 1972.
10. J. J. Perona and J. O. Blomeke, Parametric Study of Shipping Casks for Solid Radioactive Waste, ORNL-TM-3651, Oak Ridge National Laboratory, Oak Ridge, TN, February 1972.

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