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ASSESSMENT OF RADIOISOTOPE HEATERS FOR REMOTE TERRESTRIAL APPLICATIONS

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Abstract

This paper examines the feasibility of using radioisotope byproducts for special heating applications at remote sites in Alaska and other cold regions. The investigation included assessment of candidate radioisotope materials for heater applications, identification of the most promising cold region applications, evaluation of key technical issues and implementation constraints, and development of conceptual heater designs for candidate applications. Strontium-90 (Sr-90) was selected as the most viable fuel for radioisotopic heaters used in terrestrial applications. Opportunities for the application of radioisotopic heaters were determined through site visits to representative Alaskan installations. Candidate heater applications included water storage tanks, sludge digesters, sewage lagoons, water piping systems, well-head pumping stations, emergency shelters, and fuel storage tank deicers. Radioisotopic heaters for water storage tank freeze-up protection and for enhancement of biological waste treatment processes at remote sites were selected as the most promising applications.

Background

Waste byproducts from government facilities involved in the processing of nuclear materials contain radioisotopes that have potential applications in public health, medicine, industrial technology, national security and energy. Many radioisotope applications are well established and these range from irradiation sources for sterilization of medical equipment to energy sources for powering thermoelectric generators (see Table 1). The purpose of the work reported here was to determine the technical, logistical, and economic feasibility of using radioisotope byproducts for special heating applications at remote sites in Alaska and other cold regions. This work was sponsored by the U.S. Air Force (USAF) as part of a continuing program to conserve energy and to better utilize available resources.

In the 1950s the Atomic Energy Commission conducted a program to develop isotopic systems and to demonstrate their technical feasibility. The developmental work led to the fabrication of Radioisotopic Thermoelectric Generators (RTGs) used for a number of purposes in oceans and space, as well as in terrestrial applications.[1-4] In the mid-1970s, DOE's predecessor, the Energy Research and Development Administration (ERDA), funded a program on Cold Regions Isotopic Applications.[5] Beneficial uses of isotopes identified included potable water heating systems, septic tank and sewage lagoon heating systems, and use of RTGs to power aircraft navigational aids and meteorological instruments in remote locations. DOE and other organizations have continued to

Table 1 Radioisotope applications

Heat Power Sources

- Energy sources for
  - Small ORC turbines
  - Thermoelectric generators
  - Thermionic generators
  - Stirling engines
- Weather station relays
- Remote power generation
- Military communication/intelligence systems
- Remote unattended heaters
- Heart pacemakers
- Undersea navigation power
- Satellite space power sources

Irradiation Sources

- Sterilization of medical equipment
- Food preservation
- Sludge irradiation to eliminate pathogens

Self-power Lighting (radioluminescent lights)

- Remote aircraft runways
- Navigation aids
- Instrument dials

identify and evaluate beneficial uses of isotopes to meet long term energy requirements.[6] There are numerous installations in Alaska and other cold regions of the northern hemisphere where opportunities exist for using radioisotopic heaters to supply heat for potable water/domestic water and sewage systems. Implementation of such heater systems requires determination of specific site application requirements, resolution of problem areas (e.g., safety, logistics and security issues), design/fabrication of actual isotopic heater units, and field demonstration at selected sites.

Technology Assessments

The nuclear industry generates waste products that contain radioisotopes that must be shielded and cooled because of the radiation and heat that is produced by radioactive decay of the materials. To ease the general problem, these isotopes that generate the most radiation and/or heat are often separated from the remaining isotopes. This simplifies the provisions required for shielding and cooling since a smaller volume of material is involved. Strontium-90 (Sr-90) is an example of an isotope commonly separated from nuclear waste because it is a strong heat producer. Capsules made for containing separated Sr-90 produce about 1 kW (thermal) when new, have a half-life of 29 years, and are typical of the radioisotopic materials that can be employed.

Initial efforts involved a reassessment of earlier study results, involving radioisotopic heaters, in light of current technology and energy needs. Since the application areas of prime interest involved remote USAF installations, economic and logistic constraints differed from those involving civilian applications.

Radioisotopic Fuels

Desired characteristics for radioisotopic heater fuels include: non-fissionable, good availability, low cost, chemical stability, high power density, long radioactive half-life and moderate gamma (γ) radiation levels. The need for characteristics such as non-fissionability, good availability, and low cost are obvious. Chemical stability is desired to insure that the radioisotope does not react with container materials, such as stainless steel, or natural elements it is likely to come in contact with. The power density (thermal watts per unit weight or volume) is important in restricting the physical size, and hence, cost of a heat source. This attribute is considerably more important for space applications with stringent weight constraints, than for ground based applications. A long "half-life" for a radioisotope extends the useful period over which a given heat source can operate before refueling is required. Radiation sources with high γ radiation levels require thicker shielding (with increased weight and cost) for biological protection of personnel than is required for most other types of radiation.

Candidate radioisotopic fuels of major interest are summarized in Table 2. Extremely rare and/or unstable isotopes, along with fissionable elements capable of chain reactions, have been omitted from the table. Based on a selection criteria requiring a 20-year or greater half-life, the preferred fuels list is reduced to Sr-90, Cs-137, Ac-227, U-232, Pu-238 and conditionally Cm-244 (half-life 18 yr). From this group, Sr-90 was selected as the most viable fuel for radioisotopic heaters in remote terrestrial applications. Cs-137, for example, has a power density which is lower than that of Sr-90 by a factor of 3.4. Current availability of processed Ac-227, U-232, Pu-238 and Cm-244 materials is considerably less and the costs are much greater than that for either Sr-90 or Cs-137. Ac-227 and U-232 have the additional disadvantage of strong γ-ray emissions and the associated thick shielding requirements. The high costs of radioisotopes such as Pu-238 can be justified for space missions applications because of the long half-life and minimal radiation shielding requirements for alpha-particle emitters. However, Pu-238, as well as Cm-244, was eliminated from further consideration as a heat source for terrestrial installations due to very high procurement costs, lack of unallocated stockpile reserves, and heavy security restrictions associated with the use of significant amounts of plutonium in any form.

The selection of Sr-90 as the preferred fuel is enhanced by past experience obtained from over sixty terrestrial power generators. Most of this past experience involved radioisotope thermoelectric generators (RTGs) such as the series of SNAP and Sentinel units used for a variety of land-based and undersea applications.[2,4,7] Dynamic power systems (based on Brayton, Rankine and Stirling cycles), fueled by radioisotopes, have also been investigated for remote installations.[8]

Strontium-90 is processed from nuclear waste materials at the Waste Encapsulation and Storage Facility (WESF) near Hanford, WA. It is chemically stabilized as a strontium fluoride (SrF_2) compound in double wall capsules that are 20.1 in. long and 2.625 in. diameter.[9] Each capsule initially contains 150,000 Curies (Ci) of Sr-90 and generates about 1 kW of thermal energy. Since a 1 kW source is relatively small compared to many conventional heat sources, several fuel capsules may be needed for a particular heater application.

Site Applications

The work reported here is primarily concerned with the use of radioisotopic materials solely for thermal heating purposes, as contrasted to electrical power generation. With the exception of small (~1 watt thermal) heater units for maintaining critical instrumentation and other components in spacecraft at their desired temperature, most other radioisotopic energy sources have been developed to power either static or dynamic electric generators.[10,11] Due to the mission requirements of these power generators, the associated radioisotopic sources are at a relatively high level of sophistication that cannot be economically justified for most terrestrial heating applications. Hence, cost effective heater concepts must be developed to justify the use of radioisotopic materials for land-based heating applications. Due to the high initial cost of radioisotopic heaters (fuel processing, radiation shielding, etc.) relative to conventional furnaces and boilers, they are best suited for unattended remote sites in cold regions where reliability is an important concern.

An assessment of radioisotope heater applications in cold regions (Alaska, etc.) and their economic feasibility was carried out under ERDA sponsorship during the mid-1970s.[5,12] The investigation focused on civilian sites, and recommended radioisotopic heater applications were primarily concerned with the needs of Alaskan Native Villages. The current efforts include an updated appraisal of such applications with the focus on government installations.

Opportunities for the application of radioisotopic heaters were determined through site visits to representative Alaskan installations. The site visits included major Air Force bases as well as a number of radar sites located in remote regions of Alaska. Heater application areas

Table 2 Summary of candidate radioisotopic fuels

Radioisotope	Chemical Symbol	Half-Life, yr	Specific Power,* W/g	Comments
Tritium	${}_{1}H^{3}$	12.3	0.36	High cost
Cobalt-60	${}_{27}Co^{60}$	5.3	9.0	High γ-radiation
Krypton-85	${}_{36}Kr^{85}$	10.4	0.55	Gaseous
Strontium-90	${}_{38}Sr^{89}$	29.0	0.93	Good availability
Ruthenium-106	${}_{44}Ru^{106}$	1.0	31.0	Low lifetime
Cesium-137	${}_{55}Cs^{137}$	30.0	0.27	Low power density
Cerium-144	${}_{58}Ce^{144}$	0.78	25.0	Low lifetime
Promethium-147	${}_{61}Pm^{147}$	2.5	0.37	Low lifetime
Actinium-227	${}_{89}Ac^{227}$	21.2	15.0	High γ and cost
Thorium-228	${}_{90}Th^{228}$	1.91	161.0	Low life and high γ
Uranium-232	${}_{92}U^{232}$	74.0	4.8	High γ
Plutonium-238	${}_{94}Pu^{238}$	89.0	0.55	Strategic material
Curium-244	${}_{96}Cm^{244}$	18.0	2.8	Limited availability

*Specific power values given are for the pure elements only; values for applications involving compounds of the radioisotope will be somewhat lower, in general.

judged to be of primary interest are listed in Table 3. Relative heating needs for a particular geographic area can be characterized by the annual degree-days, which ranged from about 11,000 for areas near Anchorage to over 17,000 at some remote installations (for comparison, Chicago has about 6000 annual degree-days).

Table 3 Candidate radioisotope heater applications

- Water storage tanks
- Water piping systems
- Sludge digesters
- Sewage lagoons
- Well-head pumping stations
- Emergency shelters
- Remote seismic and weather stations
- Fuel storage tanks
- Low IR signature energy sources

Preventing freeze-up of water storage tanks represents the largest single class of applications since all remote sites have structures to store water for both potable uses and fire protection. Typical structures are insulated 100,000 gallon tanks with diameter = 24 feet and height = 30 feet. Required heater capacities range from 2 kW to 8kW per tank, depending on winter design temperature for the site and how well the tank is insulated. Protection against water tank and pipeline freeze-up is currently provided by electricity (immersion heaters, electric tape, etc.) in most cases because of the convenience in application. Electricity at remote installations is provided by diesel generator sets, and loss of power would adversely impact both potable and fire protection water storage systems.

The operation of sewage lagoons and digesters could be significantly improved with radioisotopic heaters, since the biological digestion processes become dormant at low temperatures. Adequate sewage treatment occurs only during the short summer months at most remote regions of Alaska; consequently, the sewage is poorly treated. The candidate heater applications listed in Table 3 involving emergency shelters and structures housing well-head pumps, seismic instrumentation and weather stations are somewhat similar in nature. Radioisotopes could provide reliable, self-powered, heater units that operate for ~25 years without refueling. Such heaters would prevent freeze-up, enhance the operation of sensitive instruments in the arctic cold, provide warmth for personnel during inspection/service tours, and also provide electricity if integrated with a thermoelectric generator or other conversion device. The weather stations and control centers required for incoming aircraft at remote site airfields are a prime applicable for reliable heaters that are not dependent on a fuel supply or electric power lines.

The fuel storage tank application of Table 3 involves the use of heaters to eliminate water vapor condensation and consequent ice crystal formation that clogs fuel lines and metering valves. Radioisotope heaters are ideal for fuel tank applications because they do not involve open flames and do not use wires that could cause sparks, consequently reducing the potential for accidental ignition.

Radioisotopic Heater Evaluation/Design

Critical issues and potential problems associated with the implementation of radioisotopic heaters were evaluated for the application areas listed in Table 3. Conceptual designs were developed for applications involving (i) water storage tank freeze-up protection and (ii) thermal enhancement of sewage lagoon/digester biological waste treatment processes.

Key Issues

Key technical, economic, and institutional factors were examined that included technical feasibility, costs, reliability, operation requirements, environmental/safety issues, logistics, licensing requirements, and security issues. Radioisotopic heaters consist of a Sr-90 fuel compound packed into double-walled cylindrical containers or capsules, which in turn are enclosed in an appropriate heat exchanger structure that is surrounded by thermal and/or biological shielding. The heaters are mechanically simple since there are no moving parts, other than a need for a pump in the attached piping network to circulate the heat transfer fluid. The fact that radioisotopic heat sources have been used extensively with thermoelectric generators clearly demonstrates their technical feasibility, since RTG spacecraft units are considerably more complex than proposed heater applications at terrestrial sites. Although technical feasibility is established, good engineering judgement must be used to insure compatibility of containment materials, maintain thermal stresses at safe limits, and provide emergency cooling safeguards against overheating.[13,14]

The main environmental and safety issues of concern are directly related to the fact that a radioactive material is being used as a heat source. Proper safety precautions must be followed during fabrication, transportation, and site application of the Sr-90 fuel elements. The major safety issues are to insure structural integrity of the fuel capsule and the surrounding cask enclosure to prevent possible leakage of the Sr-90 isotope material, and to provide adequate biological shielding against radiation. The radiation of concern involves high energy (1 MeV average) bremsstrahlung photons emitted by the Yttrium-90 decay product of Sr-90.[15] Radiation shielding is required to protect both operating personnel and nearby equipment. The shielding also serves as a heat transfer interface, since absorption of the bremsstrahlung radiation results in the conversion of electromagnetic energy into thermal energy. This thermal energy must then be transferred to the end-use application (sewage lagoon/digester, water tank, etc.) of interest. Safety problems can be resolved through the use of suitable heat exchanger cask designs, adequate γ-ray shielding, and manpower work scheduling to limit exposure times for any one individual.

The economic viability of isotope heaters, relative to the costs of diesel-generator powered electric heaters currently used at USAF Alaskan sites, was examined through a cost analysis. Cost-effectiveness relies on the premise that Sr-90 fuel can be made available by DOE for USAF applications on a long term loan basis, with the only fuel cost being for packaging and transportation to the site. Hence, the primary cost of radioisotopic heaters is basically that associated with initial fabrication and installation, since there are no daily fuel supply requirments in the usual sense. Typical shielding materials include lead, iron and concrete--listed in order of decreasing cost. The total Sr-90 heater cost also depends on whether the transportation cask is reusable or whether or not it doubles as the site heat exchanger vessel. Shipping and transportation are major cost items because of licensing requirements and safety/security constraints when dealing with radioactive materials.

The question of fuel availability is of some concern, since new SrF_2 capsules are not currently being processed at WESF/Hanford. Also, the available inventory of WESF capsules exhibits a wide variation in Sr-90 content due to aging and other factors.[6] The availability of Sr-90 for terrestrial heater applications can be enhanced through use of DOE's inventory of "aged" fuel capsules, whose energy levels have decreased to the 0.6 kW thermal level or less. Use of low power SrF_2 capsules for heaters allows the higher power density units to be reserved for higher priority RTG applictions.

Design Options

Alternative design options were evaluated and a number of Sr-90 heater conceptual designs developed, both for protection against water storage tank freeze-up and enhancement of biological waste treatment processes. Each heat exchanger cask holds several Sr-90 capsules, the exact number depending on the application, seasonal heating requirements at the site in question, and thermal output of the capsules. Mechanical simplicity is stressed in radioisotopic heater designs to provide reliable systems that are essentially maintenance-free for remote site applications.

Heat exchangers containing Sr-90 capsules can either be placed physically within a water tank, with heat transferred by free convection, or located outside the tank. In the latter case, heat would be transferred to the tank by water circulation through a connecting pipeline or by a "heat pipe" thermal transfer device. In all cases, the Sr-90 capsules have to be properly encased within the heater closure to prevent contact of strontium with the water system. This is accomplished through double encapsulation of the Sr-90 fuel, use of non-corrosive container alloys, protective thermal/radiation shielding, intermediate heat exchangers that physically separate the heater from the water tank, and other safety precautions. It is recommended that initial water storage tank heating applications involve non-potable water such as in tanks reserved for fire protection. This would allow verification of Sr-90 heater performance and establishment of operational/maintenance procedures, prior to interfacing such heaters with potable water systems.

Figure 1 illustrates one concept for aerobic sewage treatment in which a radioisotopic heater is simply plumbed into the pipeline between the aeration pump and the lagoon air distribution system. This design layout should also resolve the common problem of water freezing in the aeration pipeline. Since the biological digestion process is essentially dormant during a major portion of the year at remote Alaskan sites, such applications of radioisotopic heaters can significantly improve the treatment process. Alternative concepts to that of Fig. 1 include: submersion of an Sr-90 heater directly into the lagoon (with a suitable foundation or support pad), with heat transfer taking place via natural convection or by using thermosyphon principles; circulating lagoon liquids directly through an Sr-90 fuel source heat exchanger; or transferring heat to the lagoon using finned heat pipes.

Most applications require radiation shielding, which can be minimized by using dense materials (e.g., lead, iron or cement) that are efficient absorbers of γ-radiation. Emergency cooling precautions are also necessary to prevent possible damage of the fuel capsules due to accidental overheating. In the case of an application involving an Sr-90 heater unit submerged in a small sewage lagoon to enhance the aerobic digestion process, the lagoon water alone would provide adequate biological shielding for humans since the effective γ-ray shielding ability of water relative to steel is in the ratio of one to six.[16] Consequently, 6 feet of lagoon water would be equivalent to a 1 foot thick iron shield. In practice, however, some shielding would always be used in order to provide adequate protection during periods associated with source removal and inspections, to insure complete integrity of the Sr-90 capsule(s) contained within, to absorb as much of the radiative energy as possible for transfer to the surrounding liquid, and to reduce the dosage levels such that microorganisms necessary for the digestion process are not harmed.

Concluding Remarks

Useful radioisotope byproducts exist in the high-level nuclear wastes of the civilian and defense production cycles. Management and disposal of these waste materials can be facilitated by first separating out constituents that are strong emitters; the relatively low-level wastes that remain can then be handled through geologic disposal or other means. The strong emitters can be utilized for special applications such as irradiation, radioluminescent lighting and long-term heat/power sources. This assessment concludes that radioisotopes, such as Strontium-90, can be effectively utilized as thermal energy sources for a variety of terrestrial heating applications. Military installations at remote Alaskan sites offer many potential advantages such as the presence of trained technical personnel, reduction of security problems relative to civilian sites, and the fact that the

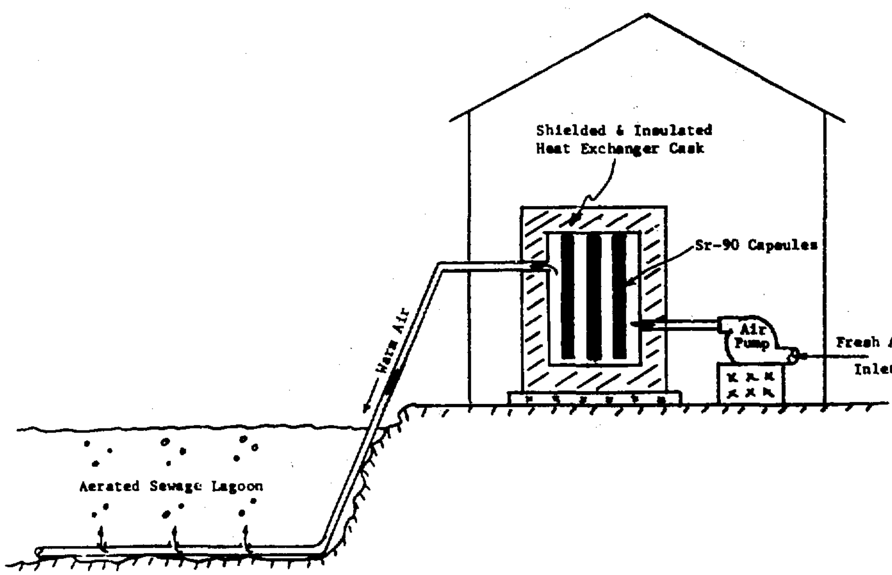

Fig. 1 Schematic of radioisotope heated sewage aeration system.

radioisotopic materials remain under government surveillance/jurisdiction at all times.

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