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Department of Energy Plan for Recovery and Utilization of Nuclear Byproducts from Defense Wastes

August 1983

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U.S. Department of Energy
Assistant Secretary for Defense Programs
Office of Defense Waste and Byproducts Management

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Department of Energy Plan for Recovery and Utilization of Nuclear Byproducts from Defense Wastes

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U.S. Department of Energy
Assistant Secretary for Defense Programs
Office of Defense Waste and Byproducts Management
Washington, D.C. 20545

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1.0 INTRODUCTION

Nuclear wastes from the defense production cycle contain many uniquely useful, intrinsically valuable, and strategically important materials. These materials have a wide range of known and potential applications in food technology, agriculture, energy, public health, medicine, industrial technology, and national security. Furthermore, their removal from the nuclear waste stream can facilitate waste management and yield economic, safety, and environmental advantages in the management and disposal of the residual nuclear wastes that have no redemptive value. This document is the program plan for implementing the recovery and beneficial use of these valuable materials. An "Executive Summary" of this document, DOE/DP-0013, Vol. 1, January 1983, is available.

Program policy, goals and strategy are stated in Section 2. Implementation tasks, schedule and funding are detailed in Section 3. The remaining five sections and the appendixes provide necessary background information to support these two sections. Section 4 reviews some of the unique properties of the individual byproduct materials and describes both demonstrated and potential applications. The amounts of byproduct materials that are available now for research and demonstration purposes, and the amounts that could be recovered in the future for expanded applications are detailed in Section 5. Section 6 describes the effects byproduct recovery and utilization have on the management and final disposal of nuclear wastes. The institutional issues that affect the recovery, processing and utilization of nuclear byproducts are discussed in Section 7. Finally, Section 8 presents a generalized mathematical process by which applications can be evaluated and prioritized (rank-ordered) to provide planning data for program management.

2.0 PROGRAM POLICY, GOALS AND STRATEGY

2.1 POLICY

Because of the potential value of byproduct recovery and utilization as well as the desire to convert a perceived national liability into a national resource, it shall be the policy of the Department of Energy's (DOE) Defense Programs to encourage widespread use of byproducts in meeting unique national needs and in solving societal problems. In concurrence with this policy, goals have been set for an integrated research, development, and demonstration program with byproducts from defense and other nuclear activities. The program includes the recovery of byproducts, the exploration and demonstration of end-use applications, and analyses and evaluations of the impact of byproduct recovery and utilization on nuclear waste management and disposal. The Department of Energy shall work cooperatively with other Federal agencies, states, international groups, and industry and shall transfer the technologies developed into the private sector as rapidly as possible. Priority will be given to projects with the best prospects of economic viability and/or strategic significance.

2.1.1 Policy Implementation

The DOE Plan for Defense Byproducts, to be updated as needed following comprehensive program reviews, outlines the program's structuring, objectives, resource priorities, and schedules. The program is based on the use of resources and facilities of the Department's field offices, laboratories, and contractors at multiple sites where Defense Programs activities are conducted and will actively solicit cooperation and involvement of universities and industry. The three primary program elements are: byproduct recovery, byproduct utilization, and the impact of these activities on waste management. The program elements will be implemented in safe, cost-effective operations.

For byproduct recovery, an integrated multi-byproduct approach will be emphasized and will be coordinated with waste management activities within the Defense Programs complex to ensure mutual compatibility of goals, including byproduct recovery and treatment, end-use of materials, and eventual treatment, storage, and ultimate disposal of wastes.

Past commercialization of, or private investment in, nuclear-based ventures, regardless of their technical merit, have been discouraged by unanticipated restrictive regulation, a variable national policy and fluctuating public acceptance. Programs that foster commercial utilization of byproducts from nuclear waste must include actions that solve these problems as well as technical issues. In implementing its policy of encouraging widespread use of byproducts, the DOE proposes sufficient engineering demonstrations of first-of-a-kind byproduct applications that technical operability, safety, environmental and public acceptability, and cost-effectiveness are established for each generic application. Such rapid and effective technology transfer will ensure the developmental maturity required to stabilize market conditions and attract private investment.

Consistent with this strategy, the DOE will emphasize joint ventures with interested parties in other Federal agencies and in States, cities, and industry in which each partner has an economic stake and pays some portion of the cost. DOE participation will normally be limited to one engineering demonstration of a specific type of new technology or a specific new application of technology. In some instances, second or third demonstrations may be necessary to accomplish the objectives cited above, in which case DOE involvement would be minimized and focused primarily on conceptual design, health, safety and environmental control. DOE, through its contractors, will supply byproduct materials for demonstrations and commercial applications. DOE will accept the return of radioactive materials at the end of their useful life for storage or disposal. Costs for these services will be established. The DOE's commitment to the operation of an engineering prototype will be defined in the initiating agreements and will be limited to 4 years, after which the facility and its operation will be the sole responsibility of the user agency. Technologies will be emphasized that appear ready for widespread use without future DOE funding. The DOE will continue to seek opportunities for byproduct utilization that require minimal or no incremental funding.

2.1.2 Legislative Authority

The Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1983 (H.R. 6329, Report No. 97-551)

authorizes the recognition and expansion of the Defense Byproducts Program as a separate budgetary line item within the Defense Nuclear Waste Management Program.

"First, byproducts beneficial uses should be authorized as a separate item The Committee recommends removal of the beneficial use program from long-term waste management technology where it is now carried. . . .

"The Committee is encouraged by the enthusiasm of the new management group for defense nuclear waste. While health and safety remain paramount considerations, the DOE now stresses beneficial use of surplus structures, the recovery of valuable materials, and the reduction of future maintenance costs.

"Byproduct beneficial use provides two immediate benefits. The removal of the fission products . . . reduces the thermal and radioactive content of the waste material destined for ultimate disposal. The second benefit derives from the economics of using the extracted fission products."

2.2 PROGRAM GOALS AND OBJECTIVES

2.2.1 Purpose of Plan

The Plan establishes the policies, goals and objectives, and strategies of the program and provides the approaches for its implementation.

The purpose of the Plan is to focus program resources upon those targets of opportunity having the highest probability of success and/or maximum potential national benefit. The program is flexibly structured a) to meet critical defense-related requirements, b) to permit individual byproduct applications to proceed according to supply and demand factors, and c) simultaneously to help resolve long-term national issues such as nuclear waste disposal, resource conservation and recovery, and strategic material independence.

The program activities and resources will be reprioritized, as necessary, during the annual program review process.

2.2.2 Scope of Plan for Defense Byproducts

The primary scope of the program encompasses the recovery and the utilization and/or recycle of byproduct materials from the defense production cycle.

The scope includes research, development, and demonstrations (RD&D) of byproduct applications for both the defense and commercial sectors. Because byproduct recovery processes are integral with the main defense production and the attendant waste management processes and facilities, the scope of the defense byproduct program overlaps with the activities of the defense production program.

The scope of the Plan for Defense Byproducts includes the program policy, goals and objectives, strategy, institutional factors, byproduct applications, the inventories of potential byproducts or scrap materials at defense program sites, waste management impact, program priorities, and program cost and schedule.

2.2.3 Program Goals

The program goals are to accomplish the following:

- Recover useful byproducts from the defense production cycle.
- Utilize byproducts in military and civilian applications.
- Facilitate the management and disposal of nuclear wastes from the defense production cycle.
- Resolve the institutional issues.
- Expeditiously transfer byproduct recovery and utilization technology to user government agencies and to private industry.

2.2.4 Program Objectives

Byproduct Recovery

- Assess the feasibility and economics of recovering various byproducts.
- Assess the compatibility of byproduct recovery processes with production and waste management processes.
- Recover, recycle, and conserve national resources and strategic materials

- Provide a current inventory of byproducts, scrap materials, and other potential resources in the defense production complex and in the civilian fuel cycle.

Byproduct Utilization

- Identify applications and assess the technical and economic viability of specific byproduct applications.
- Identify specific military requirements that can be advantageously satisfied by byproducts and support the Department of Defense (DOD) in developing and testing materials or devices for such use.
- Perform complete systems analyses to ensure that cost/benefits of byproduct recovery and utilization scenarios compare favorably with alternative solutions.
- Determine byproduct quality criteria and user requirements that will facilitate recovery, utilization, and final disposal.
- Deploy Engineering prototype systems and transfer byproduct technology to users expeditiously.
- Ensure that each application incorporates due consideration of environmental, safety, and health factors.

Waste Management Facilitation

- Identify mechanisms by which byproduct extraction can improve waste management and/or disposal operations and facilities.
- Seek compatibility of byproduct recovery with waste management processes.
- Determine the economic impact of byproduct recovery on waste management operations from reactor discharge to disposal of all wastes and end-of-life disposal of byproducts.

2.3 PROGRAM INTERFACES

Numerous internal and external program interfaces will be required in the Defense Byproducts Program. The early identification of these interfaces and

their closure will enhance the program's management and progress. Interface agreements will be prepared, as appropriate.

Regulatory agencies with which interfaces will occur include: the Food and Drug Administration (FDA); Nuclear Regulatory Commission (NRC); Environmental Protection Agency (EPA); and Department of Transportation (DOT).

There will be a broad range of interfaces with many participants and users: the Department of Defense (DOD); DOT/Federal Aviation Administration (FAA); National Aeronautics and Space Administration (NASA); State Department/Agency for International Development (AID); U.S. Department of Agriculture (USDA); industry and industrial associations; universities; states; and municipalities.

Interfaces of an international nature, too, will be a part of the program. These will involve the International Atomic Energy Agency (IAEA); several foreign states; and United Nations agencies--World Health Organization (WHO), etc.

2.4 STRATEGY

2.4.1 Tactical Approach

The initial supply of byproducts recovered will be modest but will be sufficient to satisfy the needs of various RD&D applications, testing their technical and economic viability. As such applications are proved viable, parallel recovery RD&D will be pursued on promising byproducts at Hanford and Savannah River to test the feasibility and economics of large-scale recovery processes to deliver the byproducts in end-use forms and configurations. A coincidence of success on both byproduct recovery and application will warrant program and resource priority for that byproduct. This is the short-term tactical approach.

Priority will also be given to byproduct applications where economic factors are secondary to strategic material needs or military applications, or where the byproduct application is the preferred alternative.

It is implicit that each byproduct application will satisfy considerations of health, safety, environment, public acceptance and cost-benefit before

technology is transferred. For example, the technical, health, safety, and environmental advantages to the public of each byproduct application will be weighed against alternative solutions employing effective conventional methods of doing the same job. A determination will be made of how many demonstration units of a given generic type are required for each application.

A primary tactic will be for DOE to enter into cooperative, cost-shared applications programs with interested commercial and military users to accelerate the transfer of technology to the marketplace. In most cases, users will be involved early in the development of an application.

2.4.2 Strategic Approach

To accomplish the long-term goals and objectives of the Defense Byproducts Program and to maximize the national benefit of program resources, the three primary program elements will be implemented by the following actions:

1. remove from the defense waste those byproducts which, by their removal, benefit management of the residual waste
2. make the recovered byproducts available for beneficial use
3. find meaningful applications for other byproducts and recover them for beneficial use when doing so is economically attractive
4. recover strategically valuable byproducts and store them for later use rather than disposing of them now in waste repositories
5. transfer the valuable technologies developed by Defense Byproduct Program activities to user agencies and private industry.

When possible, program actions will be integrated to achieve synergy. The recovery of individual byproducts or groups of byproducts can potentially enhance both ends of the waste management cycle. For example, the extraction of process mercury at SRL is required before high-level waste (HLW) sludges are vitrified. Substantial fractions of rhodium and palladium are extracted from the waste into the mercury phase. Therefore, if the mercury is separated from the waste before the mercury is distilled, the amalgamated rhodium and palladium will also be removed from the waste. They are then left behind when the mercury is purified by distillation prior to recycle to the plant dissolving cycle.

The removal of cesium-137 and strontium-90 is another example of positive synergy. In waste liquids the presence of strontium and cesium requires waste tanks to be cooled. Thirty years after reactor discharge they constitute 98 percent of the thermal energy and 97 percent of the penetrating radiation in HLW and dominate the design restrictions on the waste canister and repository. Removal of those two byproducts has the same effect as aging the wastes hundreds of years. The additional removal of neptunium, americium, and technetium will "age" the wastes thousands of years more.

3.0 TASK DESCRIPTIONS, MILESTONES AND FUNDING

Byproduct activities (or tasks) were selected on the basis of their support of the program policy, goals and objectives stated in Section 2.0. The selected tasks are described in the following sections and are organized into six generic areas: 1) heat and power sources, 2) engineering prototype irradiators, 3) self-powered lights, 4) strategic metals recovery and use, 5) inert gas applications and 6) supporting studies. Anticipated funding and associated milestones are shown for each area.

The outlined tasks and milestones are proposed in anticipation of authorization and funding at the budget levels shown. This level of funding will be needed to bring these valuable byproduct resources into use in solving national problems.

3.1 HEAT AND POWER SOURCES

The DOE long-range plan for development and deployment of radioisotope power sources is summarized in Figure 3.1. This figure reflects past activities on isotope-powered generators and outlines the planned effort to bring this resource to full maturity by 1990 as noted. This plan involves user agencies in planning as well as financing the required RD&D. The power sources used in the past were generally limited to under 100 W_e while future sources are anticipated to meet significantly higher power requirements. The four tasks which follow describe activities that implement this plan.

Task 1. Interagency Task Force

An interagency task force will be formed to identify and prioritize the needs for heat and power source development and deployment. Initially the task force will have membership representing the Department of Energy and the Department of Defense. Membership from other Federal and State agencies will be added as needed. The primary objective of the task force is to identify applications for heat and power sources fueled by strontium-90, plutonium-238, promethium-147 or other isotopes. The task force will then evaluate the availability of materials, determine a priority for development, demonstration and deployment, and report their findings.

FIGURE 3.1. Radioisotopic Power Supplies

Task 2. Systems Comparison Analyses

A complete systems analysis will be done for applications recommended by the task force report. Each analysis will include technical feasibility, a cost/benefit comparison with conventional heat and power sources, and a cost analysis for the complete system, including byproduct supply and end-of-life disposal.

Task 3. Strontium-90 Utilization

A feasibility and cost/benefit analysis will be performed on the use of fission-product strontium containing >90% ^{90}Sr , 50 to 40% ^{90}Sr , 40 to 30% ^{90}Sr , and <30% ^{90}Sr for fueling thermoelectric, Organic Rankine and Stirling engine

power conversion systems. The analyses will include incentives for preparing high-density fuel (>95% theoretical density) versus lower density fuel (60 to 70% theoretical density).

Serious development of applications for strontium-90 heat and power sources requires a stable supply of material for prototype development and initial field deployment. This interim need will be satisfied by using strontium-90 capsules stored in the Hanford Waste Encapsulation and Storage Facility (WESF) pool and recovered strontium-90 held as solution in B-Plant tanks awaiting conversion to strontium fluoride and encapsulation (see Section B.2). Hot-cell facilities can be pressed into temporary use to provide supplementary services not now available at WESF. Under the present plans, the current inventory of strontium-90 and cesium-137 will all be encapsulated by 1986. During the interim before waste generated from future operation of the Hanford PUREX Plant is partitioned, the WESF facilities may be upgraded to provide capsules more suited for byproduct use. Task 3 will define the capsule design and provide the justification for renovations at WESF.

Task 4. Construction of Prototype Power Sources

This task will produce two strontium-90-fueled prototype power sources in the 100-to-500-W_e range during the 1983-1984 time period for demonstration and evaluation purposes. The task will be continued in the follow-on years to provide up to two additional advanced-technology power sources that incorporate technology developed from construction and testing of the first two sources. It is anticipated that the second-generation power sources will have major input from users. The size, performance requirements, deployment, and other details of the follow-on power sources will be defined as tasks 1, 2 and 3 are completed and the engineering prototypes are evaluated under field conditions.

The first prototype power source will be a 500-W_e strontium-90-fueled RTG using state-of-the-art technology. The heat source will be modified capsules of strontium fluoride from the WESF. Standard capsules of appropriate power levels will be retrieved from the storage basin, the outer container of each capsule will be removed, and each inner capsule will be re-encapsulated in an impact-resistant outer capsule. This RTG is expected to have a thermal-to-electrical power conversion efficiency of 7 to 8%. The purposes for this

prototype are to extend the current technology to a significantly larger RTG (the previous maximum output for a strontium-90-fueled RTG is 100 W_e) and to field test the larger unit. The program will identify and resolve a number of engineering and materials problems, will provide an engineering basis for accurately evaluating the long-term use of such a power source, and will provide input on using currently available strontium-90 capsules.

The second prototype power source involves the development of a radioisotope power generator using thermomechanical conversion (RTMG) rather than thermoelectric. This process is less developed than thermoelectric conversion but has the potential for a large improvement in efficiency. The RTMG prototype will be designed to generate 500 W_e with a thermal-to-electrical power conversion efficiency of at least 20% and will use re-encapsulated WESF capsules. Because of the higher efficiency, the RTMG will require only one-third as much strontium-90 as the RTG to produce the same amount of power. Thermomechanical converters with conversion efficiencies of 17 to 25% have demonstrated long-life performance (10 years without maintenance), and converters with efficiencies of 33 to 38% have the potential of long-life performance. Construction and field demonstration of an advanced RTMG will, in many respects, complement the prototype RTG and will provide potential users with an option in matching power source technology to their specific requirements. The single largest advantage of RTMGs is that the limited supply of strontium-90 can be used to generate 3 to 6 times more electrical power than can RTGs.

For the immediate future the only source of strontium-90 for heat or power source use is concentrates now stored in B-Plant tanks at Hanford pending processing and encapsulation at WESF and encapsulated strontium-90 stored in the WESF pool. A moderate degree of flexibility exists at WESF. The facility will continue to be used to process, encapsulate and store the strontium-90 currently held in B-Plant tanks until that mission is concluded. In this process, strontium fluoride is compacted by cold compaction methods to a bulk density of 60 to 70% of theoretical in standard WESF storage capsules. Previously encapsulated strontium fluoride can be retrieved from the storage pool and re-encapsulated as described previously. Existing or modified Sentinel-25

capsules could be filled to the same density with relatively minor modifications to the existing equipment.

If the analyses described in Task 3 show that improved methods of compaction and/or an improved fuel form are feasible and there is sufficient identified incentive to make the changes, new capability can be installed in WESF at the conclusion of the current processing schedule.

Heat and Power Source Milestone Schedule

▽ Major Milestones
 ▼ Milestones Completed
 ◇ Transfer of Technology

Heat and Power Source Costs
(\$ in Millions)

	<u>FY-1983</u>	<u>FY-1984</u>	<u>FY-1985</u>	<u>FY-1986</u>
Operating	1.0	2.8	7.0	6.0
Capital	0	0	0	0
Capital equipment	0	0.0	0.0	0.5

3.2 CESIUM-137 IRRADIATOR DEMONSTRATIONS

The cesium-137 irradiator program has been ongoing for several years, much of the preliminary planning has been done, and the development of technology is well along. Consequently, this program is directed toward the design, construction and evaluation of prototype demonstration irradiators and transfer of the technology to the private sector.

Figure 3.2 summarizes the DOE long-range plan for sewage sludge irradiators. The long-range plan for food irradiation is shown in Figure 3.3. Both figures show the joint participation of DOE with user agencies in planning and implementing activities designed to fully develop commercialization of this technology by the 1987-1988 time period. The required near-term implementation activities are described in more detail under the following tasks.

Task 1. Operation of the Sandia Irradiator

This pilot irradiator was built and is operated by the Sandia National Laboratory. The irradiation source is one megacurie of cesium-137 in standard capsules fabricated in the Hanford WESF. This is the only irradiation facility in the U.S. currently using cesium-137. Sewage sludge, grapefruit and mangos have thus far been irradiated. Continued operation of this irradiator is required to conduct radiation experiments on a pilot scale, to extend the technology and to generate data for the design of generic demonstration irradiators.

Task 2. Sewage Sludge Engineering Demonstration Irradiators

By agreement with the City of Albuquerque, New Mexico, a sewage sludge irradiator is being designed and is scheduled for construction. Initially this irradiator will use 5 MCi of cesium-137 in the form of WESF capsules. A

Figure 3.2. Cesium-137 Sewage Sludge Irradiation

planned future expansion (about 1995) will increase the source to 18 MCi of cesium-137. This irradiator will function as a commercial demonstration facility to validate and quantify the concept of sewage sludge processing by cesium-137 irradiation. The treated sludge will be used, at least initially, as a soil conditioner for nearby public lands.

A second sewage sludge irradiator demonstration plant will be implemented to provide additional operating environments, siting requirements, and significantly different parameters relating to sludge preparation, marketing and utilization. Preliminary planning has been done on a second plant to be located at Idaho Falls, Idaho. The specific objective of this plant is to convert the sludge to a marketable product for sale to farmers and ranchers in the area.

FIGURE 3.3. Low-Dose Cesium-137 Food Irradiation

Task 3. Food Engineering Demonstration Irradiators

A small transportable cesium-137 irradiator (TPCI) has been conceptually designed and will be under construction in 1983. This irradiator is an important research tool in the continued development of irradiation technology for agricultural products. For fruit, nut and field crops, the dose requirements to establish the effectiveness of radiation and to observe any deleterious effects or any positive effects such as delayed ripening, etc., can be accurately determined only by means of pilot tests near the harvest site. This onsite research eliminates anomalies caused by varying stages of fruit maturity, handling, packaging, and transportation. In the TPCI concept, the irradiation sources will be transported separately in a DOT-approved cask. The irradiator will be constructed in a semi-truck trailer so it can be readily transported.

Following successful research and development testing in TPCI, the next step in technology transfer toward commercialization is the construction of a near-commercial-sized fixed facility. The design of the prototype will be optimized within selected criteria so that all operational phases will realistically represent a fully operational plant including product handling. The feasibility of a multiproduct facility for irradiating many other agricultural commodities will be carefully evaluated. This demonstration unit will provide sufficient product to evaluate consumer acceptance of irradiated food, and operational data will be used for decisions on full-scale deployment of the technology.

The fruit, nut and field crop irradiator is proposed as a joint venture between DOE and one or more user agencies or corporations. The U.S. Department of Agriculture is an ideal candidate for cosponsorship with other users. The DOE will take the lead responsibility in selecting appropriate participants and establishing management agreements.

The need for performing engineering, economic and comparative analyses for the food irradiation project parallels the needs discussed for the strontium-90 application. The food irradiator analyses will include:

1. A technical feasibility analysis and conceptual design.
2. A cost estimate of the total demonstration program, including end-of-life disposal of the spent cesium-137 capsules.
3. A cost/benefit analysis comparing a cesium-137 food irradiation plant with alternative methods of disinfestation or pasteurization, including irradiation by cobalt-60 and by x-ray machines.

The irradiation plant will be operated as a demonstration facility for an agreed-upon period (perhaps 4 years) to satisfy the need for verification of design, operation parameters, the economics of the process, and public acceptance of irradiated food products. All technology developed during this period will be in the public domain. Title and operation of the plant would then revert to private ownership or the plant be sold to private ownership and operated subject only to the provisions of an NRC license.

Irradiation of pork at dosages of 10 to 30 krad has been shown by researchers to disinfest this product of the parasite responsible for trichinosis in man. Presently, infestation of pork by this parasitic nematode, Trichinella spiralis, severely limits domestic uses of pork and its export to world markets, resulting in a reduced economic potential for the pork industry. A major step toward commercial-scale disinfestation of pork by irradiation is the current plan for a joint venture for the construction and testing of a demonstration-scale cesium-137 irradiator. The principals in this joint venture would be DOE and a Federal laboratory, an educational institution, or a commercial processor. Operation of this irradiator will establish the efficacy of the process and provide information applicable to full-scale commercial irradiator designs. Details of the need for such a facility are given in Section A.3.2. The implementation plan for a pork irradiator is similar to that described previously for a fruit, nut and field crop irradiator.

The use of food irradiation as a resource conservation measure is particularly applicable to the problem of world hunger. The U.S. Agency for International Development (AID) in conjunction with DOE is investigating irradiation for prevention of food loss. Cesium-137, with a 30-year half-life and relatively low shielding requirements, has major advantages for use in emerging nations using low-technology food production and distribution schemes.

Task 4. Supporting Activities

Improved Cesium-137 Irradiation Capsule

The currently-used WESF cesium-137 capsule (2 in. in diameter) was designed for water basin storage of cesium chloride as a waste material. Because of the large diameter, a significant amount of the gamma activity is absorbed in the capsule, with the consequent temperature increase of cesium chloride; thus the capsule is a less efficient gamma radiation source than desirable. The current TPCI conceptual design offers an opportunity to

investigate a smaller diameter capsule. Optimization of the capsule design will consider: 1) minimum self-absorption, 2) minimum cost of fabricating the empty capsule parts, 3) minimum cost for filling, sealing, and nondestructive testing of the capsule, 4) maintaining waste storability of the capsule, and 5) licensability of the capsule.

An analysis will be performed to quantitatively determine the incentives for improving the capsule design for future irradiation facilities. If sufficient incentive exists to improve the capsule design, then the analysis will be continued to define the design requirements and determine the costs of producing cesium-137 capsules of the improved design at WESF or elsewhere. Coordination will be maintained among the design team and users to ensure that users can obtain the necessary NRC license.

Capability can be installed in WESF to produce cesium-137 capsules of the improved design from future PUREX waste and/or to continue to fill the current storage capsules with cesium chloride. The production schedule will be guided by the projected need for cesium-137 irradiation sources.

Cesium-137 Capsule Transport Cask

A key element in the operation of engineering prototype irradiators is a licensed cask that can safely transport cesium-137 capsules between the Hanford WESF Plant and an irradiator. The design of such a cask, titled the Sewage Solids Irradiator Transportation System (SSITS), will be completed by March 1983 at the Sandia National Laboratory. Construction of the first unit will be completed a year later. Pursuant to obtaining a license, the cask safety analysis report will be submitted to DOE for approval early in 1983 and will be submitted by DOE to NRC about June 1983. The cask will be ready for use in early 1984.

Cesium-137 Irradiator Demonstration Milestone Schedule

New Facilities

Cost estimates have been prepared for the new demonstration irradiator facilities. These costs are based on the conceptual design and are only preliminary.

	<u>Completion Date</u>	<u>Cost Estimate (\$ Million)</u>
Transportable Cesium-137 Irradiator	1985	3.0
Albuquerque Sewage Sludge Irradiator	1985	3.5
Pork Irradiator	1985	2.5
Fruit, Nut and Field Crop Irradiator	1985	4.0
Idaho Falls Sewage Sludge Irradiator	not determined	not determined

Cesium-137 Irradiator Demonstration Costs (\$ in Millions)

	<u>FY-1983</u>	<u>FY-1984</u>	<u>FY-1985</u>	<u>FY-1986</u>
Operating	3.0	5.0	3.0	3.5
Capital	5.0	5.0	0	5.0
Capital equipment	0.65	0.6	0.4	0.1

3.3 SELF-POWERED LIGHTS

Low-level lighting devices using both krypton and tritium byproduct radio-nuclides can satisfy many military and civilian needs. The uniqueness of a light that requires no maintenance or power supplies, lasts a long time (8 to 10 years), and is not affected by environmental extremes provides the incentive to optimize it to be used for many specific applications. As with many technical advances, military requirements lead the way to civilian applications.

The DOE plan for development of self-powered lights is summarized in Figure 3.4. The program has, in some instances, reached the hardware development and demonstration stage. Military airfield lighting for runway distance markers and for taxiway marking are into field testing. Edge and threshold lighting for unimproved runways used by rapid deployment forces is in the demonstration stage, and instrument lighting that is compatible with night vision equipment is in the early R&D stages. Special lights for underwater marking for use by special forces and civilian law enforcement applications are

FIGURE 3.4. Tritium and Krypton-85 Self-Powered Lighting

under review or in actual R&D phases. The work to date has been jointly funded by DOD and DOE with the DOD-funded effort directed to specific requirements and DOE funding supporting major R&D efforts. As noted in Figure 3.4, the self-powered lights will be fully commercialized in the 1985-1990 time period.

Task 1. Light and Hardware Development

Phosphor Development

Phosphors are manufactured chiefly for use with cathode ray tubes and fluorescent lighting. The energy source for both applications can be varied to maximize light output from standard phosphor formulations. In the case of tritium and krypton-85, the beta rays are emitted at fixed energies and rates. The variable parameter for optimization, therefore, is the phosphor formulation. During FY-1983 and FY-1984 work will be done on phosphor formulations specific for tritium and krypton-85 to improve phosphor efficiency for light production and color.

Improved Efficiency of Light Production

A fundamental weakness in all fluorescent lighting systems is the loss of light due to the phosphor coating on the light-emitting window (usually the tube). Affixing the phosphor to a surface placed inside the light tube containing the activating radionuclide can reduce this loss of light. As much as a 50 percent improvement in efficiency is anticipated. Methods of quality control for phosphor thickness and reactions between the binder and the phosphor require development. Other problems involve establishing optimum geometry for the beta energy of the radionuclide. Lights of various colors are needed for special applications, especially in airdrop guidance control. A research and development program will be conducted during FY-1983 through FY-1985 to solve these problems.

Ruggedizing Lighting Devices

While both krypton-85 and tritium used in lighting devices have a low order of relative hazard, and currently used hardware is resistant to damage, many applications currently considered indicate the need to survive combat and hard use conditions. Work will be carried out to develop devices that are highly resistant to breakage under conditions of impact, vibration, pressure, and vacuum. Physical testing to set limits of durability will be performed. This work will provide data for licensing of lighting devices and product specifications for commercial manufacturers and DOD users.

Krypton-85 Shielding and Optics

First-generation krypton-85 lights have shown the advantage of the higher energy beta in the production of light from phosphors. Field tests have proven their potential for taxiway marking at military airfields. The reliability of the system, along with a favorable cost of deployment and use over existing systems, permits an optimistic appraisal of the potential for using byproduct krypton-85 in this application. The gamma ray associated with krypton-85 must be shielded through an optics system that nevertheless allows the light to be efficiently projected. Further developmental work should yield significant improvements in the light output and shielding.

Task 2. Applications Development

Instrument and Instrument Panel Lighting

The rapid advances in night-vision equipment and instrument lighting for aircraft and armored vehicles have been partially negated because the infrared component of incandescent lights now used causes a response in night-vision equipment that interferes with observing the outside environment. Radioluminescent lights have been demonstrated that do not initiate this response because the infrared spectrum is absent. Instrument lighting will be emphasized during the FY-1983 through FY-1985 period in the development of special-geometry light tubes, establishing the correct geometry for illumination of the instrument readout and for control of light intensity. Developments will be responsive to identified applications.

Infrared (IR) Radioluminescent Lights

Radioluminescent lights that do emit in the infrared spectrum have important applications in the military and in civilian crime control. Most of these applications involve operations with night-vision equipment and where light visible to the naked eye would betray a mission. The RD&D effort will involve selection of useful phosphors and, if indicated, phosphor development to obtain spectral output that is optimum for night-vision equipment response. The effort will involve optimizing the coating of phosphors onto the inner surface of light tubes and developing geometry of lights for special applications in marking both small and large perimeters. This work is highly R&D-oriented since the use of infrared illuminators is new and of increasing importance. Testing of devices for the extremes of vacuum/pressure and temperature cycling will permit deployment in space applications as well as terrestrial applications.

Underwater Applications

The potential for use of lights in underwater applications includes the marking of retrievable submerged items and marking for positioning. Such devices will supplement sonic markers. Special considerations in the development of underwater lights involve sealing against water leakage, light

spectrum for maximum viewing, anchoring, and corrosion resistance. This is a new environment of application and will require approximately 16 months of R&D prior to full-scale testing.

Cost-Benefit Analyses

Applications identified to date involve both those that can be satisfied only by radioluminescent devices and those that may be desirable but subject to normal cost-benefit considerations. Cost-benefit analyses will be performed on identified applications.

Task 3. Field Testing

For maximum utility, lighting devices require evaluation under actual field test conditions. To date, progress in modifying engineering models and expanding the number of applications has been achieved through field testing. These tests allow first-hand evaluation by user groups and identify problems in design, light characteristics, deployment methods, and physical qualities. Tests may be short-term (1 to 5 days) or long-term (weeks to months). They involve 1) assembly of enough devices to realistically represent the test parameters and 2) transport of the devices to a test site (usually a military reservation).

Hardware production for full-scale test demonstrations is needed to evaluate promising applications. This production may be in-laboratory or through contracts with commercial fabricators. For commercial fabrications, technology transfer is accomplished and large-scale demands can be met with minimum lead time.

Task 4. Technology Transfer

Some military and civilian lighting applications have reached the stage of development and testing so that routine manufacturing could now be done by private companies. An active effort will be made to identify companies, encourage their interest and transfer the technology to them.

Self-Powered Lights Milestone Schedule

Self-Powered Lights Costs
(\$ in Millions)

	<u>FY-1983</u>	<u>FY-1984</u>	<u>FY-1985</u>	<u>FY-1986</u>
Operating	0.75	0.75	0.9	0.5
Capital	-	-	-	-
Capital equipment	0.05	0	0.1	0

3.4 STRATEGIC PLATINUM GROUP METALS RECOVERY AND APPLICATIONS

Figure 3.5 summarizes the DOE plan for the recovery and beneficial use of the strategic platinum group metals palladium, rhodium and ruthenium and of the similar metal technetium. The tasks required to implement this plan are shown below.

FIGURE 3.5. Strategic Platinum Group Metals

Task 1. Process Development

The objective of this task is to develop recovery methods that are compatible and economically synergistic with fuel and waste-management processes. Since the latter processes are still in the development stage and platinum group metals recovery processes suitable for one facility may not have the same advantages at another, the examination of multiple options is under way. Major emphasis will continue on the development of the lead extraction process for the recovery of rhodium, palladium, ruthenium and technetium during the vitrification of defense or civilian wastes. Other options being examined include recovery of rhodium and palladium during recovery of mercury from the SRP wastes, and the possible use of solvent extraction, ion exchange or special sorbate processes for recovery during aqueous processing. As part of the latter effort, the chemical species of the platinum group metals will be determined at opportune locations in the PUREX process.

Task 2. Utilization Development of Fission-Product Platinum Group Metals

The identification of uses for recovered fission-product platinum group metals will be supported by work in three interrelated areas:

- Fission-product rhodium, ruthenium and palladium each contain isotopes that are radioactive. Technetium-99 is also radioactive. A general assessment will be made of time-dependent dose rates, regulatory needs, and other health-physics issues required for introducing these metals into use. The assessment will be specific for the most promising uses identified.
- Contacts will be made with suppliers and users of these metals to identify possible applications and means of introducing these fission products into the market place.
- A complete systems analysis will be performed that includes 1) the economics of extracting the platinum-group metals from various fission product wastes, 2) the feasibility and economics of achieving the required decontamination from other radioactive materials in the waste, 3) the feasibility and economics of separating the radioactive isotopes from the stable fission-product platinum group metals, and

4) the economics of using these metals in strategic and civilian uses. Costs of extracting, separating, and purifying the platinum group metals from fission products, including incremental costs for subsequent waste-form production, will be estimated. All operations required for the separation and purification of these elements and their associated costs will be identified. The systems analysis will be periodically reviewed and updated as needed.

Strategic Platinum Group Metals Milestone Schedule

Strategic Platinum-Group Metals Recovery
and Applications Development Costs
(\$ in Millions)

	<u>FY-1983</u>	<u>FY-1984</u>	<u>FY-1985</u>	<u>FY-1986</u>
Operating	0.4	1.0	1.0	1.0
Capital	-	-	-	-
Capital equipment	0.2	0	0	-

3.5 INERT-GAS APPLICATIONS

The potential availability of krypton and xenon from future processing of defense and commercial spent fuel is given in Tables B.11 and B.12. The actual supply of these inert-gas fission products is currently limited to the capacity of a cryogenic recovery plant and the processing schedule of the INEL fuel processing plant to which a cryogenic gas recovery plant is attached. Except for a relatively brief period in the immediate past, the available supply of inert gas has exceeded the demand.

Current EPA regulations that limit atmospheric release of krypton-85 from the commercial fuel cycle to 50,000 Ci/gigawatt-year of electrical energy generated from nuclear fuel after January 1, 1983, will make these inert gases much more available if processing of commercial fuel is restarted. The EPA limitation on the release of krypton-85 will undoubtedly require the separation of the much greater amount of accompanying xenon to minimize the volume of gas that must be stored or disposed. This action will make large quantities of nonradioactive xenon (see Section B.4) available at an attractive price for commercial use. It is prudent to develop additional beneficial uses for fission-product krypton, enriched krypton-85, and separated xenon.

Task 1. Applications Development

The use of krypton-85 for nondestructive flaw detection in metals and electronic components is an expanding commercial business. The DOE-funded program to commercialize the use of krypton-85 for self-powered lights is described in Section 3.3. Other uses and many potential uses for krypton and xenon are described in Sections 4.3, 4.4, A.4 and A.5.

Contacts will be established in industry and medicine with potential users of the inert gases to assess and establish realistic uses. Cooperative

programs will then be implemented to perform the necessary research, development or demonstration activities that will fully establish the most promising uses of these byproduct gases.

Task 2. Inert-Gas Supply

An engineering analysis will be made of the feasibility of increasing the recovery of inert gas by expansion and renovation of the existing recovery facilities or by design and construction of new facilities. New facilities might be located at INEL, SRP, Hanford or the Barnwell commercial processing plant if timely decisions are made to start up that plant. The analysis will include an evaluation of future requirements to establish the needed recovery capacity, a site evaluation, and an economic analysis to determine incentives for increased recovery capacity. Finally, the analysis will evaluate and determine the optimum recovery and purification processes. The feasibility analysis will be the basis for a DOE decision to: a) continue as is, b) increase the output of existing facilities, or c) construct and operate new facilities. The feasibility and need of applying advanced isotope separation technology to the enrichment or purification of krypton-85 is addressed in Section 3.6.

Milestone Schedule for Inert-Gas Applications Development

	81	82	83	84	85	86	87	88	89	90
1. Applications assessment				▽						
2. Recommended recovery technology							▽			

Applications Development Funding (\$ in Millions)

	<u>FY-1983</u>	<u>FY-1984</u>	<u>FY-1985</u>	<u>FY-1986</u>
Operating	0.1	0.2	0.2	0.2
Capital	-	-	-	-
Capital equipment	-	0	0	0

3.6 BYPRODUCT RECOVERY AND UTILIZATION SUPPORTING ACTIVITIES

Those activities that are not oriented to a specific application but support general byproduct utilization are included in this section.

Task 1. Byproduct Recovery Impacts on Waste Management

The preliminary qualitative assessment made of the impact of removal of selected byproducts from defense wastes (see Section 6) concludes that:

- Byproduct recovery options that include recovery of TRU elements together with strontium and cesium will have major beneficial impacts on waste management.
- Byproduct recovery options that do not include the recovery of TRU elements will have small impacts on waste management.

Comprehensive engineering analyses are required to quantitatively define these impacts at each of the three major DOE defense production sites, SRP, Hanford and INEL. This effort will require close correlation and continuing interaction with waste management and repository development efforts. These analyses, some of which will be performed by waste management rather than byproducts, are summarized in Section 6.3.

Task 2. Improved NDE Technology for Byproduct Capsules

Careful nondestructive examination (NDE) is made of every WESF capsule, both strontium and cesium, immediately after filling. NDE of radioisotope-filled capsules is complicated because the capsules are really two concentric capsules, they are thermally not, and they have high gamma dose rates. The NDE procedure at WESF is satisfactory for the intended deployment of the capsules, i.e., extended storage in a water-filled pool on the Hanford site. However, as radioisotope-filled capsules are deployed for use at locations physically separated from a government production site and the attendant specialized facilities, it may be necessary to periodically examine the capsules nondestructively to identify and measure any capsule anomaly so that corrective action can be taken before there is any detectable leakage of radioactive material from the capsule.

Technology developed for examining nuclear fuel will be utilized to develop NDE equipment and methods for examining weld quality, stress-corrosion crack development, intergranular corrosion and wall thinning by internal or external chemical corrosion on capsules filled with radioisotopes and deployed for beneficial use. Such examinations should be made soon after filling, and, especially for cesium-137 irradiation sources, repeated periodically in the irradiation facility. This will greatly enhance the safety and the public confidence in the safety of the irradiator.

This effort will 1) establish the design and inspection criteria for capsules and liner closures to ensure inspectability, 2) establish the feasibility for continuous or periodic monitoring of the capsule in use, 3) design and build an inspection system, and 4) design and build a prototype monitoring station.

Task 3. Byproduct Beneficiation by Isotope Enrichment

Some of the advantages to the byproducts user of isotopically enriched strontium-90, krypton-85, and even cesium-137 are noted in Section 4. If isotope enrichment became feasible, much higher specific activities could be achieved for strontium-90, krypton-85 and cesium-137 sources. Strontium and cesium feedstocks that are now degraded to unusable isotopic ratios could be enriched and used. The isotope sources could be used for significantly longer periods, and recycle of the active isotope at the end of life of the source could be accomplished by chemical separation. Removal of the radioactive isotopes from the platinum group elements could make those materials immediately available.

Preliminary calculations imply that isotopic enrichment by one of the advanced separation techniques may be both technically and economically feasible. Because the advantages are so great, detailed feasibility and cost-benefit analyses will be performed. If the engineering analyses look attractive, then one or two brief experimental tests, using inert materials, will be performed to validate the feasibility. Promising results from the engineering analyses and preliminary tests with inert materials would lead to a pilot-scale demonstration for one or more of the most promising products.

Any new facilities required for the installation and operation of an advanced isotope separation machine will be defined in the engineering analyses.

Task 4. Recycle of Contaminated Materials

The Resource Conservation Recovery act (RCRA) of 1976 (Public Law 95-580) and the changing supply situation for the world's strategic materials provide dual motivation for reviewing defense-related materials resources. The materials included in the scope of this task are those of high economic value that are and have been used at DOE sites, have become contaminated by radioactive isotopes during that use, and cannot be recycled to unrestricted use through normal scrap or salvage practices, i.e., copper, stainless steels, gold, and platinum. A second kind of material is those manufactured, at great cost, into unique shapes and whose cleanup and recycle could obviate the cost of manufacturing replacement shapes.

Advances in component decontamination and in smelting, casting and forging technologies used in decontamination processes for classified components hold new promise for recovering valuable materials from radioactively contaminated wastes. These advances are expected eventually to significantly reduce the volume of solid wastes. Cleanup of contaminated material to reusable levels and/or to permit controlled reuse represents a twofold savings: 1) the storage/disposal costs are reduced and 2) the replacement costs are eliminated.

This task consists of two parts: 1) preparation of an updated assessment of the availability, recoverability, and value (market, replacement or strategic) of valuable contaminated materials in current use or stored as scrap at each DOE site and 2) demonstration recovery projects for economically recyclable materials at appropriate sites. The demonstration projects will be defined by the engineering assessment and could involve decontamination sufficient for return to unrestricted use or recycle to restricted use at a DOE site.

Supporting Activities Milestone Schedule

	81	82	83	84	85	86	87	88	89	90
1. Complete analysis of impact of byproduct recovery and utilization on waste management				▽						
2. Determine feasibility of advanced NDE for byproduct capsules				▽						
3. Complete testing of NDE monitoring station						▽				
4. Complete validation assessment of isotope enrichment of strontium-90, krypton-85, and platinum group metals					▽					

Supporting Activities Costs (\$ in Millions)

	<u>FY-1983</u>	<u>FY-1984</u>	<u>FY-1985</u>	<u>FY-1986</u>
Operating	0.25	0.25	0.5	1.6
Capital	-	-	-	-
Capital equipment	0.1	0	0	0.15

4.0 REVIEW OF DEMONSTRATED AND POTENTIAL BYPRODUCT APPLICATIONS

The purpose of this section is to summarize the extensive byproduct utilization activities of the past 20 years, review the most significant applications that have been identified, and provide a positive viewpoint that nuclear byproducts are an asset that can be used beneficially to satisfy unique national needs. Detailed descriptions of the individual byproduct materials, their unique properties, demonstrated and potential applications, and appropriate literature references are provided in Appendix A.

The recovery of byproducts from nuclear waste and their beneficial use depend on one or more of the following guidelines:

- The byproduct must have unique properties that match unique requirements of a specific application.
- The byproducts must be present in sufficient quantities in defense HLW to justify recovery and beneficial use.
- Recovered byproducts must be marketable at an economic advantage acceptable to the user and the producer.
- High value may be assigned to a byproduct or recycled material because the material meets a critical military or national strategic need.
- Removal of selected byproducts may reduce the cost for managing the residual waste.

Nearly 500 isotopes are produced in nuclear reactors by fission and irradiation processes. Several of these can be considered recoverable at the present time using the above guidelines, and others may be recoverable as future conditions warrant. Candidates for recovery and utilization at this time include the following:

Process irradiation

cesium-137

Radioisotopes for heat and power

strontium-90
cesium-137
krypton-85
promethium-147
plutonium-238 (from neptunium-237)
curium-244

Special value and unique isotopes or elements

americium-241
technetium-99
ruthenium
rhodium
palladium
krypton-85
xenon

Byproducts useful as targets for production of other elements

neptunium-237
americium-241
curium-244

Byproducts useful for luminescence applications

tritium
krypton-85
promethium-147

Tritium is included in the above list because it is used in the same applications as byproducts.

4.1 STRONTIUM-90 APPLICATIONS

Power Source Applications

Large quantities of strontium-90 have been recovered, purified and encapsulated for use as energy sources for radioisotope-fueled thermoelectric generators (RTGs). Other isotopes, as identified later, also have been used and proposed as power sources for RTGs. Strontium-90 has been studied as a fuel

for thermomechanical generators (RTMGs), e.g., Rankine, Brayton and Stirling cycle engines, and for thermionic power. One- to one-hundred-watt electrical (W_e) RTG units have been built, and RTGs having capacities of 500 to 1000 W_e are possible.^(a)

Early RTGs used $SrTiO_3$ or Sr_2TiO_4 as the fuel form, but more recent designs have used SrF_2 . Failures are rare and manufacturers^(a) report over 5,000,000 hours of successful operation. These devices require no maintenance, and can be designed to resist natural or man-directed destructive forces.

Strontium-90-powered RTGs have been successfully used to provide electric power for remote weather stations, remote surveillance stations, navigational aids and command, control, communications and intelligence (C^3I) systems (see Table 4.1 and Figure 4.1). Strontium-90-powered RTMGs have similar potential, and both could be used for low-power radar systems and remote emergency power.

Heat Source Applications

Properly encapsulated and shielded, strontium-90 could be used for heat sources for Arctic, petroleum and military applications. Heater sizes would be comparable to those needed as energy sources for RTG applications. Thus power sources recovered from used RTGs or strontium-90 that is unacceptable as an RTG fuel might be used for heater applications. Specific criteria for these uses will be application-dependent, but most will relate to thermal need, reliability and life-cycle requirements.

(a) Information furnished by John McGrew, Teledyne Energy Systems, Inc.

TABLE 4.1. Terrestrial Applications of Isotope-Fueled Electric Generators

Generator Model	No. Mfd.	Power, Watts	Year	Application	Status
<u>^{90}Sr-fueled</u>					
Sentry	1	10	61	Arctic Weather Station	2 years service demo
SNAP-7 series	6	10-60	61-65	USCG - USN	In storage defueled; 4 in storage
Sentinel 25	24	25	66-77	Subsea communications, weather	20 operating or being refurbished
Sentinel 3	3	3	67	Subsea	In storage
Sentinel 8	23	8	68-82	Weather communications	Operating
Sentinel 100F	1	100	72	Computer power source	Scheduled USAF, Alaska
Sentinel 15	4	1	82	Communications relay	Operating
<u>^{238}Pu-fueled</u>					
High Performance Generator	8	150	76-82	Power	Operating
75 Milliwatt	25	0.075	76-82	Power	Operating
5 Watt	4	5	84	Power	To be delivered

FIGURE 4.1. Some RTG Applications as Navigational Aids

4.2 CESIUM-137 APPLICATIONS

Several activities have been undertaken to investigate and implement the use of fission-product cesium-137 in ways that benefit mankind. Gamma radiation from this isotope has been shown to be effective in reducing pathogens in sewage sludge to levels where reuse in public areas meets current regulatory criteria for protection of public health. Food irradiation at doses of 1000 krad or less has been found by international expert committees to be wholesome and safe for human consumption. Cesium-137 can be used as a means of enhancing particular properties of various food commodities by sterilization, insect disinfestation, delayed aging and ripening, and sprout inhibition.

A cesium-137 pilot-plant irradiator (see Figure 4.2) has been constructed and placed in operation at the Sandia National Laboratories. The irradiation source is 1 MCi of cesium-137 capsules from the Hanford Waste Encapsulation and Storage Facility (WESF). A high degree of flexibility has been incorporated into the pilot plant. Material moves through the irradiation chamber in buckets on a continuous conveyor system. The function of this pilot plant is

Figure 4.2. Cesium-137 Pilot-Plant Irradiator at Sandia National Laboratory

to irradiate many kinds of materials, optimize irradiation conditions, and provide design data for generic demonstration plants. Sewage sludge, grapefruit, and mangos have been irradiated.

Other engineering demonstration irradiators in the planning stage include a pork irradiator to eliminate the trichinosis problem, irradiators in Florida, California, and Washington to disinfest fruit, and municipal sewage sludge irradiators at Albuquerque, New Mexico, and Idaho Falls, Idaho.

4.3 KRYPTON APPLICATIONS

Power Source Applications

Krypton-85 has been proposed as an energy source for small isotopic batteries, e.g., RTGs. Capsules produced by ion implantation in a sputter-deposited metal alloy may be useful for making heat sources for small 1- to 2-watt RTGs for a variety of purposes if highly enriched krypton-85 is made available. Using highly enriched krypton-85, thermal power levels greater than 0.6 watt per cubic centimeter could be produced by encapsulating krypton-85 in metal matrices. Thus 20 cubic centimeters of metal containing krypton-85 would be needed to produce 1 watt of electric power.

Beta (Self-Powered) Lights

Self-powered light sources using beta-emitting radioisotopes to activate phosphors have been under investigation for many years. The radioisotopes most used for this application are tritium, krypton-85 and promethium-147.

Television viewers remember pictures of the first spacecraft docking using promethium-147-powered lights to guide final maneuvering. Recent demonstrations of tritium-activated lights for military aircraft runway and other combat applications have shown excellent potential for expanded use. These demonstrations have also shown that self-powered lights can be used in the civilian sector as well. The major advantage of self-powered lights is that they require no electric power for their operation. Thus the logistics of supplying batteries or electric power are eliminated for remote or tactical applications. Three types of self-powered lights are shown in Figure 4.3.

Tritium-Activated
Hand-Held Wand

Tritium-Activated Light Fix-
ture for Lighting Remote
Runway

Krypton-85-Activated
Light

FIGURE 4.3. Three of Several Configurations of Self-Powered Lights
Being Developed at Oak Ridge National Laboratory

Nondestructive Testing

Nondestructive testing applications of krypton-85 are primarily for flaw detection in metals and electronic components, gauging, leak detection, sensing and indicating. Some of these are reasonably well developed, e.g., flaw detection, leak detection and gauging, while others are not as well developed.

Nonradioactive Fission-Product Krypton

The major use for krypton gas is to fill fluorescent and incandescent lights, where its thermal and spectral properties are superior to the alternatives, nitrogen or argon. Krypton gas is also used in instrumentation and for research applications. Since natural krypton is scarce, the non-radioactive fraction of fission-product krypton could be used for existing

applications if it could be separated at high purity from the radioactive krypton-85. (Natural krypton is recovered by cryogenic process from air, where it exists in concentrations of 1.14 parts per million.)

4.4 XENON APPLICATIONS

Of all likely byproducts recoverable from spent fuels, xenon is the most abundant. Furthermore, the very short half-life of all its radioactive isotopes ensures that the element will be essentially stable by the time of fuel processing (one or more years after discharge from reactors).

Most xenon applications require a very high decontamination from krypton-85. Xenon can then be used for filling fluorescent and incandescent lights and electronic tubes, as an anesthetic, and for other medical purposes. (Natural xenon is recovered from air, where it exists in concentrations of 0.087 parts per million.)

4.5. PLATINUM GROUP METALS APPLICATIONS

The platinum group metals--platinum, palladium, rhodium, iridium, ruthenium and osmium--are used extensively as catalysts, in electronics, in medical-dental applications, and for many other purposes. These metals find uses when their high melting points, chemical inertness (in elemental form), catalytic properties, and refractoriness are needed. The vital character of these metals in meeting national needs was expressed by the National Research Council⁽¹⁾ as follows: ". . . in industrial use they [the platinum metals] are generally either the only material that can be used or the most cost effective of the available options, and, therefore, replacement seems unlikely to be significant. Indeed, the usage trend seems likely to accelerate more rapidly over the forecast period than at any other time in history."

During the past several years the price for these metals has fluctuated dramatically. A significant factor is the uncertainty of supply. Most of the world production is in South Africa (46 percent), the USSR (48 percent) and Canada (5 percent). The U.S. uses approximately 35 percent of the total yearly world production of approximately 1.96×10^5 kilograms and relies on importing

89 percent of its requirements each year. Thus there is concern that the largest producers could limit the availability of these crucial metals for political reasons. Imports also contribute to the negative U.S. balance of payments.

Spent nuclear fuel contains three of the platinum group metals, ruthenium, rhodium and palladium, plus the metal technetium, which is nearly absent in nature. U.S. consumption of natural palladium, rhodium and ruthenium during the period 1979 to 1983 is shown in Figure 4.4 for comparison.

The technical feasibility of substituting fission-product palladium, rhodium and ruthenium for their natural counterparts in specific applications will be determined (see Section 3.4). Processes for their recovery and decontamination are under development. Utilization of these materials will require 1) development of processes and construction of facilities that will adequately separate them from the other fission products and 2) proper management of the radioactive palladium, rhodium and ruthenium isotopes. Removal of the radioactive isotopes of palladium, rhodium and ruthenium by advanced isotope separation processes is being evaluated. This would remove all barriers to the use of these strategic metals.

4.6 PROMETHIUM-147 APPLICATIONS

Fission-product promethium consists primarily of the radioisotope promethium-147, with low levels of three additional isotopes, promethium-146, promethium-148 and promethium-148m.

Promethium's low shielding requirements and low toxicity make it of interest for power sources, lights, and other devices that may be used on a wide scale. Its use has been demonstrated in both military and civilian application for human heart assist devices, portable power sources (RTGs), beta lights, portable X-ray devices, gunsight applications, and other areas where its unique properties can be used. In nearly all these applications it is similar to krypton-85, described previously, but requires considerably less shielding.

FIGURE 4.4a. Palladium Metal Uses and Consumption

FIGURE 4.4b. Rhodium Metal Uses and Consumption

FIGURE 4.4c. Ruthenium Metal Uses and Consumption

4.7 PLUTONIUM-238 AND NEPTUNIUM-237 APPLICATIONS

These two isotopes are discussed together because neptunium-237 is the precursor of plutonium-238, which is useful as a source of heat and power. Neptunium-237 is routinely recovered, exposed to neutrons and converted to plutonium-238.

Plutonium-238 has been used for instrument heaters and to fuel RTGs for space power systems. Table 4.2 lists the space nuclear power systems launched by the U.S.A. between 1961 and 1977 and planned for the near future. These power systems, using plutonium, have been highly reliable, providing up to 500 watts of continuous, stable direct-current power to spacecraft used in NASA and DOD space missions. Missions to the planets would have been impossible without such heat and power sources.

TABLE 4.2. Summary of ^{238}Pu -Fueled RTG Power Systems Launched in Space by U.S.A.

<u>Mission</u>	<u>No. of Missions</u>	<u>No. of Generators</u>	<u>Power, watts</u>	<u>Launch Dates</u>	<u>Status</u>
Transit	6	6	2.5-25	61-72	5 in orbit; 1 aborted
Nimbus	2	4	30	68-69	1 in orbit; 1 aborted
Apollo	6	6	70	69-72	5 on moon; 1 aborted
Pioneer	2	8	40	72-73	Successfully operated to Jupiter and Saturn
Viking	2	4	40	75	On Mars
LES	1	4	150	76	In orbit
Voyager	2	6	150	77	Successfully operated to Jupiter (79), Saturn (80-81). In transit to Uranus (86) and Neptune (89).
Galileo	1	2	285	86	To be delivered
Solar Polar	1	1	285	86	To be delivered

4.8 AMERICIUM-241 APPLICATIONS

Americium-241 is the useful americium isotope which can be recovered as a byproduct from defense HLW. In the foreword to W. W. Schulz's monograph The Chemistry of Americium,⁽²⁾ published in 1976, F. P. Baranowski states, "Probably no actinide isotope has more uses than americium-241." Among the most significant uses are oil-well logging, static elimination, and smoke detection. Many lives are saved annually by americium-241 smoke detectors.

REFERENCES

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2. W. W. Schulz, The Chemistry of Americium. TID-26971, Energy Research and Development Administration, 1976.

5.0 BYPRODUCT INVENTORIES

The nuclear byproduct materials of interest include strontium-90, cesium-137, krypton-85, xenon, palladium, rhodium, ruthenium, technetium-99, promethium-147, neptunium-237, americium-241 and curium. These materials are potentially available from currently stored waste and from future processing at Hanford, at the Savannah River Plant (SRP), at the Idaho Chemical Processing Plant (ICPP), and from commercial spent fuel. In addition, technetium-99 is recovered during uranium isotope enrichment and americium-241 is recovered during reprocessing of previously purified plutonium.

Commercial spent fuels represent a major source of byproducts if reprocessing of commercial fuels is restarted. The current inventory of commercial spent fuel, through 1981, is about 8000 metric tons of initial heavy metal (MTIHM).

Although a byproduct may be potentially recoverable from a given source, it does not necessarily follow that recovery is either technically or economically feasible. At present, facilities for recovering purifying and packaging of byproducts are limited. Cesium-137 and strontium-90 are recovered, packaged, and stored in water basins at Hanford for waste management purposes. Past emphasis has centered on safe, cost-effective management of cesium and strontium waste, not on the production of optimized heat or radiation sources. The activity levels are less than desirable for most of the capsules and less than minimum useful values for many of the stored waste capsules. In future processing, changing the emphasis to byproduct packaging and the imposition of appropriate controls will ensure high-quality sources. Cesium-137 recovery, but not packaging, is currently planned at SRP for waste management purposes. The recovered cesium-137 may be added to the sludge and vitrified, separately vitrified, or converted to a suitable byproduct form and packaged for byproduct use. Neptunium-237 is recovered at SRP and irradiated to plutonium-238. Krypton and xenon are recovered at ICPP and purified at ORNL.

The quality of the material that can be obtained from a specific source can affect potential recovery for beneficial uses. For example, the cesium-137 content of cesium recovered from spent fuel or stored wastes will depend on the

time since the cesium (fuel) was discharged from the reactor. Thus fuel or wastes stored for long periods may not be a suitable source of high-quality cesium-137. On the other hand, cesium recently discharged from the reactor contains a high concentration of cesium-134, which may adversely affect the quality of the cesium-137 for specific applications. The quality of strontium-90 recovered from fuel or wastes also depends on the time since the strontium was discharged from the reactor. The quality of the strontium-90 obtainable can also be degraded by additions of natural strontium during processing of the spent fuel and waste treatment.

Almost all the byproducts could be recovered from both existing and future wastes at the Idaho Chemical Processing Plant. However, except for krypton and xenon, there are no facilities at ICPP for such recovery. Since the amounts available at ICPP are only about 10 percent of the amounts available at SRP or Hanford, any new recovery capability should be installed at SRP or Hanford. Accordingly, isotope inventory data from ICPP are not included in the following sections.

Overall, several factors can affect the potential recovery of nuclear byproducts for beneficial use, and all the factors must be considered in evaluating the materials available from the various sources. The reader is cautioned that the inventory data provided are the best currently available but that they are valid only for the stated assumptions. Refinements in computer calculations, additional sampling and analysis, changes in fuel processing schedules, or changes in byproduct purity requirements will change the inventory. The byproduct inventory is summarized in this section while details are provided in Appendix B.

One point must be explained regarding energy data presented for various radiosotopes. The energy values given are for the entire decay chain. For example, the power values shown for strontium-90 in watts (t) are the combined values for the decay of the strontium-90 and the yttrium-90 daughter.

5.1. STRONTIUM-90

The estimated available high-quality ($^{90}\text{Sr}/\text{Sr} \geq 40\%$) strontium-90 through the year 2000, with applicable assumptions, is shown in Figure 5.1.

FIGURE 5.1. Cumulative Inventory of Heat Source Grade Strontium-90 ($^{90}\text{Sr}/\text{Sr} > 40\%$) Available for Recovery from High-Level Wastes

The data show that 80 kW_t of high-quality strontium-90 is available now at Hanford. This is enough material to fuel several power-generation demonstration units, depending upon their size, between 1983 and 1988. Successful performance of these units may then justify construction of the needed facilities at SRP to make significantly more material available. Immediate steps should be taken at SRP to ensure that the strontium-90 in future waste will not be degraded by inert strontium added via process chemicals. When commercial fuel processing is restarted, the need for including strontium recovery facilities should be carefully evaluated. Their inclusion greatly increases the available strontium-90 after 1990 (see Figure 5.1).

5.2 CESIUM-137

The minimum cesium-137 content of fission-product cesium acceptable for use in cesium-137 irradiators has not been specified. If it is assumed that

the cesium-137 remains useful for one half-life following reactor discharge, the minimum useful cesium-137 content would be about 20 percent. Very little of the recoverable cesium at Hanford or SRP could have decayed to this level, and the average would be somewhat higher. In the absence of any isotopic analyses on the cesium wastes, it was assumed that all recoverable cesium at both Hanford and SRP could be used. Cesium-137 recovery at SRP would require construction of encapsulation facilities. The estimated cumulative inventory of recoverable cesium-137 is shown in Figure 5.2. These data show that 90 MCi of cesium-137 is currently available at Hanford for irradiator utilization. A "typical" irradiator would use 2 to 10 megacuries, so the current inventory is sufficient to fuel 10 to 40 "typical" irradiators. If facilities are constructed at SRP for the recovery and packaging of cesium-137, the cumulative amount of cesium-137 recoverable from Hanford operations and from SRP by 1990 will be about 250 megacuries. This amount alone will support a substantial

FIGURE 5.2. Cumulative Inventory of Cesium-137 Available from High-Level Wastes for Beneficial Use

irradiation industry. Beyond 1990 the available cesium-137 could be greatly increased by including cesium-137 recovered from commercial power reactor fuel.

5.3 KRYPTON-85/XENON

At present, krypton and xenon are recovered from fuel processing operations at ICPP and are purified at ORNL. The current shortfall in the supply of krypton-85 is caused by limited recovery capacity and the fuel processing schedule, not by availability. The current estimated annual need for krypton-85 is 20 to 30 kCi, or about 3 percent of the annual release of krypton-85 from SRP. Planned construction of improved recovery facilities at ICPP should meet current market needs. Additional supply will require construction of facilities at Hanford or at SRP.

5.4 STRATEGIC PLATINUM GROUP METALS

Fission-product platinum group metals are not now recovered at any site. The current defense wastes at Hanford and SRP contain an estimated 1400 kg of palladium, 2000 kg of rhodium, 6800 kg of ruthenium and 3300 kg of technetium. Continued processing through the year 2020 at currently anticipated schedules will increase these inventories by 40 to 50 percent. Spent commercial fuel is by far the most significant source of fission-product platinum group metals. By the year 2021 this fuel will contain an estimated 180,000 kg of palladium, 66,000 kg of rhodium, 330,000 kg of ruthenium and 120,000 kg of technetium. Utilization of these materials will require 1) development of processes and construction of facilities that will adequately separate them from the other fission products and 2) proper management of the radioactive palladium, rhodium and ruthenium isotopes.

5.5 NEPTUNIUM

Neptunium-237 is currently recovered at SRP and is irradiated for the production of plutonium-238. Current needs are met by this source, and recovery of neptunium-237 is not planned when the Hanford PUREX plant restarts.

5.6 PROMETHIUM-147 AND AMERICIUM-241

The current requirements for americium-241 are satisfied by recovery from processing of previously purified plutonium. Promethium-147 is not currently recovered at any site, but over 14 million curies have been recovered and purified at Hanford in the past. Optimistically projected needs for promethium-147 and americium-241 represent less than 10 percent of the amounts of these materials that could be recovered at SRP or Hanford production sites. Some additional processing equipment and facilities would need to be installed.

5.7 CURIUM-244

Curium-244 may be used in selected applications where the spontaneous fission can be tolerated. There are no significant amounts in defense wastes, but current commercial spent fuel contains 93 kg (262 kW_t), and by the year 2020 the amount will increase to 1800 kg (5200 kW_t).

6.0 EFFECTS ON WASTE MANAGEMENT OF BYPRODUCT RECOVERY AND UTILIZATION

Consideration of the recovery and utilization of selected byproducts from high-level defense wastes must properly take into account possible impacts of such recovery on the future management and disposal of the depleted high-level waste. In particular, the ultimate cost of the byproduct recovery is the cost of separating and packaging the byproducts combined with the increase or decrease in waste management costs attributable to byproduct separation and packaging.

6.1 ISOTOPIC COMPOSITION OF NUCLEAR WASTES

Partitioning, or the separation of the waste into parts, to permit the separate disposal of the various levels of radioactivity and heat has long been considered in the management of nuclear waste.⁽¹⁾ The advantages of this approach are apparent in the much smaller volumes of selected material needing specialized treatment to protect people and the environment. For example, if the major heat-producing isotopes were removed for beneficial use, the volume of this high-heat-producing material would be only a small fraction of the total and could be disposed of in a relatively small facility designed for this purpose. In addition, if the long-lived transuranium isotopes were reduced to a specified level (say, 100 nCi/g), the remaining large-volume fraction of the waste would require much less control and handling for safe disposal.

Figures 6.1 and 6.2⁽²⁾ are log-log plots of the heat and radiation produced by the primary contributing elements in commercial nuclear waste as a function of decay time. Figures 6.3 and 6.4⁽³⁾ are similar plots for the Hanford defense waste. The small inset graphs are plotted linearly to illustrate clearly the effect on both heat and radiation of removal of cesium and strontium. These plots show that this removal will reduce both the heat and radiation from the remaining waste by 55% on fuel out of the reactor three years. If decay time is in the range of 10 to 100 years, the reduction in heat and radiation from removal of both strontium and cesium is greater than 90%. This large reduction in heat loading could greatly alleviate concerns about the integrity of the waste form and repository when they are subjected to high

FIGURE 6.1. Thermal Power as a Function of Time for Major Heat-Producing Isotopes in Commercial Nuclear Fuel

FIGURE 6.2. Radioactivity as a Function of Time for Major Radiation-Producing Isotopes in Commercial Nuclear Fuel

FIGURE 6.3. Thermal Power as a Function of Time for Major Heat-Producing Isotopes in Hanford Defense Waste

FIGURE 6.4. Radioactivity as a Function of Time for Major Radiation-Producing Isotopes in Hanford Defense Waste

temperatures generated during ultimate disposal.⁽⁴⁾ In addition, removal of the long-lived transuranium isotopes can be considered as a method to reduce the need for control of the major waste volumes over very long time periods.

Thus, recovery of byproduct elements from high-level wastes may benefit their management by decreased heat generation rates, reduced long-term radioactive hazards, and/or reduced volume of waste requiring geologic disposal.

Possible unfavorable impacts of byproduct recovery on management or disposal of the depleted wastes may include increases in chemical toxicity and/or mobility of residual radionuclides occasioned by chemicals (e.g., organic complexing agents) added during byproduct recovery operations, increases in waste volumes, and increases in worker exposure. In addition, the disposal of the radioactive byproducts is only deferred, not eliminated, and end-of-life disposal must be considered.

6.2 BYPRODUCT RECOVERY SCENARIOS

The purpose of this section is to identify and qualitatively assess the impacts on management of high-level defense wastes in six specific byproduct recovery scenarios as follows:

- Recover cesium-137 only.
- Recover strontium-90 only.
- Recover cesium-137 and strontium-90.
- Recover only TRU^(a)
- Recover strontium-90 and TRU.^(a)
- Recover cesium-137, strontium-90, and TRU.^(a)

These six cases were chosen because of their perceived high impact in reducing heat-generation rates and long-term radioactive hazards and, possibly, in producing a depleted waste fraction that could be safely disposed of in other than deep geologic formations. It is recognized that further analysis of the

(a) In this context the recovery of TRU is defined as the removal of TRU elements from the waste to the extent that the content of TRU in the residual waste is <100 nCi/g of waste solids.

impacts of byproduct recovery on management of defense wastes may indicate the need to consider effects of the recovery of radionuclides other than those considered here (e.g., technetium-99).

Impacts of byproduct recovery on waste management were assessed on the basis of three key assumptions:

1. TRU elements can be removed from high-level wastes to the extent that the TRU content in the residual waste is ≤ 100 nCi/g of waste solids.
2. High-level wastes generated from future processing of irradiated fuel need not be placed in a geologic repository if the TRU content is less than 100 nCi/g. Conversely, if the TRU content is greater, the waste will be placed in a geologic repository.
3. Short-lived ($t_{1/2} \leq 100$ yr) byproduct sources (i.e., capsules) need not be placed in a geologic repository for end-of-useful-life disposal. Long-lived TRU sources must be placed in a geologic repository for end-of-useful-life disposal.

6.3 QUALITATIVE IMPACTS OF RECOVERY PROCESSES ON WASTE MANAGEMENT

The following sections first discuss waste management plans for both Hanford and Savannah River and then describe the impacts envisioned to occur with each of six recovery strategies.

6.3.1 Hanford Waste Management Plan

Strategies for near-term and ultimate disposal of future waste streams from the Hanford PUREX Plant (although still being formulated) are indicated by alternatives (A) and (B) in the simplified schematic diagram, Figure 6.5. This plan assumes that alkaline supernate streams, after a solids-liquid separation and cesium removal, will contain less than 100 nanocuries of TRU per gram of salt (<100 nCi/g) and can be disposed of in situ in double-shell tanks after drying. The solidification process is envisioned as a combination of vacuum evaporation (or wiped-film evaporation) and microwave drying.

FIGURE 6.5. Plans for Future Hanford Waste Management
(Including Deferred Cesium Separation)

The separated HLW sludge stream is expected to carry greater than 100 nCi TRU/g and, as such, will require disposal in a geologic repository. Alternatives (A) and (B) reflect current uncertainties in the mode of disposal at the repository. If the costly mode of canister emplacement in boreholes is required for defense HLW (alternative A), a glass immobilization process may be selected for its ability to minimize the volume of immobilized product. Alternatively, if a bulk, "cast in situ" mode of emplacement without canisters can be proven acceptable, a grout mixing process may be used (alternative B), offering a significant cost savings over alternative (A).

The disposition of zirconium-bearing sludge wastes (from chemical decladding of N fuel) may or may not have bearing on the overall impact of byproduct recovery. As Figure 6.5 suggests, the TRU content of zirconium sludge may be proven acceptable for near-surface disposal (e.g., grout in existing tanks). Otherwise, the zirconium sludge may require immobilization and repository disposal along with the HLW sludge waste. Depending on the economics of immobilizing the zirconium waste and of its ultimate disposal, it may be cost-effective to install (as soon as possible) a TRU separation processing step in or adjacent to the PUREX canyon to render the zirconium decladding stream acceptable for surface (in-tank) disposal. Due to timing constraints, however, production of a significant quantity of TRU-contaminated zirconium sludge cannot be avoided. Furthermore, the relatively low TRU quantities in the zirconium-bearing ($ZrO_2 \cdot 2H_2O$) sludge plus its difficult dissolution chemistry will make this stream otherwise unattractive as a feed for byproduct recovery.

6.3.2 Savannah River Waste Management Plan

Figure 6.6 presents a simplified schematic of the currently recommended waste treatment and disposal plan for Savannah River Plant HLW.⁽⁵⁾ Similar to the Hanford plan, alkaline HLW soluble salts are to be separated from insoluble solids and ultimately disposed in near-surface engineered vaults in accordance with criteria for shallow-land burial of low-level waste. The Savannah River plan, however, calls for the removal of cesium from this supernate stream and the immobilization of the residual salts in cement to reduce the hazard

FIGURE 6.6. Plan for Savannah River Waste Management Plus Addition of Byproduct Recovery Options

potential associated with near-surface disposal. This difference between the plans for Hanford and Savannah River is directly related to the fact that ground-water levels are much further below the surface at Hanford. The Savannah River separated cesium and strontium are then combined with the washed sludge slurry and fed to a continuous glass melter. Canisters of glass are then to be stored onsite awaiting the availability of a national geologic repository for high-level defense waste.

6.3.3 Byproduct Recovery Impacts at Hanford

The following six byproduct recovery options are analyzed for possible favorable impacts on Hanford waste management operations:

1. cesium recovery only
2. strontium recovery only
3. cesium and strontium recovery
4. TRU only
5. strontium and TRU recovery
6. cesium, strontium, and TRU recovery.

The major impacts of each option on alternatives (A) and (B) are qualitatively summarized in Tables 6.1 and 6.2. Existing B Plant facilities are used in all options to extract cesium and in certain options to extract strontium from PUREX waste. Although options (2) and (3) will remove strontium heat from the HLW sludge stream, vitrification and repository disposal will still be necessary because of the residual TRU. Some repository cost saving is expected if the glass product can be packaged in canisters larger than 24 in. in diameter. No increase in HLW glass volume is anticipated, either, since the significant chemical additions made in the strontium recovery process are expected to go to the HLW supernate stream.

Options (4), (5), and (6) will remove TRU nuclides from alkaline HLW sludge, thereby allowing its disposal in double-shell tanks or other near-surface disposal system, using a grout or some other immobilization process. With no removal of strontium (option 4), this immobilized waste must be

TABLE 6.1. Qualitative Impacts on Hanford Waste Management
Alternative A (Vitrification)

<u>Byproduct Recovery Option</u>	<u>Waste Processing and Near-Surface Disposal Impacts</u>	<u>Repository Impacts</u>
1. Cs recovery only	Small	Small
2. Sr recovery only	Small	Small
3. Cs + Sr recovery	Small	Small
4. TRU recovery	Small	Large cost saving
5. Sr + TRU recovery	Large cost saving	Large cost saving
6. Cs, Sr, TRU recovery	Large cost saving	Large cost saving

TABLE 6.2. Qualitative Impacts on Hanford Waste Management
Alternative B (Bulk Emplacement as Grout)

<u>Byproduct Recovery Option</u>	<u>Waste Processing and Near-Surface Disposal Impacts</u>	<u>Repository Impacts</u>
1. Cs recovery only	Small	Small
2. Sr recovery only	Small	Small
3. Cs + Sr recovery	Small	Small
4. TRU recovery	Large cost increase	Large cost saving
5. Sr + TRU recovery	Small	Large cost saving
6. Cs, Sr, TRU recovery	Small	Large cost saving

distributed over 30 to 40 double-shell tanks because of heat limitations. If the strontium is removed (options 5,6), the immobilized waste can be placed in one or two double-shell tanks.

The impact of option (1) on the waste management plan is small since the cesium is removed for waste management purposes. In this option beneficial use of cesium does result in a modest saving in interim cesium waste management storage costs. The impact of option (2) is likewise small because the TRU sludge will occupy the same repository space, with or without strontium, since heat is not a limiting factor in determining repository space for Hanford

defense waste. Option (3) is simply a combination of options (1) and (2); therefore the impact of option (3) is judged to be larger than (1) or (2) but still small.

Option (4) would allow surface or near-surface disposal of all the non-TRU waste, but because of the heat generated by strontium, the waste must be distributed among many expensive new tanks or equivalent facilities. There is, however, a saving in processing and canister cost for alternative (A) (vitrification). The glass plant could be smaller, and fewer canisters would be filled. A more detailed study is required to determine the net cost impact of option (4). On the other hand, the removal of strontium along with the TRU (option 5) allows surface or near-surface disposal of the immobilized waste in as few as two tanks, with a consequent large savings in repository costs compared with the base plan. In alternative (A) the smaller glass plant and fewer canisters would also result in a large cost savings for waste processing and near-surface disposal compared to the base plan. Option (6) is similar to option (5), with the small added benefit of saving interim storage costs for cesium.

The question of whether the costly vitrification process and basalt repository disposal mode can be altogether avoided by options (4), (5), or (6) appears to hinge on several factors:

- in situ immobilization of most of the sludge now stored in single-shell tanks
- acceptability of disposing of non-TRU high-level waste in near-surface disposal facilities (assumption 1)
- the disposition of zirconium-bearing sludges (near-surface disposal would be a necessary condition)
- the degree of TRU removal from HLW sludge (99.5 percent removal of americium would be necessary to significantly reduce the vitrification plant size).

6.3.4 Byproduct Recovery Impacts at Savannah River Plant

Figure 6.6 illustrates where, conceptually, a strontium or TRU separation process might be superimposed on the Savannah River Plant waste management plan. Obviously, cesium recovery (option 1) could be implemented with little impact, either positive or negative, on the costs of waste management.

The removal of strontium-90 heat from Savannah River product glass may result in significant repository cost savings. Additional engineering studies are required to quantify the cost savings. The question of whether TRU removal can permit a switch to a less expensive mode of waste disposal [e.g., near-surface disposal (dry wells) at the Hanford Site] is more uncertain.

6.4 CONCLUSIONS AND PLANNED FOLLOW-ON STUDIES

Preliminary qualitative assessments were made of the impact of removal of selected byproducts from future Hanford and Savannah River Sites PUREX Plant high-level wastes upon their long-term management and disposal. The significant conclusions derived from these preliminary evaluations are that:

- Byproduct recovery options that include recovery of TRU elements together with strontium will have major beneficial impacts on waste management.
- Byproduct recovery options that do not include recovery of TRU elements will have small impacts on waste management.

Much more comprehensive engineering analyses are required to validate the introductory assumptions and define quantitatively the impacts of byproduct recovery upon management of high-level wastes at each of the three major DOE defense production sites (Hanford, Savannah River, Idaho). These follow-on engineering studies should address, but not necessarily be limited to, these issues:

- Validate the in situ disposal of sludge now stored in single-shell tanks at Hanford.
- Determine the feasibility and cost of removing TRU elements from the high-level waste down to the 100 nCi/g limit.

- Identify and quantify costs of byproduct recovery, the distribution of costs between byproducts and waste management, and the effects on overall costs of waste management/disposal.
- Determine the acceptability of disposing non-TRU high-level waste and end-of-life byproduct capsules in near-surface facilities.
- Identify the optimum group of byproducts whose recovery has maximum beneficial impact on waste management and/or disposal of specific high-level wastes generated at each of the three DOE production sites. Determine the status and applicability of byproduct recovery technology at each production site, including deficiencies and needed R&D, if any.
- Identify, at each DOE production site, available or potentially available byproduct recovery facilities, including required new facilities and/or upgrading of existing facilities.
- Quantify short-term risks of byproduct recovery versus potentially reduced long-term risks from disposal of the residue resulting from byproduct recovery.
- Establish requirements and procedures for handling recovered byproducts at the end of their useful life.

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7.0 INSTITUTIONAL ISSUES

7.1 HEALTH AND SAFETY

It is the policy of the DOE to:

- a. Assure protection of the environment, the safety and health of the public, and Government property against accidental loss and damage.
- b. Provide safe and healthful workplaces and conditions of employment for all employees of DOE and DOE contractors.
- c. Assure compliance with applicable statutory requirements affecting Federal facilities and operations.
- d. Assure that research, development, demonstration, and production activities are performed in a controlled manner; that components, systems, and processes are designed, developed, constructed, tested, operated, and maintained according to sound engineering standards, quality practices, and technical specifications; and that resulting technology data are valid and retrievable.

This policy shall apply to all byproducts activities.

Additionally, joint programs with users will be conducted in conformance with applicable user agency health and safety policies, the Code of Federal Regulations, and Nuclear Regulatory Commission licenses and regulations, as appropriate.

Each byproduct application will undergo a safety analysis and evaluation. The evaluation will assure that health and safety factors are considered in the hardware and facility designs, and in operations to protect operating personnel and the public.

7.2 ENVIRONMENTAL PROTECTION

The Defense Byproducts Program will be managed to conform with applicable environmental laws and regulations such as the National Environmental Policy

Act of 1969 (NEPA). This includes Environmental Assessments of byproduct applications that have potential environmental impact. Environmental Assessments will be prepared and reviewed by appropriate agencies during the planning stage of an applications project. Upon review of the Environmental Assessment for major byproduct projects, the Environmental Protection Agency may require an Environmental Impact Statement. Sufficient time must be allowed for completion of the EIS process before any activities are begun that can affect the environment.

It is significant that a number of current and potential byproduct applications compete with conventional alternatives that have known environmental impacts. For example, the use of cesium-137 irradiation to disinfest foods or sterilize medical supplies is an alternative to the use of chemical fumigants that are suspected carcinogenic agents. Careful trade-off analyses of byproduct applications versus conventional alternatives will be performed to determine the most appropriate environmental alternative.

7.3 PUBLIC INFORMATION

The Byproducts Plan is a first step in informing the public of the goals and objectives of the Defense Byproduct Program. The plan will be made available to Congress, the public, and other interested parties.

The public residing in the vicinity of byproduct demonstration or operational projects will be informed of the project with briefings or other appropriate communications. For example, in the case of the Albuquerque Sewage Sludge Irradiator, a Citizen's Advisory Committee of 15 individuals from the community met 21 times during the NEPA process to allow citizen input and to ensure that all issues were considered in selecting and evaluating sludge management alternatives.

Normally the public information programs will be managed by users (cities, states, Federal agencies) of specific byproducts in specific applications at specific user sites. The Department of Energy will support users in public information activities.

7.4 COMMERCIAL APPLICATIONS

Commercial applications will be licensed and regulated by the Nuclear Regulatory Commission according to the Code of Federal Regulations. This includes consumer products as well as medical and industrial applications. Equipment manufacturers and/or byproduct users will be responsible for obtaining general or specific licenses. Byproduct materials recovered, purified, converted to a product form and sealed in containers at DOE facilities will be prepared so as to meet applicable license requirements, but the Atomic Energy Act (Section 91B) exempts activities at DOE facilities from NRC license and regulation. Transfer of any material from a DOE site will be subject to Department of Transport regulations.

A report entitled Environmental Assessment of Consumer Products Containing Radioactive Materials (NUREG/CR-1775) describes the regulatory aspects of typical consumer products using byproducts. A brochure entitled What Is Nuclear Medicine? has been prepared by the American College of Nuclear Physicians; it describes the estimated 80 to 100 million nuclear medicine procedures performed yearly in the United States as well as the attendant regulatory controls.

Safety analysis reports will be required for major commercial byproduct facilities. These reports will treat the health and safety aspects of the application and of the facility and its operation. Such reports can be either generic or site specific.

In some cases Department of Transportation permits will be required for shipping byproduct hardware. This may involve the certification of shipping containers.

7.5 MILITARY APPLICATIONS

Most military applications of byproduct materials will be managed and funded through an interagency task force. All activities associated with byproduct material recovery, processing, and product form conversion at DOE sites are exempt from NRC regulations. The Department of Defense and the NRC will determine the need to regulate materials and/or applications after the materials have been transferred to the DOD.

7.6 JOINT PROGRAMS

To accelerate transfer of byproduct applications to the marketplace, joint programs between the Department of Energy and users are encouraged. A joint byproduct applications program on sewage sludge irradiation has been successfully conducted by the Department of Energy, the Environmental Protection Agency, the City of Albuquerque, and New Mexico State University. Another joint program on self-luminous light sources is under way with participation by the the Department of Energy and Department of Defense.

Joint programs are generally formulated with a Memorandum of Understanding (MOU) between the Department of Energy and the user. The MOU is usually preceded by a letter of interest from the user to the Department of Energy. The MOU treats budgetary matters, the mutual objectives of the joint project, and the management arrangements. The MOU may be mutually amended as the program proceeds toward technology transfer.

8.0 PRIORITIZATION OF POTENTIAL DEFENSE BYPRODUCT APPLICATIONS

This section presents an overview of a general process for evaluating and rank-ordering applications for byproducts on the basis of their potential benefits and costs. The use of such explicit procedures to estimate the benefits and costs of public programs has been strongly recommended for government financial planning.^(1,2) Analysis results from applying this process will provide DOE staff with important technical information for reviewing programs and preparing program budgets. The ranking procedure is a highly useful tool for technically evaluating a complex set of application alternatives. This process does not make budgeting decisions, but rather it provides invaluable information to program management staff for their use in making decisions. Furthermore, it is an effective way to clearly document the data used in making decisions.

The discussion begins with a statement of the purpose of ranking byproduct applications and indicates the supportive nature of the analysis results for program decision-makers. Then a general description of the major steps in the procedure is provided. Where possible, comments are given on how the steps would be completed. The final section contains some comments on use of the method's results. Some of the steps with example components and calculations are described in Appendix C.

8.1 PURPOSE OF THE APPLICATION RANKING ANALYSIS

Comprehensive program planning for the recovery, research and allocation of defense byproducts requires consideration of many complex technical, economic, institutional and social factors. These factors have varying degrees of importance relative to each other, and this importance often shifts as technical progress and public attitudes change. Even in a well-defined planning environment, these factors imply that important value trade-offs must be made in deciding which byproduct technologies and applications to support.

To establish a Defense Byproducts Program responsive to national needs and defined on the basis of cost-effective applications, program planning must be conducted on a sound technical basis using systematic analytical methods. The complex factors named above must be evaluated on the basis of what is important to the nation from byproduct applications and how much to pay for developing them. The technical method established for this purpose includes a framework for identifying the important benefits, impacts, and costs associated with the development of byproduct applications as well as a set of calculations to produce relative rankings of the applications considered based on those factors. Explicit criteria, which allow the use of engineering judgment, are employed to analyze and compare the options studied.

The method produces a ranked (prioritized) list of the applications from most to least cost-effective relative to program objectives. These rankings are an input to the application decision process. The advantage of such a method in program planning is that the basis for program decisions can be clearly established and carefully documented.

8.2 FRAMEWORK FOR RD&D PLANNING

Two important aspects of RD&D planning are built into the framework. First, the set of applications funded each year should have certain characteristics that are important in the budgeting process. These characteristics are established through program analysis and are a function of the overall planning climate. For instance, the program should contain applications that serve national goals and the organizational mission. The applications should have characteristics that are consistent with specific program objectives to allow for program evaluation and review. The program itself should also show certain desirable features such as a rationale for economic sectors served, attention to national security, and adherence to established agency policies. In the byproducts planning framework, program analysis is used to meet these needs. It is defined as the process by which projects are initially appraised, budget funds are allocated, and funded projects are subsequently reviewed.

Second, to obtain information for program analysis, technical aspects of the byproduct application systems must often be studied. This is called

systems analysis in the planning framework and includes studies to determine the technical and economic performance of the byproduct technology hardware. For instance, a systems analysis of the market potential, environmental impacts, and waste management impacts is important to understanding the merits of an application. This information would be used as input data to a program analysis of byproduct applications that are candidates for funding.

The framework presented in this section integrates system and program analysis. This is done through the evaluation and ranking process whereby applications are prioritized prior to budget review. The ranking procedure does the following:

- uses a readily understandable rationale
- uses objective data where possible but allows the use of expert technical judgment where needed
- includes consideration of important value trade-offs
- is auditable and reproducible
- provides a standardized basis for comparison of diverse byproduct applications.

In this way the purpose of the method can be accomplished and the overall planning process can be enhanced.

Each byproduct application under review is characterized by a set of factors that ultimately define its attractiveness. For example, in some applications the byproduct materials are scarce, whereas in others they are plentiful. Some applications require strict handling for safety and security, and others may be used without such controls. Some materials have important adverse environmental effects, whereas others are relatively free of strong adverse impacts. The set of factors used in the planning process are defined as attributes; their function is to measure the extent to which each application meets the program objectives.

The prioritization of applications involves important value trade-offs among various program objectives and application attributes. These trade-offs

are analyzed through the use of numerical weighting factors that indicate the relative importance of each objective and the relative value to each attribute for an application's performance.

8.3 PLANNING PROCESS STEPS

The major steps of the Byproducts Program planning process are shown in Figure 8.1. Each block is numbered to indicate the approximate sequence in which the steps are completed. Actual use of the method occurs as a variation to these general steps, since the activities are generic in nature and are usually specified in more detail to suit particular planning needs. Each major step shown in Figure 8.1 is discussed and illustrated below:

1. Define Program Objectives - Overall objectives for the program are established to define the basic rationale which the funded applications must support. These objectives are chosen to be consistent with the agency mission and are designed to be measurable enough to allow comparisons of the applications. A set of candidate objectives that demonstrate the national importance of the Byproducts Program and indicate its overall mission was presented in Section 2.2.4.
2. Select Application Attributes - Various technical, policy and management variables that describe the important performance aspects of each application are specified in this step. These attributes must be measurable in quantitative terms since they will form the basis for the ranking calculations. Moreover, these variables must 1) be clearly understood by all participants in the process and 2) avoid excessive data collection. As an example, the attribute "estimated year of 1st market penetration" could be used to measure an application's contribution to the objective "deploy byproducts as rapidly as possible."
3. Select Candidate Applications - In this step, the byproduct applications to be analyzed are identified and defined. The need for analysis of the application's impacts and its data availability is also assessed to ensure that it is a meaningful candidate for the current program.

FIGURE 8.1. General Defense Byproducts Program Planning Process

4. Develop Ranking/Scoring Equations - The desired method of calculating a figure of merit (FOM) for each application is established in this step by defining equations for the numerical attributes data from step 2. These equations are generally based on the projected benefits, impacts, and costs for bringing an application to commercialization. An example of a general FOM equation for the Byproducts Program is shown below:

$$\text{FOM} = \frac{\text{net economic benefit} + \text{waste management cost reduction}}{\text{DOE RD\&D costs}} \quad (1)$$

When specified in more detail for a specific analysis, this calculation should be clear and uncomplicated and allow for easy analysis of changes in data and the numerical importance weights.

5. Define Government Planning Factors - Certain issues important to RD&D program decisions that cannot be easily quantified are specified in this step. These issues are often subjective factors that reflect general agency policies and constraints. For instance, constraints on isotope availability or fixed allocation agreements for critical materials are policy issues that affect the RD&D program but are not easily included in benefit calculations. These subjective factors are used in the final program budget allocation decision.
6. Develop Allocation Procedure - At this point the method and the participants for deciding the final budget and allocation of byproduct materials are defined. The procedure is implemented in step 13. A full range of methods (from explicit group consensus building to informal use of expert judgment) is possible for use in the final choices. This step is designed to include more sensitive political or organizational factors that are important in the final program budgeting process.
7. Assign Weights to Objectives and Attributes - Numerical weights are assigned to each objective (from step 1) and each application attribute (from step 2) to indicate their relative importance in the

overall ranking calculations. These weights are included as part of the FOM calculation to show application project performance against the most valuable objectives and attributes. In this way those projects that contribute most to the important objectives can be readily identified.

8. Review Value Trade-offs - Here the trade-offs among objectives and attributes are reviewed, discussed, and finalized. Since the numerical weights assigned in step 7 will imply particular trade-offs between objectives that are either complementary (support each other) or competitive (duplicate each other), their consistency with the preferences of the program staff must be established. This will be done by iteratively adjusting the weights until the proper consensus is obtained.
9. Collect and Review Attributes Data - Data for each application are collected according to the attributes defined in step 2. These data will be analyzed later using the equations in step 4, and thus a formal review of some of the findings by an outside expert panel may be desirable to ensure unbiased and current results. Some data may require analysis (step 10), but all data are subject to open confirmation and review.
10. Perform Systems Analysis - Some applications will require extensive analysis to develop needed appraisal data and to further reduce uncertainty in the nature and extent of their impacts. These analyses are defined by the nature of the application and its problems. Some applications may require very little study, whereas others are not well enough understood to include them in the current program. Additional environmental, economic, or engineering analysis may be necessary to define the application's expected performance.
11. Compute Technical Figure of Merit Scores (Ranks) - The FOM for each application is computed here using the equations from step 4 and the data from steps 9 and 10. An example of a specific FOM equation from step 4 is explained and used in Appendix C. These results form the

basis for establishing a ranked list of applications from most to least cost-effective. The ranking may be established by using the single FOM results or by using more complex multiple-ranking statistical procedures.

12. Collect and Review Planning Data - Data on the subjective government planning issues are obtained in this step for use in the final allocation process. The form of the data depends on the issues involved. For instance, further information may be required concerning legal or regulatory statutes or about national security needs for a material. Usually these data will not be quantitative.
13. Allocate Funds and Materials - Final decisions regarding applications to be funded and materials to be assigned to users are completed in this final step. Both the numerical ranking data and the subjective factor inputs are available as guidance to the final budget allocation.

8.4 USE OF THE RANKING ANALYSIS RESULTS

As discussed previously, the ranking results produced from the quantitative analysis can be used as valuable inputs to the ultimate program budgeting process. They provide useful evidence to program decision-makers as to which applications are most cost-effective in serving the program objectives. However, this process can also provide other important insights into various aspects of the Byproducts Program.

First, the models used allow the completion of various sensitivity analyses. In particular, understanding the effects of changes in the weights (both for objectives and for attributes) would be valuable. For instance, if the weights for national security objectives were reduced, the effect on the rank ordering of the program application projects could change; this change could be seen by rerunning the analysis with new weighting factors that show a reduced importance for national security.

Second, the results could be used to determine the effects of errors in the data on the final ranking. Changing quantitative data inputs to the FOM

calculation for an application by, say 15 percent, could show the effect of data errors in the final ranks. Moreover, this type of analysis would be beneficial in deciding where extra effort into better data collection yields the greatest payoff. If potential errors in some variables, say, environmental impact, have little or no effect on the ranks relative to, say, market size, then better information on market potential would be more useful than additional environmental systems analysis.

Finally, this method could be used to compare the characteristics of various generic RD&D program types. For instance, changing the objectives to only national security concerns versus only environmental issues would show how the application ranks change under different general program thrusts (a national defense emphasis versus an environmental emphasis). The same type of analysis could also be performed for different sets of attributes. Emphasizing technical achievability versus year of market entry would give an indication of the changes in the program due to a shifting emphasis on near-term techniques as opposed to long-term more research-dependent applications.

These uses of the method just described provide the Byproducts Program management staff with added valuable insight into the merits and shortcomings of particular program designs compared to other possibilities.

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APPENDIX A
A REVIEW OF THE UNIQUE PROPERTIES AND THE APPLICATIONS OF
NUCLEAR BYPRODUCT MATERIALS

A REVIEW OF THE UNIQUE PROPERTIES AND THE APPLICATIONS OF NUCLEAR BYPRODUCT MATERIALS

A.1 INTRODUCTION

Nearly 500 isotopes^(1,2) are produced in nuclear reactors by fission, capture or decay processes. Most are produced in too low a concentration, have half-lives that are too short, or have properties that are not sufficiently different from those of lower-cost natural materials to justify recovery from the nuclear fuel cycle. Others are produced by special irradiation of selected target materials.

The isotopes or elements that do have uniquely valuable properties and are abundant in the nuclear fuel cycle are listed in Section 4.0 and classified according to currently perceived uses. Some of the unique properties of the individual byproduct materials and their applications are discussed in this appendix. A generalized schematic flowsheet for the recovery of these byproducts is shown in Figure A.1

FIGURE A.1. Byproduct Recovery Sequence

A.2 STRONTIUM-90 APPLICATIONS

Strontium-90 is the only strontium isotope produced by nuclear fission with a uniquely useful property. It has a half-life of 28.8 years and decays by beta emission to yttrium-90, which has a half-life of only 64 hours and decays by beta emission to stable zirconium-90. Both decays are accompanied by significant gamma from bremsstrahlung conversion. The strontium-90 maximum energy is a modest 0.55 MeV, but the yttrium-90 maximum energy is 2.27 MeV and requires heavy shielding. The decay sequence yields 0.93 W_t (watts thermal) per gram of strontium-90,^(2,3) 17 percent of which is from the strontium-90 decay and 83 percent from the yttrium-90 decay.^(4,5) Thus strontium-90, with its short half-life daughter, is an excellent energy source. Technology for its recovery and conversion to useful chemical forms is well established.

When discharged from a nuclear reactor, the ratio of the strontium-90 to strontium is in the range of 0.55 to 0.62. Nonradioactive strontium fission-product isotopes and any natural strontium introduced during chemical processing steps dilute the desired isotope and thus detrimentally affect the desired property in the final product. The strontium-90 content is further reduced by the natural decay process; thus, in time the product can become so dilute that too little heat is produced to be usable in most applications. Existing designs for power-generation equipment require a minimum strontium-90/strontium ratio of 0.4 or greater at the start of life, but some thermal applications may use material with a ratio of 0.3 under special conditions.^(1,3,4,5)

A.2.1 Power Source Applications

Strontium-90 has been used as the energy source for over 60 RTGs used in terrestrial applications (see the summary in Table 4.1). Strontium-90 has been investigated as the energy source for Rankine, Brayton and Stirling cycle engines, and for thermionic converters.^(2,6) Past activities in developing applications have concentrated on exploiting the high reliability of thermoelectric generators. This emphasis is reflected in the following applications sections. New developments in long-life, high-performance Stirling engines^(7,8) indicate that advantage can now be taken of their much higher conversion efficiency (25 to 35% compared with 5 to 8% for RTGs) in many of these same applications.

Early RTGs used SrTiO_3 or Sr_2TiO_4 as the fuel form, but more recent designs have used SrF_2 . Failures are rare and manufacturers^(a) report over 5,000,000 hours of successful operation. These devices require no maintenance, are not affected by climatic conditions or electromagnetic shock, and can be designed to resist natural or man-directed destructive forces. Specific applications of this technology using strontium-90 are discussed here.

Remote Weather Stations

Strontium-90-powered RTGs were used during the 1960s to power remote weather stations at Axel Heiberg Island in the Canadian Arctic (Figure A.2) and at other locations (Figure A.3).^(5,9,10) The packages used consisted of the RTG and a data telemetry package in various configurations suited to the particular application.

The weather station at Axel Heiberg operated from August 1961 through August 1963.⁽⁵⁾ The strontium-powered RTG operated reliably throughout the life of the station, but failures in the electronics and meteorological sensors occurred. One of these, e.g., a failure in the timing devices in the data-telemetry package, terminated the work. RTGs were used to power weather

FIGURE A.2. Artist's Conception of Remote Weather Station at Axel Heiberg Station

FIGURE A.3. RTG-Powered Navigational Aid at Lake Clark Pass in Alaska

(a) Information furnished by John McGrew, Teledyne Energy Systems, Inc.

station equipment at the McMurdo Sound, Antarctica, and for Navy Oceanographic and Meteorological Automatic Devices (NOMAD) barge-type weather stations. In general, the experience was the same as that at Axel Heiberg; the RTGs performed reliably, but some failures were reported in the electronics-data-telemetry package.

Command, Control, Communications and Intelligence (C³I)

As most C³I equipment systems powered by RTGs are classified, details concerning their use of RTGs are unavailable. The RTGs employed, however, are conventional in their construction and are not classified. Power requirements have ranged from 1 to 100 W_e, and these RTGs have operated reliably for as long as 15 years in these applications. No failures of the power systems have been reported. RTGs in C³I applications have the advantages that they are not affected by the electromagnetic pulse from a nuclear explosion and they can be hardened to withstand blast effects.

Low-Power Radar

Low-power radar systems will require unattended, reliable 2-kW_e power generators for their operation. This requirement can be met by strontium-90-powered RTGs. As mentioned earlier, single units having 100 W_e electrical power capacities have been built. The extension of existing technology to 500-W_e units and the use of multiple units to provide 2 kW_e is expected to be readily achievable. Features of this type of power system include: demonstrated Arctic compatibility, minimal developmental cost, heat for thermal conditioning, continuous infrared signature, nondestructible in fire, beneficial use of reactor byproduct, and highest reliability at lowest maintenance.

Remote Surveillance Station

RTGs have been used to power surveillance equipment at remote locations. The most notable of these is the installation at Fairway Rock, Alaska, where the Navy has powered surveillance equipment from August 1966 through May 1981⁽¹¹⁾ using a single Sentinel 25A RTG. The unit was then replaced with two Sentinel 25s (Figure A.4) to provide increased power because the power output of the former unit was near the minimum needed to operate the electronic equipment. The original RTG required no maintenance or fuel during its entire

usable life and was retained on Fairway Rock as a spare. Total operating time on this unit approached 130,000 hours of continuous, reliable operation without failure.

Navigational Aids

Many marine navigational aids require power levels in the range of 10 to 100 W_e .⁽⁵⁾ RTGs have been demonstrated for lighting systems in Chesapeake Bay and in Sweden and the United Kingdom. Proposed and demonstrated uses include underwater navigation beacons, surface channel markers, buoys and other navigational aids in inaccessible locations. The SNAP-25 series RTG manufactured by Teledyne Energy Systems was in fact designed for such deep-sea operations, i.e., for pressures approaching 8000 psi.

FIGURE A.4. RTG Replacement Units en Route for Installation at Fairway Rock in Alaska

RTGs have also been proposed for powering both civilian and military aircraft navigational aids (see Figure 4.1). Many of these applications require remote, very reliable, low-maintenance power for their operation, and isotopic power sources can effectively meet these needs.^(a)

Remote Emergency Power

In most remote locations of human habitation, conventional diesel electric or gas turbine power generating equipment is used to supply power for lighting, communications, and other life-support uses. A failure of the main power source can spell disaster for a population if the unit cannot be repaired and communications are lost unless another source of power is available. This power source does not have to be large, just sufficient to operate a radio, perhaps power a few lights, and supply enough power to keep essential life-support control systems in operation and some heat to keep people from freezing. A properly designed RTG system, if available, could meet many of these requirements.

A.2.2 Heat Source Applications

Properly encapsulated and shielded, strontium-90 could be used for heat sources for Arctic, petroleum and military applications.^(9,10) Heater sizes would be comparable to those needed as energy sources for RTG applications. Thus power sources recovered from used RTGs or strontium-90 that is unacceptable as an RTG fuel might be used for heater applications. Specific criteria for these uses will be application-dependent, but most will relate to thermal need, reliability and life-cycle requirements. In the following sections, several of these possibilities are discussed. Further refinement, applications engineering and adaptation will be required to use "isotope" heat in these applications.

Arctic Sewage Treatment Heaters

In the Arctic, sewage is usually collected by "honeybuckets" and/or sewage tank trucks and carried to a central location for disposal. Normally the disposal site is a pond, tank, or other holding area that is exposed to the

(a) Information furnished by John McGrew, Teledyne Energy Systems, Inc.

environment and remains frozen during the long Arctic winter. Digestion and further treatment occurs only during the short summer or by use of expensive, energy-intensive sewage treatment facilities when and where available. Because the digestion process is dormant when sewage is frozen, large volumes of sewage are poorly treated and the potential for disease and pollution is high. The problem could be alleviated by using strontium-90 heaters in specially designed digesters to keep the sewage from freezing and permit continuous digestion year-round. Fluid circulation in the digester could be produced by designing the heater blocks as thermosyphons to perform the required pumping. The result would be a self-powered unit operating for 10 to 15 years without refueling--a substantial savings in fuel oil.

Arctic Utilidore, Water Distribution System or Sewage Collection System Heaters

Utilidores are insulated and heated conduits that contain utility piping, e.g., sewage, potable water, power cables, etc., and connect these services between Arctic housing and a central sewage, water treatment or power facility. Existing systems use electric heaters wound around the piping for heating, and thermal differences within the utilidore can vary as much as 35°F.

Where utilidores are not used, potable water is delivered by truck, and sewage is collected in honeybucket trucks on occasion. A few locations have small potable water distribution systems or sewage collection systems, but freezing is a chronic problem and reliable heaters are needed to ensure that the system works. Fire control systems are nonexistent because of the problem of freezing.

Use of isotopic heat produced by strontium-90 heat sources would be a reliable and low-maintenance alternative to existing methods for keeping water distribution and sewage collection systems from freezing. The sources would be placed at appropriate intervals in utilidores or piping systems to provide the needed heat lost to the environment. Proper design of the piping and its insulation could minimize the number of sources and still meet the heat loads required.

Heaters for Petroleum Tanks and Collection Systems

Heaters for petroleum tanks and collection systems are similar to those described in the previous section for Arctic water and sewage system heaters. In addition, strontium-90 heaters installed in tanks in cold locations would keep the oil warm and pumpable using thermosyphon principles.

Downhole Heaters for Enhanced Oil Recovery

Currently 48 percent of the oil produced in the U.S. is recovered by primary methods; 48 percent is recovered by a secondary method, water injection, and the remainder by other enhancement recovery methods.⁽¹²⁾ Thermal stimulation using steam and electrical heat, an alternative method, has limited value because of technical limitations and cost. Conventional bottom-hole heaters produce about 70,000 Btu, or 20.5 kW_t, and are technically and economically usable at depths less than 5000 ft.

Encapsulated strontium-90 could be placed at the bottom of the hole and the decay heat used to stimulate production.⁽⁹⁾ If the well failed prior to the decay of the strontium-90 source reaching nonproductive levels, the source could be moved to another well and used further. Since heat sources used for this purpose could be used for at least two half-lives, well stimulation is a viable option provided capsule integrity is sufficient. Use of the method is independent of well depth, and retrieval is possible with current well drilling and operating technology. At present, a limited amount of work, of a proprietary nature, has been done on these concepts.

A.3 CESIUM-137 APPLICATIONS

Five cesium isotopes are produced by nuclear fission. Cesium-133 is stable, and cesium-135, with a half-life of 2×10^6 years, is nearly stable. Cesium-134 and -136 have relatively short half-lives (2.1 years and 13 days) and low abundance. Cesium-137 has a half-life of 30.2 years, a specific activity of 87 curies per gram (100% basis), and produces 0.42 W_t per gram (100% basis). The ¹³⁷Cs/Cs ratio is about 0.43 in freshly discharged fuel.^(1,2)

The major use of fission-product cesium will be as a radiation source for sterilizing sewage and disinfesting food products, agricultural products and other items. Fission-product cesium has been considered for production of heat and power, and the uses are similar to those identified in the previous section. A number of engineering demonstration projects are under way and others are at the discussion stage. These activities and applications for radiation with cesium-137 are summarized in the following subsections. The summary is by no means exhaustive, and additional scenarios can and should be developed to meet national and international needs.

A.3.1 Sandia Cesium-137 Irradiator

The cesium-137 engineering demonstration irradiator now in operation at the Sandia National Laboratory⁽¹³⁾ (see Figure 4.1) is a key element in the successful use of byproduct cesium-137 in the irradiation industry. This irradiator uses capsules from the Hanford Waste Encapsulation and Storage Facility (WESF) containing a total of 1 MCi of cesium-137. The Sandia irradiator is being used to evaluate the use of byproduct cesium-137 to irradiate many kinds of materials, to optimize irradiation conditions, and to develop design data for generic demonstration plants. Sewage sludge, grapefruit, and mangos have been irradiated.

A.3.2 Control of Pork Trichinosis

The "trichinosis stigma" costs the U.S. pork industry substantial losses in domestic and world markets. Current research results, illustrated in Table A.1, show that irradiation at doses as low as 10 to 30 krad disinfests pork of the parasitic nematode, *trichinella spiralis*, responsible for trichinosis in man.⁽¹⁴⁾ As shown in the table, reproduction of larvae is stopped by doses as low as 10 krad. The life cycle of *trichinella spiralis* in man is shown in Figure A.5. An ongoing cooperative effort among the USDA, DOE, and the pork industry is evaluating the impact of trichinosis in the U.S. and the potential benefit from a pork irradiation program using cesium-137. Existing technology is being used to demonstrate the feasibility of producing pork "certified trichina-safe" by gamma irradiation of split hog carcasses. A major step toward commercial-scale use is the construction and testing of a

TABLE A.1. Trichina Survival Data^(a)

<u>Radiation Dose,</u> <u>krad</u>	<u>5-Day Adults,</u> <u>per rat</u>	<u>Muscle Larvae,</u> <u>per rat</u>
0	1,800	325,000
5	1,800	84,000
10	900	<1
20	<1	0
30	0	0
50	0	0

(a) Data obtained from the USDA Agricultural Research Service, Beltsville, MD.

demonstration-scale irradiator by a Federal laboratory or an educational institution to establish the feasibility of the process and to obtain information required for full-scale commercial implementation.

A.3.3 Disinfestation of Citrus Fruits

Florida citrus is currently fumigated with ethylene dibromide (EDB) for insect disinfestation. The EPA proposes to ban EDB, a suspected carcinogen, from further use after June 1983.⁽¹⁴⁾ Irradiation with cesium-137 is being investigated as an alternative to disinfestation by EDB fumigation. Recent research on irradiation of Florida-grown grapefruit infested with Caribbean fruit fly larvae indicate that disinfestation occurs at a dose of 25 krad. Conversion from current fumigation practices to irradiation would cost only an additional 1 to 2 mills per pound of fruit processed.⁽¹⁴⁾

A.3.4 Control of Codling Moth

The codling moth infests numerous agricultural crops of significant economic value. Host commodities include apples, pears, crab apples, quince, cherries, walnuts, and many others. High-cost pest-control measures greatly reduce the damage but cannot eliminate this pest.

Apple production in the U.S. is projected to increase by 40 to 60 percent by 1988. Potential major markets include Japan and Korea, where the codling moth does not exist. To prevent its introduction, these countries impose

FIGURE A.5. Life Cycle of *Trichinella Spiralis*

Source: J. B. Vilella, "Life Cycle and Morphology," Chap. 11 in Trichinosis in Man and Animals, S. E. Gould, ed., 1970, Courtesy of Charles C. Thomas, Publisher, Springfield, Illinois.

embargoes on host commodities such as apples. Therefore satisfactory disinfection procedures must be developed before these markets can be realized. Gamma irradiation with cesium-137 is effective as a quarantine treatment.⁽¹⁴⁾ Irradiation of larvae, at dosages less than 16 krad, has prevented emergence of 99 percent of adult moths. Absorbed doses of 40 krad have been shown to sterilize adults. Most varieties of apples tolerate doses as high as 100 krad, permitting flexibility in irradiator design. An economically attractive international market potential is therefore created with the use of gamma irradiation as a quarantine treatment.

Further research to verify efficacy and quantify optimum treatment protocols and doses is needed to develop the full potential of the cesium-137 treatment process. An expanded research program is now under consideration by the USDA. Major facilities for cesium-137 irradiation, however, exist only in Albuquerque, New Mexico. Samples transported long distances for tests are subject to transportation damage, ripening, time of irradiation after harvest, and other such effects, which can all create anomalies in research results. A transportable irradiator research facility is needed to support the many research needs at significantly different locations and/or different seasons of the agricultural year. This transportable cesium-137 irradiator concept is shown in Figure A.6. A "binary" design enabling separate transport of the irradiator chamber and the cesium-137 source appears promising for the transportable unit.

A.3.5 Disinfestation of Dried Fruits and Tree Nuts

Some fumigants used in disinfestation of nuts and dried fruits leave residues that can limit the marketability of these commodities. Although the quantities produced are very large, some treatment by irradiation may prove to aid in solving the infestation problem. Pests such as navel orange worm, codling moth, Indian meal moth, red flour beetle, and sawtoothed grain beetle are all susceptible to gamma irradiation. Fifty krad will control even the most resistant beetle species and immature stages of moths. Even lower doses (20 krad) are expected to control reproduction and growth of young larvae. A joint industry/USDA/DOE research program to examine the potential of irradiation as a treatment for raisins, prunes, walnuts, almonds, pistachios, etc., is being investigated.

FIGURE A.6. Transportable Cesium Irradiator

A.3.6 Irradiation of Municipal Sludge for Agricultural Uses

With more restrictive regulations and expanding populations, the processing and disposal of municipal sewage sludge is an ever-increasing problem for many cities. Irradiation of the sludge by cesium-137 is being examined as a method for solving the problem by converting a liability to an asset.

Two principal uses of municipal sewage sludge have been investigated:⁽¹²⁾ 1) as a low-analysis fertilizer and soil conditioner and 2) as feed for livestock to provide nitrogen, minerals and energy. To eliminate the potential health risk, sludge is irradiated with cesium-137 before it is applied to agricultural land or marketed to the public for general use. Irradiation with cesium-137 can eliminate bacterial, parasitic, fungal, and viral pathogens contained in the sludge.

Algae produced as a byproduct of municipal waste-water treatment can be fed to cattle, swine, poultry, or fish as a quality protein supplement.⁽¹²⁾ The algae are irradiated with cesium-137 to eliminate pathogenic hazards. In

this way, irradiation permits the safe introduction of a quality product, grown on human waste, into the human food chain. This food conservation cycle is shown in Figure A.7.

Two cities, Albuquerque, New Mexico, and Idaho Falls, Idaho, are investigating use of these technologies. The city of Albuquerque has entered into a cooperative agreement with DOE for construction of a full-scale cesium-137 sludge irradiation facility. Application of irradiation at Albuquerque is a critical step in gaining widespread acceptance of the technology and in encouraging its use at other municipal waste-water treatment plants.

Idaho Falls, Idaho, has found that additional treatment capability is necessary to handle its increasing volume of sewage solids. At the request of the City, sludge irradiation has been evaluated and found to be an economical

FIGURE A.7. Algae for Feedstuff Production

and feasible method for treating the sludge and for producing a saleable sewage solids product. The City currently desires to enter into a cooperative agreement with DOE for construction and demonstration of the technology.

A.3.7 Cesium-137 Irradiation for Secondary Oil Recovery

As stated previously, nearly 48 percent of current U.S. oil production is acquired by water injection into existing oil wells when they cease flowing by natural processes. Recovery efficiencies by water injection range from 40 to 50 percent of the oil in the reservoir at the time water injection starts. Both fresh water and seawater are used where available. Both, however, contain organisms which, under the anaerobic conditions in the well, produce hydrogen sulfide; this can sour the whole oil field, causing severe safety and processing problems.

A means proposed for preventing the organisms from souring oil wells is to sterilize the water before it is pumped into the well. Irradiating the total volume of water pumped into the well would not be feasible because of the quantities of isotope required. Experience has shown that large filters can be used, with a high degree of efficiency, to trap algae and other marine biota. Continuously irradiating the filter beds where these organisms are held up, concentrated or trapped seems to be an effective option for destroying the biota. Process methods have not been studied in detail, and further evaluations are required although some proprietary work has been done by industry.

A.4 KRYPTON APPLICATIONS

Krypton-85, produced in nuclear reactors, is diluted with inert fission-product krypton. Krypton-85 has a half-life of 10.72 years and decays to stable rubidium-85 by emission of betas having a maximum energy of 0.687 MeV accompanied by a low yield (0.41%) gamma having an energy of 0.514 MeV. The heat produced by krypton-85 decay is 0.623 W_t per gram, and the specific activity is 392 curies per gram.^(1,2,4) Thus krypton-85 is a useful heat source, its beta energy can be used to produce light, and the gamma activity can be used in NDT applications.^(5,15,16)

Fission-product krypton has a yield of about 27 grams of krypton-85 per tonne of fuel when discharged from the reactor and consists of about 7 percent krypton-85 (Table A.2).^(2,4,16) Existing fuel recovery methods reduce this concentration further because of air inleakage or air sparging during the fuel dissolution step, where the krypton is released. Natural decay reduces the concentration still further. Because both the nonradioactive krypton and the krypton-85 can be used in unique and mutually exclusive applications, it would be desirable to separate the isotopes as cleanly as possible by advanced isotope separation processes in the future. All the krypton produced in nuclear reactors could possibly be used if a good isotope separation of the radioactive krypton-85 could be achieved. Existing and proposed uses of fission-product krypton are discussed in the following paragraphs.

A.4.1 Power Source Applications

Krypton-85 has been proposed as an energy source for small isotopic batteries, e.g., RTGs. The Pacific Northwest Laboratory (PNL) is developing a sputtering process for encapsulating fission-product krypton into a metal matrix for storage and disposal. Capsules produced by this process may be useful for making heat sources for small 1- to 2-watt RTGs for a variety of

TABLE A.2. Comparison of the Isotopic Concentration of Fission-Product and Atmospheric Krypton^(4,16)

<u>Isotope</u>	<u>Atomic %</u>		<u>Fission Product Half-Life</u>
	<u>Atmospheric</u>	<u>Fission Product^(a)</u>	
78	0.4		stable
80	2.3		stable
81		6.0×10^{-6}	2.1×10^5 yr
82	11.6	0.3	stable
83	11.5	11.2	stable
84	56.9	30.8	stable
85		6.1	10.72 yr
86	17.3	51.6	stable

(a) Taken from ORIGEN code (1 year after reactor discharge).

purposes if highly enriched krypton-85 is made available. Such units would be environmentally acceptable, could be easily shielded, and would be about the size of a softball. Should the power supply be destroyed, the krypton-85 would dissipate to the environment with minimal hazard since krypton is not retained by biological forms. Many of the uses are similar to those described in Section A.2 for strontium-90. Additional uses that can be identified for krypton-85 power units include: power supplies for biologists for tracking whales, sharks, seals and large Arctic terrestrial animals; environmentally acceptable RTGs for powering remote or Arctic telephones; repeater and other civilian communications equipment; military C^{31} uses and a multitude of other small 5- to 10-year-lifetime power battery uses.

A.4.2 Beta (Self-Powered) Lights

Self-powered light sources using beta-emitting radioisotopes to activate phosphors have been under investigation for many years.⁽¹⁶⁻¹⁸⁾ The radioisotopes most used for this application are tritium, krypton-85 and promethium-147. Application and engineering development needs for lights require satisfying a supply-demand situation, improving the phosphors and light pipe configurations to get higher intensities, design and testing for specific applications, and meeting the institutional and societal requirements such as licensing. The applications for these lights discussed in the following subsection are not exhaustive, but they do identify the wide range of possible uses for this technology.

Runway Lighting and Marking

Self-powered beta lights have been manufactured and demonstrated for runway, taxiway, landing pad, threshold, visual approach slope indicator (VASI) landing and marking purposes for both fixed-wing and rotary-wing aircraft. Military and civilian applications are similar, and examples are portrayed in Figure A.8. Three configurations of lights are shown in Figure 4.3. For military purposes the lights can be designed to be transportable, rugged, and easily installed. They would be employed to locate drop zones and for remote or temporary runway lighting or other tactical uses. In the civilian sector the need and application is characterized by observing that there are 1022 airfields in Alaska. Most are for fixed-wing, land-based aircraft; however,

FIGURE A.8. Remote Runway Lighting Using Self-Powered Beta Lights

some are used for rotorcraft and seaplanes. Only 10 percent of these runways have lighting. The Civil Aeronautics Board (CAB) has classified 410 U.S. airfields as Essential Air Service (EAS) fields. Over half (i.e., 222) of these are in Alaska and only 37 of these are lighted. The Alaska State Department of Transportation and Public Facilities (DOTPF) is anxious to identify means to reduce the number of unlighted airports to meet safety, emergency, and other remote Alaskan needs.^(a) Lighting of the remaining airfields will be costly by conventional means; self-powered lights may offer a lower cost alternative and are being considered for this purpose. They also have the advantage that they do not significantly affect night vision during landing or other nighttime operations and will lose only half their intensity in 10 to 12 years.

(a) Discussions with L. E. Leonard and L. R. Sweet, Alaskan DOTPF, Fairbanks, Alaska, February 9 and 10, September 2, 1982.

Marine Navigational Aids

Self-powered lights also can be used as channel markers, for navigational aids and buoy lighting, underwater marking, and other marine purposes. Some of these uses are pictured in Figure A.9. Ordinarily battery-powered lights are now used. Batteries must be replaced regularly, but in many situations this is dangerous and expensive. In addition, some needed navigational lighting is not in place because the means for conveniently supplying power or servicing the site are not available. Self-powered lights using either tritium or krypton-85 could meet the needs in these applications if the installations are properly designed. Since the intensity will approximate the half-life of the isotope used, i.e., 10 to 12 years for krypton-85 or tritium, the only cost will be for the lights and the scheduled replacement to maintain the needed visibility. This application should increase the safe use of our waterways.

FIGURE A.9. Marine Uses of Beta Lights

Roadway and Safety Lighting

Tritium lights have been used many years for safety lighting, exit signs in aircraft and buildings, and aircraft and other instrument lighting. For example, tritium-illuminated phosphors are used in exit signs in aircraft to indicate location of doors and in watch faces or instruments to allow night visibility. These sorts of uses could be expanded with a larger supply of tritium. Another use of the lights would be for remote highway lighting and marking (Figure A.10). In these applications, krypton-85 could be used if the installation is properly designed. The reduction in costs for this purpose could be significant and would add to the safety of highway travel.

FIGURE A.10. Roadway and Safety Lights

A.4.3 Nondestructive Testing

Nondestructive testing applications of krypton-85 are primarily for flaw detection in metals and electronic components, gauging, leak detection, sensing and indicating.^(15,19) Some of these are reasonably well developed, e.g., flaw detection, leak detection and gauging, while others are not as well developed. Kryptonation, the process normally used for flaw detection, involves impregnating a material or component with krypton-85. Krypton-85 can be forced into a material by ion bombardment or pressurization. Using either technique, surface condition, i.e., wear patterns and flaws such as microcracks can be identified with good sensitivity. Thus, the method has been used for detection of cracks in gas turbine and aircraft turbine blades. Radiographic techniques are used to locate the defects and measure their severity.

Krypton-85 has also found limited use as a leak detector to guarantee the integrity of hermetically sealed containers. Sensitivity and economy are the major advantages of these tests. Components are soaked in krypton-85 gas at 100 to 120 pounds per square inch for 2 to 16 hours. Leaky components will partially fill with krypton-85 gas during the soak. The krypton gas in the chamber is then recovered, and the exterior of the component is cleaned by partial vacuum. The krypton-85 in leaking components can then be measured by scintillation counting.

Gauging applications are straightforward and use the beta energy for measuring thickness and weight. Krypton-85 sources are self-contained and are unaffected by temperature and humidity. Both backscatter- and transmission-type systems are used to measure thickness or weight of material passing the detector. Transmission gauges are used in the paper, plastics and rubber industries, employing sources containing from 500 millicuries to a few curies of krypton-85 per source.

A.4.4 Nonradioactive Fission-Product Krypton

The major use for krypton gas is filling fluorescent and incandescent lights, where its thermal and chemical properties are superior to the alternatives, nitrogen or argon.⁽²⁰⁾ Krypton gas is also used in instrumentation and for research applications. Since natural krypton is usually scarce, the

nonradioactive fraction of fission-product krypton could be used for existing applications if it could be separated at high purity from the radioactive krypton-85.

A.5 XENON APPLICATIONS

Xenon is the most abundant of all likely byproducts recoverable from spent fuel, and, because all its radioactive isotopes have very short half-lives, recovered xenon will be essentially stable by 1 year after discharge of the spent fuel (see Table A.3).^(1,2,4,16)

Xenon's similarity to krypton makes it very likely that if the release of krypton-85 to the atmosphere is prohibited, both xenon and krypton will be recovered in the same stream. Then, because of the far greater volume of xenon, it would be separated from krypton to minimize the total volume of krypton that may have to be stored securely. Thus xenon would be obtainable under very favorable economics since up to this point all processing would be

TABLE A.3. Isotopic Comparison of Fission-Product and Atmospheric Xenon

<u>Isotope</u>	<u>Atomic %</u>		<u>Fission Product Half-Life</u>
	<u>Atmospheric</u>	<u>Fission Product^(a)</u>	
^{124}Xe	0.096	--	--
^{126}Xe	0.090	--	--
^{128}Xe	1.92	0.06	stable
^{129}Xe	24.44	0.31	stable
^{130}Xe	4.08	0.23	stable
^{131}Xe	21.18	8.22	stable
^{132}Xe	26.89	20.47	stable
^{134}Xe	10.44	27.51	stable
^{136}Xe	8.80	43.19	stable

(a) Taken from ORIGEN code (1 year after reactor discharge).

required to prevent release of krypton-85 to the environment. The only additional cost applicable to xenon would be that for refining it to an acceptably low residual krypton-85 content. The cryogenic processing technology to ensure such quality is available and is similar to that used in recovering xenon from air.

Experimental quantities of fission-product xenon have been obtained with the krypton-85 content reduced to below 1 microcurie of krypton-85 per liter of gaseous xenon; that is, xenon of 99.9 percent purity has been produced. This recovery may lower the price of gaseous fission-product xenon to about one dollar per liter, or about one-tenth the price of large-volume sales today. At that price level many applications may be possible that could not be considered previously.

A.5.1 Lighting Systems

These uses are similar to those described earlier for nonradioactive krypton. Light bulbs or electronic tubes filled with krypton or xenon gas give greater illumination at lower power and last longer than conventional light bulbs.

A.5.2 Xenon as an Anesthetic

Xenon-oxygen mixtures were demonstrated as an anesthetic⁽²¹⁾ over 30 years ago. Several experiments were completed on human subjects to identify pain thresholds using xenon-oxygen and nitrous oxide-oxygen mixtures. The results were favorable, and two operations were performed to evaluate more critically the effectiveness of xenon as an anesthetic drug. In both operations nominally 20 percent oxygen-xenon mixtures were used. One operation was an orchiectomy, and the other a ligation of the Fallopian tubes. Upon discontinuance of the anesthetic and within 2 minutes, both patients could identify themselves clearly, and within 5 minutes they could orient themselves accurately and clearly. Recovery was reportedly uneventful. Thus xenon, if available in quantity, could be a widely used anesthetic for many surgical procedures. In particular, it might be valuable as a battlefield anesthetic, where extremely rapid recovery without residual effects is desirable.

A.5.3 Other Applications

When the electronic structure of xenon is excited by a high voltage, it produces a spectrum that is used in laser applications. It also serves as a filler gas in the X-ray tube, where its thermal properties help extend the life of the device. Xenon is employed in instrumentation and research applications. Xenon also forms compounds with other elements. For example, the use of xenon fluoride compounds as fluorinating agents in pharmaceutical manufacturing has been proposed.

A.6 PLATINUM METALS APPLICATIONS

A.6.1 Ruthenium

Ruthenium is one of the rarest of the natural platinum group metals. It is also potentially the most useful. Concentrations contained in spent nuclear fuel are 500 to 3000 times higher than those found in natural deposits. Ruthenium metal is extremely refractory and hard and is an excellent catalyst. Increased uses could be reasonably anticipated as the availability of ruthenium is increased by recovery from nuclear waste.

Fission-product ruthenium contains several stable isotopes plus the radioactive isotopes ruthenium-103 ($t_{1/2} = 39$ days) and ruthenium-106 ($t_{1/2} = 367$ days).^(1,2) Both radioisotopes are present in freshly discharged fuel in very high activity levels, but ruthenium-103 decays to undetectable levels in about 3 years. Because of the longer half-life, at least 30 years are required before the ruthenium-106 decays to concentrations permitting unrestricted use.

Ruthenium-106 controls the beneficial use of inert fission-product ruthenium and, through possible cross-contamination, also affects the beneficial use of fission-product rhodium and palladium as well. Ruthenium-106 decays by beta emission to rhodium-106 ($t_{1/2} = 30$ sec), which decays by beta emission to stable palladium-106. This decay chain mandates complete separation of ruthenium from rhodium and palladium to avoid compromising their radiochemical properties.

The specific power of ruthenium-106 is 33.1 watts per gram; thus if it were separated by isotope separation processes, it might be used as a power or

heat source in metallic form in applications that were described earlier for krypton-85 and strontium-90. When the heat source reaches its end of life, the pure stable palladium would be recovered and any ruthenium-106 would be recycled.

A.6.2 Rhodium

Fission-product rhodium is almost entirely stable rhodium-103, with only trace amounts of the radioisotopes rhodium-102m ($t_{1/2} = 206$ days) and rhodium-102 ($t_{1/2} = 2.9$ years). Two other radioisotopes, rhodium-103m and rhodium-106, are present from the decay of fission-product ruthenium but decay to undetectable levels in the rhodium in a few days after separation from ruthenium.^(1,2)

Rhodium-102 and rhodium-102m are present in freshly discharged fuel in low concentrations: up to about 2600 and 400 μCi per gram of rhodium, respectively. Because of its longer half-life and gamma decay activity, rhodium-102 has the major effect on beneficial use of fission-product rhodium that has been adequately separated from ruthenium. A decay time of 35 years would reduce the activity to approximately 0.6 $\mu\text{Ci}/\text{gram}$ of rhodium.

Fission-product rhodium has been alloyed with platinum for use as the catalyst for manufacture of nitric acid.^(a) Tests in an Engelhard Industries pilot plant were completed with no detectable carry-over of catalyst activity into the product stream and good conversion characteristics.

A.6.3 Palladium

Fission-product palladium consists of several stable isotopes and the radioisotope palladium-107. Palladium-107 is a very low-energy beta emitter with a half-life of 6.5×10^6 years.^(1,2) Depending on reactor conditions, fission-product palladium will contain 80 to 100 μCi of this isotope per gram and the activity is essentially constant because of the long half-life. The surface dose rate of highly purified fission-product palladium was measured with an extrapolation chamber and found to be 0.8 r/hr.⁽²²⁾ Fortunately, the range of the beta is only 4 mg/cm^2 and is easily shielded. Human skin will

(a) Information furnished by C. A. Rohrmann, Pacific Northwest Laboratory.

totally absorb it. Almost any kind of gloves will shield workmen from external radiation from fission-product palladium. Internal deposition characteristics must be identified for fission-product palladium.

A.6.4 Technetium

The only available supply of technetium is as a fission product in spent nuclear reactor fuel, where it occurs in quantities approaching 800 grams per tonne of heavy metal in spent power reactor fuel. Fission-product technetium is essentially all technetium-99, a long-lived (2.1×10^5 year) weak beta emitter (0.292 MeV). The beta activity is quite high, about 0.02 Ci/gram, and is essentially constant because of the long half-life.^(1,2) This activity must be properly considered in all technetium applications.

Information available on the properties and use of technetium is limited, making verification and further developments necessary if its unique properties are to be utilized. It has shown promise as a catalyst in reforming gasoline and in other chemical reactions, where it could replace platinum, palladium or rhodium, and as a corrosion inhibitor or an antifouling agent for surfaces exposed in marine environments. It could also replace the rare and costly rhenium in some alloys and catalytic applications.⁽⁴⁾ Brief discussions on these uses follow.

Technetium Catalysts

Technetium was evaluated as a catalyst for organic reactions in the early 1970s in laboratory- and bench-scale experiments.^(23,24) Catalysts were prepared by impregnating alumina with ammonium pertechnetate solutions and then reducing the pertechnetate with hydrogen. The catalysts proved effective for converting n-heptane to toluene at 500°C and were thus effective in dehydrogenation and ring formation reactions similar to those that are used in producing gasoline. A significant factor was the tolerance of the catalyst to sulfur. Mercaptan or other organic sulfur had only minimal effect on the catalyst activity. The catalyst was easily regenerated.

Because it could possibly be an alternative for platinum as a catalyst in many organic reactions, technetium should be evaluated further for possible classification as a strategic material.⁽²⁵⁾

Technetium as a Corrosion Inhibitor

The superior effectiveness of the pertechnetate ion as a corrosion inhibitor was identified in early 1952. Subsequent work throughout the intervening period has given rise to many theoretical studies concerning the mechanisms displayed by inorganic inhibitors in preventing corrosion.⁽²⁶⁻³⁰⁾ In all these studies the superior effectiveness of the pertechnetate ion as a corrosion inhibitor in aqueous solutions was identified. Pertechnetate concentrations ranged from 1 to 10 ppm in these studies, and corrosion inhibition was believed to be related to passivation of the metal surface by a thin layer of pertechnetate ion.

A 20-year corrosion inhibition experiment was performed when a carbon steel coupon was placed in an aqueous solution containing 10 ppm chloride and 5×10^{-4} molar KTcO_4 . A control coupon was placed in distilled water. After 13 years the coupon in the pertechnetate solution had no weight loss, the solution was clear, and the metal looked like new. The control was badly corroded and the solution was murky. Similar short-term tests at ambient and higher temperatures have given comparable results.

Unfortunately, the work to date, although promising, is not definitive. More work is necessary to identify and take advantage of the corrosion-prevention properties of this unique metal. For example, in addition to its use as an additive as described above, it might be alloyed in metals to give superior corrosion resistance and strength.

Technetium as a Coating To Prevent Biofouling

Several U.S. and foreign patents describe the use of technetium as a means of preventing biological fouling on surfaces exposed to seawater.⁽³¹⁻³⁵⁾ Buildup of biota is often a major contributor to the malfunction of equipment exposed in marine environments, and its prevention is paramount to successful use of optical systems, heat transfer surfaces, rack and pinion controls, and other operating equipment. Thus a good inhibitor is needed to prevent organisms from attaching to these surfaces. Although several patents exist, there is little technical literature on the use of technetium for this purpose. A

definitive study is needed. The use of technetium in coatings or alloys needs to be explored and tested, particularly for naval and other military applications.

A.7 PROMETHIUM-147 PROPERTIES

Fission-product promethium consists primarily of the radioisotope promethium-147 with low levels of three additional isotopes, promethium-146, promethium-148 and promethium-148m. Promethium-147, which is the isotope of interest for beneficial use, is primarily a beta emitter with a half-life of 2.62 years. Promethium-147 has a specific activity of 928 curies per gram and produces $0.333 W_t$ per gram. The promethium-148 ($t_{1/2} = 5.4$ days) and promethium-148m ($t_{1/2} = 43$ days) are present in low concentrations in fuel freshly discharged from the reactor, and decay to nondetectable levels within a few years after discharge. The promethium-146 ($t_{1/2} = 5.53$ years) is a beta-gamma emitter, and its presence can significantly affect potential applications for the promethium-147. The promethium-146 content for freshly discharged promethium can range from about 0.25 ppm (by activity) for promethium from production reactors up to about 5 ppm for promethium from commercial power reactors.⁽¹⁻⁴⁾

A.8 PLUTONIUM-238 AND NEPTUNIUM-237 APPLICATIONS

These two isotopes are discussed together because neptunium-237 is the precursor of plutonium-238, which is useful as a source of heat and power (Figure A.11). Neptunium-237 has been routinely recovered, exposed to neutrons and converted to plutonium-238. Plutonium-238 is an alpha emitter, having a half-life of 87.7 years. It produces $0.56 W_t$ per gram and requires minimum shielding.^(1-5,10)

Table 4.2 lists the space nuclear power systems launched between 1961 and 1977. These power systems, using plutonium, have been highly reliable, providing up to 500 watts of continuous, stable direct current to spacecraft used in NASA and DOD space missions. Missions to the planets would have been impossible without such heat and power sources.

FIGURE A.11. Plutonium-Powered RTG

Plutonium-238 has also been used in miniature RTGs for heart pacemakers and could be used as a power source for heart pumps and prosthetic devices if such devices become feasible. Additional possibilities exist and are similar to those described earlier under strontium.

A.9 AMERICIUM-241 APPLICATIONS

Americium-241 was discovered by Seaborg and his coworkers in 1944. It was created by beta decay of plutonium-241 that had been produced during plutonium production. Nearly all americium-241 that has been made available for public use has come from the same source. Americium-241 could, however, be recovered directly from spent defense or commercial nuclear reactor fuel but would contain some americium-243 as a diluent.

Americium-241 has a half-life of 433 years and emits principally 5.4 to 5.5 MeV alpha particles, 60 keV gamma rays and some X-rays. Selected uses of americium-241 for gauging, oil-well logging and other purposes, identified in Table A.4, show the wide range of applications for this isotope.

TABLE A.4. Summary of Uses for ^{241}Am (36)

Type	Radiation	Application	
	Property	Field/Industry	Specific Use
Gamma	Transmission	Medicine	Determine mineral content of bone and body composition
		Industrial gauging	Determine thickness of metals and plate glass
		Soil science	Measure soil moisture and density
		Hydrology	Radiation logging of groundwater
		Mineralogy	Determine ore concentration
Gamma	Backscatter ^(a)	Meteorology	Determine atmospheric density
		Coal	Determine ash content of coal
Gamma	X-ray excitation source	Mineralogy	On-stream analyses of minerals and slurries
		Gauging	Measure thickness of metal coatings on steel and paper weight density
Gamma	Absorption radiography	Metallurgy	Radiography of thin sheets of Al and Mg
		Aerospace	Nondestructive testing of steel tubing
Alpha	Ionization	Gas density	Ionization gauge for gas densities
		Gas chromatography	Ionization detector
		Building	Air conditioning, lightning rods, smoke-density detectors
		Gauging	Determine uniformity of thin films
Alpha	(α, n) Neutron source	Petroleum	Well logging
		Soil science	Determine soil density and moisture content
		Moisture meter	Moisture content of coke
		Activation analysis	Determine carbon in fly ash, fluorine in ores, silicon in cast iron and phosphorus in bone

(a) Backscatter methods depend on Compton scattering of gamma rays to return degraded source gamma rays to a detector near the source.

A.10 CURIUM-242 AND -244 APPLICATIONS

Both curium-242 and -244 are included here because of their possible use as heat sources and as a target material for production of heavier elements. Curium-244 has a half-life of 18.1 years and produces 2.84 W_t per gram of isotope. Its primary decay mode is by alpha particle emission with a gamma component which will impose a substantial shielding requirement. The use of curium-244 or -242 may be limited by neutron emission from spontaneous fission. The isotopic purity of curium-244 on recovery would be 95 percent if recovered 2 to 3 years after discharge from the reactor. If recovered earlier, it would be accompanied by curium-242, which has a half-life of 0.45 years and produces 120 W_t per gram of isotope. A 900-watt SNAP-11 generator fueled with curium-242 was fabricated by Oak Ridge National Laboratory, and a thermoelectric battery containing 400 mg of curium-242 was fabricated in Europe. The short half-life of this isotope severely limits its usefulness. Unfortunately, neither isotope is produced in sufficient quantities in defense fuel to be considered for recovery. However, sufficient quantities of curium-244 (18 g/MTIHM) are produced in low-enrichment power reactor fuels exposed at 30,000 MWd/MTIHM to be considered for recovery when these become available.

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APPENDIX B
DETAILS OF BYPRODUCT INVENTORIES

DETAILS OF BYPRODUCT INVENTORIES

B.1 INTRODUCTION

A very large number of both inert and radioactive isotopes are produced in defense production reactors and in civilian power reactors.⁽¹⁾ This section provides a detailed assessment of the quantity, quality and availability of twelve of the most useful of these byproducts from the principal sources. The summary given in Section 5 is a useful preface to the more detailed analysis provided in this section.

One point must be repeated regarding energy data presented for various radiosotopes in the following tables. The energy values given are for the entire decay chain. For example, the power values shown for strontium-90 in watts (t) are the combined values for the decay of the strontium-90 and the yttrium-90 daughter.

B.2 STRONTIUM-90

Fission-product strontium contained in freshly discharged spent fuel consists primarily of the stable isotope strontium-88 and the radioactive isotopes strontium-89, strontium-90 and strontium-91. Because of their relatively short half-lives, the strontium-89 ($t_{1/2} = 50.5$ days) and strontium-91 ($t_{1/2} = 9.5$ hr) concentrations in the strontium will decrease to negligible levels in a year. Additions of natural strontium during fuel processing and strontium recovery will also affect the isotopic composition of the recovered strontium. An isotopic analysis of strontium recovered from Hanford wastes in 1975 showed the following composition:⁽²⁾

<u>Isotope</u>	<u>Atomic Percent</u>
strontium-90	55.1
strontium-88	43.8
strontium-87	0.4
strontium-86	0.6
strontium-84	0.1.

The waste had aged sufficiently at the time of strontium recovery that the strontium-89 and strontium-91 had decayed to nondetectable levels. The strontium-84, strontium-86 and strontium-87 in the strontium resulted from the additions of natural strontium.

The quality of the strontium-90 recovered from various sources will depend on the time since the strontium (fuel) was discharged from the reactor. If fission-product strontium is recovered from recently discharged fuel, the strontium-89 content could possibly affect the use of the strontium-90 for some applications. Chemical impurities added during processing operations could also degrade the quality of the strontium-90.

Table B.1 gives the estimated inventories of strontium-90 for the various sources. Not all of the strontium-90 listed, however, is potentially recoverable for beneficial use.

B.2.1 Hanford⁽³⁻⁶⁾

At Hanford strontium has been recovered from the stored high-level wastes. The recovered strontium is being purified, converted to SrF_2 and doubly encapsulated in small (1000 cm^3), high-integrity metal containers. The encapsulated SrF_2 is stored in water basins at WESF. The encapsulated SrF_2 at Hanford represents the only major U.S. source of currently available strontium-90.

For various reasons, only part of the strontium-90 (about 40 percent) has been recovered from the current stored wastes. The remaining 60 percent of the strontium-90 is contained in insoluble sludge layers in the single-shell storage tanks. This strontium-90 is not currently considered recoverable for beneficial use.

The SrF_2 produced at Hanford contains chemical impurities, such as NaF and rare earth fluorides. The SrF_2 product is not analyzed on a routine basis, but a limited number of analyses indicate that chemical impurities in freshly prepared SrF_2 can approach 10 wt%.

The strontium-90 content of the SrF_2 prepared from current wastes is relatively low because of the age of the wastes and the chemical impurities. The strontium-90 isotope fraction of the total strontium varies from about 20

TABLE B.1. Estimated Inventories of Strontium-90 from Various Sources (1,3-8)

Source		Effective Inventory Date	kg	Ci	Watts (t)
Hanford	- SrF ₂ capsules through 7-82	1/83	140	1.9×10^7	1.3×10^5
	- SrF ₂ capsules 7/82 through 86	1/83	240	3.4×10^7	2.3×10^5
	- Stored wastes (a)	1/83	500	7.0×10^7	4.7×10^5
	- Future wastes	1/91	240	3.4×10^7	2.3×10^5
Savannah River Plant	- Current wastes (b)	1/83	860	1.2×10^8	8.1×10^5
	- Future wastes (through 2000)	1/2001	660	9.1×10^7	6.2×10^5
Commercial Spent Fuel	- Accum. through 1981	1/82	2.7×10^3	3.7×10^8	2.5×10^6
	- Accum. through 2020	1/2021	5.8×10^4	7.9×10^9	5.3×10^7

(a) Strontium-90 contained in current stored wastes, but not considered to be recoverable.

(b) Ninety percent of strontium-90 (1.2×10^8 Ci) contained in current wastes is in 12 storage tanks. The remaining 10 percent of the strontium is not included in inventory.

to 50 percent. Table B.2 provides a summary of the SrF_2 encapsulated through July 1982.⁽⁹⁾ The variations in curie content among capsules reflect the differences in the strontium-90 content of the strontium, the chemical impurities in the SrF_2 , differences in compaction density, and levels to which the capsules are filled. Many of the capsules shown in Table B.2 which contain less than 60,000 Ci strontium-90/capsule contain accumulated processing wastes and thus are not representative of the standard SrF_2 production capsules. This accounts for the very low estimated strontium-90 isotopic content of the strontium in these capsules. Future capsules of SrF_2 prepared from current stored wastes will probably show similar variations in curie content. A total of 36 megacuries (April 1982) of strontium-90 from current wastes remains to be converted to SrF_2 and encapsulated.⁽⁶⁾ Encapsulation of this strontium should be completed by the end of 1986.⁽⁶⁾ The recovered strontium is contained in seven process tanks in B-Plant (see Table B.3). Assuming a processing efficiency of 95 percent, about 33.5 megacuries of the strontium-90 would be converted to SrF_2 .

Strontium can be recovered from future PUREX high-level wastes using procedures similar to those used with current wastes. It is estimated that up to 95 percent of the strontium can be recovered from future wastes. The strontium obtained from future wastes will have a significantly higher strontium-90 content than that recovered from current wastes. The chemical purity of SrF_2 prepared from future wastes will probably be similar to SrF_2 obtained from current wastes. Table B.4 provides an estimate of the strontium-90 available from future wastes from 1984 through 1990, assuming reprocessing starts in 1984.⁽⁶⁾

For heat source use it is desirable that the SrF_2 capsule provide at least 850 W_t energy (≥ 125 kCi strontium-90/capsule). From Table B.2 it can be seen that only a few of the SrF_2 capsules prepared to date meet this requirement. Some improvement in power density of the strontium-90 in the encapsulated SrF_2 could be obtained by repackaging. In the current process the SrF_2 is compacted to 65 to 75 percent of theoretical density in the storage capsule. Using improved techniques, such as hot-pressing or melt-casting, it should be possible to obtain bulk densities approaching 95 percent of theoretical density.

TABLE B.2. Strontium-90 Encapsulated at Hanford as Strontium Fluoride^{(a)(9)}

⁹⁰ Sr/Capsule, kCi	No. of Capsules	Average ⁹⁰ Sr Isotopic Content, (b) at.%	Total ⁹⁰ Sr, kCi	Average ⁹⁰ Sr/ Capsule, kCi	Average Watts (t)/ Capsule
<30	22	10	398	18	122
30-40	10	17	333	33	225
40-50	21	23	959	46	308
50-60	40	21	2,223	56	375
60-70	39	23	2,496	64	432
70-80	5	30	390	78	527
80-90	7	35	597	85	576
90-100	40	36	3,826	96	646
100-110	43	39	4,532	105	712
110-120	23	42	2,640	115	775
120-130	6	45	752	125	847
130-140	1	49	137	137	926
>140	0				
	257		19,283		

(a) As of July 1, 1982. An additional 35,600 kCi of strontium-90 will be recovered from current wastes and encapsulated as SrF₂ by the end of 1986.

(b) Estimated from heat output and net weight of the SrF₂ in the capsule, assuming a chemical purity of 95 wt% for the SrF₂.

TABLE B.3. Strontium-90 from Current Waste Remaining To Be Encapsulated As of 7/82⁽⁶⁾

Tank No.	Strontium-90 Isotopic Content, Atomic Percent	Ci		Watts (t)	
6-1	38	8.25 x 10 ⁶		5.54 x 10 ⁴	
6-2	29	6.68 x 10 ⁶		4.48 x 10 ⁴	
7-2	29	7.36 x 10 ⁶		4.94 x 10 ⁴	
8-1	50	3.63 x 10 ⁶		2.44 x 10 ⁴	
8-2	29	3.34 x 10 ⁶		2.24 x 10 ⁴	
36-1	34	0.49 x 10 ⁶		0.33 x 10 ⁴	
39-5	29	5.50 x 10 ⁶		3.69 x 10 ⁴	
		35.25 x 10 ⁶		23.66 x 10 ⁴	

TABLE B.4. Strontium-90 Content of Future Hanford PUREX High-Level Waste - By Fiscal Year^{(a)(6)}

Fiscal Year	Effective Inventory Date	Strontium-90 Isotopic Content Atomic Percent	Ci		Watts (t)	
1984	9/84	59	3.4 x 10 ⁶		2.3 x 10 ⁵	
1985	9/85	62	6.6 x 10 ⁶		4.4 x 10 ⁴	
1986	9/86	58	10.6 x 10 ⁶		7.1 x 10 ⁴	
1987	9/87	59	7.9 x 10 ⁶		5.3 x 10 ⁴	
1988	9/88	61	2.7 x 10 ⁶		1.8 x 10 ⁴	
1989	9/89	61	2.7 x 10 ⁶		1.8 x 10 ⁴	
1990	9/90	61	2.6 x 10 ⁶		1.7 x 10 ⁴	
Total	9/90		33.6 x 10 ⁶		2.25 x 10 ⁵	

(a) Assumes reprocessing starts 4/84, starting with the oldest fuel.

B.2.2 Savannah River Plant⁽⁷⁾

High-level wastes generated at the Savannah River Plant contain large quantities of strontium-90. Ninety percent of the strontium-90 in the wastes produced through December 1981 is contained in 12 storage tanks. The

remaining 10 percent of the strontium-90 is not considered available for recovery and is not included in the strontium-90 inventory. The strontium-90 is present in the insoluble sludge layers in the 12 tanks. Data on the strontium-90 in the tanks are given in Table B.5.

Analyses of strontium from sludge in the H-Area tanks show that the strontium-90 isotopic content is only 12 percent. This indicates considerable dilution by inert strontium added during waste neutralization. Analyses of the sludge from F-Area tanks will be available in early 1983. At present it is assumed that none of the strontium-90 in current wastes at SRP will be usable for heat-source applications without isotope enrichment.

Future annual recovery of strontium-90 at SRP is estimated at 6×10^6 Ci per year, with a strontium-90 isotopic content of the strontium being about 60 percent. Assuming plant operation through the year 2000, the total strontium-90 inventory at the end of year 2000 would be about 9.2×10^7 Ci

TABLE B.5. Strontium-90 Contained in Current Stored Wastes at SRP - As of 1/1983

<u>Tank No.</u>	<u>Sludge Volume, gal</u>	<u>Ci</u>	<u>Watts (t)</u>
4-F	127,000	1.14×10^7	7.65×10^4
5-F	41,000	0.86×10^7	5.77×10^4
6-F	25,000	0.86×10^7	5.77×10^4
7-F	221,000	0.76×10^7	5.10×10^4
8-F	236,000	0.48×10^7	3.22×10^4
11-H	175,000	0.86×10^7	5.77×10^4
12-H	257,000	0.95×10^7	6.38×10^4
13-H	403,000	0.95×10^7	6.38×10^4
15-H	395,000	1.43×10^7	9.60×10^4
32-H	137,000	1.81×10^7	12.15×10^4
34-H	26,000	0.29×10^7	1.95×10^4
35-H	<u>62,000</u>	<u>1.62×10^7</u>	<u>10.87×10^4</u>
Total	2,105,000	12.01×10^7	80.61×10^4

(6.2×10^5 W_t). Considering the high strontium-90 isotopic content of the strontium, all the strontium-90 from future SRP waste should be suitable for heat source use.

Currently there are no facilities at SRP for recovering, purifying or packaging strontium-90. Such facilities could be constructed when the need for strontium-90 justifies the expanded capacity.

B.2.3 Commercial Spent Fuel(1)

Commercial spent fuel in storage at the end of 1981 contained an estimated 4570 kg of fission-product strontium. The DOE further estimates that spent fuel discharged from commercial reactors through the year 2020 will contain about 112,000 kg of strontium (assuming no interim reprocessing). The strontium-90 content of the strontium recovered from commercial spent fuel now in storage and future discharged fuel will depend on the time elapsed between fuel discharge and use. The average composition and characteristics of the strontium in the spent fuel are given in Table B.6 for (a) the fuel in storage at the end of 1981 and (b) the fuel that will accumulate through the year 2020.

The availability of strontium-90 from commercial spent fuel will depend on the restart of commercial fuel processing and on the decision to recover strontium during processing. Assuming that market conditions provide the incentive, fuel processing and strontium recovery schedules could probably be tailored to give the quantity and quality of strontium-90 required.

B.3 CESIUM-137

Fission-product cesium in spent fuel freshly discharged from the reactor consists of the stable isotope cesium-133 and the radioactive isotopes cesium-134, cesium-135, cesium-136 and cesium-137. Substantial quantities of cesium-137 are potentially recoverable from current and future high-level wastes and from commercial spent fuel. Its quality will depend primarily on the time since the fuel was discharged because cesium-137 content decreases with time due to decay. Due to their much shorter half-lives, cesium-134 and cesium-136, present at high activity levels initially, decay at much faster rates. The activity ratio of the cesium-134 to cesium-137 in the cesium

TABLE B.6. Average Composition and Characteristics of the Strontium in Commercial Spent Fuel⁽¹⁾

	Isotope	Isotopic Content, at.%	kg	Ci	Watts (t)
Fuel in storage at the end of 1981	Strontium (stable)	41.7	1,879	-	-
	Strontium-89	0.13	6	1.71×10^8	5.92×10^5
	Strontium-90	58.2	<u>2,683</u>	<u>3.66×10^8</u>	<u>2.46×10^6</u>
Total			4,568	5.37×10^8	3.05×10^6
Fuel accumulated through the year 2020	Strontium (stable)	48.7	53,890	-	-
	Strontium-89	0.03	33	9.47×10^8	3.27×10^6
	Strontium-90	51.3	<u>58,010</u>	<u>7.92×10^9</u>	<u>5.31×10^7</u>
Total			111,933	8.87×10^9	5.64×10^7

decreases by a factor of about two every 2 years. The activity ratio of the cesium-136 to cesium-137 decreases by a factor of two about every 13 days. Cesium-135, which emits a low-energy beta, has a half-life of 2.3 million years. The cesium-135 activity has no effect on potential uses of cesium-137, but the mass of the cesium-135 does dilute the cesium-137 content recovered. Depending on the effectiveness of the recovery and purification schemes, the cesium could also contain substantial amounts of chemical impurities.

Table B.7 gives the estimated inventories of cesium-137 available from the various sources. As discussed in the following sections, only a fraction of the cesium-137 listed in Table B.7 is potentially recoverable for beneficial use.

B.3.1 Hanford(3-5,10)

At Hanford cesium has been recovered from stored high-level wastes. The recovered cesium is being purified, converted to cesium chloride, and doubly encapsulated in small capsules of the same design as those for strontium. The encapsulated cesium chloride is stored in water basins at WESF. Cesium can similarly be recovered from future wastes generated in the processing of N-Reactor fuel. This encapsulated cesium chloride represents the only major U.S. source of currently available cesium-137.

About 80 percent of the cesium in the stored wastes has been recovered and is being converted to cesium chloride. The remaining 20 percent is contained in insoluble sludge layers in the waste tanks, salt cake, and double-shell slurry (residual liquor). This cesium is not considered available for recovery at the present time. It is estimated that up to about 95 percent of the cesium could be recovered from future PUREX wastes and converted to cesium chloride.

The cesium-137 content of the cesium chloride is generally quite low because of the age of the current waste. The chemical purity of the cesium chloride also varies, depending on several factors. The chlorides of sodium, potassium, rubidium, calcium and barium are the principal impurities. Other impurities result from corrosion of the processing equipment. Overall,

TABLE B.7. Estimated Inventories of Cesium-137 from Various Sources^(1,3-5,7,8,10)

Source		Effective Inventory Date	kg	Ci	Watts (t) ^(a)
Hanford	- Cesium chloride capsules through 6/82	1/83	731	6.36×10^7	3.06×10^5
	- Cesium chloride capsules through 6/84	1/83	318	2.77×10^7	1.33×10^5
	- Stored wastes ^(b)	1/83	301	2.6×10^7	1.26×10^5
	- Future wastes	1/91	445	3.87×10^7	1.86×10^5
Savannah River Plant	- Current wastes	1/83	1170	1.02×10^8	4.90×10^5
	- Future wastes	1/2001	1250	1.09×10^8	5.24×10^5
Commercial Spent Fuel	- Accum. through 1981	1/83	6.0×10^3	5.2×10^8	2.5×10^6
	- Accum. through 2020	1/2021	1.3×10^5	1.1×10^{10}	5.5×10^7

(a) Values include decay of daughter products.

(b) Cesium contained in current waste, but not considered recoverable.

impurities in the cesium chloride should be less than 10 wt%. Exact compositions are unknown because the cesium chloride product has not been subjected to chemical analysis.

Table B.8 provides a summary of the cesium chloride encapsulated through 6/82. Variations in curie content among capsules not only reflect differences in the cesium-137 content and chemical purity of the cesium chloride, but, in some cases, the extent to which the capsules were filled. Future capsules of cesium chloride prepared from current stored wastes will probably show similar variations in curie content.

The cesium chloride produced at Hanford is encapsulated in 316L stainless steel canisters. The inner capsule has an inner diameter of 2 inches and an inner length of about 19 inches. Each capsule can hold up to about 3 kg of material.

Cesium recovered from future PUREX wastes would have a significantly higher cesium-137 content than that recovered from the current wastes.

TABLE B.8. Cesium-137 Encapsulated at Hanford as
Cesium Chloride^(a) (10)

¹³⁷ Cs/Capsule, kCi	No. of Capsules	Total ¹³⁷ Cs, kCi	Average ¹³⁷ Cs/ Capsule, kCi	Average Watts (t)/Capsule
<10	5	27	5.4	26.0
10-20	1	16	16.2	77.9
20-30	10	262	26.2	126
30-40	40	838	36.0	173
40-50	257	11,950	46.5	224
50-60	762	42,182	55.4	266
60-70	149	8,310	64.6	311
70-80	10	715	71.5	344
>80	0	0	-	-
	1,234	64,300		

(a) As of 7/82. An additional 2.8×10^7 Ci of recovered cesium will be encapsulated by the end of 1984.

Chemical purity of the cesium chloride prepared from future wastes will probably be similar to cesium chloride prepared from current wastes unless process improvements are initiated.

B.3.2 Savannah River Plant⁽⁷⁾

The high-level wastes currently stored at the Savannah River Plant contain large quantities of cesium-137. Eighty percent of cesium-137 in the waste is contained in 11 storage tanks. The remaining 20 percent, not considered recoverable for beneficial use at this time, is not included in the inventory. Pertinent data on the cesium-137 in the tanks are given in Table B.9. The cesium-137 isotopic content of the cesium in the tanks is estimated to range from 20 to 40 percent.

Future generation of cesium-137 at SRP is estimated at 7×10^6 Ci/year, with the cesium-137 isotopic content of the cesium being about 40 percent.

TABLE B.9. Cesium-137 Contained in Current Stored Waste at Savannah River Plant - As of 1/83⁽⁷⁾

<u>Tank No.</u>	<u>Waste Volume,^(a) gallons</u>	<u>Ci Cesium-137</u>	<u>Watts (t) Cesium-137</u>
1-F	555,000	7.8×10^6	3.7×10^4
4-F	552,000	6.8×10^6	3.3×10^4
27-F	983,000	10.7×10^6	5.1×10^4
33-F	955,000	6.8×10^6	3.3×10^4
34-F	892,000	6.8×10^6	3.3×10^4
29-H	1,060,000	8.8×10^6	4.2×10^4
31-H	1,107,000	9.8×10^6	4.7×10^4
32-H	790,000	10.7×10^6	5.1×10^4
35-H	1,188,000	9.8×10^6	4.7×10^4
36-H	1,216,000	13.7×10^6	6.6×10^4
37-H	<u>1,244,000</u>	<u>9.8×10^6</u>	<u>4.7×10^4</u>
Total	10,542,000	101.5×10^6	48.7×10^4

(a) Liquid and salt.

Assuming production through the year 2000, the total cesium-137 inventory from future wastes at the end of the year 2020 would be about 1.09×10^8 Ci.

There are currently no facilities at SRP for purifying or packaging cesium-137. Such facilities could be constructed if increased demand for cesium-137 justifies the added capacity.

B.3.3 Commercial Spent Fuel⁽¹⁾

Commercial spent fuel in storage at the end of 1981 contained an estimated 14,000 kg of cesium. The isotopic composition and characteristics of the cesium in the fuel vary with the time since the fuel was discharged from the reactor. The average composition and characteristics of the cesium in the fuel at the end of 1981 are given in Table B.10.

DOE estimates that spent fuel discharged from commercial reactors through the year 2020 will amount to about 279,000 MTHM.⁽¹⁾ Assuming no interim processing, this stored fuel will contain an estimated 350,000 kg of cesium by the year 2020. Table B.10 shows the average isotopic composition and characteristics of the accumulated cesium (at the end of the year 2020).

Availability of cesium-137 from commercial spent fuel will depend on the restart of commercial fuel processing. If processing is restarted, the quality of the cesium-137 available for beneficial use can vary over wide ranges, depending on the age of the fuel being processed.

B.4 KRYPTON-85/XENON

In the PUREX process krypton and xenon are released during the dissolution of the spent fuel and end up in the dissolver offgas. If the fuel elements are sectioned prior to leaching, a small fraction of the krypton and xenon (usually less than 2 percent) is released during the operation.

There are no reprocessing operations in the U.S. where krypton and xenon are routinely recovered. At the INEL a cryogenic distillation pilot facility has been operated intermittently for years to recover krypton-85 from dissolver offgas. The krypton-85 recovered at INEL is further purified at ORNL and then sold to meet commercial and R&D needs. The annual production of krypton at INEL fluctuates broadly, depending on the kind of fuel processed. About 12,000 Ci were recovered in 1982, but 20,000 Ci will be recovered in 1983.

TABLE B.10. Average Composition and Characteristics of Cesium in Commercial Spent Fuel⁽¹⁾

Source	Effective Inventory Date	Isotope	Isotopic Analysis, at.%	kg	Ci	Watts (t)
Fuel in storage at the end of 1981	1/82	Cesium-133 (stable)	44.3	6,104	-	-
		Cesium-134	1.8	245	3.17×10^8	3.22×10^6
		Cesium-135	11.9	1,659	1.91×10^3	0.66
		Cesium-136	0.0002	0.027	1.98×10^6	3.05×10^4
		<u>Cesium-137</u>	42.00	<u>5,958</u>	<u>5.19×10^8</u>	<u>2.51×10^6</u>
		Total		13,966	8.38×10^8	5.76×10^6
Fuel in storage at the end of 2020 ^(a)	1/2021	Cesium-133 (stable)	49.6	172,900	-	-
		Cesium-134	0.5	1,795	2.32×10^9	2.36×10^7
		Cesium-135	13.8	48,980	5.64×10^4	19
		Cesium-136	0.00004	0.15	1.08×10^7	1.66×10^5
		<u>Cesium-137</u>	36.1	<u>129,700</u>	<u>1.13×10^{10}</u>	<u>5.46×10^7</u>
		Total		353,375	1.36×10^{10}	7.84×10^7

(a) Assumes no interim processing.

Because of this fluctuation, and the relatively small amounts, INEL data are not included in Tables B.11 and B.12.

Tables B.11 and B.12 list krypton-85 and xenon potentially recoverable from future fuel processing operations. Since krypton and xenon would be recovered from the dissolver offgas, which contains significant quantities of air, the krypton and xenon obtained would have isotopic compositions somewhat different from that of fission-product krypton and xenon because of dilution by natural krypton and xenon in the air.

B.4.1 Hanford

There are no current plans to recover krypton and xenon when processing of N-Reactor fuel is restarted at Hanford. New facilities will be required if recovery of the noble gases is undertaken. Because the dissolvers in the Hanford PUREX plant operate with a large air sparge and sweep, the concentrations of krypton and xenon in the dissolver offgas are quite low. This greatly increases the volume of gas that must be processed and dilutes the krypton-85 with additional inert krypton.

The total xenon available through 1990 is estimated to be 3000 kg. The krypton-85 accumulated through the year 1990 will amount to 5×10^6 Ci; this corresponds to about 210 kg of krypton-85.

B.4.2 Savannah River Plant⁽⁷⁾

Krypton and xenon are not recovered in the fuel reprocessing operations at SRP. Recovery would require installation of new facilities. The estimated availability is 50 kg/year of krypton having a krypton-85 content of 6 percent, or 1.2×10^6 Ci of krypton-85 per year. The estimated production rate of xenon is 340 kg/year.

B.4.3 Commercial Spent Fuel⁽¹⁾

Current and future commercial spent fuels represent a large potential source for krypton-85 and xenon, assuming the restart of commercial fuel processing. Krypton and xenon recovery could be readily incorporated, and may