THE BENEFICIAL UTILIZATION OF NUCLEAR WASTE PRODUCTS - George P. Dix

I. INTRODUCTION

The 1974 Nuclear Waste Management Symposium[1] was dedicated to the processing, solidification, and immobilization of high level nuclear waste, engineered storage in the near term, and ultimate geological or extraterrestrial disposal in the long term. The hypothesis of this paper is that high level nuclear waste represents a potential national resource comprised of unique and useful energy sources and materials for radiation, thermal, and electrical applications and processes.

The beneficial utilization of many high level waste isotopes will not relieve the fuel reprocessing industry of the need to dispose of residual waste isotopes which do not have uses and those isotopes removed for beneficial applications whose energy is eventually expended. Rather, another view to waste management is advanced in which isotope by-products could be used to derive an income. At the same time these by-products, by virtue of their unique properties, can be used to solve national problems. It appears that various isotopes contained in the wastes, have a collective future potential value of billions of dollars. For the first time the potential exists for a large supply of low cost isotopes from the nuclear fuel reprocessing cycle. At the same time there is a potential for a large market for these isotopes because of changing energy, economic, and technological patterns both here and abroad.

The Energy Research and Development Administration in cooperation with several other government agencies has embarked on a modest program to explore the hypothesis of the beneficial utilization of nuclear waste products with emphasis upon the safety and economic considerations associated with the extraction and utilization of specific by-product isotopes and suites of isotopes from the high level waste stream. This program is in parallel and in cooperation with the programs of the Waste Management and Transportation and Production and Materials Management Divisions of ERDA. In addition, contacts have been made with commercial fuel reprocessors and industry regarding the possibilities of extracting specific isotopes from the waste stream and future markets for various isotopes. The purpose of this paper is to set forth the potential of beneficially using certain isotopes and to suggest that the opportunity and flexibility to extract useful isotopes from the waste stream not be foreclosed upon in the future because of today's exigencies in nuclear fuel reprocessing.

II. BACKGROUND

It is estimated that several billion dollars will be spent in the U.S. in the next 25 years on the extraction of uranium and plutonium from the spent fuel elements from nuclear power plants and on the packaging, storage, and disposal of residual fission products and transuranium elements. The extraction of uranium and later plutonium is essential to preserve a national nuclear power industry. This paper will treat the beneficial utilization of the wastes, viewing them as useful resources of energy having large potential intrinsic value, comparable in magnitude to the uranium and plutonium recycle costs.

The thought of beneficial use is not a new one; the concept is about 20 years old having been advanced by industry[2], by Oak Ridge National Laboratory[3], by the Pacific Northwest Laboratory who estimated the values of nuclear waste isotopes[4] and, more recently, by the Japan Atomic Industrial Form[5] who view the nuclear fuel cycle as a closed system beneficially utilizing its own waste products. In the early 1960's programs both here and abroad utilizing various isotopes found in nuclear wastes led to the demonstration of a myriad of applications. Many of these programs still exist today in a dozen foreign countries and in the U.S.

So, what is new? The constraints upon the programs of the 1960's and 1970's were the unavailability of separated by-products and high unit cost because of the small scale of separation facilities at that time. One or two of a kind of demonstrational thermal, electrical, or irradiation units were built and deployed then. There were no large inventories of separated by-products to sustain the program, and large scale by-product applications were not systematically sought and examined from a long range economic viewpoint, considering the complex interactions of commercial fuel reprocessors, the nuclear fuel cycle, and large multi-unit or massive system applications of isotope by-products. At the same time, today and tomorrow are eras of energy shortages and balance of payments deficits. There is a desire to minimize fossil fuel costs and minimize manpower costs through automation, particularly in remote regions and in national defense. Perhaps the general situation is exemplified by the Solid Waste Disposal Act[6] applicable to non-nuclear wastes which states: "More efficient conservation, recovery, and use of the nation's energy resources must be promoted through increased energy and resource recovery from waste." Energy production is a singular innate characteristic of nuclear wastes and their reliability of spontaneously producing energy is unity. Herein they are in themselves viewed as a "fuel", not to the extent of supplying total U.S. energy needs, but as a source of effective and dependable energy for performing a variety of auxiliary energy tasks that no other source of energy can reliably perform.

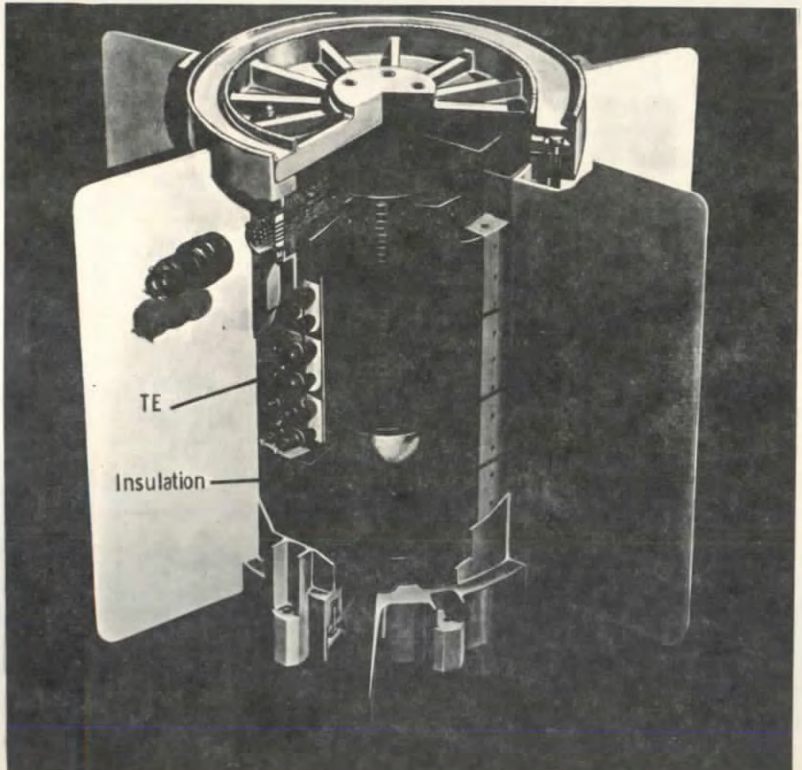
III. HISTORICAL

Fission products including ^{85}Kr, ^{90}Sr, ^{137}Cs, ^{147}Pm and transuranium isotopes including ^{238}Pu, ^{244}Cm, ^{237}Np, and $^{241-243}Am$ have been used in a variety of applications.

The workhorse is perhaps ^{238}Pu which is currently powering the first spacecraft to encounter the planets Jupiter and Saturn and the first manmade object to leave the Solar System. It is also powering five unmanned stations on the lunar surface and is also being used in undersea applications, and in coronary pacemakers. Figure 1 shows the SNAP-19 generator for two Pioneer spacecraft, a simplethermoelectric generator having no moving parts. These spacecraft are more than one-half billion miles from earth and continue to operate in a hostile environment several years after launch. ^{238}Pu is made artificially today in plutonium production reactors from ^{237}Np, a transuranium waste product, which is irradiated with neutrons to produce ^{238}Pu. It is also a

FIGURE 1

RADIOISOTOPE THERMOELECTRIC GENERATOR (SNAP 19)



constituent (~2-3% in PWR's) in elemental plutonium to be recovered from fuel reprocessing plants for reuse in fission reactors. ^{238}Pu can also be derived from the irradiation of ^{241}Am. The success of our national scientific and military space programs may ultimately depend solely upon this radioisotope and other transuranium nuclides.

^{90}Sr has been the primary radioisotope utilized by the U.S., and other countries for terrestrial and marine remote power. It has been used to power weather stations in the Arctic and Antarctic, buoys, lighthouses, undersea oil well control systems, marine and terrestrial data acquisition systems, undersea devices and other applications. Worldwide, some 50-60 ^{90}Sr devices have been made and deployed, until the supply of fuel grade ^{90}Sr was essentially exhausted late in 1974.

An outstanding example of a ^{90}Sr application is a U.S. Navy oceanographic data acquisition system on Fairway Rock in the Bering Straits that has produced the required power for 8 years, completely unattended, which replaced a propane fueled power supply that had incurred prohibitive technical problems and excessive logistic and maintenance costs. Figure 2 shows Fairway Rock, and Figure 3 shows the nuclear power supply and telemetry station. ^{90}Sr electrical generators which also produce heat may have widespread future applications in the Arctic for both military and commercial interests. ^{90}Sr has a 30 year half-life and constitutes about 8% of the initial heat of nuclear wastes after a short cooling period.

^{137}Cs has various medical radiotherapy applications, has been used to produce power, and can be used as a substitute for ^{60}Co, an artificially-produced radioisotope widely known for its ability to combat cancer. This subject is treated extensively by R. W. McKee(7) who concludes that substitution of ^{137}Cs for ^{60}Co is well within the realm of economic feasibility for commercial fuel reprocessors in the 1980's. Perhaps more important are the potential massive food irradiation and sanitary engineering applications of ^{137}Cs which will be discussed later. ^{137}Cs has a 30 year half-life and constitutes about 9% of the initial heat in nuclear wastes after a short cooling period.

^{147}Pm is another unique energy source. It has been used extensively as light-emitting rendezvous targets on our Apollo lunar landing missions, for commercial aircraft instrument illuminators, for cardiac pacemakers, and for other applications. It has a 2.6 year half-life and low radiation dose.

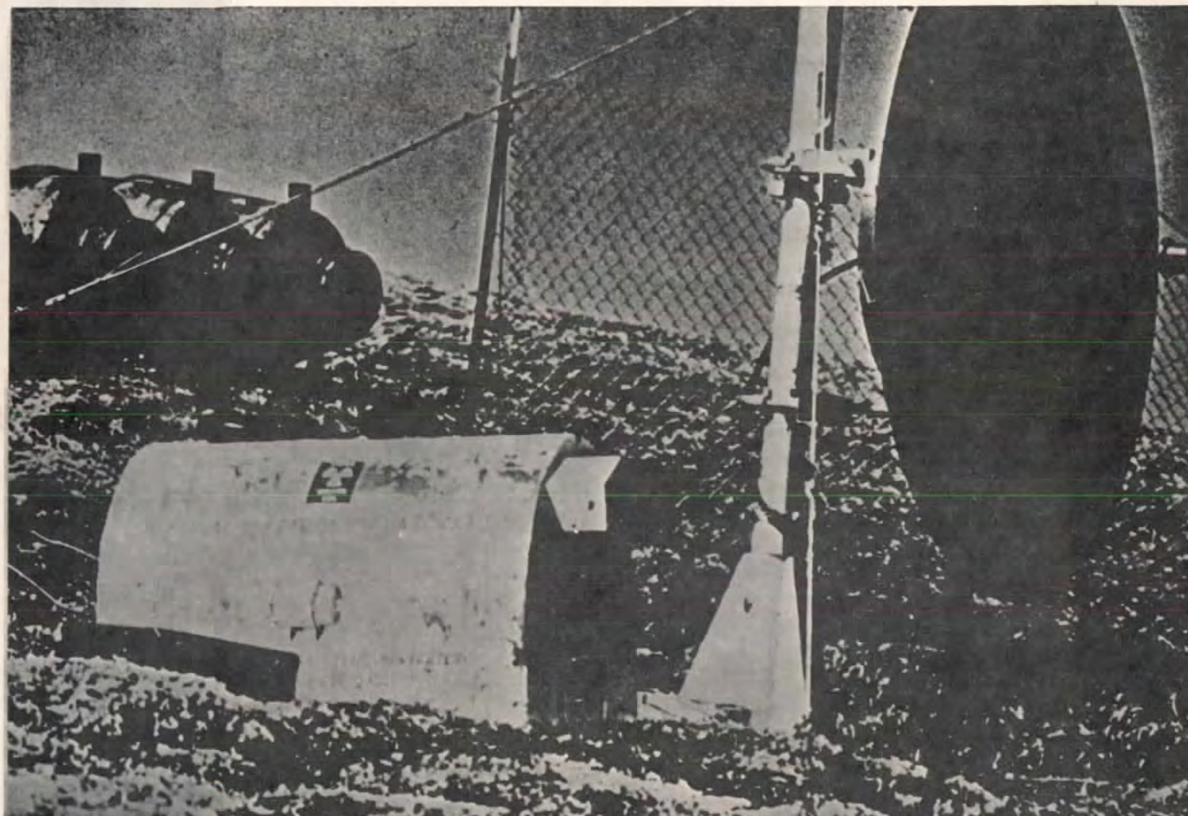
^{85}Kr is a self-heating noble gas with a 10 year half-life. It is in use as a radiotracer, has been used as a "betalite", to induce light via phosphorescence and has promising medical applications. ^{85}Kr (and Xenon) is evolved immediately from fuel elements in the front end of the reprocessing cycle and will be held up to meet criteria for radioactive releases. ^{85}Kr will be readily available without modification of reprocessing plants.

A number of other radioisotopes such as $^{241-243}Am$, $^{242-244}Cm$, ^{252}Cf, ^{144}Ce, ^{67}Cu, ^{153}Gd, the radioiodines, ^{33}P, ^{3}H and ^{110}Ag have been used for various applications(8).

FIGURE 2

FAIRWAY ROCK SITE-BERING STRAIT

FIGURE 3 **NUCLEAR POWER SUPPLY AND TELEMETRY STATION**
(NOTE USED PROPANE TANKS)



The isotope development program of the 1955-1970 period both here and abroad appeared to suffer from the following: (1) The program came before its time when future supplies of fission product and transuranium isotopes were not readily available to sustain such an applications program, (2) Nuclear fuel reprocessing on a massive scale was not foreseen within a reasonable time, (3) Industry and government could not sustain cost-effective separation and encapsulation facilities, and (4) A massive market for isotopes could not be sustained because of wide uncertainties in isotope availability and cost. The current exploratory program on the beneficial utilization of nuclear waste products must be conducted with the above lessons in mind.

IV. NUCLEAR WASTE INVENTORIES

The purpose of this section is to describe the nuclear waste inventories through the year 2000. Although there are currently uncertainties in projecting the installed nuclear electric capacity in the U.S., variances by small factors are not particularly important. Given similar assumptions for installed capacity, there is a wide variance (factor of 10 or so) in inventory depending upon the assumed time after reactor discharge when the by-product isotope inventory is measured. However, it is obvious that a large inventory of thermal and radiation energy is available for a myriad of applications.

Table I[9] shows the cumulative high level waste inventory at the Federal Repository assuming a 10 year storage period at fuel reprocessing sites. According to this reference, the year 2000 waste inventory will be 731 megacuries (24 megawatts) of actinides and 15,500 megacuries (50 megawatts) of fission products. High level solid waste will be placed in steel canisters, shown in Figure 4, and each canister would have a nominal 0.3 megacuries producing about 4000 BTU/hr or about 1 kilowatt after 10 years. The current waste management program is oriented toward nonpartitioning of actinides and fission products, reduction of wastes to solids in canisters, and engineered storage until an ultimate disposal mode is selected.

Table II[10] shows the waste inventories by the year 2000 for both total wastes and selected nuclides and indicates a total thermal inventory of 810 megawatts by the year 2000. A more recent reference, WASH-1297[11], indicates a total year 2000 thermal inventory of 660 megawatts but measures the inventory 90 to 365 days after spent fuel discharge from the reactors. Table II is referenced to a 30-90 day period after discharge from the reactor. The year 2000 thermal inventory of ^{90}Sr will be 67 megawatts, based upon 149 curies of ^{90}Sr per watt. The year 2000 inventory of ^{137}Cs will be 74 megawatts based upon 209 curies ^{137}Cs per watt. There will also be a total of 1.8 megawatts of ^{85}Kr, 1 megawatt of ^{238}Pu, 8.9 megawatts of ^{244}Cm and 2.9 megawatts of ^{147}Pm by the year 2000. When viewed as potential energy for auxiliary electrical power, thermal power, and radiation applications, the quantities of individual radionuclides would be appreciable. For example, based upon processes under study more than enough ^{137}Cs would exist to disinfect all of the sewage sludge in the United States or to disinfect the cereal crops that the U.S. currently exports.

TABLE I[9]

CUMULATIVE HIGH-LEVEL WASTE INVENTORY AT FEDERAL REPOSITORY ASSUMING 10 YEARS STORAGE AT FUEL PROCESSING SITE[c]

FISCAL YEAR	ACTIVITY (MCi)		THERMAL POWER (MW)	
	ACTINIDES[a]	FISSION PRODUCTS[b]	ACTINIDES[a]	FISSION PRODUCTS[b]
1983	0.065	8.76	0.0019	0.0288
1984	0.409	55.2	0.0120	0.181
1985	1.66	224	0.0488	0.733
1986	3.76	507	0.111	1.66
1987	6.05	816	0.178	2.66
1988	8.99	1,210	0.264	3.94
1989	12.5	1,690	0.369	5.48
1990	27.7	2,250	0.868	7.28
1991	60.2	2,950	1.95	9.55
1992	113	3,790	3.73	12.2
1993	185	4,760	6.12	15.3
1994	273	5,780	9.09	18.6
1995	378	6,940	12.6	22.3
1996	474	8,260	15.8	26.5
1997	561	9,730	18.7	31.2
1998	635	11,400	21.1	36.6
1999	691	13,400	22.9	42.8
2000	731	15,500	24.1	49.8
2001	755	18,000	24.7	57.6
2002	765	20,700	24.9	66.3
2003	779	23,700	25.1	75.8
2004	799	26,900	25.5	86.1
2005	823	30,400	26.0	97.2
2006	852	34,200	26.7	109
2007	887	38,300	27.5	122
2008	926	42,500	28.4	135
2009	970	47,000	29.5	149
2010	1,020	51,700	30.7	164

[a] Assumes 0.5% of the U and Pu in LWR in LWR and LMFBR fuels, 0.5% of the U and Th in HTGR fuel, and 100% of the other actinides in the fuels report to waste.

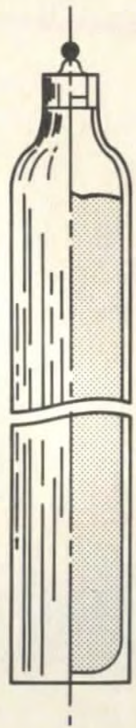
[b] Totals include 0.1% of iodine and bromine, and none of the noble-gas and tritium fission products.

[c]

	YEAR	10^9W(e)
INSTALLED CAPACITY	1980	134
	1990	504
	2000	1201

FIGURE 4

WASTE CANISTER



SIZE

6 TO 24 in. IN DIAMETER

2 TO 10 ft. IN LENGTH

12 in. IN DIAMETER x 10ft. IN LENGTH TYPICAL

MATERIAL

300 SERIES STAINLESS STEEL

HEAT

<1 TO 20 kW

5 kW TYPICAL

TABLE II

NUCLEAR WASTE INVENTORIES BY THE YEAR 2000[1]

Nuclides	Inventory[2] (Megacuries)	Annual Generation Rate (Megacuries)	Thermal Inventory (Megawatts)	T-1/2 (Years)	Thermal Output (Megawatt-hours[3])
^{90}Sr	10,000	770	67	28.6	12,500,000
^{137}Cs	15,600	1,500	74	30	14,600,000
^{85}Kr	1,200	150	1.8	10	118,000
^{238}Pu	31	0.2	1	87.8	576,000
^{244}Cm	260	23	8.9	18.1	1,057,000
^{147}Pm	8	1.1	2.9	2.6	64,000

(1)

	YEAR	10^9W(e)
INSTALLED CAPACITY	1980	153
	1990	368
	2000	735

(2) LWR fuel processing inventory 90 days and LMFBR 30 days after discharge from reactor.

(3) Computed over 1 half-life of the radioisotope.

V. WESF CAPSULES CALCINED WASTES AND WASTE CANISTERS

The Richland Waste Encapsulation and Storage Facility (WESF) currently is in operation and will produce hundreds of ^{90}Sr and ^{137}Cs capsules by the early 1980's. The characteristics of these capsules are shown in Figure 5.

Since the WESF capsules represent the only significant inventory of separated ^{90}Sr and ^{137}Cs, they are viewed by international isotope sales groups and beneficial utilization advocates with appreciable interest as a marketable commodity either in their present form or reencapsulated for various special purpose thermal, electrical, and radiation applications to be discussed later. The ^{90}Sr capsules (150 kilocuries each) will produce 1 KWT initially and about 1/2 KWT after 30 years, and the ^{137}Cs capsules (60 kilocuries each) will produce about 300 watts initially and provide a significant amount of long-term process radiation as a substitute for ^{60}Co. The current geometry of the ^{137}Cs WESF capsules is not optimized for radiation applications. In addition, the Richland waste management process has potential by-products such as ^{147}Pm and various platinium family metals of interest.

The WESF capsules are being viewed for various applications by various organizations. Foreign isotopes sales groups have considered extracting ^{90}Sr and ^{137}Cs for reencapsulation into different fuel forms and geometries. Domestic groups have considered the ^{90}Sr capsules potentially for radioisotope thermoelectric generator heat sources, heat sources for cold regions process heaters, and oil companies have viewed them as possible down-hole heaters to stimulate the flow of petroleum. The ^{137}Cs capsules have been considered for potential radiation and thermoradiation applications.

Thus, one of the beneficial use programs in the future will be to determine if the WESF capsules can be used, as is, if an additional outer capsule can make them usable in the field, or if the ^{90}Sr or ^{137}Cs can be reencapsulated economically into special configurations for demonstrating various applications to build a future market for by-product isotopes.

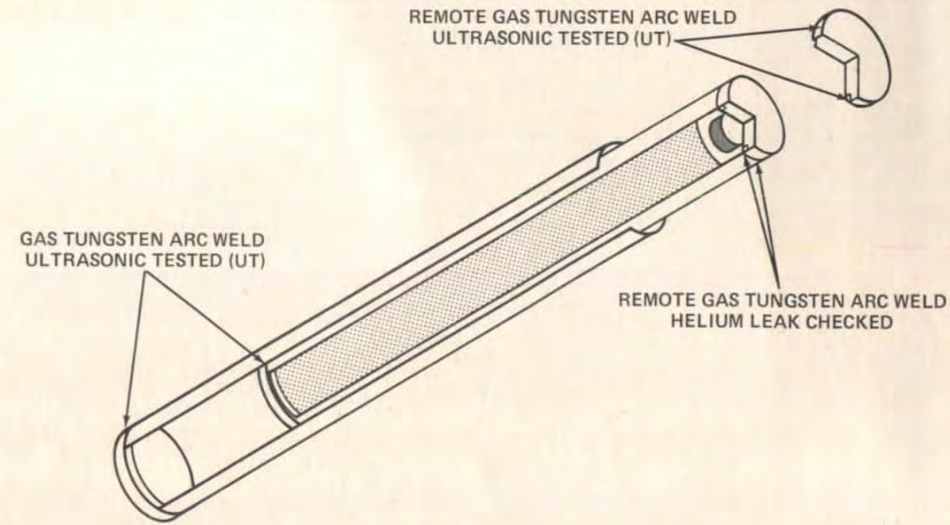
The reference gross waste canisters shown in Figure 4 are being considered by the Army Corps of Engineers for modular heating plants for Army installations. Their heat output would be highly variable, depending upon the time of manufacture (20 KWT down to <1 KWT). For process heat applications, the canisters and/or the contained nuclides may be somewhat problematical because, assuming no partitioning, the working fluid could be slightly activated by neutron capture. The contents of the canisters will not be available until 1979-1981 and the future design of the canisters has some apparent flexibility. It may be possible to divert these canisters to space heating applications before they are ultimately stored in a Federal Repository.

Thus, the WESF capsules represent a near-term source of ^{90}Sr and ^{137}Cs for demonstrating beneficial utilization of nuclear wastes, calcined gross waste products represent a potential resource, and the canisters may have applications in space heating.

FIGURE 5

HANFORD WASTE ENCAPSULATION AND STORAGE FACILITY CAPSULES

	FORM	LOADING	PERCENT OF THEORETICAL DENSITY BASED ON TOTAL VOID SPACE OF CAPSULE	TEMPERATURE			
				AIR		WATER	
				CENTER LINE	SURFACE	CENTER LINE	SURFACE
STRONTIUM FLUORIDE	COMPACTED POWDER	150 KCi	78	860°C	430°C	660°C	71°C
CESIUM CHLORIDE	MELT-CAST	60 KC	65	450°C	200°C	327°C	58°C



VI. APPLICATIONS

Applications fall into at least four categories: (1) radiation processes, (2) thermal sources, (3) heat sources for electrical power supplies, and (4) miscellaneous applications, such as lighting, radiography, tracers, and medical applications. The safety aspects, cost trade-offs, and societal benefits of both new applications and augmented known applications will be studied in detail in the near future.

A. Radiation Processes

(1) Food Irradiation

The International Atomic Energy Agency[12] has treated the subject of food irradiation in developing countries. A survey paper by Goresline[13] views the situation as follows:

"Grains, such as wheat, rice, corn, millet, etc., and legumes, such as beans, lentils, peas, grams, etc., form a large part of the diet of the world's population. These products are stored as dry seeds and form an enormous reserve of food. However, all of them are subject to attack by a variety of insects that cause great damage and loss of nutritious foods, which are reflected as one of the causes of malnutrition in many lands. Subrahmanyan[14] has indicated that the world's total food supply could be increased by 25 to 30% if we could avoid the post-harvest losses of our food. Bakal, in his Mathematics of Hunger[15] estimated the annual food losses due to rats, insects and fungi at 33 million tons, enough seed foods to feed the population of the United States of America for one year. Putting it another way, Scrimshaw[16] has estimated the post-harvest losses to be equivalent to the agricultural production on over 12 million acres of land."

"There is definitely a need for action on disinfestation of grain and grain products. Radiation can play an important role in the system that must come into being to bring the problem under control. There has been too much indifference toward saving what we already have in our hands that could contribute to the world's food supply by just preventing its loss. It is time that some concern is shown about this matter through developing an action program."

The IAEA[12] concluded that:

"Preventing food losses by the application of preservation technology is a major factor in helping to solve the world food problem. With proper use of food technology the quantity of food produced today would be more than enough to feed the existing population of the earth. Thus, any process that offers a way of saving even a small percentage of the food wasted merits attention in a hungry world.

Besides traditional methods of food preservation, like heat treatment, heat removal (refrigeration), water removal (dehydration), pH control and chemical treatment, the use of ionizing radiations has proved to be promising new physical method of preservation over the past 25 years."

The prospect offered by the potential availability of massive quantities of ^{137}Cs and other gamma isotope by-products for food irradiation in the developing countries is a new consideration in helping to solve this critical societal problem. In addition, most of the traditional methods of food preservation are large consumers of fossil energy.

(2) Sanitary Engineering

The possibility of harnessing the synergism of heat and radiation to solve a major public health problem has been investigated by the Sandia Corporation. The problem of dealing with sewage sludge in the U.S. is exemplified by the following article in the Washington-Star News[17] who summarized the problem in New York as follows:

"On January 7, 1974 the U.S. Food and Drug Administration sampled bottom sediments of the Long Island beaches and took one sample about a half mile off of Atlantic Beach in which were counted 70,000 coliform bacteria per 100 grams of sediment of which 3,300 were fecal coliform bacteria--both extraordinarily high counts. In 1973 over 4 million tons of sewage sludge, with a volume of 5.8 million cubic yards, were dumped in the (New York) bight. From all this one can conclude that ocean dumping of sewage sludge in the New York Bight poses several potentially serious environmental impacts and public health hazards over the long run, that there is already a problem of some consequence, that there are virtually no satisfactory options immediately available, and that there may or may not be a substantial hazard from swimming in or eating fish and shellfish from Long Island's waters."

A major program on the radiation treatment of sewage sludge using ^{60}Co is underway in West Germany with the goal of producing a useful fertilizer and soil conditioner[18]. A high level of interest in this area also exists in Switzerland.

The Sandia process[19] utilizes methane from a conventional sludge digester to preheat the sludge. The destruction of a typical pathogenic agent in sludge by thermoradiation is shown in Figure 6. A conceptual sludge thermoradiator to serve a city of 600,000 is shown in Figure 7. One of the near term goals of the beneficial utilization program is to continue experiments on sludge disinfectation on a liter per minute scale using 200,000 curies of ^{137}Cs. Such an effort could lead to a massive economical application of ^{137}Cs if successfully demonstrated. The thermoradiation process appears potentially cost competitive with conventional sludge treatment methods and the value

FIGURE 6

COMPARISON OF THE RADIATION TREATMENT OF T-4 BACTERIOPHAGE AT ROOM TEMPERATURE AND AT 66°C

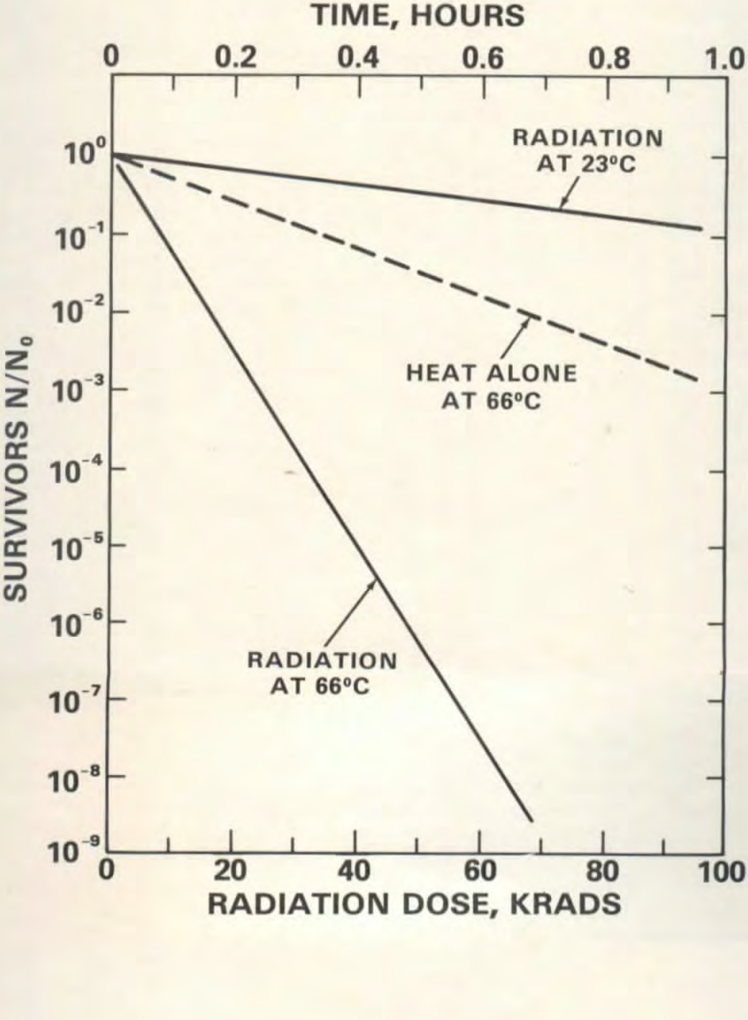
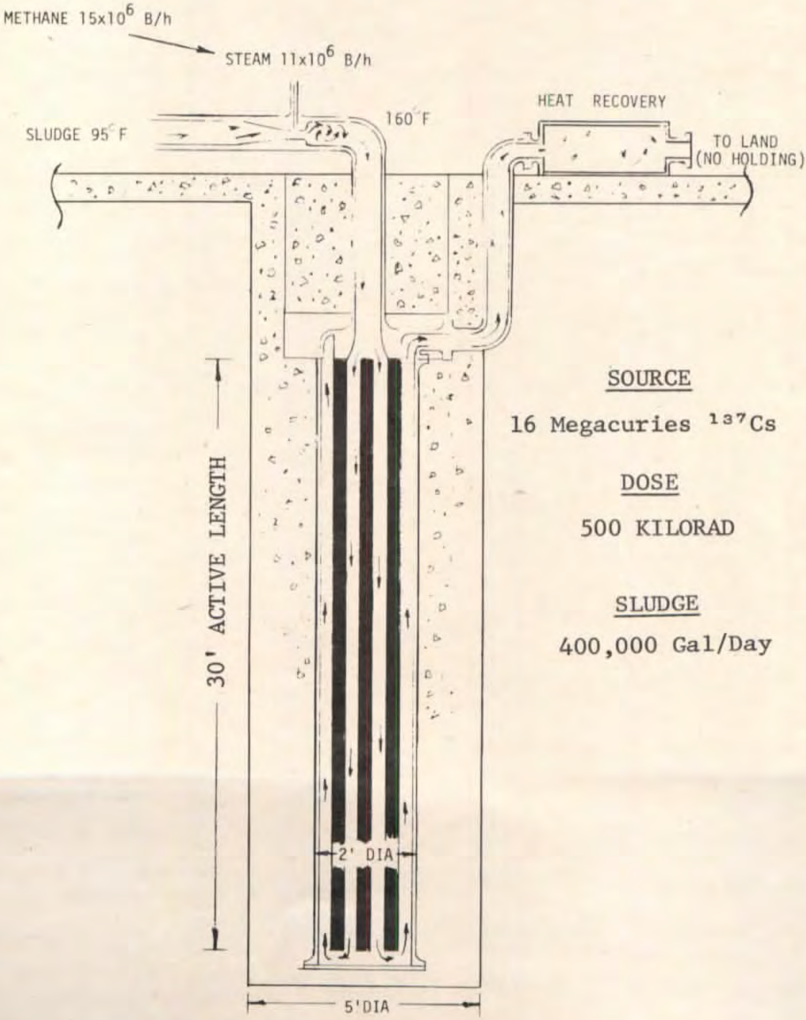


FIGURE 7

FULL SCALE FACILITY



CONCEPTUAL DESIGN OF A FULL-SCALE FACILITY TO TREAT DIGESTED SEWAGE SLUDGE WITH THERMORADIATION. GAMMA RADIATION IS PROVIDED BY CESIUM CHLORIDE FROM NUCLEAR REACTOR WASTE.

of sludge as a plant nutrient (Phosphorous, Nitrogen, Potassium) and organic soil conditioner is of growing interest because of the rapidly rising prices of these commodities in world markets and the rising energy costs associated with their extraction and processing.

(3) Platinum Family Metals

Battelle Pacific Northwest Laboratories[20] has performed an excellent market analysis of the platinum metals Palladium, Ruthenium, Rhodium, and the transitional metal Technetium in nuclear wastes and has concluded that they will ultimately become a major national economic resource. The annual inventories of platinum metals from nuclear reactors as well as the U.S. mineral reserve of these metals is given in the following table:

Fission Products (Troy Oz Per Year)

	Pd	Rh	Ru	Tc
1980	65,000	36,000	173,000	63,500
1985	142,500	79,500	376,000	148,500
1990	271,000	143,000	662,500	257,500

United States Mineral Reserves (Total Troy Oz)

Pd	Rh	Ru	Tc	Pt
10,000	30,000	5,000	(Artificial)	3,000,000

The current values of the as-fabricated platinum metals ($/troy oz) are Pd $150, Rh $350, and Ru $230. When separated from wastes Palladium can be used immediately in some catalytic processes. Rhodium must be held for 20 years and Ruthenium for 25 years to reduce their radioactivity to usable levels. Several years ago it was estimated by Battelle that the capital cost for adding a platinum metals recovery line to an existing fuel element reprocessing plant would be about $6,000,000.

The use of radioactive platinum metals in catalytic processes has not been fully investigated but appears feasible as long as the product is not contaminated by the radioactive catalyst. It is also clear that the cost of these metals will continue to rise and that their availability will continue to decline, such that from a balance of payments standpoint their use may ultimately be a necessity.

(4) Cesium as a Substitute for ^{60}Co

Pacific Northwest Laboratories also performed an excellent comprehensive study on the future market for ^{137}Cs[21]. They reached the following conclusions: "Steady market growth can be anticipated for both ^{137}Cs and ^{90}Sr if it is priced at levels compatible with market requirements. The market for cesium is a share of the gamma source market currently supplied almost exclusively by ^{60}Co. Private separation and marketing of ^{137}Cs in the late 1970's or early 1980's by nuclear fuel reprocessors is well within the realm of economic feasibility. However, the visible market will have to be substantially larger than current markets to permit pricing at levels compatible with market requirements."

^{137}Cs is a source of high intensity gamma radiation often as a direct competitor to ^{60}Co[22]. It has been estimated that the annual radiation market will be nominally 16 megacuries of ^{60}Co, or its equivalent, by 1980, and as high as 25 megacuries by that time[21] based upon past projections. ^{137}Cs, $^{137}Cs/^{134}Cs$ mixtures, or ^{60}Co can be used interchangeably for many radiation applications. Cesium has been used for sterilization of medical supplies, medical teletherapy, chemical polymerization, food sterilization, and pasteurization and other applications.

^{60}Co has been used extensively for industrial radiography and in many of the above applications. The cost of ^{60}Co is about 45¢/curie and current annual world production is about 12-15 megacuries per year worth about $7,000,000.

B. Thermal Applications

Radioisotope heaters are currently in use on interplanetary spacecraft and will be used on future spacecraft. They are used to heat various instruments (magnetometers, sensors, etc.) and to heat gas in the spacecraft thruster engines. Their 100% reliability for producing heat has led to great accuracy and confidence in controlling spacecraft attitudes and trajectories to achieve planetary encounters and making instruments function years after launch and more than one half a billion miles from earth.

The terrestrial applications of heaters [up to 100 Kw(t)] in cold regions is particularly important in systems where reliability is a dominant factor. These applications include emergency shelters, water systems, and sanitary engineering systems in remote regions. Conventional heaters rely upon fuel oil and human factors for the fueling and operation of the heating systems. Arrays of ^{90}Sr-fueled WESF capsules each producing 1 KWT could enhance the reliability of these critical systems and also provide cost-effective energy for extended periods.

There has been some interest by oil companies in "down-hole" heaters for oil wells. There is experimental evidence that the flow of depleted wells can be stimulated by electrical heaters in the 15 KWT range. Other heating applications being investigated include the lowering of viscosity of heavy crude to induce flow, hot solvent treatment, and reliable heaters in pipeline or refining processes that must operate all the time. Though it is clear that sufficient energy to completely heat an oil-bearing formation is not available from isotopic heat, special purpose petroleum heaters may contribute to the extraction and processing of petroleum. Such heaters would be subject to retrieval and ultimate disposal.

Other thermal applications include heaters for essential equipment and vehicles in cold regions, and for space heating of small manned or unmanned facilities.

In addition the Defense Advanced Research Projects Agency has sponsored a feasibility study[23] and a conceptual design of a system which would produce steam for military installations from fission-product waste canisters. It is found that about 40 plants each having a 5 MW thermal output could be fueled by gross wastes by the year 2000.

C. Electrical Power Supplies

(1) Static Systems

Radioisotope thermoelectric generators fueled with ^{90}Sr have been built and used by the U.S., U.K., Germany, France, Italy, Netherlands, and U.S.S.R. Foreign sales of ^{90}Sr have been about 1 megacurie to date.

The U.K. has fabricated a number of RIPPLE generators [10 mW(e) to 60 W(e)] which have been supplied to the Danish Lighthouse Authority, Swedish Board of Shipping and Navigation, and to U.K. navigation organizations. The U.S.S.R. recently reported installing a similar unit in the Baltic Sea.

The French have deployed units in the Antarctic (ISOTAFF-1), in submerged oil installations (Marguerite, Marseille, Gisele V) and in various undersea applications in power ranges from 100 mW(e) to 25 W(e). The Italians have developed a 5 W(e) unit for subsea oil wellhead use.

In the U.S. dozens of units up to 100 W(e) have been used on land and underwater by the Navy, Coast Guard, oil companies, Weather Bureau (in unmanned meteorological stations), and in the Arctic and Antarctic. Table III is a partial listing of these generators and their status.

Static systems fueled with both ^{238}Pu and ^{147}Pm are gaining widespread use in cardiac pacemakers. The reliability of these units have been demonstrated in a number of individuals.

TABLE III

PARTIAL LISTING OF U.S. STRONTIUM-FUELED THERMOELECTRIC GENERATORS

DESIGNATION	QTY.	APPLICATION	USER
Sentry	1	Weather Station	Weather Bureau
SNAP 7A	1	Light Buoy	Coast Guard
SNAP 7B	1	Light House Oil Platform	Coast Guard Phillips Petroleum
SNAP 7C	1	Weather Station	Navy
SNAP 7D	1	Weather Buoy	Navy
SNAP 7E	1	Acoustic Beacon	Navy
S - 25A	1	Oceanography	Navy
S - 25B	1	Undersea	ESSO
S - 3	1	Navy Use	Navy
S - 3	2	Wellhead Control	Sinclair Oil & Gas
S - 3	1	Spare	Offshore Systems
S - 25C-1	1	Oceanographic	Navy
S - 25A	1	Evaluation Testing	USAF
S - 25D	3	NOMAD Weather Buoy	Navy
S - 25E	3	Navy Oceanographic Program	Navy
S - 8	1	Weather Station	Navy
S - 25C-3	1	ESSA Experiment	Navy/ESSA
S - 25F	5	Marine and/or Terrestrial Use	Navy
S - 8S	3	Commercial	Commercial
S - 8S	1	Commercial	Commercial
S - 100F	1	Navy	Navy
S - 8S	3	Commercial	Commercial

S = Sentinel

All Sentinels total accumulated hours equal to 1,129,177 as of January 1, 1974.

(2) Dynamic Systems

Few isotope powered dynamic systems, aside from the artificial heart pump prototype have been designed. It appears that stirling, organic rankine, and other dynamic systems, when matched to heat sources consisting of arrays of WESF capsules, could produce reliable power and readily compete with fossil fueled systems in remote regions. The dynamic systems would have the virtues of higher power levels [~2 KW(e)], higher efficiencies, and lower costs than static systems.

(3) Future Applications

Future applications of a commercial and military nature center around requirements for long life, automated systems, and critical systems for use in cold regions, remote areas, and underseas. Sonar-type marine navigation aids implanted on the bottom of critical ship channels (e.g., Valdez tanker channel) to supplement or replace conventional navigation aids have future promise. In addition, remote terrestrial radar and beacons for aircraft navigation powered by isotopes could replace those currently powered by propane-fueled systems and may be more reliable and cost-effective. These applications are currently undergoing conceptual and economic studies. However, a large potential market exists for ^{90}Sr in these and other electrical power applications.

An ever increasing market exists for ^{238}Pu fueled space power systems. Since 1961 about 20 thermal kilowatts of ^{238}Pu have been launched into space. In the 1975-1977 period about 26 thermal kilowatts will be used in new space missions.

D. Miscellaneous Applications

IAEA(24) conducted a survey of industrial radioisotope economics and uses in 1965, principally for industrial gauging, radiographic, ionizing, and tracer applications. It was concluded that: "The global savings from the industrial applications of isotopes in the early 1960's can be presented as U.S. $296-400 million per year." The survey though incomplete (partial responses from 21 countries) revealed that at least 4589 sources were in use at that time.

VII. ISOTOPES FROM COMMERCIAL FUEL REPROCESSORS

The dominant supply of isotopes for this program starting in the 1980's must come from commercial fuel reprocessors because the government supplies will be essentially exhausted. Several reprocessors have been interviewed regarding their thoughts on extraction of useful isotopes from the waste stream. A market for these isotopes is generally recognized, however, the size of the market has not yet been established. Thus, commercial reprocessors are willing to provide the opportunity (plumbing) for tapping the waste stream at specific points, but are naturally unwilling to invest in separations units for specific isotopes or suites of isotopes at this time. Thus, until a sustaining market is established and/or cost-effective methods to facilitate isotope extraction are developed, the commercial reprocessors will maintain their present course. It is universally recognized that post-facto separation of isotopes from calcined or vitreous solid wastes will probably not be economically viable. However, by virtue of the large quantities generated in the future glassification and by-product extraction could both coexist, depending upon the market situation for by-products.

VIII. CONCLUSIONS

A. A sufficient supply of isotopes exists to conduct demonstrational experiments in the 1975-1980 time frame to stimulate a market for waste products.

B. A large potential market exists for a number of waste products, measured in terms of billions of dollars.

C. Actinide by-products can become a feed stock for producing other energy-producing isotopes by neutron irradiation whose value may exceed that of the fission products.

D. Commercial reprocessors will not invest in the extraction and separation of isotopes from the waste stream until a proven market has evolved.

E. Economic studies must be performed to establish the trade-offs between the beneficial use or disposal of wastes. Fundamental to these studies are process economics, safety analyses applications studies, and market analyses, both domestic and foreign.

F. Regardless of the degree of beneficial utilization of wastes, some residual material from wastes not utilized and spent by-products after utilization will have to undergo ultimate disposal.

G. Isotopic waste products have the potential for solving a number of societal and national security problems and represent a unique source of energy and materials.

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