LIFE-CYCLE COST OF A RADIUM STORAGE AND PROCESSING FACILITY

By

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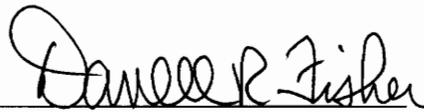
Master of Science

in

Systems Engineering

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(Abstract)

This report presents the results of a study to determine the life-cycle cost of a radium storage and processing facility with respect to cost control, design control, cost reduction, radium supply and demand, disposal alternatives, and economic viability.

The following recommendations were made:

1. The study should be refined so that one function exists for each cost estimating relationship, and costs could be controlled functionally.

2. The life-cycle model should be modified and used for tradeoff studies of alternatives for radium storage.

3. Operations and maintenance offer the greatest opportunity for cost control. Particular attention should be given to studying radium processing.

4. A systems dynamics study should explore relationships including supply and demand of radium and the desired mix of derived isotopes.

5. Studies should explore how this facility should be made economically attractive for radium custodians in contrast to present means of disposal. Consideration should be given to recycling byproducts such as platinum.

6. The entire field of alpha-particle emitters deserves a life-cycle study from the production of raw material to the use of the material in medicine. Such a study would help define the facility mission.

Besides providing the above recommendations, the life-cycle study showed that successful application of alpha-particle emitters to one type of cancer could make the project economic. Further opportunities for life-cycle cost studies of the project abound.

DEDICATION

This paper is dedicated to the following friends and family who were victims of cancer. In struggles with this project, the author remembered each of them and their life and death struggle. These are only representatives known to the author. They ultimately represent all cancer victims. They gave inspiration to complete this project.

- Larry E. Arnette
- Gerry Atkinson
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- James L. Ash
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- John Fitzgerald Spencer
- Geraldine Tipton
- Ken White
- Michael George Zech

"And these all, having obtained a good report through faith, received not the promise: God having provided some better thing through us, that they without us should not be made perfect." *Hebrews 11: 39-40.*

ACKNOWLEDGMENTS

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SECTION 1: INTRODUCTION

Background

Radium was discovered in 1898 by Pierre and Marie Curie (Mould, 1993) (Quinn, S., 1995). For many years radium was used for purposes such as treatment of cancer, providing a source of radiation for luminous dials, and supplying sources of neutrons. As a medical treatment, it has largely been replaced by other isotopes such as cesium-137. Radium was placed within platinum needles that were then emplaced in tumors. The radium remained within the tumors until gamma radiation killed the tumor, and the surgeon removed the needles.

Although radium treatment could prove effective, operational and maintenance problems led to the replacement of radium with other isotopes. Radium produced radon, a hazardous noble (inert) gas. Medical staff members were exposed to gamma radiation both when emplacing and extracting the needles. Family and visitors had to regard the patient in treatment as a radiological hazard. Once out of the body, the needles had to be sterilized before further use. The process of handling the needles could damage them, causing them to leak radon. After a certain amount of time, the build up of helium from alpha-particle radiation within the needle could cause failure. For these reasons, needles had to be leak-tested for radon gas and maintained. If the radium had to be disposed of, consideration of its 1,600 year half life was important. For these reasons, radium was a prime candidate for replacement, once the mechanics of other isotopes had been worked out. For example, cesium-137 has half life of approximately 30 years and emits only beta particles. In contrast, radium emits alpha, beta, and gamma radiation. The Environmental Protection Agency encouraged most owners of radium to dispose of it in proper facilities. Only one facility in the United States now takes radium for disposal, and that facility limits quantities to 50 milligrams per shipment or approximately 50 millicuries (Devine, May 20, 1996).

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Because of new research, new medical uses have been developed for alpha-particle emitting isotopes derived from Radium-226. Alpha particles are the nuclei of helium atoms, consisting of two protons and two neutrons. Alpha-particle emitting isotopes are linked to (conjugated with) immunoglobulins (monoclonal antibodies, hormones, or growth factors) to treat cancer. Several alpha-particle emitting isotopes can be used including Bi-212, Ac-225, Bi-213, Ra-223, and cyclotron-produced At-211. Ra-223, Ac-225, and Bi-213 can all be produced by neutron irradiation of Ra-226 (Fisher *et al.*, 1993). As of July 1996 plans were being made for Dr. David Scheinberg of Memorial Sloan-Kettering Cancer Center to use Bi-213 to treat acute leukemia during the fall of 1996 (Fisher, 1996), (Scheinberg, 1996). This would be the first use of alpha-particle emitting isotopes in integrated cell therapy with monoclonal antibodies within the U.S. In the treatment of cancer, alpha particles are 2,000 to 3,000 times as effective as beta particles in killing cancer cells (Schenter *et al.*, 1995). Also, because of short linear energy transfer, alpha particles tend to kill cancer cells without killing the surrounding healthy tissue.

Present plans call for producing generators of desired radioactive isotopes. Kozak *et al.* (1986) describe a generator as ". . . a long-lived nuclide that decays into a short-lived nuclide that can be physically or chemically isolated from its parent." Kozak *et al.* (1986) also point out that ". . . the ease with which the antibody can be generated could be an important factor in designing practical antibody-conjugated agents." The two desired generators produced by the addition of neutrons to radium-226 are thorium-229 and actinium-227.

Finding a radium-226 feedstock for making these isotopes is a problem. Fisher (1995) has estimated the need for 200 to 2,200 grams of radium. Transmuting the radium from radium-226 to actinium-227 and thorium-229 depends on the addition of neutrons to the radium by means of a nuclear reactor. Production of thorium-229 requires the addition of three neutrons to the radium-226 atom, but production of actinium-227

requires the addition of only one neutron. The more neutrons added, the less efficient the process of transmutation. Thorium 229 is an ingrowth daughter product of aged urainium-233 stockpiles. Enough thorium-229 may be available for present clinical trials of the bismuth-213 procedure and few years' production, but may not be sufficient for large numbers of patients. The amount of either thorium-229 or actinium-227 needed for the future is not known.

Systems Context

Systems engineering looks at an interdisciplinary project throughout the project's life cycle from concept through research and development, implementation, operations and maintenance to decommissioning. In developing any system, the greatest opportunity for influencing the system life-cycle cost is at the beginning phases of the project (Fabrycky and Blanchard, 1991). The opportunity to use such an approach obviously depends on timing. Recently a radium storage and processing facility has been proposed to solve a disposal problem for owners of radium and to solve a supply problem for scientists needing radium as feedstock for producing new alpha-particle emitting isotopes. Because the project is in the early part of the life cycle, the time for the greatest savings is now.

The radium storage and processing facility is best described as a subsystem of an even larger system designed to control radioactive wastes in such a manner as to benefit humanity. An illustration of the relationship of the radium storage and processing facility to other subsystems is shown in Figure 1. Benefits of the system include reducing the risk of radioactive damage and making use of the material to its greatest potential. The actual system to be dealt with is confined to the organization, personnel, and materials who will plan, implement, operate and maintain, and decommission the facility.

Dr. Don Drew in his class notes for Applied Systems Engineering (Drew, 1994) defined systems problems with the acronym, STEP. A STEP problem contains social,
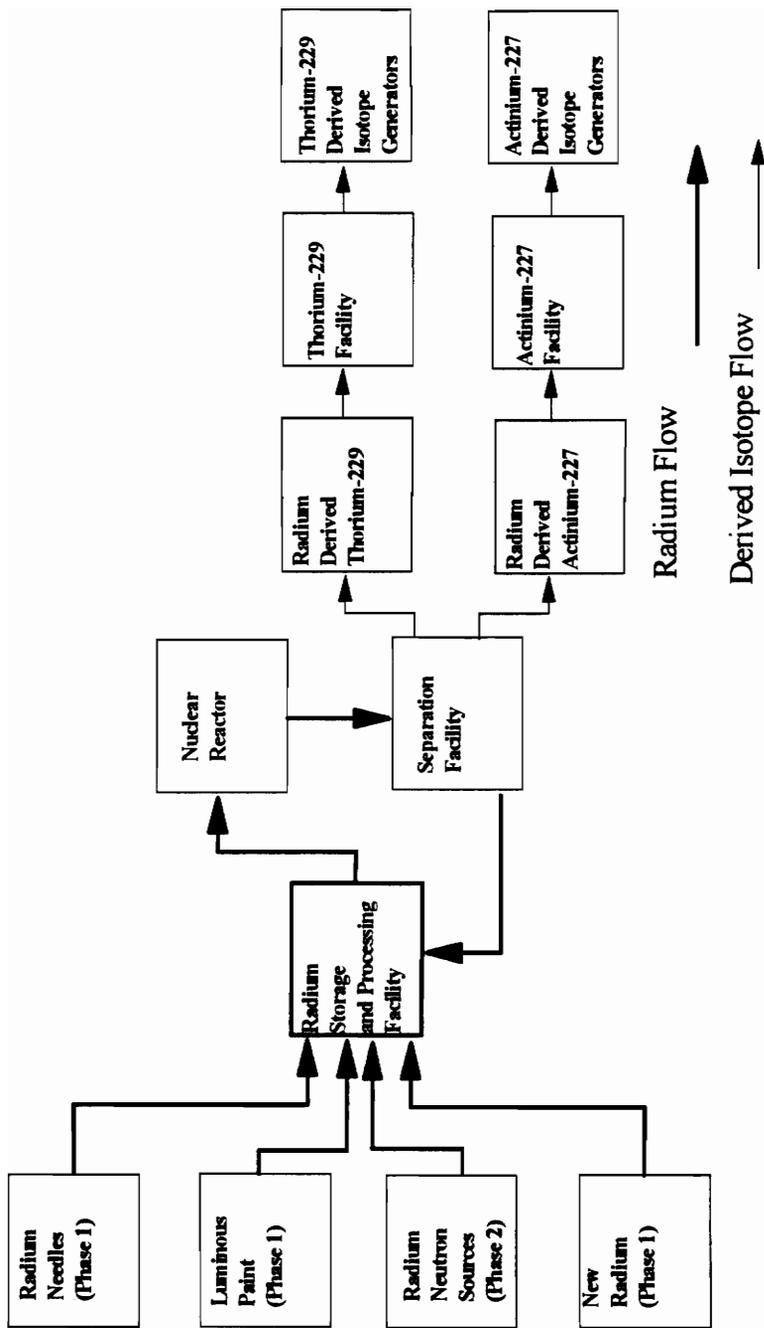
Figure 1: Relation of Radium Storage and Processing Facility to Other Entities

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technological, economic, and political components. All these elements are present in the design of a radium storage and processing facility.

Social implications of this problem could be extremely large. Table 1, based on data from *Scientific American* (1996) shows the diagnosis of twelve major types of cancer along with the expected death rates. Estimates from this table show that more than 400,000 deaths a year result from these twelve major types of cancer. Some estimates of the eventual effectiveness of alpha-particle emitting therapy range as high as 50 per cent of these cancers.

Technologically, the radium storage and processing facility depends on the advance of medical science for justification. Full implementation of the program could involve many technologies including, but not necessarily limited to, new radium extraction processes, radium purification processes, radon control, antibody development, nuclear reactor technology, chemical bonding, production of isotope generators, and development of clinical protocols. Progress in using alpha-particle emitting isotopes will determine the demand for radium. Demand will also be affected by competing technologies. Within the alpha-particle emitting field, the demand for radium will depend on what mixture of isotopes will be required. More radium will be required if the isotopes derived from thorium-229 predominate, and less radium will be required if the isotopes derived from actinium-227 predominate. Increased demand for radium could also result in the need for new radium from outside sources.

Economic implications of this problem are clear. The costs of building and operating a radium storage and processing facility range in the millions of dollars. On the other hand, potential for increased productivity among former cancer patients is great. According to statistics in Scientific American, only 11.4 per cent of patients with acute myelogenous leukemia survive five years or more. Should the new treatment with alpha-particle emitting isotopes work, then perhaps a good portion of the remaining 88.6 percent

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Table 1: Rates of Diagnosis and Death for Twelve Major Types of Cancer (*Scientific American*, 1996)

Type of Cancer	New Diagnoses per Year	Deaths per Year
Prostate	317,100	41,400
Breast	185,700 (Including 1,400 among men)	44,560 (Including 260 men)
Lung	177,000	158,700
Colorectal	133,500 (94,500 for colon, 39,000 for rectum)	54,900 (46,400 for colon, 8,500 for rectum)
Bladder	52,900	11,700
Non-Hodgkin's Lymphoma	52,700	23,300
Uterine	49,700 (15,700 for cervical, 34,000 for endometrial)	10,900 (4,900 from cervical, 6,000 from endometrial)
Melanoma of the Skin	38,300	7,300
Kidney Cancer	30,600	12,000
Leukemia	27,600	21,000
Ovarian	26,700	14,800
Pancreatic	26,300	27,800
Total: All Cancers	1,118,100	428,360

of the remainder should survive. The incomes of these patients could then contribute considerably to the overall economy.

Building a radium storage and processing facility is also a political problem. The facility could be built at Hanford in an existing United States Department of Energy building such as Building 325. Initial funds for the project would have to come from the public treasury. Radium is hazardous with potential value. Viability of the project may depend on whether the radium storage and processing facility is perceived as an asset or a liability. This evaluation in turn may depend on technological progress in clinical trials, the economics of any treatment, and the social impact of the success or failure of clinical trials.

Objective and Scope

The purpose of this study was to prepare a life-cycle cost analysis of a radium storage and processing facility to be built within an existing building at the Hanford Nuclear Reservation near Richland, Washington. This approach of using existing facilities was chosen to take advantage of the many facilities at Hanford going out of service. Otherwise, a new building could add $3,000,000 to $5,000,000 to the project cost, and a new hot cell could add $500,000 to $750,000. Such an approach not only provides a more economical source of a building and a hot cell, but also provides a useful alternative to demolition and disposal of existing facilities. Given the changing mission of the United States Department of Energy at Hanford, many such facilities should be available.

This analysis provides a baseline of costs for future work. Cost profiles were provided both on an actual and discounted basis. The analysis identified high cost contributors and determined the sensitivity of cost to price variation along with risk.

Because a modern radium storage and processing facility has not been available for at least fifteen years, a conceptual design of the system had to be made. To facilitate that design, requirements were determined by use of a questionnaire prepared by the Fernald

Environmental Restoration Management Corporation (1995). Answers for each question were provided by the author to various experts for review so that a set of reasonable requirements could be derived from the questionnaire.

Once the requirements had been defined, a functional flow diagram was constructed down to the level necessary to determine a reasonable life-cycle cost. For purposes of this study, the first level functions of the system corresponded to the four main life-cycle phases of the system including planning, implementation, operations, and decommissioning. Life-cycle phases generally correspond to organizational phases of the life cycle (Fabrycky and Blanchard, 1991). Functional analysis thus served two main purposes:

- Defining the system to a level where appropriate hardware, software, and operations could be defined.

- Organizing the system into components that could more easily be accommodated by a cost breakdown structure corresponding to the life-cycle phases of the system.

The functional flow analysis also served as a basis for the conceptual design. Conceptual design was only carried out to the extent necessary to provide a top-level estimate of life-cycle costs. For example, a conceptual design of the transfer cask showed only the general shape, size, and capacity of the container and how much material would be needed for radioactive shielding. Actual details of the design of the cask including how the cask would interface with plugs on the storage cells, cranes, forklifts, and conveyors would be part of a more advanced design.

The conceptual design for this report helped define a cost breakdown structure and cost estimating relationships. Thus the design consisted of a general layout of the facility within an existing building, a general schedule of design and construction activities, a schedule of operational and maintenance operations, and a schedule of decommissioning activities. The main parameters defining the design were the amounts of radium to be

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processed, the permissible levels of radiation, and the control measures necessary for radon gas.

The cost breakdown structure and cost estimating relationships were defined only to a level that would give a comprehensive overview of the costs as defined by a conceptual design. Construction of the cost breakdown structure was simplified because the functional flow diagram had been designed along lines parallel to the life-cycle phases of the project including research and development, implementation, operations and maintenance, and decommissioning. Some costs could be defined in detail because they are well known from past operations of nuclear facilities. These included the costs of maintaining and operating a hot cell. Other costs were not so easily defined. These included the actual processing costs for radium and the control of radon. Although radium has been processed before, the regulations with respect to radiation and radon control were not so strict as would be required in a modern regulatory environment.

Cost estimating relationships varied in detail according to the knowledge available at the beginning stages of the project. More research might be needed concerning radium processing and radon control. Detail designs of equipment may also provide more refined relationships.

Cost estimating relationships formed the basis of finding life-cycle costs. Costs for each category were accumulated by year and by major cost breakdown division. These costs were then calculated by means of a spreadsheet. Costs accumulated by year formed the basis of cost profiles throughout the life of the project. Both actual and discounted profiles were calculated.

After costs had been determined and profiles had been calculated, an evaluation was made to determine whether recovery of radium would be a good investment in terms of patients cured. Estimates were made based on assumed costs of treatment per patient cured for five years in addition to costs for the facility and additional income of the patients.

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Because costs had been accumulated by means of a cost breakdown structure, high cost contributors could be identified. Using sensitivity analyses, areas of risk could be identified. Managers using this report could make decisions about establishment of priorities using this report.

SECTION 2: FACILITY CHARACTERISTICS AND FUNCTIONAL FLOW ANALYSIS

Establishing Facility Characteristics

Before estimating cost breakdown structures, cost estimating relationships, or costs, some method had to be devised to establish characteristics of the proposed radium storage and processing facility. The United States Environmental Protection Agency (EPA) had at one time maintained a facility for storing radium in Montgomery, Alabama. This facility served as the basis for the present design of the facility. The facility consisted simply of a series of thirty lined holes in the ground, each approximately 10 feet deep and eight inches in diameter. Each hole was designed to hold approximately 10 grams of radium (Sensintaffer, E., Personal Communication, 1996). The EPA facility provided a basis for building this facility.

Meanwhile since the EPA facility had been closed, new regulations had been promulgated by the EPA itself. A new facility was needed that would not only provide a means of disposal of radium, but also a means of processing that same radium. Some means also had to be devised to handle leaking radium sources that might be received at the facility.

To minimize the cost of this project, efforts were made to use an existing facility rather than a new building. Although up to 2,000 grams of radium were needed, a facility of 500 grams was arbitrarily chosen with the idea that after a certain amount of time, the radium would be transmuted into other products. This capacity was also believed to be adequate to hold readily available quantities of approximately 200 grams of radium in the United States plus other sources that might come from new production.

Given these parameters, some systematic means was needed to determine the characteristics of the radium storage and processing facility in more detail. Fortunately a functional requirements document questionnaire produced by the Fernald Environmental

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Management Corporation (1995) could be used for this purpose. A sample questionnaire was first prepared with all of the questions answered. Once the questionnaire had been prepared, it was then circulated among several nuclear engineering experts. Using responses from these experts, the answers to the questionnaire were then reformulated into Table A-1 entitled, "Description of the Characteristics of the Radium Storage and Processing Facility." This table was again modified to the extent practicable to be consistent with subsequent activities including the functional flow analysis and development of the conceptual design, cost breakdown structure, and cost estimating relationships. All of these activities were preliminary in nature. Should the facility be built, then all activities would then have to be done again in more detail.

Functional Flow Analysis

Once characteristics including requirements had been defined, then a functional flow diagram was prepared. In systems engineering, a functional flow diagram shows what a particular system is supposed to do rather than how the system is to perform (Blanchard and Fabrycky, 1990). Major functions of the system are broken down into subfunctions, which in turn are broken further into subfunctions.

Once the radium storage and processing facility has been built, then its functions may be described as receiving, storing, processing, and shipping radium. This classification of functions is useful in describing the functions of the completed facility, but it is incomplete for use in life-cycle costing. For purposes of the life-cycle costing, the hierarchy needed to be increased to a level that included not only materials, but also personnel and the organization that would run the facility. Ultimately the hierarchy needs to be developed to an even higher level. The United States Department of Energy needs to develop a study to determine a radium policy for the entire country as to health, environmental, economic, technical, and political needs.

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A particular virtue of functional flow analysis is that it permits an overview of a project down to the level necessary to solve a particular problem. In this part of the report, the functional flow is shown down to second level for an overview. (See Figures 2-6.) A more complete diagram is shown in the Appendix. The four main functions of the radium storage and processing system include planning, establishing, operating, and decommissioning the facility.

Planning

The planning function is subdivided into seven major subfunctions. After advanced research has been performed, the system is designed down to the appropriate level of detail for the particular phase of the project. In this phase of the project, a conceptual design would be sufficient for the beginning phases of life-cycle costing. After the engineering activity began but before it had finished, environmental work would begin.

Part of the planning process would include the beginning phases of equipment procurement. This would include the construction and testing of prototypes and the beginning phases of procurement of equipment requiring long lead times.

The planning phase would also be a good time to organize training for the facility. This early phase would be a good time to consider the human factors involved in handling any equipment. Trainers and human factors engineers could interact at this time to identify more efficient ways to use personnel.

Establishing the Facility

Once planning had been completed, the actual work of establishing the facility could begin. This could begin with remodeling of office space to accommodate personnel. An existing hot cell would have to be reconfigured to accommodate the receipt, processing, and shipping of radium. Radium storage would need to be constructed while the hot cell was being reconfigured.

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Functional Flow
Diagram

For Radium Storage and Processing
Facility

1.0	2.0	3.0	4.0
Plan Facility	Establish Facility	Operate Facility	Decommission Facility

Legend

Function Block

Reference Block

Functional Flow Arrows

Reference Arrows

AND — Summing Gate for Parallel Functions

OR — Summing Gate for Alternative Functions

2.2.1 — Function Number:
Level of indenture equals
number of decimals plus one
except for numbers ending in zero.
For numbers ending in zero,
level of indenture equals number
of decimals.

Install HVAC

Figure 2: Functional Flow Diagram Showing Top Level Functions
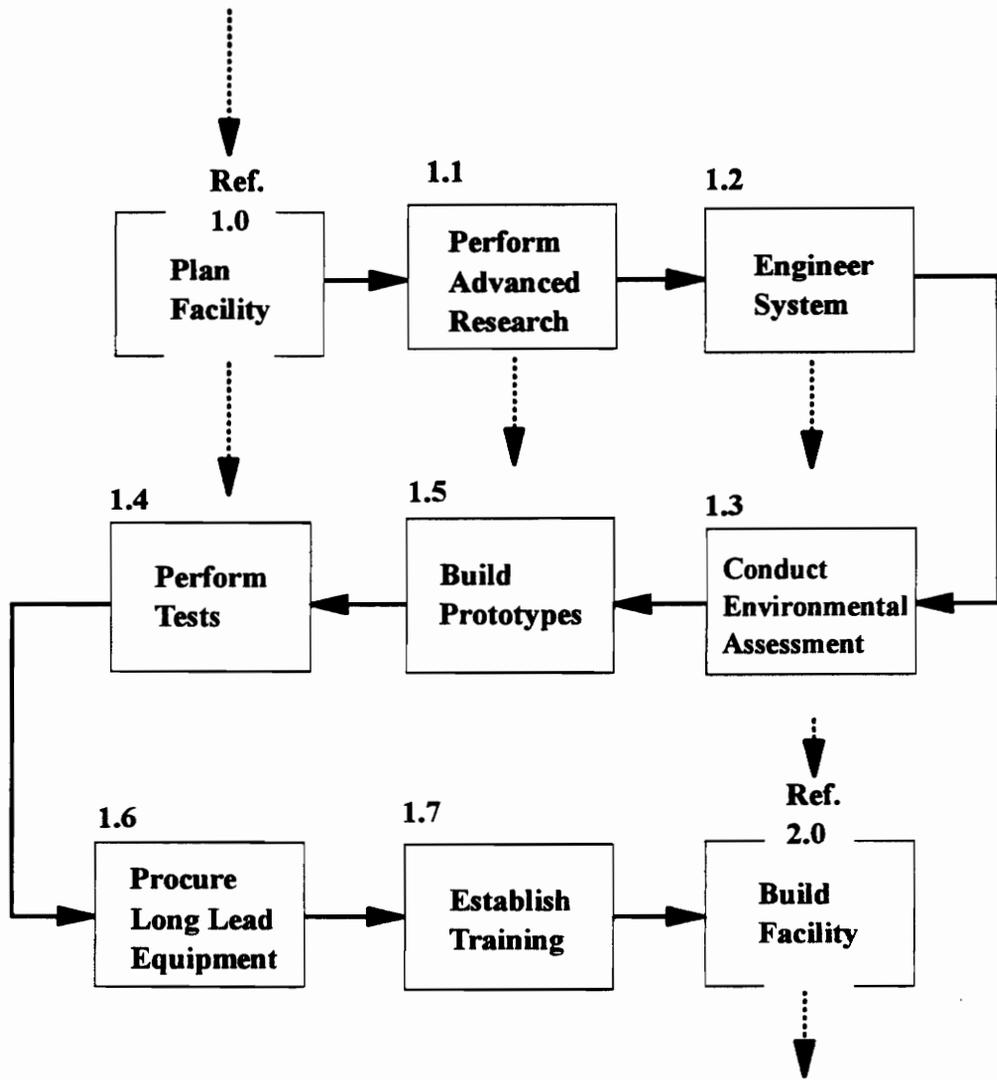
Figure 3: Subfunctions of Function 1.0
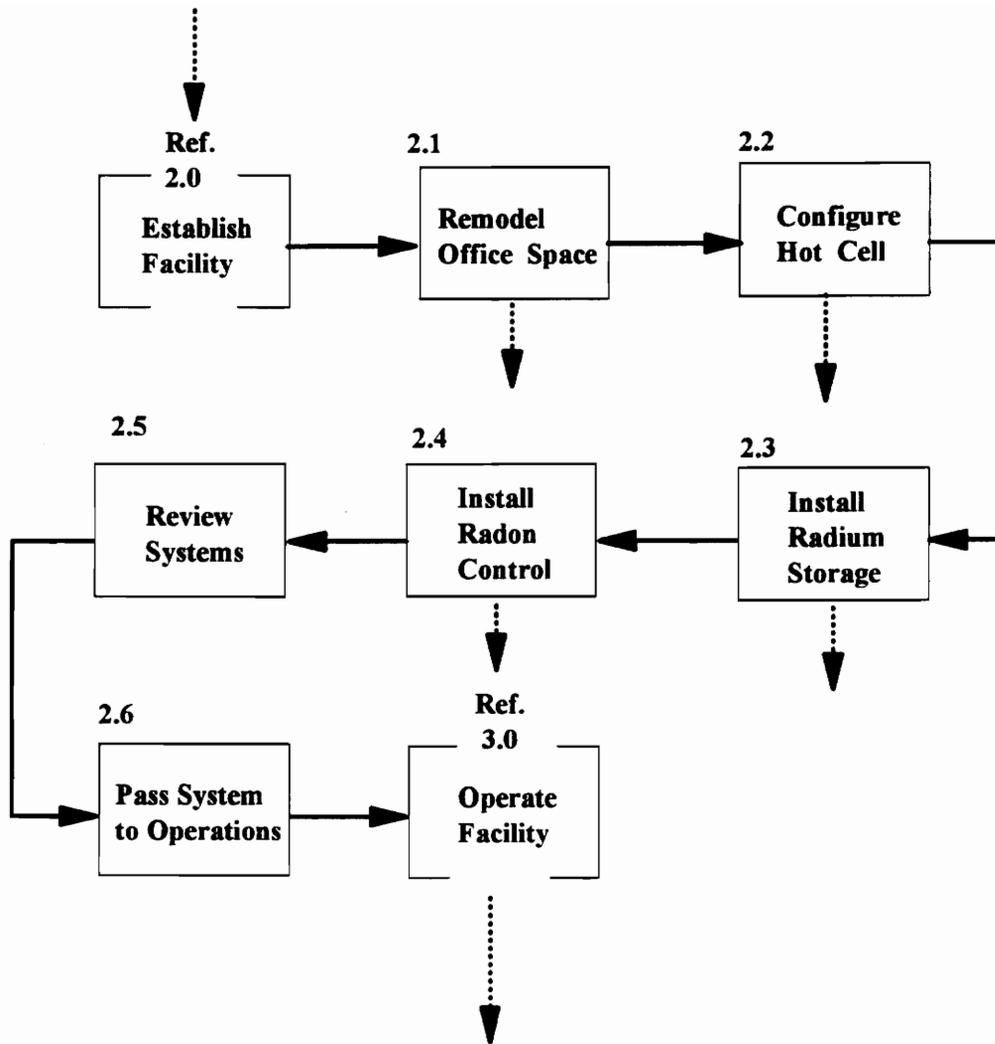
Figure 4: Subfunctions of Function 2.0

16
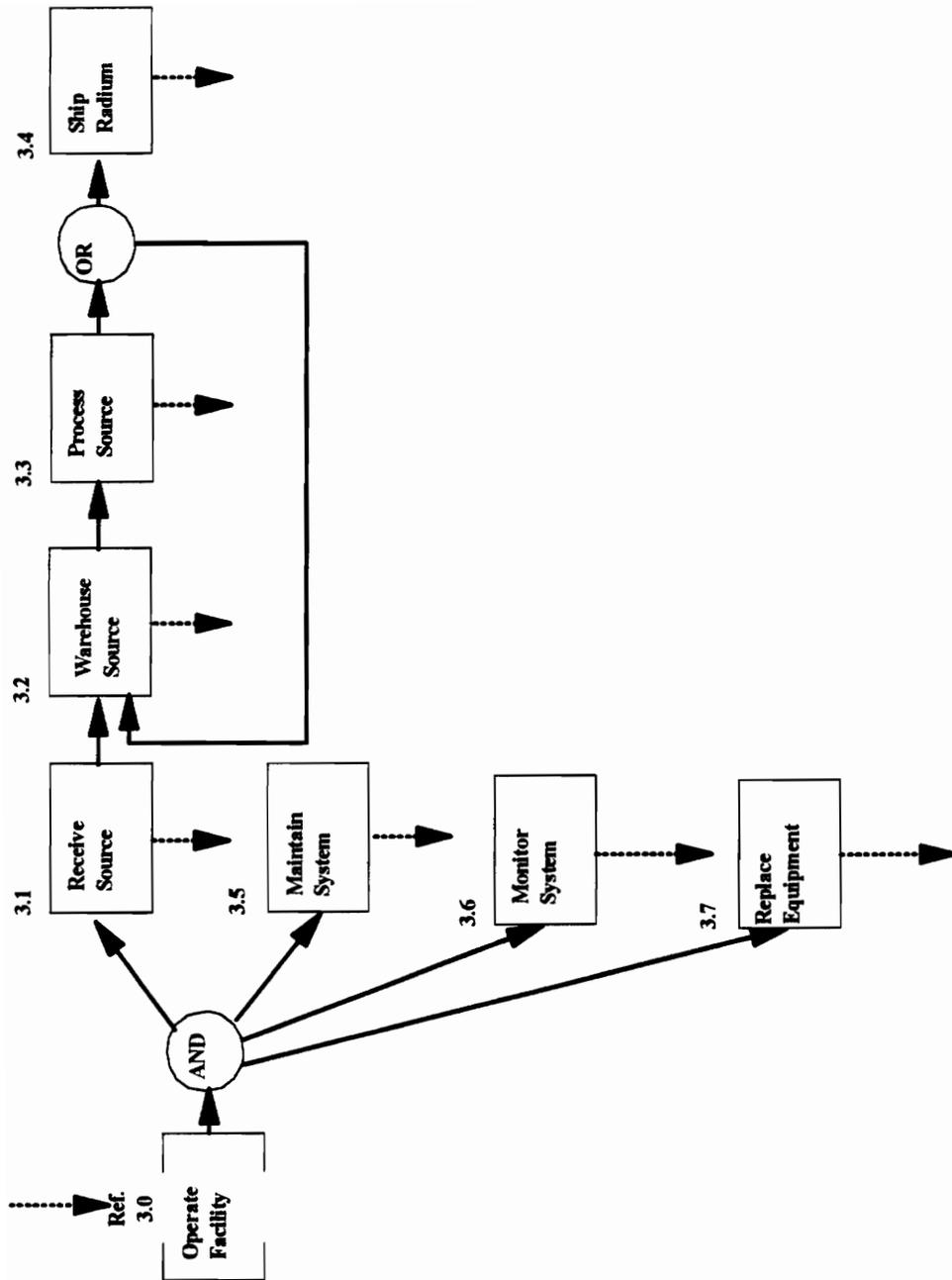
Figure 5: Subfunctions of Function 3.0

17
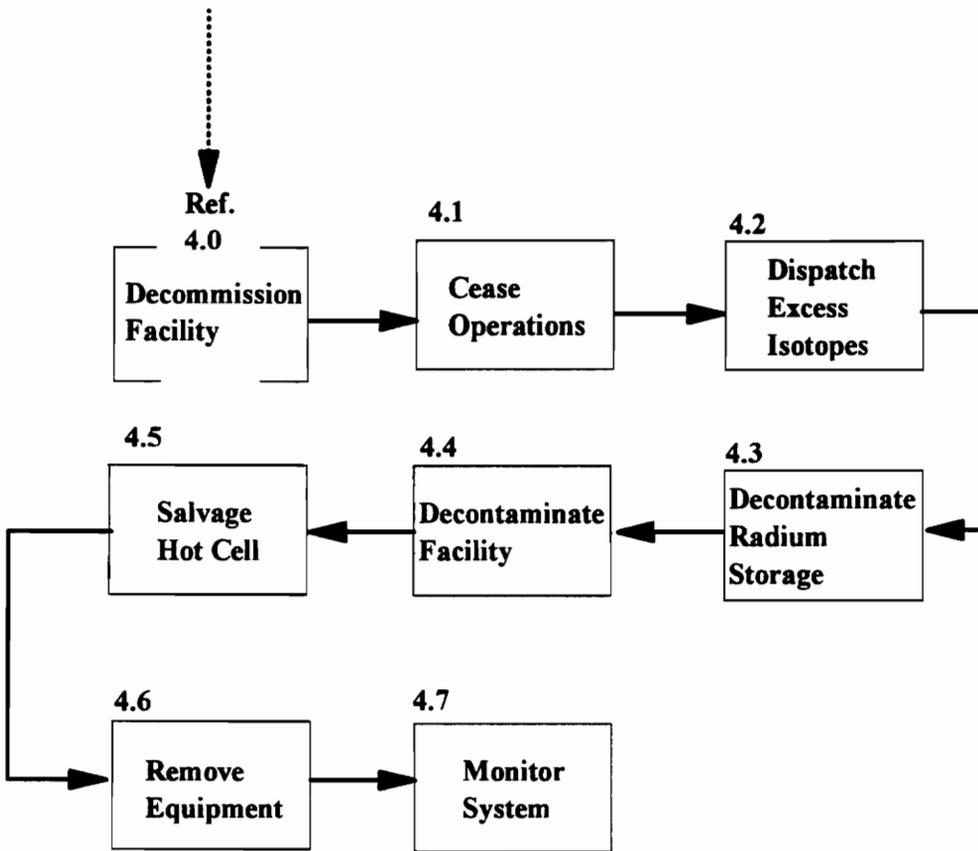
Figure 6: Subfunctions of Function 4.0

Radium storage would be the major construction activity of this project. For the baseline proposed in this paper, radium storage consists primarily of a series of holes in the floor with stainless steel liners. Because the integrity of the floor needs to be assured, the floor would need to be removed, holes would need to be drilled, and new, reinforced concrete would have to be emplaced. The functional flow diagram was designed so that another alternative could also fulfill the function of radium storage. This alternative would involve placing the radium in horizontal holes in a mausoleum-like structure. Either alternative would then be surrounded by radiation shielding walls of an appropriate construction material.

Both the reconfigured hot cell and the radium storage facility would require radon control. Radon control would be a major problem because of the concentration of radium. Again, the functional flow diagram does not go into detail about how radon would be controlled. This plan assumes the construction of a radon control apparatus. Actual control of radon might be allocated partially to appropriate structures and partially to operational procedures. Individual sources could be sealed by welding or placed in canisters with removable but radon-tight lids.

Both the hot cell and the radium storage would require some other global construction activities besides radon control. These would include such activities as con construction of security systesms and heating, ventilation and air conditioning.

Once these facilities had been completed, the system would be reviewed and turned over to operations.

Operations

Operational functions of the facility would begin with receipt of material. Shipping of radium to the facility would be the responsibility of present owners of radium. This facility would be providing a service to the owners that is now either nonexistent or extremely expensive. Radium received at the facility would first be inspected for any

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damage to the containers. It could then be placed in a temporary container and warehoused until a ten-gram quantity of material had accumulated. This material could then be processed, welded into a more permanent container and stored or shipped.

Three other functions work in parallel with the receipt and processing of radium. These include maintaining the system, monitoring the system, and replacing equipment as required. The maintenance concept for a nuclear facility differs from most other facilities because items frequently cannot be shipped offsite for repair. Consequently, most of the maintenance will consist of repairing equipment on site or replacing it. A minor exception might include the calibration of instruments. These would be sent to a facility that would still be on the Hanford Nuclear Reservation.

Decommissioning

Decommissioning of a nuclear facility is a major consideration. Also, the requirements for this process will probably change considerably by the time the decommissioning phase begins. Because of the uncertainty involved in this phase of the project, the functional flow diagram outlines this phase of the project in broad categories including: a shutdown phase; dispatching of excess isotopes, which may or may not be necessary; decontaminating the radium storage and the facility, salvaging the hot cell, removing equipment, and monitoring the system for a specified amount of time.

SECTION 3: CONCEPTUAL DESIGN

The Radium Problem

Design of a radium storage and processing facility depends on the control of gamma radiation and the control of radon emissions. Radium and its daughter products emit alpha, beta, and gamma radiation. The first daughter of radium-226 is radon-222, a gaseous radionuclide that decays into short-lived, alpha-particle-emitting isotopes (Turner, 1995). The decay scheme of radium is shown in Table 2.

Should radium be combined with beryllium, then it can become a neutron emitter. Although some of these radium-beryllium emitters could provide substantial sources of radium, they were not included in this study because of the problem of dealing with neutron emissions, and because the beryllium is a carcinogen. Design of a facility for handling these materials would be part of a Phase II study.

The Radium Design System

A prime consideration in the design of a radium storage and processing facility is how much radium will be processed at any one time. That quantity of radium determines the quantity at any one time in the hot cell, the temporary storage cask, the permanent storage cask, and the storage cell. In turn the amount of radium determines how much shielding will be required for hot cell shielding walls, storage cell plugs, the transfer cask, and shipping casks. Because shielding has considerable weight, the amount of radium will determine the size of cranes, conveyors, and forklifts required to maneuver the radium. The size of these devices will then determine the size of doors, permissible spacing between storage cells, size of passage ways, and size of hot cells required to handle the material.

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Table 2: Decay Chain for Radium 226 (Source: Negin, 1986)

Radionuclide	Half Life	Radiation Types
Radium-226	1,600 Years	Alpha, Gamma
Radon-222	3.82 Days	Alpha, Gamma
Polonium-218	3.05 Minutes	Alpha
Lead-214	26.8 Minutes	Beta, Gamma
Bismuth-214	19.9 Minutes	Beta, Gamma
Polonium-214	26.8 Minutes	Alpha, Gamma
Lead-210	22.26 Years	Beta, Gamma
Bismuth-210	50.13 Days	Beta, Gamma
Polonium-210	138 Days	Alpha
Lead-206	Stable	None

Radiation Shielding

Conceptual design for shielding consisted of choosing appropriate shielding materials and calculating required thicknesses based on shielding calculations for gamma and beta radiation. Alpha radiation can be stopped by a sheet or two of ordinary paper.

Complicating the problem of radiation shielding is the toxicity of one of the most common shielding materials, lead. Should lead become radioactively contaminated and subsequently become a waste, then it would be a mixed waste, subject to laws for both radioactive and hazardous waste disposal. Consequently, lead is not the most desirable material for lead shielding. Nonetheless, lead is appropriate in certain situations. In the proposed radium facility, lead would be used in transfer casks and doors. Any lead used in such a fashion would be encased in stainless steel, a substance that gives structural strength to lead-containing fixtures and a substance that can be radioactively decontaminated with relative ease.

An alternative for radiation shielding is magnetite concrete. Magnetite concrete was chosen, because it was nontoxic, and because it was denser than regular concrete. Greater density provides greater shielding capacity. Concrete could easily be formed into walls and floors.

Radiation shielding was computed using a computer program entitled ISO-PC (Rittmann, P. D., 1995). Calculations assumed that the radium was in equilibrium with its daughter products including radon-222, lead-214, lead-210, bismuth-214, and bismuth-210. Polonium isotopes were not included in the calculations because they were mostly alpha-particle emitters with some insignificant gamma radiation.

The computer program assumed that all of the radiation was concentrated as a point source next to a slab shield. Calculations were made to show radiation detected by a detector immediately next to the slab and directly opposite the source. Calculations were repeated until enough shielding was added to bring radiation levels down to a value of less than 0.0001 roentgen per hour.

Because dose rate in millirems is less numerically than radiation levels in roentgen, this radiation level would be equivalent to a radiation dose level of less than 200 millirems per year for a worker working 40 hours per week with two weeks off for vacation. This level is further mitigated for two reasons:

- Work time for any worker in the facility will be less than 100 per cent of work time.

- Dose rate will be considerably mitigated by distance from the defined "detector" surface.

The value of 200 millirems per year is twice the value of the annual effective dose equivalent for the general public from natural background radiation, but well within the values for an occupational worker. In other words, an occupational worker is expected to be better equipped to handle radiation than a member of the general public. (U. S. DOE, 1989.) Values of shielding material thickness versus values of radiation, are shown in Figures 7, 8, and 9.

Figure 10 shows the layout of the facility. The facility will be built within an existing building on the Hanford Nuclear Reservation near Richland, Washington. Capacity of the repository is expected to total 500 grams. This is virtually equivalent to 500 curies of radium, because the historical definition of a curie was, ". . . the activity ascribed to one gram of Radium-226."(Turner, 1995). Only 20 grams of radium are expected to be processed at any one time. For that reason, thicknesses of walls, plugs, and lead doors were based on reducing levels of radiation from 20 curie amounts of radium to a level of 0.0001 roentgen per hour. Actual amounts of radium to be emplaced in any one storage cell would normally be ten curies.

Before emplacement of storage cells, concrete would be removed from the floor of the storage area to accommodate enough new magnetite concrete to shield the entire inventory of 500 curies of radium to a level of 0.0001 roentgens per hour. Before emplacement of the concrete, fifty boreholes, ten feet in depth, would be drilled to
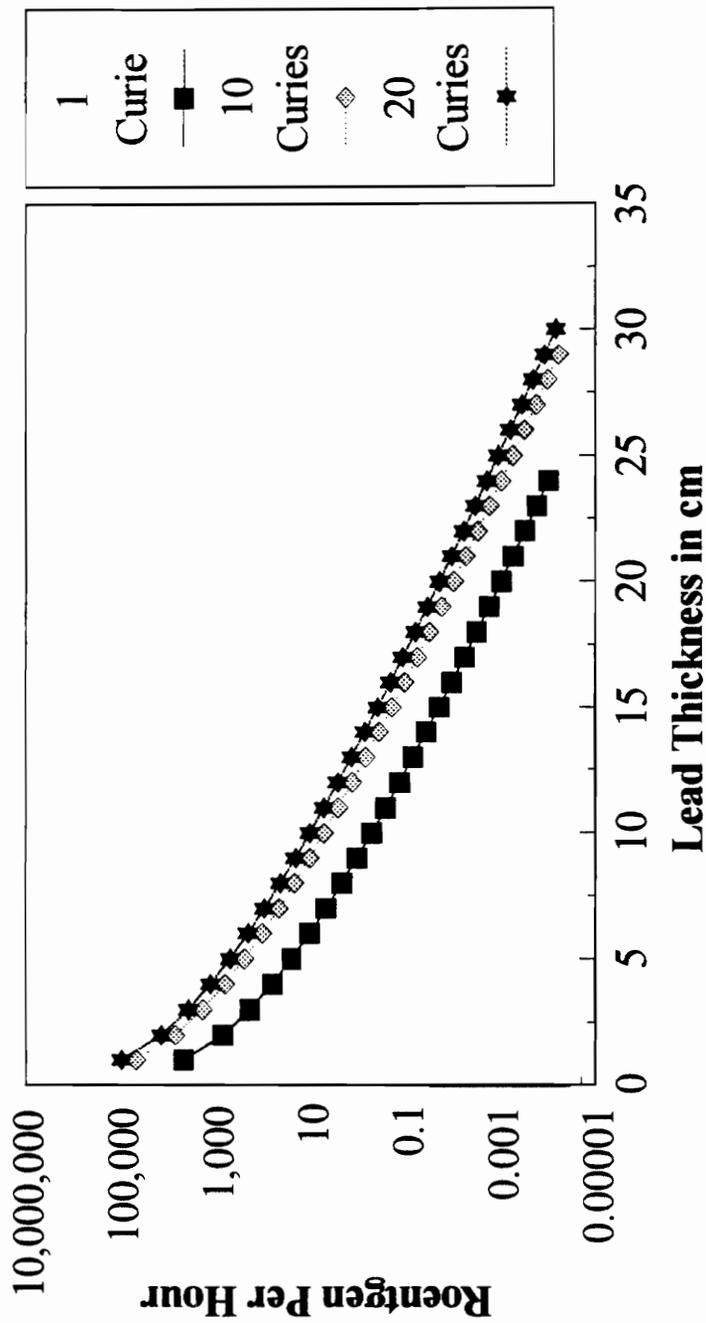
Figure 7: Radiation Levels Vs. Lead Thickness for Various Levels of Radium

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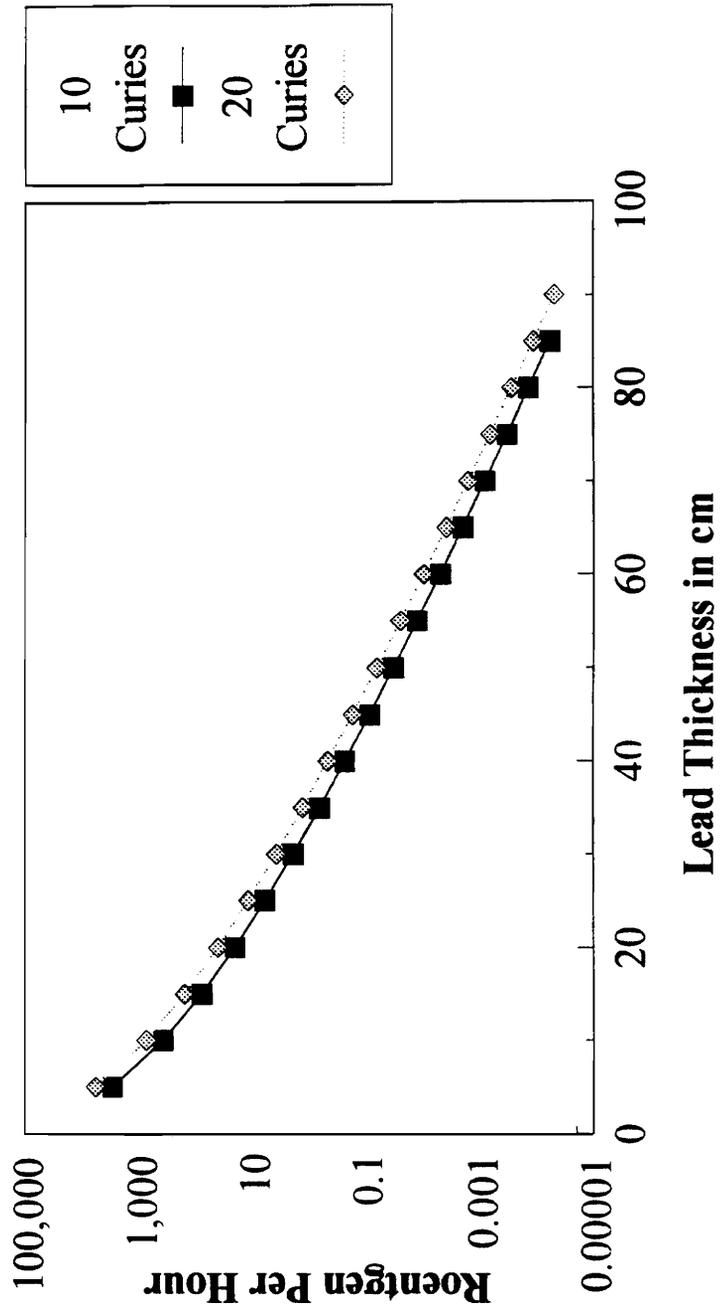
Figure 8: **Magnetite Concrete Thickness Vs. Radiation for Various Levels of Radiation**

Figure 9: Magnetite Concrete Thickness Vs. Radiation for 500 Curies Radium

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Existing Outside Basement Wall   Lead Door

Pass-Through

Lead Doors

Hot Cell

Door

Storage Cells

Not to Scale
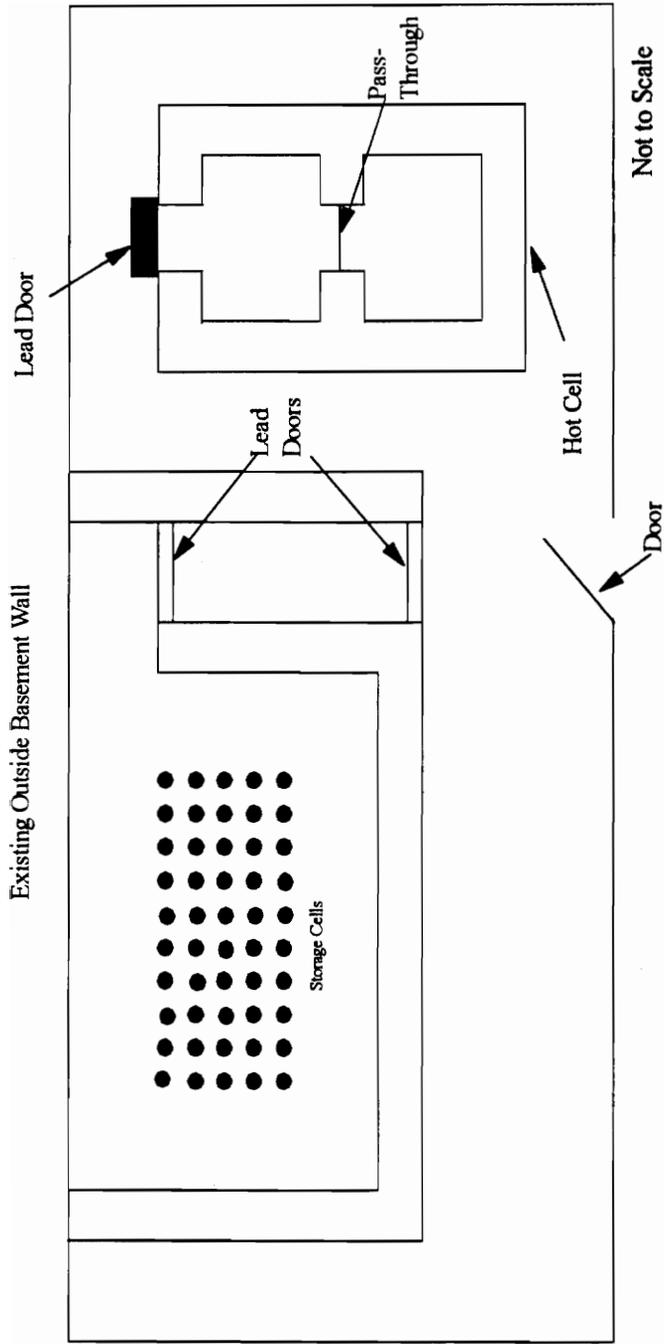
Walls are 10 feet tall and three feet thick.

There are two one foot thick lead doors on the storage area and one two foot thick lead door on the hot cell.

Walls are made of magnetite concrete.

The fifty black dots symbolize storage cells in the floor.

Each storage cell will be eight inches in diameter. Spacing is on two foot centers in each direction.

Each storage cell will be 10 feet deep with a 3 foot plug of magnetite concrete within stainless steel.

Figure 10: Layout of Radium Storage and Processing Facility

accommodate seamless, stainless steel tubing with an inside diameter of eight inches. The tubing would be welded on its lower end with a stainless steel plate.

Radium would be handled with a remotely controlled forklift, remotely controlled cranes, conveyors, and manipulator arms. During transport, radiation protection would be assigned primarily to the lead shielded transfer cask. This cask would be a lead-filled, stainless steel transfer cask approximately four feet high and 30 inches in width. The cask could accommodate two transfer casks with dimensions of approximately one foot by eight inches. Two types of storage cask would be produced. One would be a temporary storage cask with an easily removable top for accumulating various types of radium containing devices, and the other would be a more permanent storage cask that could be welded to contain radon from processed radium.

Monitoring equipment for the facility would include radon detectors plus alpha, beta, and gamma monitoring equipment. The facility would be constantly monitored with video cameras to assure security against accidents or possible sabotage. A computer system would be available to inventory the radium.

Because the facility would be part of the larger Hanford complex, it could use chemicals, laboratory equipment, and possibly utilities from the rest of the site. Should decontamination be needed, then other facilities on the site could be used.

Radon Control

Heating, ventilation, and air conditioning would need to be made to accommodate the facility itself. Radon within the facility would be controlled by use of differential pressures. Pressure outside the facility would be higher than in the working area for technicians. In turn air pressure in the storage area and the hot cell would be less than in the working area. Air exchanges would be eight times per hour in the working area, five times per hour in the storage area, and twice per hour in the hot cell. Air flow would thus achieve radiation control in two very different ways. In the area for workers, the high

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exchange rate would help keep radon levels down. In the hot cell the low exchange rate would help prevent the spread of powdered radionuclides. (Sharp, 1996).

Radon treatment would require a separate radon-control apparatus. This would probably consist of a series of activated carbon beds designed to entrap the radon and allow for decay. Radon control for the facility would also be accomplished by sealing sources wherever possible. Although plugs filled with concrete would be used to seal the storage cells, they would be carefully machined to assure a good seal. A virtue of stainless steel would be its ability to be decontaminated of radon daughter products by many readily available means of decontamination.

SECTION 4: COST BREAKDOWN STRUCTURE
AND COST ESTIMATING RELATIONSHIPS

Cost Breakdown Structure

Procedures in systems engineering generally proceed from a top down structure. In other words, work proceeds from the general to the specific. Functions are broken down to subfunctions. Such an arrangement provides a means for managers to go into as much or as little detail as necessary to delve into a problem. Within this report the functional flow diagram was the first example of such a structure. The second example is the cost breakdown structure.

The cost breakdown structure for the radium storage and processing facility was modeled after the functional flow diagram. These four major cost categories were research and development, implementation, operations and maintenance, and decommissioning. These categories were further broken down into appropriate subcategories consistent with each phase of the project. An illustration of the cost breakdown structure is shown in Figure 11.

Once the cost breakdown structure had been defined, cost estimating relationships had to be found. For certain activities such as advanced research and development, the cost estimating relationships were defined as the summation of a series of activities. In this report most such activities consisted of the work of engineers or other professionals. Costs of these activities were then determined based on the salaries of these individuals. Most salaries were determined based on a 1993 survey of engineers' salaries (National Society of Professional Engineers (NSPE), 1993). These salaries were first divided by the work hours in a year with time out for vacation and holidays, then escalated at a rate of 3% inflation to the end of year 1996 and tripled. Tripling the salaries considered factors such as social security, workers' compensation, health insurance, overall utilities, public affairs, and accounting. The results of this calculation were then used to determine costs for activities. This analysis assumed that existing laboratory facilities at Hanford could be

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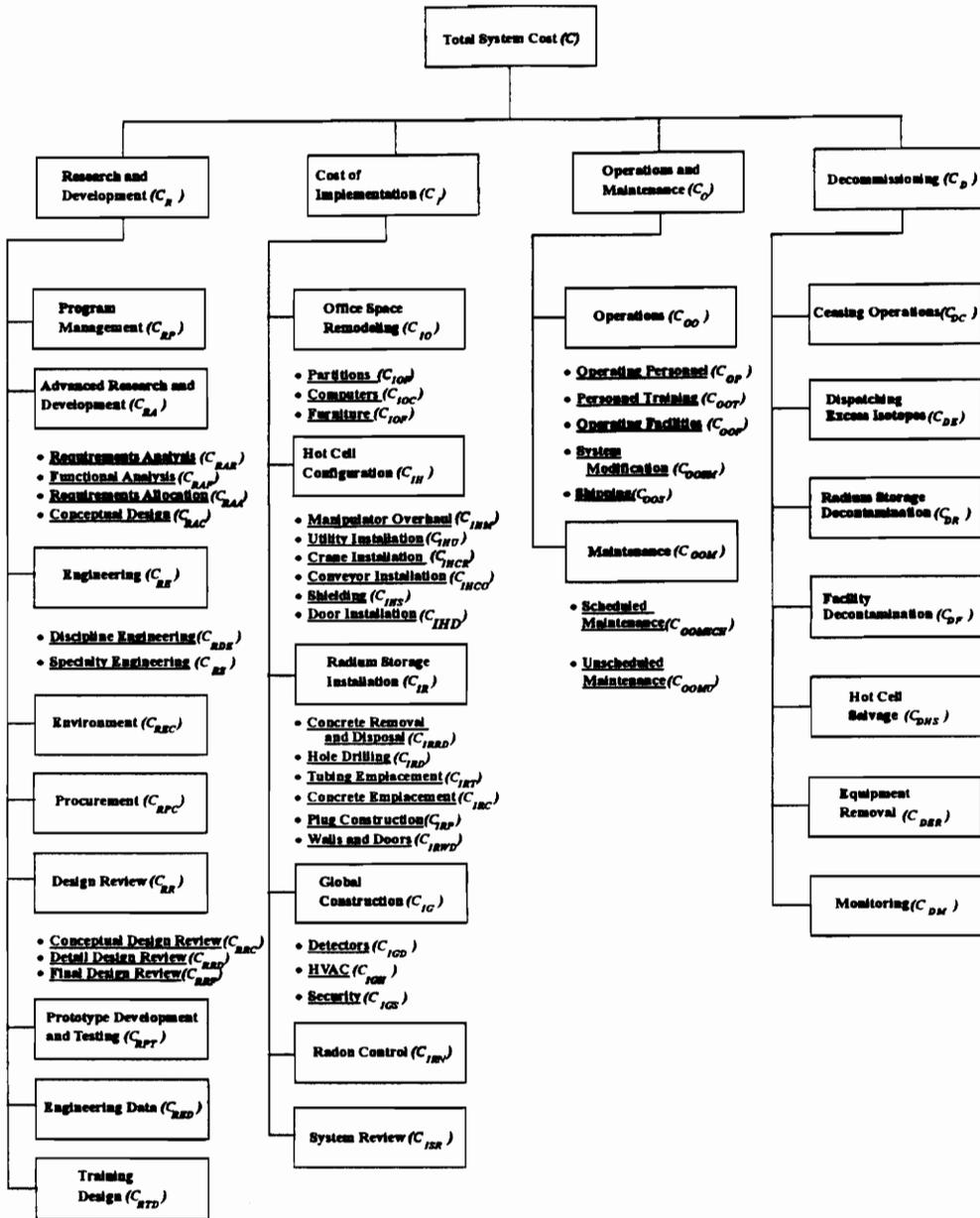
Figure 11: Cost Breakdown Structure

used for research. Nuclear transmutation studies involving reactors would be outside the mission of this facility. Salaries not found in the NSPE publication were calculated based on appropriate ratios for those salaries. (See Table 3.)

Cost Estimating Relationships

Although the radium storage and processing facility is being built limited by new rules and regulations, most of the concepts involved in constructing the facility are well known. Most of the cost estimating relationships in this report were derived from interviews with vendors and other individuals in the nuclear industry. A few relationships were rules of thumb. For example, the cost of unscheduled maintenance was estimated to be 0.4 times the total scheduled maintenance. A summary of these relationships is given in Table A-2 entitled, "Cost Estimating Relationships." A summary of terms within the cost estimating relationships is given in Table A-3

Part of the procedure for completing life-cycle cost estimation included comparing the cost estimating relationships with the functional flow diagram. Functions are listed under each cost category in Table A-2. The comparison showed that the relationship between cost estimating relationships and functional requirements was a many-to-many relationship. Although many functions showed a one-to-one relationship with cost estimating relationships, certain functions correspond to more than one cost estimating relationship, and certain cost estimating relationships correspond to more than one function.

An example of more than one cost estimating relationship corresponding to a single function concerns the installation of storage media. In this study, cost estimating relationships for emplacement of tubing, concrete emplacement, and plug construction and emplacement all correspond to the function of installing storage media. This relationship was the baseline case. Another alternative would be for a mausoleum-like structure to be build with tubing and plugs in a horizontal position. This second alternative would allow

Table 3: Estimation of Salaries

Personnel	Salary	Inflation Factor	Time Off With Pay	Hourly Rate	Multiplier	Rate
Program Manager	$75,200	1.12	184	$44.42	3	$133.27
Contracts/Procurement Manager	$60,160	1.12	184	$35.54	3	$106.61
Administrative Assistant	$41,160	1.12	184	$24.31	3	$72.94
Regulatory Specialist	$60,900	1.12	184	$35.97	3	$107.92
Systems Engineer	$63,978	1.12	184	$37.79	3	$113.38
Structural Engineer	$52,500	1.12	184	$31.01	3	$93.04
Nuclear Engineer	$69,388	1.12	184	$40.99	3	$122.97
Electrical Engineer	$58,282	1.12	184	$34.43	3	$103.28
HVAC Engineer	$55,143	1.12	184	$32.57	3	$97.72
Process Engineer	$60,870	1.12	184	$35.96	3	$107.87
Mechanical Engineer	$55,143	1.12	184	$32.57	3	$97.72
Maintenance Engineer	$53,228	1.12	184	$31.44	3	$94.33
Reliability Engineer	$53,228	1.12	184	$31.44	3	$94.33
Human Factors Engineer	$53,228	1.12	184	$31.44	3	$94.33
Biologist	$54,000	1.12	184	$31.90	3	$95.70
Geologist	$54,000	1.12	184	$31.90	3	$95.70
Toxicologist	$54,783	1.12	184	$32.36	3	$97.08
Health Physicist	$62,449	1.12	184	$36.89	3	$110.67
Meteorologist	$46,830	1.12	184	$27.66	3	$82.99
Sociologist	$50,000	1.12	184	$29.54	3	$88.61
Hydrologist	$52,033	1.12	184	$30.74	3	$92.21
Engineering Liaison	$60,870	1.12	184	$35.96	3	$107.87
Trainer	$50,000	1.12	184	$29.54	3	$88.61
Construction Worker	$37,440	1.12	184	$22.12	3	$66.35
Computer Engineer	$50,000	1.12	184	$29.54	3	$88.61
Work Crew Leader	$45,000	1.12	184	$26.58	3	$79.75
Radiochemist III	$71,782	1.12	184	$42.40	3	$127.21
Radiochemistry Tech	$57,425	1.12	184	$33.92	3	$101.77
Radiation Control Tech	$53,324	1.12	184	$31.50	3	$94.50

the use of existing facilities without the problems associated with possibly radioactively-contaminated concrete. Because the actual project is in the conceptual phases of design, this relationship of may cost estimating relationships to one function allows flexibility in meeting functional requirements. In conceptual phases of the project, this approach is appropriate, because alternatives can be considered on paper before financial commitments are made.

An example of many functions corresponding to a few cost estimating relationships is found in the relation between operational functional requirements and cost estimating relationships. Subfunctions 3.1, 3.2, and 3.3 and their subfunctions are covered by the cost estimating relationships for operating personnel and operating facilities. Although many costs in these functions and subfunctions could be broken out, a decision was made not to break out theses costs at this time. Many uncertainties surround the question of radium processing. These include radium availability, the chemical composition of radium containing materials, the desired purity of the radium, and the desired form of the radium. Demand for radium and its desirable isotopes has not been established. Cost estimating relationships for subfunctions 3.1, 3.2, and 3.3 considered that all personnel would be used when radium was accumulating or being processed. A relationship between the time of processing and the amount of radium being processed was used to estimate costs. Utilities were considered to be required full time regardless of whether processing was continuing.

SECTION 5: COST ESTIMATION

After cost estimating relationships had been established, certain assumptions were made before cost estimation. These included the following:

- The facility would be owned by the United States Government. Consequently, the facility would be self-insured and no commercial insurance would be needed.

- The only licensing authority for the facility would be the United States Environmental Protection Agency through its agent, the State of Washington. No other agency would be involved.

- Operations for the facility would begin with the receipt of radium. Costs would not include the cost of shipping radium to the facility. Those costs would be born by the shipper and have not been considered in this analysis. Shipping material from the facility has been considered.

- For purposes of this analysis, radium is considered to go through the facility only once. In actuality, radium would probably be recirculated through the facility. A chart showing flow of radium through the facility is presented in Figure 12.

- Radium would be completely used up after 30 years of operation. No isotopes would remain for cleanup.

To ease cost estimation, a Gantt chart showing duration of activities during the first two years of operation was prepared. (See Figure 13). These durations were a compromise of the opinions of various experts. Some activities could be accelerated by the parallel efforts of many professionals. For example, requirements analysis, functional analysis, and requirements allocation will each involve the activities of ten or more professionals. Operations and maintenance activities taking place over the thirty-year period were accommodated individually. Certain items such as cameras, other security equipment, and forklift batteries were assumed to need replacement periodically. These items were easily accommodated individually in the spreadsheet.

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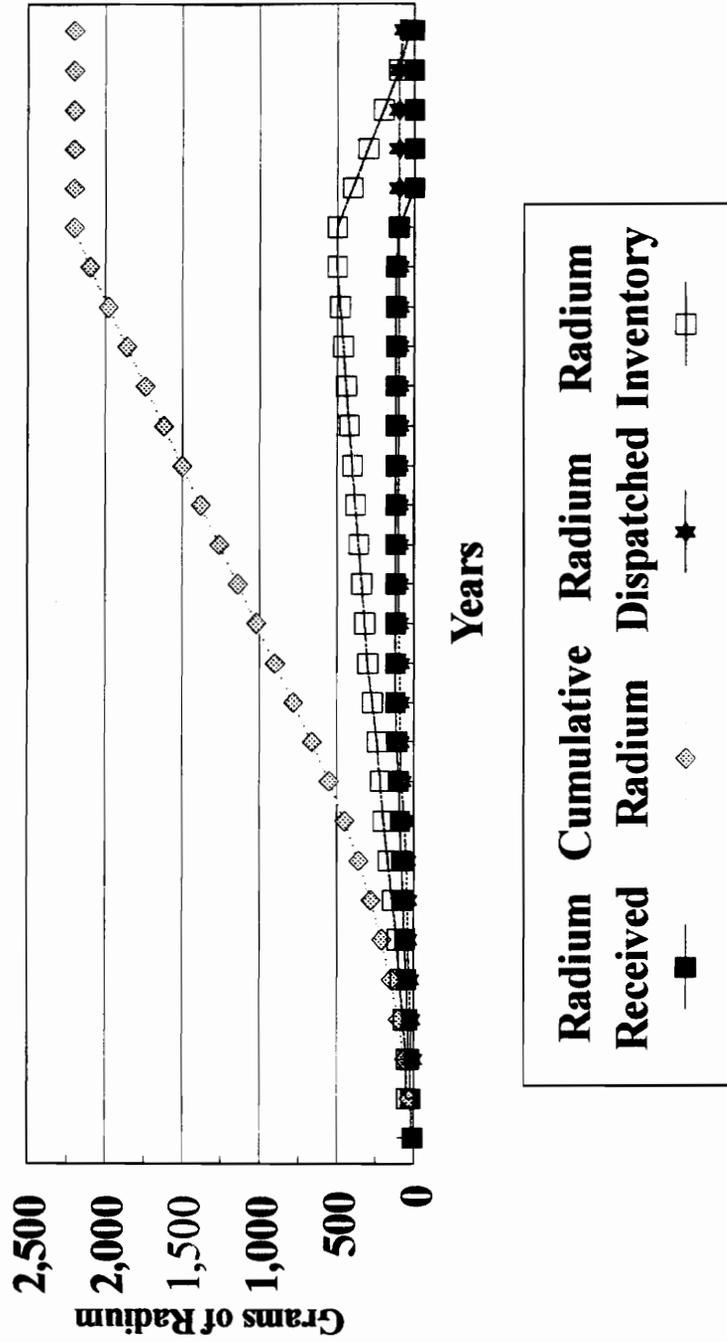
Figure 12: Flow of Radium through the Storage and Processing Facility

Gantt Chart — Research and Development and Implementation

Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Program Management	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
Requirements Analysis	█																							
Functional Analysis		█																						
Requirements Allocation			█																					
Conceptual Design				█	█																			
Conceptual Design Review						█																		
Environmental Activity				█	█																			
Procurement							█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
Discipline Engineering							█	█	█															
Specialty Engineering							█	█	█															
Detail Design Review									█															
Engineering Documentation								█	█	█	█	█												
Prototypes and Testing								█	█	█	█													
Final Design Review												█												
Training Design									█	█	█													
Offic Space Remodeling													█											
Manipulator Overhaul													█											
Utility Installation													█											
Crane Installation														█										
Conveyor Installation														█										
Shielding															█									
Concrete Removal/Disposal															█									
Hole Drilling																█								
Tubing Emplacement																	█							
Concrete Emplacement																		█						
Plug Construction																		█						
Walls and Doors																			█					
Radon Control																			█	█	█			
Engineering Testing																					█	█		
System Review																								█

Figure 13: Gantt Chart Showing Research and Development and Implementation

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After initial estimates for all cost items had been established, costs were rolled up to major subcategories for each of the four major cost categories of research and development, implementation, operations and maintenance, and decommissioning. All subsequent analyses were based on a total of 24 major subcategories rather than the greater than 200 categories that had been originally designated for this study.

Budgetary Cost Profile

The first cost profile to be determined was a budgetary cost profile in terms of future dollars. An administrator going to the United States Congress needs to know how many dollars need to be requested on a year to year basis. Costs for today were estimated in terms of future dollars by using factors for a 3 percent inflation rate. This cost estimate assumes that dollars are received at the end of the year. The estimate is shown in Appendix A in Table A-4 entitled, "Budgetary Cost Estimate."

A budgetary cost profile is shown in Figure 14. Note that costs decrease dramatically between the second and third years. This cost decrease reflects the transition from construction to operations. This line drawing does not detail the profiles of the four major cost components because the two-year research and development, one-year implementation, and one-year decommissioning are so short in relation to the 30 years of operations and maintenance. Although the dollar figure for demolition appears almost as great as the costs for research and development, the present equivalent cost of demolition is not nearly as great as this.

Present Equivalent Cost Profile

The present equivalent cost analysis formed the basis for analysis for the rest of the project. With the present worth analysis high cost contributors were identified, sensitivity of the total cost to various input parameters was determined, and an analysis of the worth of the project was made.
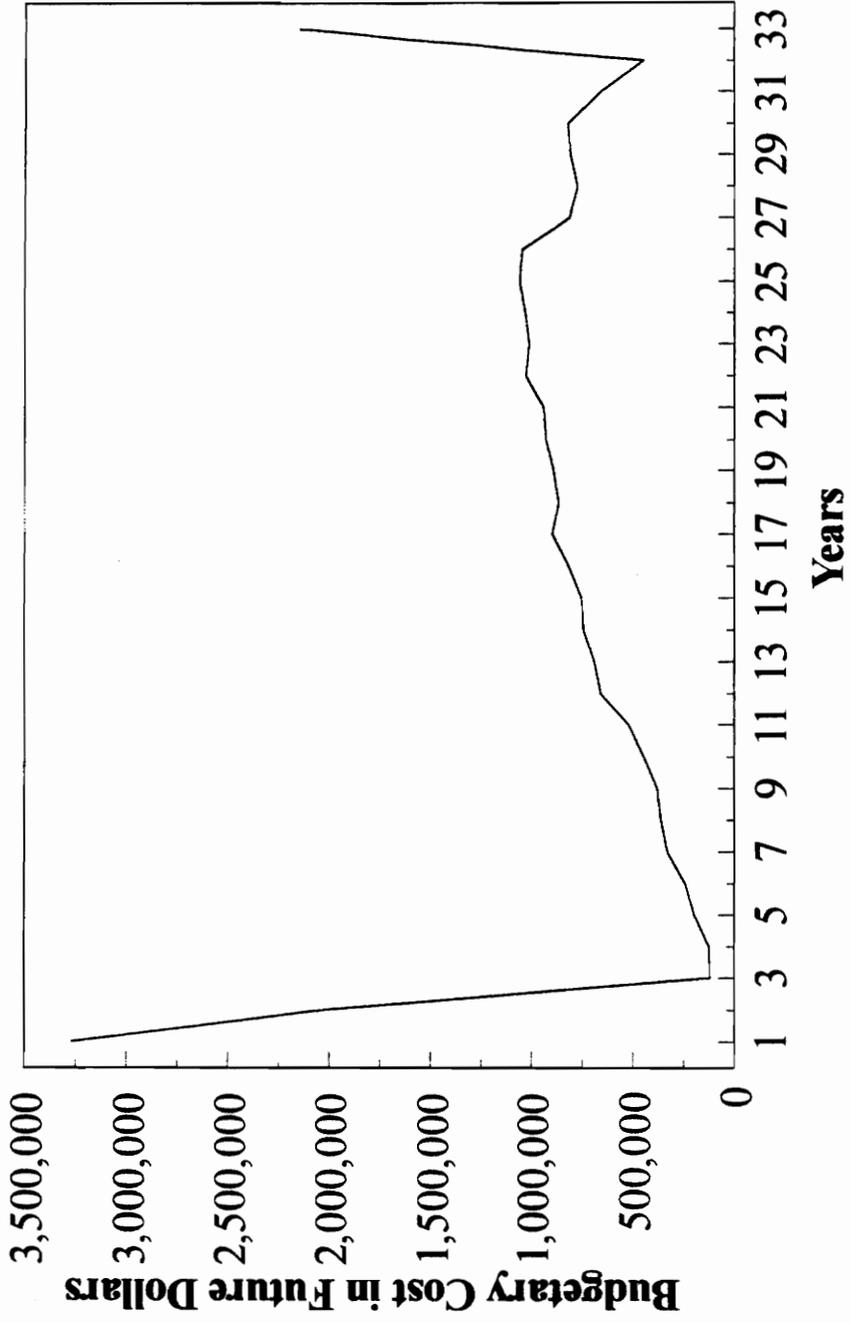
Figure 14: Budgetary Cost Profile for Radium Storage and Processing Facility

Total cost of the project on the basis of the present equivalent cost profile was $10,952,617. The cost of research and development plus implementation was $4,840,595. This cost was compared to cost of another radium disposal facility, the Eastern Environmental Radiation Facility built in Montgomery, Alabama. Conversations with Dr. Paul Bedrosian (September 17, 1996) and Mr. Herb Reed (September 18, 1996) revealed that the approximate cost of that thirty-cell facility had been $50,000 in the 1960's. By assuming a 5/3 ratio to convert the facility to a 50-cell facility and by assuming a cost of living index of 468.2 as of May 1996 in comparison to an index of 100 in 1967 (Bureau of Labor Statistics, Consumer Price Index), the cost of such a facility for engineering and construction would be approximately $390,000.

The facility at Hanford would be designed to much more stringent standards. Stainless steel would be used for the storage cells. Cranes and fork lifts would be remotely controlled. A hot cell would be added to the storage unit. Radium processing and recycling would be added to the required functions of the facility. All these additional requirements would combine to make a higher cost for the facility. Although the cost is more than twelve times the cost of the original facility, the costs are probably in line with today's standards.

High Cost Contributors

The present equivalent cost estimate is presented in Table A-5 in Appendix A. Both inflation and discounting are accounted for in this analysis. Again dollars are assumed to accumulate at the end of the year for both inflation and discounting purposes. Table 4 shows the percentage contribution to cost of each of the various input parameters. The ten most significant contributions to cost in descending order were operations, maintenance, program management, advanced research, engineering, review, procurement, environmental work, radium storage installation, and system review. The present equivalent cost profile for this analysis is shown in Figure 15. Figure 16 shows the

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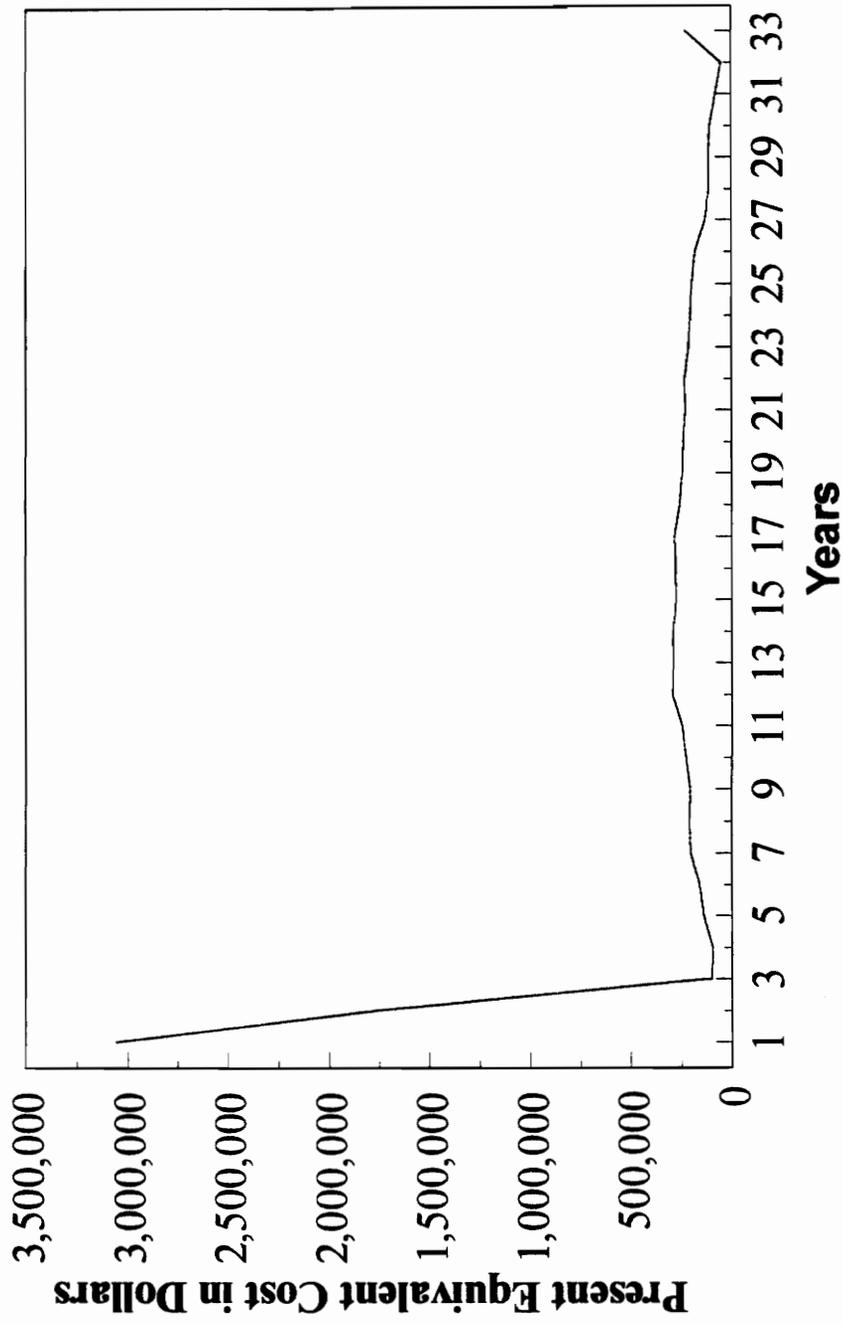
Figure 15: Present Equivalent Cost Profile for Radium Storage and Processing Facility

Table 4: High Cost Contributors

Activity	Cost	Percentage
Operations (C_{OO})	$4,245,888	38.77%
Maintenance (C_{OOM})	$1,636,113	14.94%
Program Management Cost (C_{RP})	$1,120,527	10.23%
Advanced Research (C_{RA})	$979,112	8.94%
Engineering (C_{RE})	$464,934	4.25%
Review (C_{RR})	$464,934	4.25%
Procurement (C_{RPC})	$450,437	4.11%
Environmental Work (C_{REC})	$281,743	2.57%
Radium Storage Installation (C_{IR})	$229,607	2.10%
System Review (C_{ISR})	$224,398	2.05%
Engineering Data (C_{RED})	$160,783	1.47%
Prototypes and Prototype Testing (C_{RPT})	$110,287	1.01%
Radon Control Installation (C_{IRN})	$92,663	0.85%
Hot Cell Renovation (C_{IH})	$89,782	0.82%
Global Construction (C_{IG})	$85,114	0.78%
Training Design (C_{RTD})	$80,860	0.74%
Radium Storage Decontamination (C_{DR})	$71,106	0.65%
Facility Decontamination (C_{DF})	$56,884	0.52%
Hot Cell Salvage (C_{DHS})	$46,930	0.43%
Ceasing Operations (C_{DC})	$33,770	0.31%
Equipment Removal (C_{DER})	$14,221	0.13%
Monitoring (C_{DM})	$7,111	0.06%
Cost of Office Space Remodeling (C_{IO})	$5,414	0.05%
Dispatching Excess Isotopes (C_{DE})	$0	0.00%
Grand Total	$10,952,617	100.00%

Pie Diagram Showing Relative
Contributions of Major Cost Categories
to Total Life Cycle Cost

6.77%

38.33%

2.14%

52.76%

■ R&D ▨ Implement ■ O&M □ Decommission
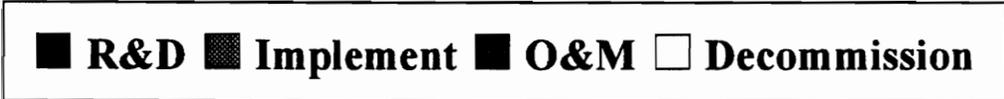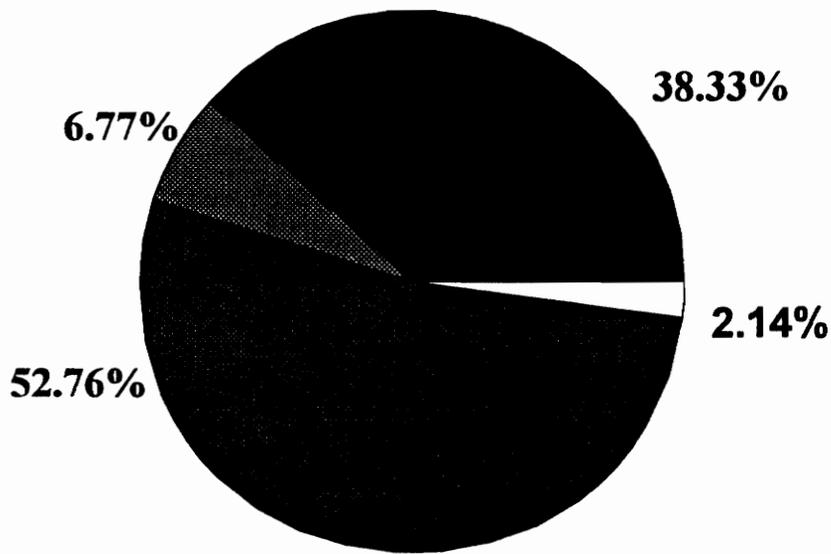
Figure 16: Pie Diagram of Major Cost Categories
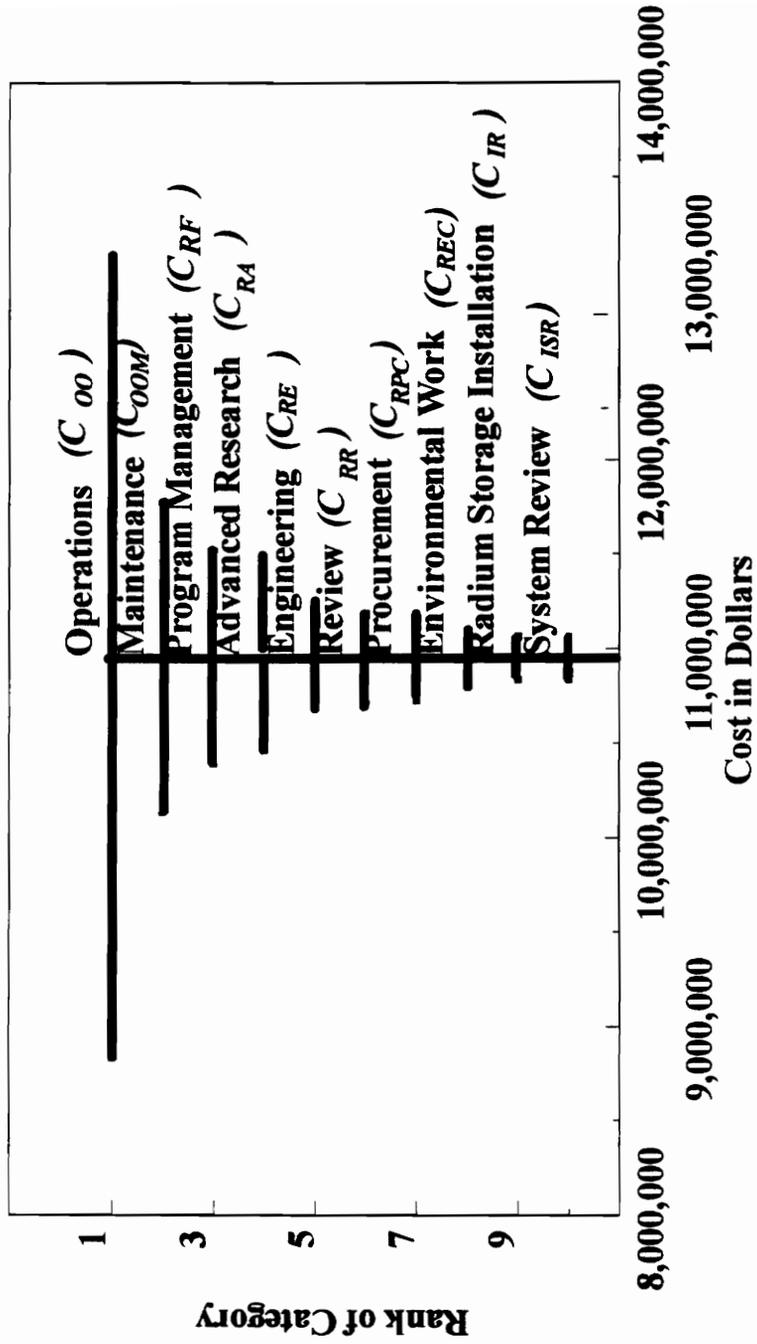
Figure 17: Tornado Diagram Showing Cost Sensitivity of Life-Cycle Cost to Major Components

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relative contributions of the four major cost categories in terms of percentage. Table 5 shows the breakdown of costs for operations and maintenance.

Sensitivity Analysis

This spreadsheet also includes sensitivity factors. In this example, all sensitivity factors were set to a value of one. During analysis, each sensitivity factor was varied up and down by a value of 0.5. Changing this factor resulted in a change in the total life-cycle cost. The ten parameters causing the most change in value were, in descending order of sensitivity, the same factors as contributed to high cost. This sensitivity is shown graphically in the tornado diagram in Figure 17.

Operations and maintenance will be the main activities over the lifetime of the storage and processing facility. Radium processing is subject to much uncertainty. Among the unknowns would be the condition of any radium to be received. Should most of the radium be radon-leaking sources then measures would have to be taken to control the leakage.

Another unknown is the chemical composition of the radium-containing materials. Radium comes in several common chemical forms, each with its own peculiar set of characteristics. Radium sulfate, the most insoluble sulfate known, sometimes occurs as radium-barium sulfate. Barium is intimately mixed with the radium and must be separated before any transmutation. The chloride form of radium is highly soluble, the oxide form might react violently with water, and the metal would be chemically unstable. Radium carbonate might be the most desirable form. Any or all these compounds might be present in sources brought to the facility. Procedures for dealing with each of these compounds would have to be developed.

The amount of radium needed is another problematic variable. Now no one knows how much radium will ultimately be needed. Medical research will need to determine this

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Table 5: Breakout of Operations and Maintenance Cost

Activity	Cost
Operations (C_O)	
Operating Personnel (C_{OOP})	$2,845,386
Radium Shipment (C_{OOS})	$1,051,085
Operating Facilities (C_{OOF})	$296,448
System Modification (C_{OOSM})	$52,969
Subtotal	$4,245,888
Maintenance (C_{OOM})	
Human Factors Maintenance (C_{OOMP})	$597,552
Waste Management (C_{OOMW})	$238,378
Equipment Service (C_{OOME})	$195,493
Hot Cell Maintenance (C_{OOMH})	$70,712
Storage Area Maintence (C_{OOMS})	$47,906
Ventilation Maintenance (C_{OOMV})	$18,611
Scheduled Maintenance (C_{OOMSCH})	$1,168,652
Unscheduled Maintenance (C_{OOMU})	$467,461
Subtotal	$1,636,113
Grand Total	**$5,882,001**

parameter. This research will include not only research with alpha-particle emitting isotopes, but also research with competing technologies.

Given the present regulatory climate, one might wonder whether this project could be built within a two-year period. Historically, the government has constructed much larger projects in a similar period. The Manhattan Project was much larger, and that project was completed in four or five years. The slow progress at nuclear sites for construction and cleanup today would suggest that perhaps a project such as this would also be extended. On the other hand, the demand for medical progress could mitigate delay. AIDS activists have caused accelerated regulatory response to approval of new AIDS drugs. In a similar fashion with cancer therapy, should clinical trials be successful with alpa-particle therapy, then the need for the therapy might mitigate delays due to nuclear concerns.

Analysis of Project Value

The true value of a life-cycle cost analysis is its ability to help managers decide the answers to economic questions. These include questions such as what alternatives should be pursued, where research should be concentrated, or even whether or not a facility should be constructed.

The radium storage and processing facility has two major purposes that include provision of a disposal mechanism for custodians of radium and provision of source material for making new medical isotopes. A discounted cash flow including patients' income minus facility expense and patients' treatment cost provides a mechanism for determining whether or not the project has merit.

Present means of treating acute myelogenous leukemia (AML) are expensive. Most successful treatments involve a bone marrow transplant. The patient's own bone marrow has to be destroyed, and the patient has to be kept in isolation for a time because all immunity is destroyed until the transplant takes place. Often the patient has to take

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treatment at a location far from home. Costs can include not only hospitalization but also housing near a major medical center for the patient and the patient's family. The duration of treatment can last months. A patient's father told the author confidentially that the cost was approximately $250,000.

In a conversation in May 1995 (Scheinberg, 1995b), Dr. David Scheinberg told the author that alpa-particle therapy might cost as little as $35,000 per patient. The procedure could be done on an out patient basis. So little dose could be given that the patient would not need to be isolated from others because of radiation concerns. No bone marrow transplant would be required.

Cancer therapy is considered successful if a patient survives for five years without a recurrence of disease. During this time the patient can be earning a living and enjoying life. Money cannot be used to determine the value of an extra few years of life, but an economic analysis can be made of the earning potential of a patient. In the United States per capita income is between $25,000 and $30,000 per year. With a $250,000 medical bill up front, an average person earning the per capita income could not hope to recover the cost of treatment within a five-year period. Recovery of a $35,000 treatment would be possible.

For purposes of this analysis, a success rate of 1,000 cases of AML per year was assumed. This is only approximately 5 per cent of the cases of leukemia in a year (*Scientific American,* 1996). Even with the additional cost of the storage and processing facility, the present worth of successful treatment of a thousand patients per year with a productive life of five years for each patient would be more than one billion dollars. The results of this analysis are shown in Table A-6 in Appendix A, and the present worth profile for this analysis is shown in Figure 18.
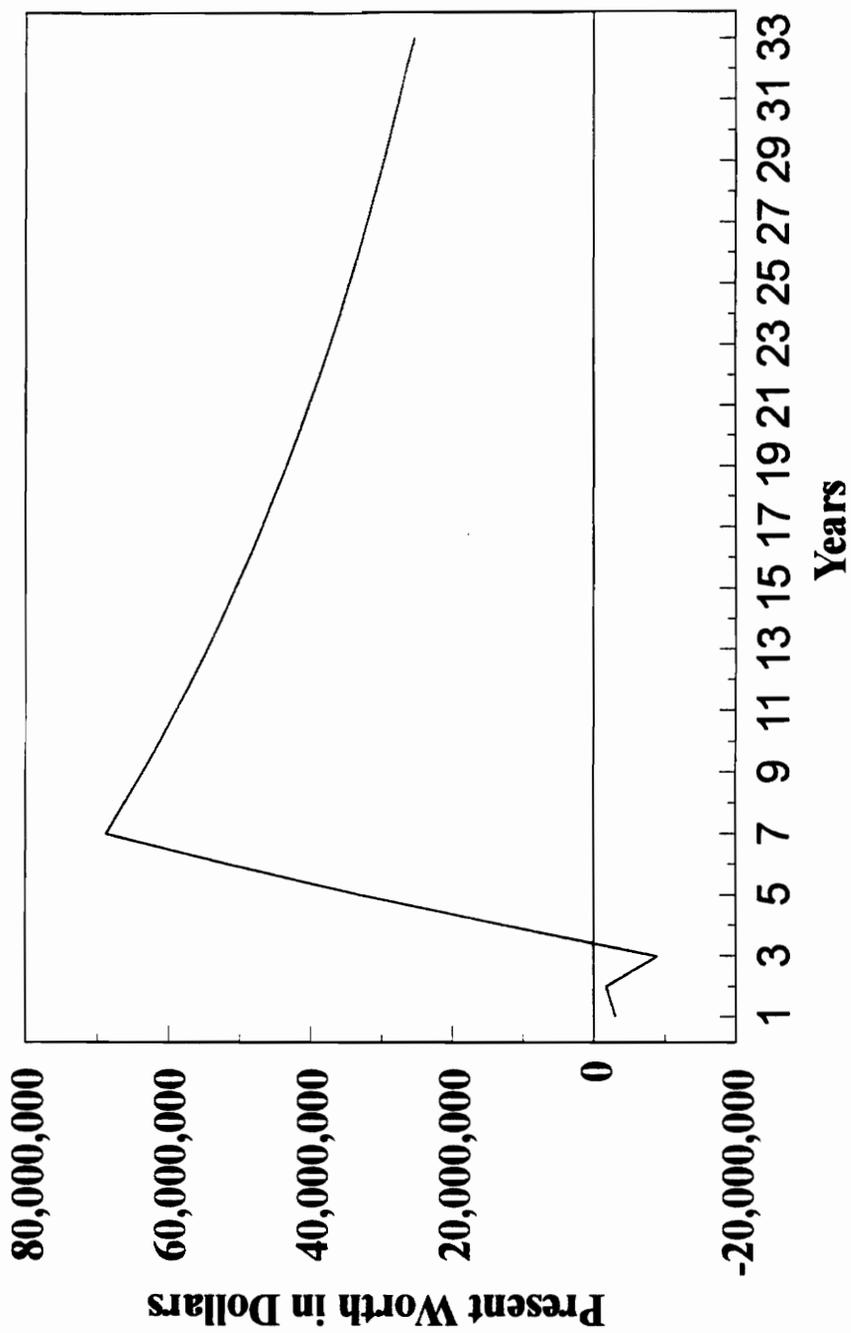
Figure 18: Present Worth of Patients' Income Minus Treatment and Facility Costs

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SECTION 6: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The exercise of life-cycle costing forced a discipline on the study of the radium storage and licensing facility and led to useful conclusions. It began with the problem of building a facility to receive radium, store radium, and process it for medical purposes. An analysis of the problem using a questionnaire led to a broader scope. The new scope included planning, implementing, operating, and decommissioning the facility. The system defined by these four major functions consisted of the organization, personnel, and materials needed to fulfill the basic mission.

Functional analysis broke down the major functions of the facility into sufficient detail to do a preliminary life-cycle cost analysis, but not enough detail to provide guidance for detailed design. At times the functional analysis provided a means of identifying potential problem areas. For example, research into developing the functions regarding the control of radon and the processing of radium revealed that these areas deserved further study. The functional analysis also formed the basis for the conceptual design and the life-cycle cost analysis.

The conceptual design process showed that a major consideration of the facility is the system dynamics of radium supply and demand. The amount of radium handled at any one time determined shielding required. This in turn determined the size of storage cell plugs, transfer casks, fork lifts, and cranes. The size of material handling equipment helped define the overall size of the facility in terms of doors, wall thicknesses, hot cell sizes, and maneuvering room. The size of the facility and the need for radon control helped determine the need for air conditioning.

The cost breakdown structure for the radium storage and processing facility paralleled the functional analysis. The research and development phase replaced planning, but implementation, operations, and decommissioning remained. Cost estimating

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relationships for the most part depended ultimately on labor rates of individuals or the costs of materials. The cost breakdown structure provided a convenient way of consolidating more than two hundred cost estimating relationships into 24 major cost categories. These categories tended to parallel functions in the functional analysis. Comparison of the cost estimating relationships and the functional analysis showed one-to-one, many-to-one, one-to-many, and many-to-many relationships.

Two cost profiles were produced including a budgetary cost profile and a present cost equivalent profile. The budgetary profile showed that funding organizations would be asked for large amounts of money at the beginning and the end of the project. The present equivalent cost profile showed that major yearly costs occur near the beginning of the project, but that the bulk of the costs occurs over the operations and maintenance phase.

Present cost evaluations were made for each of the major cost categories. These evaluations showed that operations and maintenance were the major high cost contributors. The other major cost contributors could be grouped into three major categories. These categories included management, procurement, and analysis. Program management was the third major cost contributor. Procurement and radium storage installation could both be considered as part of the procurement process. Advanced research, engineering, environmental work, and review could be considered as part of the analysis.

Operations, maintenance, and procurement activities contributed so much to the overall cost of the project, that more analysis activities might help improve costs. Although more analysis would increase the cost of the analysis phase, more analysis might also provide ideas for reducing the other costs to such an extent that the extra effort might be justified. Sensitivity analysis showed that increasing these analysis factors by a fixed percentage would have far less effect than similar increases on operations, maintenance, and combined procurement factors.

The cost analysis was used to decide whether spending money on the facility would be worth the effort in terms of lives saved. Based on a cancer survival rate of only five years and an increased cure rate of only 5 percent in one type of cancer, the analysis showed that the increased income from the resulting 33,000 cancer patients would exceed one billion dollars.

Before completion of this study, a colleague of the author asked that a preliminary abstract of the project be drawn up. That abstract concluded that high cost contributors would include such items as shielding requirements, radon control, and shipping requirements. The main recommendation for further analysis was close examination of regulations to determine how best to deal with regulatory uncertainty.

Subsequent analysis showed that operations and maintenance would be the highest cost contributors. Only shipping was a part of the operations and maintenance. This exercise of preparing an abstract before completion of the analysis showed that the results of the analysis were unexpected by the author. The contrast of prediction to results proved the value of life-cycle cost analysis.

The scope of this study was influenced by political considerations. This study came about as the result of the author's involvement with radium at the Fernald Environmental Management Project. Fernald has the World's largest supply of radium in the form of 4,500 grams of material within approximately 20,000,000 pounds of waste. As part of his work assignment, the author investigated the possibility of retrieving some of this radium for use in medicine. Also, this material was scheduled to be vitrified and disposed of in the Nevada desert. Subsequent investigation revealed that some radium in the form of old medical supplies still existed. Custodians of that radium had a problem getting rid of that material. A decision was made to investigate the present storage and processing facility.

Policy questions still exist. Should the United States Government get involved in the disposal of another radioactive waste? Should private industry take over the facility?

How much capacity will be needed? Who will be responsible for the ultimate disposal of any excess material? This project does not answer all these questions, but the model provides a means of finding the answers.

Recommendations

1. Comparison of the functional analysis to cost estimating relationships showed a one to many relationship between functions and subfunctions and cost estimating relationships and between cost estimating relationships and functions and subfunctions. Further life-cycle studies should concentrate on establishing one-to-one relationships between functions and cost estimating relationships. This analysis would allow costs to be tracked on a functional basis.

2. During this study, an alternative means of storage was examined but never fully explored. This alternative consisted of a mausoleum type structure for storing the radium. Radium could then be stored either horizontally or vertically in a structure above the floor. Such an arrangement would negate the need for removing possibly contaminated concrete and would enable the construction of a more easily evaluated containment system. The present model should be modified to evaluate these and other alternatives before detailed design and construction began.

3. The life-cycle cost analysis showed that the greatest opportunity for cost savings concerns operations and maintenance. Studies should concentrate on making this part of the life cycle more efficient. Because of the sensitivity of these items to incremental changes, dollars spent on improving this phase of the project would probably be the most cost-effective use of money.

A prime candidate for study in operations would be radium processing. This would include radium separation, purification, and chemical processing. Although radium production and processing has been done since the late part of the 1800's, these processes have not been updated within the last thirty to forty years to incorporate new chemical separation techniques, new analytical techniques, and conformance with new environmental regulations.

4. The dynamics of radium are such that a system study of radium supply and demand is justified. An arbitrary decision was made to handle radium in ten gram amounts and to limit the size of the facility to 500 grams, yet nearly every cost was connected to the total amount of radium and the amount of radium handled at any one time. A systems study, which included the mix of derived isotopes needed, the demand for radium, and the supply of radium would allow decision makers to decide the size and type of facility to be constructed.

5. Present costs for disposal of radium are high. Custodians of radium pay as much as $5,000 to $30,000 to dispose of a few milligrams of radium. This life cycle cost analysis could form the basis for comparing the cost of the storage facility to the present costs of disposal. Some costs of the storage facility could be mitigated by charging present custodians with some disposal costs. In addition, some radium would come encapsulated in platinum needles. Further cost studies might consider the merits of recycling this platinum.

6. Ultimately, a systems study would be useful for the entire alpha-particle-emitter field. This could begin with the procurement of raw materials for making the isotopes, look to the preliminary processing of these materials,

proceed to the search for appropriate antibodies and linking mechanisms, and integrate the needs of clinical researchers.

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APPENDIX A
SUPPLEMENTARY TABLES

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility

Characteristic	Description
Purpose	Serve as storage and processing facility for excess radium sources in the United States so that new, medically useful isotopes can be produced.
Location	Building 325 at the Hanford Site, 300 area. This building is near one of the three major nuclear reactors that could be used to transmute radium to other desirable isotopes. The site is also used for the production of other medically useful isotopes. The facilities contain space that is in either renovation or decontamination.
Staff	Staff are available for assignment to new projects such as radium receiving, repackaging, analysis, and shipping. Required operating staff will consist of a project manager, a radiochemist, a radiological technician, and a clerical support person.
Access	Access will be restricted to authorized personnel having appropriate credentials and dosimetry.
Loading Dock	Required. Each area has a loading dock.
Required Utilities	Electricity, air conditioning, water, sewer. Required utilities are already being used for existing facilities.
Power Requirements	Facility will need two separate feeds for electricity along with an emergency power system. Circuits will include both 120V and 240V power supplies.
Temperature and Humidity Requirements	Temperature and humidity must be kept comfortable for workers and appropriate for electronic instruments.

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description

Process Description	Receive source.
	    Check hot cell differential pressure.
	    Move radium containing material from loading dock into hot cell.
	    Scan and smear test package for alpha, beta, and gamma radiation.
	    Calibrate equipment.
	    Open package.
	    Verify identity.
	    Verify quantity.
	    Log in radium.
	    Emplace material in temporary cask.
	    Place temporary cask contents in storage cask.
	    Load storage cask in transfer task.
	    Transfer transfer cask from hot cell to storage area.
	Warehouse Source.
	    Emplace Source.
	        Receive transfer cask at storage area.
	        Check storage differential pressure.
	        Move transfer cask into storage area.
	        Remove plug
	        Remove storage cask from transfer cask.
	        Emplace storage cask in storage cell.
	        Replace plug.
	        Mover transfer cask out of storage area.
	        Store transfer cask

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description

Process Description (Continued.).	Retrieve source.
	    Check storage differential pressure.
	    Move transfer cask into storage area.
	    Move transfer cask to storage cell.
	    Remove plug.
	    Remove storage cask from storage cell.
	    Emplace storage cask in transfer cask.
	    Replace plug.
	    Move storage cask out of storage area.
	    Move transfer cask to hot cell.
	    Process or ship radium.
	Process radium.
	    Check hot cell differential pressure.
	    Move transfer cask into hot cell.
	    Open transfer cask.
	    Remove storage cask from transfer cask.
	    Open storage cask.
	    Open needles.
	    Place contents in processing vessel.
	    Calibrate chemical analysis tools.
	    Perform chemical analysis.
	    Calibrate radiological analysis tools.
	    Perform radiological analysis.
	    Purify radium.
	    Recombine radium.
	    Package radium in reactor-suitable packages.
	    Scan and smear package.
	    Log out radium
	    Store or ship radium.

Input/Output Characteristics	Material will come as needles (platinum or steel capsules containing radium), as radium left over from a transmutation process, or as radium metal from an extraction process. Most samples will be powdered compounds including but not limited to radium-barium sulfate, radium chloride, and radium carbonates.

**Table A-1: Description of Characteristics of the Radium Storage
and Processing Facility (Cont.)**

Characteristic	Description
Capacity Requirements	Handling rate of up to 120 grams/year required. Storage of up to 500 grams. This supplies 10 grams per month to a reactor for continuous production throughout the year.
Other storage areas required	Proper storage area for chemicals to be used in processing radium. Facilities for preprocessing these chemicals.
Residence time and special handling requirements	Residence time for storage should be up to 30 years. Material must be handled remotely.
Operating shifts	12 to 24 per year.

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description

Preventive maintenance	Ventilation
	    HEPA filter smoke tests yearly.
	    Change of HEPA filters once per quarter.
	Storage Area
	    Oil door hinges once per quarter.
	    Inventory radium quarterly.
	    Clean storage area as needed but at least yearly.
	    Change light bulbs as needed but at least yearly.
	    Purge storage window oil once every two years.
	Hot Cell
	    Oil door hinges once per quarter.
	    Calibrate instruments twice per year.
	    Clean hot cell as needed but at least once per year.
	    Change light bulbs as needed but at least yearly.
	    Purge storage window oil once every two years.
	    Boots--replaced every two years
	    Tongs--Mean Time Between Failure (MTBF) of Five Years--Change
	    Remotes--MTBF--Ten years--Change
	Security Cameras--Change system every five years.
	Service
	Cranes-Lubricate once per quarter
	Forklift--Lubricate once per quarter.
	    Battery--Charge after each use.
	    Change Battery--Every three years.
	Computers--change every four years.

Startup, Normal Operating Requirements, Shutdown Requirements.	Air conditioning will be required at all times. Eight air exchanges per hour in working area. Five air exchanges per hour in storage area. Two exchanges per hour in hot cell. Dual HEPA filters on so that filters can be changed without stopping operations Shielding so that total radiation is less than 300 millirems per year per employee. Power on always to detect excess radiation.

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description
Requirements for standby, emergency, and infrequent conditions.	Emergency power supply. Facilities for allowing uninterrupted transfer of materials if necessary.
Accessibility	Accessibility of storage and hot cell to fork lift. Doors on both facilities to accommodate five foot tall transfer cask with three foot diameter.
Required operator training	Forty hour OSHA training. Rad Worker II training. Respirator training. Training in the chemistry and processing of radium for initial work.
Documentation	Operations manuals. Startup manuals. Quality Assurance Plan.
Equipment and controls	Robot or shielded fork lift capable of moving transfer cask. Crane in storage room. Crane in hot cell. Manipulator arms in hot cell. Gauges and instruments for assessing radiation field.
Software requirements	Robotic requirements. Inventory control requirements.
Testing provisions	Testing of air conditioning system. Verification of operations. Testing of software. Verification of radioactive shielding. Testing of storage cells, storage casks, transfer casks, transport casks.

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description
Records during operations	Dosimetry records. Chain of custody records. Radium inventory records. Inventory of hazardous, radioactive, and mixed wastes. Safety records. Normal employment records. Verification of maintenance tests and maintenance.
Calibration requirements	Radioactivity instruments every six months. Chemical instruments every six months.
Equipment accessibility	Doors large enough for transferring casks. Hot cell windows for observing operations. Manipulator arms capable of cleaning one another.
Remote maintenance	Provision will be made for remote maintenance when accidental radioactive conditions occur.
Special Tools	Normal tools for hot cell operation.
Allowable downtime	One month.
Related processes	Transfer of material into facilities. Nuclear reactors.
Interrelationship with other processes	Inputs will come from retired medical sources, from interception at nearby radioactive disposal facilities and from extraction processes. Output will go to a reactor or to other facilities. Untransformed radium from reactor will be recycled in the facility.
Required support services	First class radioanalytical laboratory. Nearby medical facilities for decontamination. Equipment decontamination facilities. Trucks for transporting materials.
Outside facilities	Available nuclear reactor. Storage and processing facilities for derived isotopes.

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description
Radioactive materials	Decay products of radium. Radon gas and its daughter products.
Handling, packaging, storing, and transport requirements for radioactive wastes	Radioactive products will be handled with remote manipulators. Cranes and robots will be required for moving materials between facilities. Excess radium will be stored for recycling. Material will be transported in appropriate containers.
Hazardous materials	Acids and bases. Organic solvents. Flammable resins.
Handling, packaging, storage, and transport requirements for hazardous materials	Materials will be stored in appropriate containers with adequate ventilation.
Mixed materials (radioactive and hazardous)	Acids, bases, organic solvents, and resins containing radioactive materials will be produced during processing.
Handling, packaging, storage, and transportation of mixed materials.	Materials will be packaged to reduce the adverse impact of the acids and bases while providing adequate radioactive shielding protection.
Radioactive wastes	Radium itself will be purified and re-encapsulated for future irradiation. Some plating out of decay products is anticipated. These will be removed with surface decontamination methods including such possible methods as CO_2-blasting, ice-blasting, sponge-blasting, or water-blasting. These contaminants will be removed with a HEPA vacuum cleaner for proper disposal in a low-level radioactive waste facility.

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description
Hazardous waste	Efforts will be made to keep hazardous wastes from radioactive wastes. Hazardous wastes will only be allowed to accumulate for a period not to exceed 90 days. They will then be sent to an appropriate hazardous waste facility.
Mixed waste	Efforts will be made to keep production of mixed wastes to a minimum. To the extent practicable, mixed wastes will be separated into hazardous and radioactive waste streams. Mixed wastes that cannot be separated in this fashion will be sent to the only facility available--Envirocare of Clive, Utah.
Regulatory Requirements for Radium	EPA and State requirements for radiological control.
Regulatory Documentation	State permits, licenses, inspections.
Required permits	State and US EPA.
Required radioactive shielding	Shielding to a level of 0.1 millirem per hour.
Required controls for radioactivity	Appropriate alarms for alpha, beta, and gamma rays and for radon detection. Storage area and hot cell will have negative pressure relative to work area, and work area will have negative pressure relative to ambient conditions.
Expected emissions to the environment	Radon and daughter products.
Design features for environmental protection	Air conditioning will be designed with negative differential from ambient conditions to the work area and from the work area to the storage area and hot cell.

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description
Future projects	A facility for separation of radium from radium-beryllium targets. Facilities for separation of radium from radium-barium sulfates could be built.
Additional facilities	Thorium 229 and actinium 227 storage and processing facilities could be accommodated at existing Hanford facilities.
Quality Assurance Levels	Only quality assurance levels required for highly radioactive materials. Catastrophic accidents are likely to affect only the immediate surroundings.
Quality Assurance requirements	Regular inspections of the facility will be required to assure that the facility meet existing health and safety requirements. Configuration management of the procedures will be required. Operator training records must be updated on a regular basis. Chain of custody records must be maintained. Periodic surveillance will be required.
Physical safeguards requirements	Security personnel will be required throughout the life of the facility for prevention of theft. Security will be part of the overall security of the site.
Requirements for locks, detection and alarm, and remote surveillance.	Secure locks will be required with access limited to authorized persons only. Remote surveillance closed circuit television will be required.
Special security requirements	Only against sabotage and theft.
Visual communications requirements	Television in storage area for maneuvering plugs and canisters.

Table A-1: Description of Characteristics of the Radium Storage and Processing Facility (Cont.)

Characteristic	Description
Communication.	Telephone intercom for both external and internal communications. Alarm systems for radioactive release. Fire alarms. Weather alarms. Alarm systems for communicating problems from other areas.
Decontamination and decommissioning work	Shutdown of Operations. Dispatch of Excess Isotopes. Decontamination of Facility Stripping Out Utilities. Removal of Detectors. Disposal of Shielding. Salvage of Hot Cell. Dispatch of Residual Radium. Transport to disposal site.

Table A-2: Cost Estimating Relationships

Cost Category	Method of Determination	Justification
Total System Cost *(C)* (Functions 1.0, 2.0, 3.0, 4.0)	$C=[C_R+C_I+C_O+C_D]$ $C=$ Total Cost $C_R=$ Research and Development Cost $C_I=$ Implementation Cost $C_O=$ Operations and Maintenance Cost $C_D=$ Decommissioning Cost	Total cost is made up of four components: planning (research and development); implementation; operations and maintenance; and decommissioning.
Research and Development *(C_R)* (Function 1.0)	$C_R=[C_{RP}+C_{RA}+C_{REC}+C_{RPC}+C_{RE}$ $+C_{RED}+C_{RPT}+C_{RR}+C_{RTD}]$ $C_{RP}=$ Program Management Cost $C_{RA}=$ Advanced Research and Development Cost $C_{REC}=$ Environmental Cost $C_{RPC}=$ Cost of Procurement $C_{RE}=$ Engineering Cost $C_{RED}=$ Cost of Engineering Data $C_{RPT}=$ Cost of Prototype Testing $C_{RR}=$ Review Costs $C_{RTD}=$ Training Design	Research and development include all those necessary activities in the planning phases of building the warehousing and processing facility. This includes program management, advanced research and development, procurement of advance lead items, engineering, environmental studies, reviews, testing of prototypes, engineering data, and design of training.

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Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Program Management (C_{RP}) (Function 1.0)	$C_{RP} = \sum_{i=1} C_{RPi}$ C_{RP} = Program Management Cost C_{RPi} = Cost of Individual Activities N = Number of Activities	Program management includes the functions of planning, staffing, controlling, budgeting, etc. Costs include the salaries of the manager, administrative assistant, procurement and contracts, and other administrative personnel if needed. Costs include salaries and burdened costs such as taxes, insurance, benefits, and social security as well as allocated overhead.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Advanced Research and Development (C_{RA}) (Subfunction 1.1)	$C_{RA}=C_{RAR}+C_{RAF}+C_{RAA}+C_{RAC}$ C_{RA}=Advanced Research and Development Cost C_{RAR}=Cost of Requirements Analysis C_{RAF}=Cost of Functional Analysis C_{RAA}=Cost of Requirements Allocation C_{RAC}=Cost of Conceptual Design	Advanced research and development include these items: requirements' analysis to determine both regulatory and physical requirements; a functional analysis to determine the hardware, software, and personnel needed; requirements allocation to determine how requirements are allocated among various functional elements; and conceptual design.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Requirements Analysis (C_{RAR}) (Subfunction 1.1.1)	$C_{RAR} = \sum_{i=1}^{N} C_{RARi}$ $C_{RAR} = Cost\ of\ Requirements\ Analysis$ $C_{RARi} = Cost\ of\ Individual\ Activities$ $N = Number\ of\ Activities$	Covers the cost of discovering and deriving requirements. These include both regulatory requirements and requirements inherent in the design. Costs include salaries and burdened costs such as taxes, insurance, benefits, and social security as well as allocated overhead.

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Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Functional Analysis (C_{RAF}) (Subfunction 1.1.2)	$$C_{RAF} = \sum_{i=1}^{N} C_{RAFi}$$ C_{RAF} = Cost of Functional Analysis C_{RAFi} = Cost of Individual Activities N = Number of Activities	Covers the cost of breaking the functions of the system down into subcomponents until the needs of the system are defined. Work is done by a team of professionals who will ultimately be responsible for detail design of the system. Costs include salaries and burdened costs such as taxes, insurance, benefits, and social security as well as allocated overhead.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Requirements Allocation (C_{RAA}) (Subfunction 1.1.3)	$C_{RAA} = \sum_{i=1}^{N} C_{RAAi}$ $C_{RAA} = Cost\ of\ Requirements\ Allocation$ $C_{RAAi} = Cost\ of\ Individual\ Activities$ $N = Number\ of\ Individual\ Activities$	Covers the cost of allocating requirements among the functions defined in the functional analysis. Costs include salaries and burdened costs such as taxes, insurance, benefits, and social security as well as allocated overhead.
Conceptual Design (C_{RAC}) (Subfunction 1.1.4)	$C_{RAC} = \sum_{i=1} C_{RACi}$ $C_{RAC} = Cost\ of\ Conceptual\ Design$ $C_{RACi} = Cost\ of\ Individual\ Design\ Activities$ $N = Number\ of\ Activies$	Covers the cost of conceptual design based on requirements definition, functional analysis, and requirements allocation. Costs include salaries and burdened costs such as taxes, insurance, benefits, and social security as well as allocated overhead.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Environmental (C_{REC}) (Subfunction 1.3)	$C_{REC} = \sum_{i=1} C_{RECi}$ C_{REC} = Environmental Cost C_{RECi} = Cost of Individual Activities N = Number of Activities	Covers the cost of environmental work including such scientists as biologists, geologists, toxicologists, meteorologists, engineers, hydrologists, sociologists, and other environmental professionals. Also covers the costs of required permits.
Procurement (C_{RPC}) (Subfunction 1.6)	$C_{RPC} = \sum_{i=1}^{N} C_{RPCi}$ C_{RPC} = Procurement Cost for Major Items C_{RPCi} = Purchase Price of Each Item N = Number of Items	Covers the purchase cost of major items requiring advanced procurement activity. Costs of the procurement specialist are covered under program management cost.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Engineering (C_{RE}) (Subfunction 1.2)	$C_{RE}=[C_{RD}+C_{RS}]$ $C_{RE}=Engineering\ Cost$ $C_{RD}=Discipline\ Engineering\ Cost$ $C_{RS}=Specialty\ Engineering\ Cost$	This includes all design engineering that will be done before implementation of the radium warehousing and processing facility. Costs in this category are differentiated into traditional disciplines of engineering and specialty interdisciplinary types of engineering. Costs include salaries and burdened costs such as taxes, insurance, benefits, and social security as well as allocated overhead.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Discipline Engineering (C_{RDE}) (Subfunctions 1.2.1, 1.2.1.1, 1.2.1.2, 1.2.1.3, 1.2.1.4, 1.2.1.5, 1.2.1.6)	$$C_{RD} = \sum_{i=1}^{N} C_{RDi}$$ C_{RD}=Discipline Engineering Cost C_{RDi}=Cost of Individual Activity N=Number of Activities	Discipline engineering consists of the traditional engineering disciplines. Systems engineering will coordinate all the other disciplines. Structural engineering will be needed to determine if the present structure can support modifications. Heating, ventilation, and air conditioning (HVAC) will need to accommodate special differential pressure requirements. Electrical engineering will be used to accommodate HVAC modifications as well as required computers, alarms, and monitoring equipment. Chemical

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Specialty Engineering (C_{RS}) (Subfunctions 1.2.2, 1.2.2.1, 1.2.2.2, 1.2.2.3)	$C_{RS} = \sum_{i=1} C_{RS}$ C_{RS}=Specialty Engineering Cost C_{RS}=Cost of Individual Activity N=Number of Activities	These forms of engineering tend to be more global for this project. They include the disciplines of reliability, maintainability, and human factors engineering. Required reliability will be directly related to the hazard of radium. Maintainability must be designed in such a fashion to reduce radiation exposure both from radium and from radon gas. Human factors must be considered in concert with reliability and maintainability to reduce the possibility of human error.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Engineering Data (C_{RED}) (Applies across the board)	$C_{RED} = \sum_{i=1} C_{REDi}$ C_{RED} = Engineering Data Cost C_{REDi} = Cost of Individual Document N = Number of Documents	Engineering drawings, documentation of operation and maintenance procedures, test plans and results, quality assurance plan, and other documentation required for work.
Prototype Testing and Development (C_{RPT}) (Subfunctions 1.4, 1.5)	$C_{RPT} = \sum_{i=1}^{N} [C_{RPTi}]$ C_{RPTi} = Cost per Prototype Test N = Number of Tests	Includes development and testing of prototype storage casks, transfer cask, and shipping casks. Also includes development of software.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Review (C_{RR}) (Function 1.0)	$C_{RR}=[C_{RRC}+C_{RRD}+C_{RRF}]$ $C_{RRC}=Cost\ of\ Conceptual\ Design\ Review$ $C_{RRD}=Cost\ of\ Detail\ Design\ Review$ $C_{RRF}=Cost\ of\ Final\ Design\ Review$	Covers the costs of required design reviews. Costs include the costs of design and environmental professionals as appropriate. Costs include salaries and burdened costs such as taxes, insurance, benefits, and social security as well as allocated overhead.
Conceptual Design Review (C_{RRC}) (Function 1.0)	$C_{RRC}=\sum_{i=1}^{N} C_{RRCi}$ $C_{RRC}=Cost\ of\ Conceptual\ Design\ Review$ $C_{RRCi}=Cost\ of\ Individual\ Activities$ $N=Number\ of\ Activities$	Covers the cost of reviewing the conceptual design. Activities of all engineering professionals are covered.
Detail Design Review (C_{RRD}) (Function 1.0)	$C_{RRD}=\sum_{i=1}^{N} C_{RRDi}$ $C_{RRD}=Cost\ of\ Detail\ Design\ Review$ $C_{RRDi}=Cost\ of\ Individual\ Activities$ $N=Number\ of\ Activities$	Covers the cost of reviewing the detail design. Activities of all engineering professionals are covered.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Final Design Review (C_{RRF}) (Function 1.0)	$C_{RRF} = \sum_{i=1}^{N} C_{RRFi}$ C_{RRF} = Cost of Final Design Review C_{RRFi} = Cost of Individual Activities N = Number of Activities	Covers the cost of reviewing the final design. Activities of all engineering professionals are covered.
Training Design (C_{RTD}) (Subfunction 1.7)	$C_{RTD} = \sum_{i=1} C_{LPi}$ C_{RTD} = Training Cost C_{LPi} = Cost of Individual Lesson Plans N = Number of Lesson Plans	Covers the cost of training professionals designing training for both construction and operations and maintenance.
Implementation (C_I) (Function 2.0)	$C_I = [C_{IO} + C_{IH} + C_{IR} + C_{IG} + C_{IRN} + C_{ISR} + C_{IST}]$ C_I = Cost of Implementation C_{IO} = Cost of Office Space Remodeling C_{IH} = Cost of Hot Cell Configuration C_{IR} = Cost of Radium Storage Installation C_{IG} = Cost of Global Construction C_{IRN} = Cost of Radon Control Installation C_{ISR} = Cost of System Review	Covers all the cost of implementing the new system in an existing building. Costs include office remodeling, hot cell configuration, building of radium storage, construction applying globally to all subunits of the system, cost of radon control installation, cost of system review, and cost of system transition to operations.

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Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Office Space Remodeling (C_{IO}) (Subfunction 2.1)	$C_{IO}=[C_{IOP}+C_{IOC}+C_{IOF}]$ $C_{IO}=Cost\ of\ Office\ Space\ Remodeling$ $C_{IOP}=Cost\ of\ Placing\ Partitions$ $C_{IOC}=Cost\ of\ Computer\ Installation$ $C_{IOF}=Cost\ of\ Furniture\ Installation$	Covers the cost of offices for personnel operating the facility including the program manager, radiochemist, radiotechnician, and clerical help.
Placing Partitions (C_{IOP}) (Subfunction 2.1.1)	$C_{IOP}=\sum_{i=1}^{N} C_{IOPLi}$ $C_{IOP}=Cost\ of\ Installing\ Partitions$ $C_{IOPLi}=Cost\ of\ Labor\ Per\ Hour$ $N=Number\ of\ Hours$	Covers cost of installing separate working areas for each person.
Installing Computers (C_{IOC}) (Subfunction 2.1.2)	$C_{IOC}=\sum_{i=1}^{N} C_{IOCLi}$ $C_{IOC}=Cost\ of\ Computer\ Installation$ $C_{IOCLi}=Cost\ of\ Labor\ for\ Each\ Computer$ $N=Number\ of\ Computer\ Installation\ Operations$	Covers cost of installation operations including setting computers up in a network.
Furniture Installation (C_{IOF}) (Subfunction 2.1.3)	$C_{IOF}=\sum_{i=1}^{N} C_{IOFLi}$ $C_{IOF}=Cost\ of\ Furniture\ Installation$ $_{IOFLi}=Cost\ of\ Furniture\ Installation\ Labor\ per\ Hou$ $N=Number\ of\ Hours\ Installing\ Furniture$	Covers cost of installing furniture for personnel working in facility.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Hot Cell Configuration (C_{IH}) (Subfunction 2.2)	C_{IH} $[C_{IHM}$ C_{IHU} C_{IHCR} C_{IHCO} C_{IHS} $C_{IHD}]$ C_{IHM}=Manipulator Overhaul Cost C_{IHU}=Utility Installation Cost C_{IHCR}=Crane Installation Cost C_{IHCO}=Conveyor Installation Cost C_{IHS}=Cost of Shielding C =Cost of Door Installation	Covers cost of overhauling existing manipulators and installing needed utilities. Crane and conveyor are needed to maneuver radium transfer cask.
Manipulator Overhaul (C_{IHM}) (Subfunction 2.2.3)	$C_{IHM}=[C_{IHMM}+C_{IHML}]$ C_{IHM}=Cost of Manipulator Overhaul C_{IHMM}=Cost of Manipulator Materials C_{IHML}=Cost of Manipulator Labor	Covers the cost of overhauling the existing manipulators on the hot cell.
Utility Installation (C_{IHU}) (Subfunction 2.2.2)	$C_{IHU}=\sum_{i=1} C_{IHUi}$ C_{IHU}=Cost of Utility Installation C_{IHUi}=Cost of Individual Utility Installation Activity N=Number of Activities	Covers the cost of installing needed utilities into hot cell. Does not include the cost of heating, ventilation or air conditioning.
Crane Installation (C_{IHCR}) (Subfunction 2.2.4)	$C_{IHCR}=\sum_{i=1} C_{IHCRi}$ C_{IHCRi}=Cost of Crane Installation Activity N=Number of Activities	Covers the cost of installation of a crane in the hot cell to maneuver the radium transfer cask.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Conveyor Installation (C_{IHCO}) (Subfunction 2.2.5)	$C_{IHCO} = \sum_{i=1}^{N} C_{IHCOi}$ C_{IHCO}=Cost of Conveyor Installation C_{IHCOi}=Cost of Individual Conveyor Installation Activity N=Number of Activities	Covers the cost of installing conveyors in each of the two hot cells including personnel and materials.
Shielding (C_{IHS}) (Subfunction 2.2.6)	$C_{IHS} = [\sum_{i=1}^{N} C_{IHSYi} + \sum_{i=1}^{M} C_{IHSDi}]$ C_{IHS}=Cost of Shielding C_{IHSYi}=Cost of Magnetite Concrete per Cubic Yard C_{IHSDi}=Cost of Installing Shielding Door N=Number of Yards of Concrete M=Number of Doors	Covers the cost of installing shielding and lead doors on the hot cells.
Radium Storage Installation (C_{IR}) (Subfunction 2.3)	C_{IR}=Cost of Radium Storage C_{IRRD}=Cost of Concrete Removal and Disposal C_{IRD}=Cost of Hole Drilling C_{IRT}=Cost of Tubing Emplacement C_{IRC}=Cost of Concrete Emplacement C_{IRP}=Cost of Plug Construction C_{IRU}=Utility Installation	Cover s the cost of removing part of basement floor, drilling emplacement holes, and replacing original concrete with tubing and rebar enforced magnetite concrete. Also covers cost of building walls around area and installing lead doors.

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Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Concrete Removal and Disposal (C_{IRRD}) (Subfunction 2.3.3)	$$C_{IRRD} = \sum_{i=1}^{N} C_{IRCRi} + \sum_{i=1}^{M} C_{IRCDi}$$ C_{IRRD}=Cost of Concrete Removal and Disposal C_{IRCRi}=Cost of Concrete Removal per Cubic Yard N=Number of Yards Removed C_{IRCDi}=Cost of Concrete Disposal per Cubic Yard M=Number of Yards Disposed	Covers cost of removal and disposal of basement concrete that may be radioactive.
Hole Drilling(C_{IRD}) (Subfunction 2.3.3)	$$C_{IRD} = \sum_{i=1}^{N} C_{IRDi}$$ C_{IRD}=Cost of Hole Drilling C_{IRDi}=Cost of Hole per Foot N=Number of Feet	Cost of drilling holes in ground before emplacement of concrete.
Tubing Emplacement (C_{IRT}) (Subfunction 2.3.4)	$$C_{IRT} = \sum_{i=1}^{N} C_{IRTi}$$ C_{IRT}=Cost of Installed Tubing C_{IRTi}=Cost of Installed Tubing per Foot N=Feet of Tubing	Covers cost of installing stainless steel tubing for storage of radium.
Concrete Emplacement (C_{IRC}) (Subfunction 2.3.4)	$$C_{IRC} = \sum_{i=1}^{N} C_{IRCi}$$ C_{IRC}=Cost of Concrete Emplacement $_{IRCi}$=Cost of Concrete Emplacement per Cubic Yar N=Number of Cubic Yards	Covers cost of concrete emplacement. Includes rebar emplacement, tying rebars to tubing, and actual emplacement of concrete.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Plug construction and emplacement (C_{IRP}) (Subfunction 2.3.4)	$C_{IRP} = \sum_{i=1}^{N} C_{IRPi}$ C_{IRP} = Cost of Plug Construction and Emplacement C_{IRPi} = Cost per Plug N = Number of Plugs	Cost of plug construction. Covers cost of tubing, cost of magnetite concrete filling, and cost of plug machining.
Radium Storage Walls and Doors (C_{IRWD}) (Subfunctions 2.3.5, 2.3.6)	$C_{IRWD} = [\sum_{i=1} C_{IRWi} + \sum_{i=1} C_{IRLDi}]$ C_{IRWD} = Cost of Construction of Storage Area Walls and Doors C_{IRWi} = Cost per Yard of Concrete Emplacement C_{IRLDi} = Cost of Installing Individual Lead Doors N = Number of Yards of Concrete M = Number of Doors	Covers the cost of installing the walls surrounding the storage area and lead access doors.
Utility Installation (C_{IRU}) (Subfunction 2.3.2)	$C_{IRU} = \sum_{i=1} C_{IRUi}$ C_{IRU} = Utility Installation Cost C_{IRUi} = Cost of Utility Installation Activity	Covers the cost of needed utilities.
Crane Installation (C_{IRCR}) (Subfunction 2.3.7)	$IRCR = \sum_{i=1} C_{IRCRi}$ $IRCR$ = Crane Installation Activity $IRCRi$ = Cost of Individual Crane Installation Activiti N = Number of Activities	Covers the cost of crane installation in the radium storage facility.

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Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Global Construction (C_{IG}) (Subfunctions 2.2.1, 2.3.1, 2.2.8, 2.3.9)	$C_{IG} = [C_{IGS} + C_{IGH} + C_{IGD}]$ $C_{IG} = Cost\ of\ Global\ Construction$ $C_{IGS} = Cost\ of\ Security$ $C_{IGH} = Cost\ of\ HVAC\ Installation$ $C_{IHD} = Cost\ of\ Detector\ Installation$	Covers cost of construction which goes over the entire complex. Items include security, HVAC, and radiation and radon detectors.
Security (C_{IGS}) (Subfunctions 2.2.7, 2.2.8)	$C_{IGS} = \sum_{i=1}^{N} C_{IGSi}$ $C_{IGS} = Cost\ of\ Security\ Installation\ Activity$ $N = Number\ of\ Activities$	Covers the cost of installing security items.
HVAC Installation (C_{IGH}) (Subfunctions 2.2.1, 2.3.1)	$C_{IGH} = \sum_{i=1}^{N} C_{IGHi}$ $C_{IGHi} = Cost\ of\ HVAC\ Installation\ Activity$ $N = Number\ of\ Activities$	Covers the cost of labor required to install HVAC elements.
Detector Installation (C_{IGD}) (Subfunctions 2.2.8, 2.3.9)	$C_{IGD} = \sum_{i=1}^{N} C_{IGDi}$ $C_{IGD} = Cost\ of\ Detector Installation$ $C_{IGDi} = Cost\ of\ Individual\ Activity$ $N = Number\ of\ Activities$	Covers cost of radiation detectors and radon detectors.
Radon Control Installation (C_{IRN}) (Subfunction 2.4)	$C_{IRN} = C_{IRNC} + C_{IRNM}$ $C_{IRN} = Cost\ of\ Radon\ Control$ $C_{IRNC} = Cost\ of\ Radon\ Control\ Containment$ $C_{IRNM} = Cost\ of\ Radon\ Control\ Media$	Covers the cost of radon control containment construction plus cost of radon control media.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
System Review (C_{ISR}) (Function 2.0)	$$C_{ISR} = \sum_{i=1}^{N} C_{ISRi}$$ C_{ISR}=Cost of System Review C_{ISRi}=Cost of Individual Review Activities N=Number of Activities	Covers the cost of reviews before systems operation. This includes operational readiness and other similar reviews.
Operations and Maintenance (C_O) (Function 3.0)	$C_O = C_{OO} + C_{OM}$ C_O=Cost of Operations and Maintenance C_{OO}=Cost of Operations C_{OM}=Cost of Maintenance	Covers the cost of operations and maintenance of the facility. Maintenance includes human factors as well as physical facilities.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Operations (C_{OO}) (Function 3.0)	$C_{OO} = C_{OOP} + C_{OOF} + C_{OOSM} + C_{OOS}$ $C_{OO} = Cost\ of\ Operations$ $C_{OP} = Cost\ of\ Operating\ Personnel$ $C_{OOF} = Cost\ of\ Operating\ Facilities$ $C_{OOSM} = Cost\ of\ System\ Modification$ $C_{OOS} = Cost\ of\ Shipping\ Radium$	Covers the cost of personnel operating the facility including their burden as taxes, insurance, benefits, administrative costs etc. Also covers similar costs for trainers. Cost of operating facilities is mostly cost of utilities. Initial capital and replacement costs are covered under procurement. Cost of system modification includes cost of engineering personnel plus cost of construction labor.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Operating Personnel (C_{OOP}) (Subfunctions 3.1, 3.2, 3.3, and Subfunctions)	$C_{OOP} = \sum_{i=1}^{N} [(T_{OOi})(C_{OOPRi})(C_{OOHGR})]$ C_{OOP} = Cost of Operational Personnel T_{OOi} = Hours of Operation per Person C_{OOPRi} = Cost of Operational Personnel per Hour C_{OOHR} = Hours per Gram Radium N = Number of Personnel	Covers the cost of individuals operating the facility including the program manager, radio chemist, radiological technician and clerical support. Costs also cover overhead such as social security, vacation, hospitalization, administrative, and other benefits.
Operating Facilities (C_{OOF}) (Subfunctions 3.1, 3.2, 3.3, and Subfunctions)	$C_{OOF} = (C_{OOFE})(KWH) + (C_{OOFG})(MMBTU) + (C_{OOFW})(Gal)$ C_{OOF} = Cost of Facilities $_{OOFE}$ = Cost of Electricity per Kilowatt-Hour KWH = Kilowatt Hours $_{OOFW}$ = Cost of Water per Thousand Gallons Gal = Gallons of Water in Thousands	Covers the cost of utilities for the facility including electricity and water.
System Modification (C_{OOSM}) (Subfunction 3.7 Subfunctions)	$C_{OOSM} = \sum_{i=1}^{N} C_{OOSM}$ C_{OOSM} = Cost of System Modifications C_{OOSM} = Cost of Individual Modifications N = Number of Modifications	Covers the capital costs of systems modification including the replacement of equipment as well as any engineering that might be required.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Shipping (C_{OOS}) (Subfunction 3.4)	$C_{OOS} = \sum_{i=1}^{N} C_{OOS}$ C_{OOS} = Cost of Shipping C_{OOS} = Cost of Shipping Radium per Gram N = Number of Grams	Covers the cost of Shipping Radium to Reactor.
Maintenance (C_{OOM}) (Subfunction 3.5)	$C_{OOM} = C_{OOMSCH} + C_{OOMU}$ C_{OOM} = Cost of Maintenance C_{OOMSCH} = Cost of Scheduled Maintenance C_{OOMU} = Cost of Unscheduled Maintenance	Covers cost of labor and materials for maintenance actions for facility. Labor includes overhead costs.
Scheduled Maintenance (C_{OOMSCH}) (Subfunction 3.5)	$_{OOMSCH} = C_{OOMV} + C_{OOMS} + C_{OOMH} + C_{OOMP} + C_{OOMW} + C_{OOM}$ C_{OOMV} = Cost of Ventilation Maintenance C_{OOMS} = Cost of Storage Maintenance C_{OOMH} = Cost of Hot Cell Maintenance C_{OOMP} = Cost of Personnel Maintenance C_{OOMW} = Cost of Waste Management C_{OOME} = Cost of Equipment Maintenance	Covers the cost of maintenance that occurs on a regular schedule. Details are given for each of the various types of maintenance.
Ventilation Maintenance (C_{OOMV}) (Subfunctions 3.5.1, 3.5.1.1, and 3.5.1.2)	$C_{OOMV} = \sum_{i=1}^{N} C_{OOMVi}$ C_{OOMV} = Cost of Ventilation Maintenance C_{OOMVi} = Cost of Individual Ventilation Maintenance Activities N = Number of Activities	Covers such costs as testing the building containment and interlock system, smoke testing filters, and changing HEPA filters.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Storage Area Maintenance (C_{OOMS}) (Subunction 3.5.2 and Subfunctions)	$C_{OOMS} = \sum_{i=1}^{N} C_{OOMSi}$ C_{OOMS} = Cost of Storage Area Maintenance C_{OOMSi} = Cost of Individual Storage Area Maintenance Activities N = Number of Activities	Covers the cost of radium storage area maintenance. Includes oiling door hinges and servicing electric motors on lead doors, inventorying the radium, changing light bulbs, cleaning the storage area and lubricating the crane.
Hot Cell Maintenance (C_{OOMHi}) (Subfunction 3.5.3 and subfunctions)	$C_{OOMH} = \sum_{i=1}^{N} C_{OOMHi}$ C_{OOMH} = Cost of Hot Cell Area Maintenance C_{OOMHi} = Cost of Individual Hot Cell Area Maintenance Activities N = Number of Activities	Covers the cost of servicing electric motors and oiling lead-filled doors. Also includes calibration of instruments; replacement of boots, tongs, and remote cables; lubrication of conveyors and cranes; and replenishment of laboratory supplies.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Personnel Maintenance (C_{OOMP}) (Subfunction 3.5.4 and Subfunctions)	$$C_{OOMP} = \sum_{i=1}^{N} C_{OOMPi}$$ C_{OOMP}=Cost of Personnel Maintenance C_{OOMPi}=Cost of Individual Personnel Maintenance Activities N=Number of Activities	Covers the cost of all personnel maintenance activities including training, dosimetry, and medical records.
Waste Management (C_{OOMW}) (Subfunction 3.5.5 and Subfunctions)	$$C_{OOMW} = \sum_{i=1}^{N} C_{OOMWi}$$ C_{OOMW}=Cost of Waste Management C_{OOMWi}=Cost of Individual Waste Management Activities N=Number of Activities	Covers the cost of laundry and the disposal of solid, hazardous, mixed, and radioactive waste.
Equipment Maintenance (C_{OOME}) (Subfunction 3.5.6 and subfunctions)	$$C_{OOME} = \sum_{i=1}^{N} C_{OOMEi}$$ C_{OOME}=Cost of Equipment Maintenance C_{OOMEi}=Cost of Individual Equipment Maintenance Activities N=Number of Activities	Covers the cost of decontaminating equipment, servicing the computers and the forklift, and servicing radon control. Instrument service is part of calibration process. Cranes and conveyors are taken care of under maintenance for hot cell and storage area.

Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Unscheduled Maintenance (C_{OOMU}) (Subfunctions 8.0, 9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0, 17.0, 18.0, 19.0)	$C_{OOMU} = .4 * C_{OOMSCH}$ $C_{OOMU} = Unscheduled\ Maintenance$ $C_{OOMSCH} = ScheduledMaintenance$	Covers the cost of all unscheduled maintenance including maintenance items listed above when they occur more frequently than expected. Records of unscheduled maintenance can be used to modify scheduled maintenance activity.
Decommissioning (C_D) (Function 4.0)	$C_D = C_{DC} + C_{DE} + C_{DR} + C_{DF} + C_{DSH} + C_{DDR} + C_{DM}$ $C_D = Cost\ of\ Decommissioning$ $C_{DC} = Cost\ of\ Ceasing\ Operations$ $C_{DE} = Cost\ of\ Dispatching\ Excess\ Isotopes$ $C_{DR} = Cost\ of\ Decontaminating\ Storage$ $C_{DF} = Cost\ of\ Decontaminating\ Facility$ $C_{DSH} = Cost\ of\ Salvaging\ Hot\ Cell$ $C_{DDR} = Cost\ of\ Detector\ Removal$ $C_{DM} = Cost\ of\ Monitoring\ System$	Covers all the costs of decommissioning with the exception of program management.
Ceasing Operations (C_{DC}) (Subfunction 4.1)	$C_{DC} = C_{DCI} + C_{DCD}$ $C_{DC} = Cost\ of\ Ceasing\ Operations$ $C_{DCI} = Cost\ of\ Inventory$ $C_{DCD} = Cost\ of\ Documentaion$	Ceasing operations is defined here for costing purposes as inventorying the isotopes remaining and documenting same.

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Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Dispatching Excess Isotopes (C_{DE}) (Subfunction 4.2)	$C_{DE} = \sum_{i=1} [C_{DEi} + C_{DEPi}]$ C_{DE} = Cost of Dispatching Isotopes C_{DEi} = Cost of Shipping and Documentation C_{DEPi} = Cost of Packing N = Number of Shipments	Covers the cost of shipping isotopes left over after facility is closed.
Decontaminating Radium Storage (C_{DR}) (Subfunction 4.3)	$C_{DR} = \sum_{i=1}^{N} C_{DRi}$ C_{DR} = Cost of Decontaminating Radium Storage C_{DRi} = Cost of Individual Decontamination Activity N = Number of Activities	Covers the cost decontaminating stainless steel wells containing radium storage, and the room in which the wells have been placed.
Decontaminating Facility (C_{DF}) (Subfunction 4.4)	$C_{DF} = \sum_{i=1} C_{DFi}$ C_{DF} = Cost of Decontaminating Facility C_{DFi} = Cost of Decontamination Facility Activity N = Number of Activities	Covers the cost of inspecting and decontaminating facility.
Salvaging Hot Cell (C_{DHS}) (Subfunction 4.5)	$C_{DSH} = \sum_{i=1} C_{DSHi}$ C_{DSH} = Cost of Salvaging Hot Cell C_{DSHi} = Cost of Individual Salvaging Activities N = Number of Activities	Covers the cost of salvaging the hot cell.
Detector Removal (C_{DDR}) (Subfunction 4.6)	$C_{DDR} = \sum_{i=1}^{N} C_{DDRi}$ C_{DDR} = Cost of Detector Removal C_{DDRi} = Cost of Individual Detector Removal N = Number of Items Removed	Covers the cost of removal of radioactive and other types of detectors.

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Table A-2: Cost Estimating Relationships (Cont.)

Cost Category	Method of Determination	Justification
Monitoring (C_{DM}) (Subfunction 4.7)	$C_{DM}=(C_{DMC})(T subDMC)$ $C_{DMC}=Cost\ of\ Monitoring\ per\ Hour$ $T_{DMC}=Number\ of\ Hours$	Covers the cost of monitoring facility for required amount of time after closure.

Table A-3: Summary of Cost Estimating Terms

C_D	Decommissioning
C_{DC}	Ceasing Operations
C_{DE}	Dispatching Excess Isotopes
C_{DER}	Equipment Removal
C_{DF}	Facility Decontamination
C_{DHS}	Hot Cell Salvage
C_{DM}	Monitoring
C_{DR}	Radium Storage Decontamination
C_I	Cost of Implementation
C_{IG}	Global Construction
C_{IGD}	Detector Installation
C_{IGH}	HVAC Installation
C_{IGS}	Security Installation
C_{IH}	Hot Cell Renovation
C_{IHCR}	Crane Installation
C_{IHD}	Door Installation
C_{IHM}	Manipulator Overhaul
C_{IHS}	Shielding
C_{IHU}	Utility Installation
C_{IO}	Cost of Office Space Remodeling
C_{IOC}	Cost of Installing Computers
C_{IOF}	Cost of Furniture Installation
C_{IOP}	Cost of Placing Partitions
C_{IR}	Radium Storage Installation

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{IRC}	Concrete Emplacement
C_{IRCR}	Crane Installation
C_{IRH}	Hole Drilling
C_{IRN}	Radon Control Installation
C_{IRP}	Plug Construction
C_{IRRD}	Concrete Removal and Disposal
C_{IRT}	Tubing Emplacement
C_{IRU}	Utility Installation
C_{IRWD}	Radium Storage Walls and Doors
C_{ISR}	System Review
C_{ISR1}	Systems Engineering Activity
C_{ISR2}	Structural Engineering Activity
C_{ISR3}	Nuclear Engineering Activity
C_{ISR4}	Electrical Engineering Activity
C_{ISR5}	HVAC Engineering Activity
C_{ISR6}	Process Engineering Activity
C_{ISR7}	Mechanical Engineering Activity
C_{ISR8}	Maintenance Engineering Activity
C_{ISR9}	Human Factors Engineering Activity
C_{ISR10}	Reliability Engineering Activity
C_O	Operations and Maintenance
C_{OO}	Operations
C_{OOF}	Operating Facilities
C_{OOF1}	Water Utilities

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{OOF2}	Electric Utilities
C_{OOM}	Maintenance
C_{OOME}	Service Equipment
C_{OOME1}	Decontaminate Equipment
C_{OOME2}	Service Computers
C_{OOME3}	Service Forklift
C_{OOME4}	Service Radon Control
C_{OOMH}	Maintain Hot Cell
C_{OOMH1}	Oil Door Hinges
C_{OOMH2}	Service Electric Motors
C_{OOMH3}	Calibrate Instruments
C_{OOMH4}	Clean Hot Cell
C_{OOMH5}	Change Light Bulbs
C_{OOMH6}	Replace Boots
C_{OOMH7}	Replace Tongs
C_{OOMH}	Maintain Hot Cell
C_{OOMH1}	Oil Door Hinges
C_{OOMH2}	Service Electric Motors
C_{OOMH3}	Calibrate Instruments
C_{OOMH4}	Clean Hot Cell
C_{OOMH5}	Change Light Bulbs
C_{OOMH6}	Replace Boots
C_{OOMH7}	Replace Tongs
C_{OOMH8}	Replace Remote Cables

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{OOMH9}	Lubricate Conveyors
C_{OOMH10}	Lubricate Crane
C_{OOMH11}	Replenish Laboratory Supplies
C_{OOMP}	Maintain Human Factors
C_{OOMP1}	Training
C_{OOMP2}	Maintain Dosimetry
C_{OOMP3}	Maintain Medical Records
C_{OOMS}	Maintain Storage Area
C_{OOMS1}	Oil Door Hinges
C_{OOMS2}	Service Electric Motors
C_{OOMS3}	Inventory Radium
C_{OOMS4}	Change Light Bulbs
C_{OOMS5}	Clean Storage Area
C_{OOMS6}	Purge Window Oil
C_{OOMS7}	Lubricate Crane
C_{OOMSCH}	Scheduled Maintenance
C_{OOMU}	Unscheduled Maintenance
C_{OOMV}	Maintain Ventilation
C_{OOMV1}	Test Building Containment and Interlock System
C_{OOMV2}	Smoke Test Filters
C_{OOMV3}	Change HEPA Filters
C_{OOMW}	Manage Waste
C_{OOMW1}	Launder PPE

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{OOMW2}	Dispose Solid Waste
C_{OOMW3}	Dispose Hazardous Waste
C_{OOMW4}	Dispose Mixed Waste
C_{OOMW5}	Dispose Radioactive Waste
C_{OOP}	Operating Personnel (COOP)
C_{OOP1}	Receive and Store Radium
C_{OOP2}	Process Radium
C_{OOS}	Ship Radium
C_{OOSM}	System Modification
C_{OOSM1}	Replace Computers
C_{OOSM2}	Replace Security System
C_R	Cost of Research and Development
C_{RA}	Cost of Advanced Research
C_{RAA}	Cost of Requirements Allocation
C_{RAA1}	Regulatory Specialist Activity
C_{RAA2}	Systems Engineering Activity
C_{RAA3}	Structural Engineering Activity
C_{RAA4}	Nuclear Engineering Activity
C_{RAA5}	Electrical Engineering Activity
C_{RAA6}	HVAC Engineering Activity
C_{RAA7}	Process Engineering Activity
C_{RAA8}	Mechanical Engineering Activity
C_{RAA9}	Maintenance Engineering Activity
C_{RAA10}	Human Factors Engineering Activity

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{RAA11}	Reliability Engineering
C_{RAC}	Cost of Conceptual Design
C_{RAC1}	Systems Engineering Activity
C_{RAC1}	Structural Engineering Activity
C_{RAC3}	Nuclear Engineering Activity
C_{RAC4}	Electrical Engineering Activity
C_{RAC5}	HVAC Engineering Activity
C_{RAC6}	Process Engineering Activity
C_{RAC7}	Mechanical Engineering Activity
C_{RAC8}	Maintenance Engineering Activity
C_{RAC9}	Human Factors Engineering Activity
C_{RAC10}	Reliability Engineering
C_{RAF}	Cost of Functional Analysis
C_{RAF1}	Systems Engineering Activity
C_{RAF2}	Structural Engineering Activity
C_{RAF3}	Nuclear Engineering Activity
C_{RAF4}	Electrical Engineering Activity
C_{RAF5}	HVAC Engineering Activity
C_{RAF6}	Process Engineering Activity
C_{RAF7}	Mechanical Engineering Activity
C_{RAF8}	Maintenance Engineering Activity
C_{RAF9}	Human Factors Engineering Activity
C_{RAF10}	Reliability Engineering
C_{RAR}	Cost of Requirements Analysis

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{RAR1}	Regulatory Specialist Activity
C_{RAR2}	Systems Engineering Activity
C_{RAR3}	Structural Engineering Activity
C_{RAR4}	Nuclear Engineering Activity
C_{RAR5}	Electrical Engineering Activity
C_{RAR6}	HVAC Engineering Activity
C_{RAR7}	Process Engineering Activity
C_{RAR8}	Mechanical Engineering Activity
C_{RAR9}	Maintenance Engineering Activity
C_{RAR10}	Human Factors Engineering Activity
C_{RAR11}	Reliability Engineering
C_{RD}	Cost of Discipline Engineering
C_{RD1}	Systems Engineering Activity
C_{RD2}	Structural Engineering Activity
C_{RD3}	Nuclear Engineering Activity
C_{RD4}	Electrical Engineering Activity
C_{RD5}	HVAC Engineering Activity
C_{RD6}	Process Engineering Activity
C_{RD7}	Mechanical Engineering Activity
C_{RE}	Cost of Engineering
C_{REC}	Cost of Environmental Work
C_{REC1}	Biologist Activity
C_{REC2}	Geologist Activity
C_{REC3}	Toxicologist Activity

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{REC4}	Health Physicist Activity
C_{REC5}	Meteorologist Activity
C_{REC6}	Sociologist Activity
C_{REC7}	Hydrologist Activity
C_{REC8}	Regulatory Activity
C_{REC9}	Engineering Activity
C_{REC10}	Environmental Permitting
C_{RED}	Cost of Engineering Data
C_{RED1}	Quality Assurance Plan
C_{RE2}	Engineering Drawings
C_{RED3}	Operational Procedures
C_{RED4}	Maintenance Procedures
C_{RED5}	Test Plans
C_{RED6}	Software and Documentation
C_{RP}	Program Management Cost
C_{RP1}	Program Manager Activity
C_{RP2}	Procurement and Contracts Activity
C_{RP3}	Administrative Assistant Activity
C_{RPC}	Cost of Procurement
C_{RPC1}	Welder
C_{RPC2}	Conveyor
C_{RPC3}	Cranes
C_{RPC4}	Transfer Cask
C_{RPC5}	Temporary Storage Casks

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{RPC6}	Permanent Storage Casks
C_{RPC7}	Tubing
C_{RPC8}	Forklift
C_{RPC9}	HVAC Materials
C_{RPC10}	Carbon
C_{RPC11}	Detectors
C_{RPC12}	Doors
C_{RPC13}	Security Equipment
C_{RPC14}	Computers
C_{RPC15}	Laboratory Equipment
C_{RPT}	Cost of Prototypes and Prototype Testing
C_{RPT1}	Temporary Storage Cask
C_{RPT2}	Storage Cask
C_{RPT3}	Transfer Cask (Prototype is Production Model)
C_{RPT4}	Software
C_{RR}	Cost of Review
C_{RRC}	Cost of Conceptual Design Review
C_{RRC1}	Systems Engineering Activity
C_{RRC2}	Structural Engineering Activity
C_{RRC3}	Nuclear Engineering Activity
C_{RRC4}	Electrical Engineering Activity
C_{RRC5}	HVAC Engineering Activity
C_{RRC6}	Process Engineering Activity

C_{RRC7}	Mechanical Engineering Activity
C_{RRC8}	Maintenance Engineering Activity
C_{RRC9}	Human Factors Engineering Activity
C_{RRC10}	Reliability Engineering Activity
C_{RRD}	Cost of Detail Design Review
C_{RRD1}	Systems Engineering Activity
C_{RRD2}	Structural Engineering Activity
C_{RRD3}	Nuclear Engineering Activity
C_{RRD4}	Electrical Engineering Activity
C_{RRD5}	HVAC Engineering Activity
C_{RRD6}	Process Engineering Activity
C_{RRD7}	Mechanical Engineering Activity
C_{RRD8}	Maintenance Engineering Activity
C_{RRD9}	Human Factors Engineering Activity
C_{RRD10}	Reliability Engineering Activity
C_{RRF}	Cost of Final Design Review
C_{RRF1}	Systems Engineering Activity
C_{RRF2}	Structural Engineering Activity
C_{RRF3}	Nuclear Engineering Activity
C_{RRF4}	Electrical Engineering Activity
C_{RRF5}	HVAC Engineering Activity
C_{RRF6}	Process Engineering Activity
C_{RRF7}	Mechanical Engineering Activity
C_{RRF8}	Maintenance Engineering Activity

Table A-3: Summary of Cost Estimating Terms (Cont.)

C_{RRF9}	Human Factors Engineering Activity
C_{RRF10}	Reliability Engineering Activity
C_{RS}	Cost of Specialty Engineering
C_{RS1}	Maintenance Engineering Activity
C_{RS2}	Human Factors Engineering Activity
C_{RS3}	Reliability Engineering
C_{RTD}	Cost of Training Design
C_{RTD1}	Training for Handling Radium
C_{RTD2}	Training for Processing Radium

Table A-4: Budgetary Cost Estimate

Activity	Year 1	Year 2	Year 3	Year 4
Research and Development (C_R)				
Program Management Cost (C_{RF})	$610,900	$629,227	-	-
Advanced Research (C_{RA})	$1,047,650	-	-	-
Environmental Work (C_{REC})	$301,465	-	-	-
Procurement (C_{RPC})	-	$515,705	-	-
Engineering (C_{RE})	$497,480	-	-	-
Engineering Data (C_{RED})	$172,038	-	-	-
Prototypes and Prototype Testing (C_{RPT})	$53,560	$68,959	-	-
Review (C_{RR})	$497,480	-	-	-
Training Design (C_{RTD})	$86,520	-	-	-
Subtotal	$3,267,093	$1,213,891	$0	$0
		-		
Implementation (C_I)	-	-	-	-
Cost of Office Space Remodeling (C_{IO})	-	$6,198	-	-
Hot Cell Renovation (C_{IH})	-	$102,791	-	-
Radium Storage Installation (C_{IR})	-	$262,877	-	-
Global Construction (C_{IG})	-	$97,447	-	-
Radon Control Installation (C_{IRN})	-	$106,090	-	-
System Review (C_{ISR})	-	$256,914	-	-
Subtotal	$0	$832,317	$0	$0
Operations and Maintenance (C_O)	-	-	-	-
Operations (C_{OO})	-	-	$33,822	$49,145
Maintenance (C_{OOM})	-	-	$86,525	$75,325
Subtotal	$0	$0	$120,348	$124,470
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$3,267,093	$2,046,207	$120,348	$124,470

Table A-4: Budgetary Cost Estimate (Cont.)

Activity	Year 5	Year 6	Year 7	Year 8
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)	-	-	-	-
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)	-	-	-	-
Operations (C_{OO})	$91,686	$136,736	$208,425	$234,813
Maintenance (C_{OOM})	$104,287	$103,435	$121,096	$125,260
Subtotal	$195,973	$240,171	$329,521	$360,073
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$195,973	$240,171	$329,521	$360,073

Table A-4: Budgetary Cost Estimate (Cont.)

Activity	Year 9	Year 10	Year 11	Year 12
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)	-	-	-	-
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$258,444	$313,805	$372,255	$494,157
Maintenance (C_{OOM})	$121,071	$130,452	$145,422	$163,623
Subtotal	$379,515	$444,257	$517,677	$657,780
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$379,515	$444,257	$517,677	$657,780

Table A-4: Budgetary Cost Estimate (Cont.)

Activity	Year 13	Year 14	Year 15	Year 16
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)	-	-	-	-
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$532,324	$567,522	$584,547	$638,530
Maintenance (C_{OOM})	$156,001	$174,410	$167,828	$177,331
Subtotal	$688,324	$741,932	$752,375	$815,861
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$688,324	$741,932	$752,375	$815,861

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Table A-4: Budgetary Cost Estimate (Cont.)

Activity	Year 17	Year 18	Year 19	Year 20
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)	-	-	-	-
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)	-	-	-	-
Operations (C_{OO})	$689,967	$677,417	$697,740	$718,672
Maintenance (C_{OOM})	$207,693	$188,130	$191,509	$210,952
Subtotal	$897,659	$865,547	$889,249	$929,624
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$897,659	$865,547	$889,249	$929,624

Table A-4: Budgetary Cost Estimate (Cont.)

Activity	Year 21	Year 22	Year 23	Year 24
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)	-	-	-	-
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)	-	-	-	-
Operations (C_{OO})	$740,232	$799,860	$785,312	$808,871
Maintenance (C_{OOM})	$203,172	$231,191	$227,964	$224,637
Subtotal	$943,404	$1,031,051	$1,013,276	$1,033,509
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$943,404	$1,031,051	$1,013,276	$1,033,509

Table A-4: Budgetary Cost Estimate (Cont.)

Activity	Year 25	Year 26	Year 27	Year 28
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)	-	-	-	-
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$833,137	$803,301	$588,404	$561,373
Maintenance (C_{OOM})	$228,672	$245,448	$225,345	$211,838
Subtotal	$1,061,810	$1,048,749	$813,750	$773,211
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$1,061,810	$1,048,749	$813,750	$773,211

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Table A-4: Budgetary Cost Estimate (Cont.)

Activity	Year 29	Year 30	Year 31	Year 32	Year 33
Research and Development (C_R)					
Program Management Cost (C_{RF})	-	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-	-
Procurement (C_{RPC})	-	-	-	-	-
Engineering (C_{RE})	-	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-	-
Review (C_{RR})	-	-	-	-	-
Training Design (C_{RTD})	-	-	-	-	-
Subtotal	$0	$0	$0	$0	$0
Implementation (C_I)	-	-	-	-	-
Cost of Office Space Remodeling (C_{IO})	-	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-	-
Global Construction (C_{IG})	-	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-	-
System Review (C_{ISR})	-	-	-	-	-
Subtotal	$0	$0	$0	$0	$0
Operations and Maintenance (C_O)	-	-	-	-	-
Operations (C_{OO})	$578,215	$595,561	$443,080	$222,455	
Maintenance (C_{OOM})	$229,978	$224,739	$217,054	$224,129	
Subtotal	$808,192	$820,300	$660,134	$446,585	$0
Decommissioning (C_D)					
Ceasing Operations (C_{DC})	-	-	-	-	$314,920
Dispatching Excess Isotopes (C_{DE})	-	-	-	-	$0
Radium Storage Decontamination (C_{DR})	-	-	-	-	$663,084
Facility Decontamination (C_{DF})	-	-	-	-	$530,467
Hot Cell Salvage (C_{DHS})	-	-	-	-	$437,635
Equipment Removal (C_{DER})	-	-	-	-	$132,617
Monitoring (C_{DM})	-	-	-	-	$66,308
Subtotal	$0	$0	$0	$0	$2,145,031
Grand Total	$808,192	$820,300	$660,134	$446,585	$2,145,031

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Table A-5: Present Equivalent Cost Estimate

Activity	Year 1	Year 2	Year 3	Year 4
Research and Development (C_R)				
Program Management Cost (C_{RF})	$570,935	$549,592	-	-
Advanced Research (C_{RA})	$979,112	-	-	-
Environmental Work (C_{REC})	$281,743	-	-	-
Procurement (C_{RPC})	-	$450,437	-	-
Engineering (C_{RE})	$464,934	-	-	-
Engineering Data (C_{RED})	$160,783	-	-	-
Prototypes and Prototype Testing (C_{RPT})	$50,056	$60,231	-	-
Review (C_{RR})	$464,934	-	-	-
Training Design (C_{RTD})	$80,860	-	-	-
Subtotal	$3,053,358	$1,060,259	$0	$0
Implementation (C_I)				
Cost of Office Space Remodeling (C_{IO})	-	$5,414	-	-
Hot Cell Renovation (C_{IH})	-	$89,782	-	-
Radium Storage Installation (C_{IR})	-	$229,607	-	-
Global Construction (C_{IG})	-	$85,114	-	-
Radon Control Installation (C_{IRN})	-	$92,663	-	-
System Review (C_{ISR})	-	$224,398	-	-
Subtotal	$0	$726,978	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	-	-	$27,609	$37,492
Maintenance (C_{OOM})	-	-	$70,631	$57,465
Subtotal	$0	$0	$98,240	$94,957
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$3,053,358	$1,787,237	$98,240	$94,957

Table A-5: Present Equivalent Cost Estimate (Cont.)

Activity	Year 5	Year 6	Year 7	Year 8
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)				
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$65,371	$91,113	$129,797	$136,663
Maintenance (C_{OOM})	$74,355	$68,923	$75,412	$72,903
Subtotal	$139,726	$160,036	$205,209	$209,566
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$139,726	$160,036	$205,209	$209,566

Table A-5: Present Equivalent Cost Estimate (Cont.)

Activity	Year 9	Year 10	Year 11	Year 12
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)				
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$140,576	$159,522	$176,856	$219,412
Maintenance (C_{OOM})	$65,855	$66,315	$69,089	$72,651
Subtotal	$206,431	$225,838	$245,944	$292,062
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$206,431	$225,838	$245,944	$292,062

Table A-5: Present Equivalent Cost Estimate (Cont.)

Activity	Year 13	Year 14	Year 15	Year 16
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)				
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$220,895	$220,095	$211,867	$216,292
Maintenance (C_{OOM})	$64,735	$67,639	$60,828	$60,068
Subtotal	$285,630	$287,734	$272,695	$276,360
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$285,630	$287,734	$272,695	$276,360

Table A-5: Present Equivalent Cost Estimate (Cont.)

Activity	Year 17	Year 18	Year 19	Year 20
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)				
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$218,426	$200,423	$192,931	$185,718
Maintenance (C_{OOM})	$65,750	$55,661	$52,954	$54,514
Subtotal	$284,176	$256,084	$245,885	$240,232
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$284,176	$256,084	$245,885	$240,232

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Table A-5: Present Equivalent Cost Estimate (Cont.)

Activity	Year 21	Year 22	Year 23	Year 24
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)				
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$178,776	$180,539	$165,659	$159,466
Maintenance (C_{OOM})	$49,069	$52,183	$48,088	$44,286
Subtotal	$227,844	$232,722	$213,747	$203,753
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$227,844	$232,722	$213,747	$203,753

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Table A-5: Present Equivalent Cost Estimate (Cont.)

Activity	Year 25	Year 26	Year 27	Year 28
Research and Development (C_R)				
Program Management Cost (C_{RF})	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-
Procurement (C_{RPC})	-	-	-	-
Engineering (C_{RE})	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-
Review (C_{RR})	-	-	-	-
Training Design (C_{RTD})	-	-	-	-
Subtotal	$0	$0	$0	$0
Implementation (C_I)				
Cost of Office Space Remodeling (C_{IO})	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-
Global Construction (C_{IG})	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-
System Review (C_{ISR})	-	-	-	-
Subtotal	$0	$0	$0	$0
Operations and Maintenance (C_O)				
Operations (C_{OO})	$153,505	$138,325	$94,692	$84,432
Maintenance (C_{OOM})	$42,133	$42,265	$36,265	$31,861
Subtotal	$195,638	$180,590	$130,957	$116,293
Decommissioning (C_D)				
Ceasing Operations (C_{DC})	-	-	-	-
Dispatching Excess Isotopes (C_{DE})	-	-	-	-
Radium Storage Decontamination (C_{DR})	-	-	-	-
Facility Decontamination (C_{DF})	-	-	-	-
Hot Cell Salvage (C_{DHS})	-	-	-	-
Equipment Removal (C_{DER})	-	-	-	-
Monitoring (C_{DM})	-	-	-	-
Subtotal	$0	$0	$0	$0
Grand Total	$195,638	$180,590	$130,957	$116,293

Table A-5: Present Equivalent Cost Estimate (Cont.)

Activity	Year 29	Year 30	Year 31	Year 32	Year 33
Research and Development (C_R)					
Program Management Cost (C_{RF})	-	-	-	-	-
Advanced Research (C_{RA})	-	-	-	-	-
Environmental Work (C_{REC})	-	-	-	-	-
Procurement (C_{RPC})	-	-	-	-	-
Engineering (C_{RE})	-	-	-	-	-
Engineering Data (C_{RED})	-	-	-	-	-
Prototypes and Prototype Testing (C_{RPT})	-	-	-	-	-
Review (C_{RR})	-	-	-	-	-
Training Design (C_{RTD})	-	-	-	-	-
Subtotal	$0	$0	$0	$0	$0
Implementation (C_I)					
Cost of Office Space Remodeling (C_{IO})	-	-	-	-	-
Hot Cell Renovation (C_{IH})	-	-	-	-	-
Radium Storage Installation (C_{IR})	-	-	-	-	-
Global Construction (C_{IG})	-	-	-	-	-
Radon Control Installation (C_{IRN})	-	-	-	-	-
System Review (C_{ISR})	-	-	-	-	-
Subtotal	$0	$0	$0	$0	$0
Operations and Maintenance (C_O)					
Operations (C_{OO})	$81,275	$78,237	$54,398	$25,525	
Maintenance (C_{OOM})	$32,326	$29,523	$26,648	$25,717	
Subtotal	$113,602	$107,760	$81,047	$51,242	
Decommissioning (C_D)					
Ceasing Operations (C_{DC})	-	-	-	-	$33,770
Dispatching Excess Isotopes (C_{DE})	-	-	-	-	$0
Radium Storage Decontamination (C_{DR})	-	-	-	-	$71,106
Facility Decontamination (C_{DF})	-	-	-	-	$56,884
Hot Cell Salvage (C_{DHS})	-	-	-	-	$46,930
Equipment Removal (C_{DER})	-	-	-	-	$14,221
Monitoring (C_{DM})	-	-	-	-	$7,111
Subtotal	$0	$0	$0	$0	$230,022
Grand Total	$113,602	$107,760	$81,047	$51,242	$230,022

Table A-6: Present Worth of Patients' Future Income Minus Expenses

	Year 1	Year 2	Year 3	Year 4
*P. E.Facility Cost	($3,053,358)	($1,787,237)	($98,240)	($94,957)
P. E. Patient Income for Year 3			($8,919,907)	$21,466,132
P. E. Patient Income for Year 4				($8,586,453)
P. E. Patient Income for Year 5				
P. E. Patient Income for Year 6				
P. E. Patient Income for Year 7				
P. E. Patient Income for Year 8				
P. E. Patient Income for Year 9				
P. E. Patient Income for Year 10				
P. E. Patient Income for Year 11				
P. E. Patient Income for Year 12				
P. E. Patient Income for Year 13				
P. E. Patient Income for Year 14				
P. E. Patient Income for Year 15				
P. E. Patient Income for Year 16				
P. E. Patient Income for Year 17				
P. E. Patient Income for Year 18				
P. E. Patient Income for Year 19				
P. E. Patient Income for Year 20				
P. E. Patient Income for Year 21				
P. E. Patient Income for Year 22				
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P. E. Patient Income for Year 26				
P. E. Patient Income for Year 27				
P. E. Patient Income for Year 28				
P. E. Patient Income for Year 29				
P. E. Patient Income for Year 30				
P. E. Patient Income for Year 31				
P. E. Patient Income for Year 32				
P. E. Patient Income for Year 33				
Grand Total	($3,053,358)	($1,787,237)	($9,018,147)	$12,784,722
*P.E. = Present Equivalent				

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Table A-6: Present Worth of Patients' Future Income Minus Expenses (Cont.)

	Year 5	Year 6	Year 7	Year 8
*P. E. Facility Cost	($139,726)	($160,036)	($205,209)	($209,566)
P. E. Patient Income for Year 3	$20,663,660	$19,891,187	$19,147,591	
P. E. Patient Income for Year 4	$20,663,660	$19,891,187	$19,147,591	$18,431,793
P. E. Patient Income for Year 5	($8,265,464)	$19,891,187	$19,147,591	$18,431,793
P. E. Patient Income for Year 6		($7,956,475)	$19,147,591	$18,431,793
P. E. Patient Income for Year 7			($7,659,036)	$18,431,793
P. E. Patient Income for Year 8				($7,372,717)
P. E. Patient Income for Year 9				
P. E. Patient Income for Year 10				
P. E. Patient Income for Year 11				
P. E. Patient Income for Year 12				
P. E. Patient Income for Year 13				
P. E. Patient Income for Year 14				
P. E. Patient Income for Year 15				
P. E. Patient Income for Year 16				
P. E. Patient Income for Year 17				
P. E. Patient Income for Year 18				
P. E. Patient Income for Year 19				
P. E. Patient Income for Year 20				
P. E. Patient Income for Year 21				
P. E. Patient Income for Year 22				
P. E. Patient Income for Year 23				
P. E. Patient Income for Year 24				
P. E. Patient Income for Year 25				
P. E. Patient Income for Year 26				
P. E. Patient Income for Year 27				
P. E. Patient Income for Year 28				
P. E. Patient Income for Year 29				
P. E. Patient Income for Year 30				
P. E. Patient Income for Year 31				
P. E. Patient Income for Year 32				
P. E. Patient Income for Year 33				
Grand Total	$32,922,130	$51,557,049	$68,726,118	$66,144,889
*P.E. = Present Equivalent				

Table A-6: Present Worth of Patients' Future Income Minus Expenses (Cont.)

	Year 9	Year 10	Year 11	Year 12
*P. E. Facility Cost	($206,431)	($225,838)	($245,944)	($292,062)
P. E. Patient Income for Year 3				
P. E. Patient Income for Year 4				
P. E. Patient Income for Year 5	$17,742,754			
P. E. Patient Income for Year 6	$17,742,754	$17,079,474		
P. E. Patient Income for Year 7	$17,742,754	$17,079,474	$16,440,989	
P. E. Patient Income for Year 8	$17,742,754	$17,079,474	$16,440,989	$15,826,372
P. E. Patient Income for Year 9	($7,097,102)	$17,079,474	$16,440,989	$15,826,372
P. E. Patient Income for Year 10		($6,831,789)	$16,440,989	$15,826,372
P. E. Patient Income for Year 11			($6,576,395)	$15,826,372
P. E. Patient Income for Year 12				($6,330,549)
P. E. Patient Income for Year 13				
P. E. Patient Income for Year 14				
P. E. Patient Income for Year 15				
P. E. Patient Income for Year 16				
P. E. Patient Income for Year 17				
P. E. Patient Income for Year 18				
P. E. Patient Income for Year 19				
P. E. Patient Income for Year 20				
P. E. Patient Income for Year 21				
P. E. Patient Income for Year 22				
P. E. Patient Income for Year 23				
P. E. Patient Income for Year 24				
P. E. Patient Income for Year 25				
P. E. Patient Income for Year 26				
P. E. Patient Income for Year 27				
P. E. Patient Income for Year 28				
P. E. Patient Income for Year 29				
P. E. Patient Income for Year 30				
P. E. Patient Income for Year 31				
P. E. Patient Income for Year 32				
P. E. Patient Income for Year 33				
Grand Total	$63,667,483	$61,260,267	$58,941,614	$56,682,877
*P.E. = Present Equivalent				

Table A-6: Present Worth of Patients' Future Income Minus Expenses (Cont.)

	Year 13	Year 14	Year 15	Year 16
*P. E. Facility Cost	($285,630)	($287,734)	($272,695)	($276,360)
P. E. Patient Income for Year 3				
P. E. Patient Income for Year 4				
P. E. Patient Income for Year 5				
P. E. Patient Income for Year 6				
P. E. Patient Income for Year 7				
P. E. Patient Income for Year 8				
P. E. Patient Income for Year 9	$15,234,732			
P. E. Patient Income for Year 10	$15,234,732	$14,665,209		
P. E. Patient Income for Year 11	$15,234,732	$14,665,209	$14,116,977	
P. E. Patient Income for Year 12	$15,234,732	$14,665,209	$14,116,977	$13,589,240
P. E. Patient Income for Year 13	($6,093,893)	$14,665,209	$14,116,977	$13,589,240
P. E. Patient Income for Year 14		($5,866,084)	$14,116,977	$13,589,240
P. E. Patient Income for Year 15			($5,646,791)	$13,589,240
P. E. Patient Income for Year 16				($5,435,696)
P. E. Patient Income for Year 17				
P. E. Patient Income for Year 18				
P. E. Patient Income for Year 19				
P. E. Patient Income for Year 20				
P. E. Patient Income for Year 21				
P. E. Patient Income for Year 22				
P. E. Patient Income for Year 23				
P. E. Patient Income for Year 24				
P. E. Patient Income for Year 25				
P. E. Patient Income for Year 26				
P. E. Patient Income for Year 27				
P. E. Patient Income for Year 28				
P. E. Patient Income for Year 29				
P. E. Patient Income for Year 30				
P. E. Patient Income for Year 31				
P. E. Patient Income for Year 32				
P. E. Patient Income for Year 33				
Grand Total	$54,559,405	$52,507,020	$50,548,423	$48,644,903
*P.E. = Present Equivalent				

Table A-6: Present Worth of Patients' Future Income Minus Expenses (Cont.)

	Year 17	Year 18	Year 19	Year 20
*P. E. Facility Cost	($284,176)	($256,084)	($245,885)	($240,232)
P. E. Patient Income for Year 3				
P. E. Patient Income for Year 4				
P. E. Patient Income for Year 5				
P. E. Patient Income for Year 6				
P. E. Patient Income for Year 7				
P. E. Patient Income for Year 8				
P. E. Patient Income for Year 9				
P. E. Patient Income for Year 10				
P. E. Patient Income for Year 11				
P. E. Patient Income for Year 12				
P. E. Patient Income for Year 13	$13,081,231			
P. E. Patient Income for Year 14	$13,081,231	$12,592,213		
P. E. Patient Income for Year 15	$13,081,231	$12,592,213	$12,121,476	
P. E. Patient Income for Year 16	$13,081,231	$12,592,213	$12,121,476	$11,668,337
P. E. Patient Income for Year 17	($5,232,492)	$12,592,213	$12,121,476	$11,668,337
P. E. Patient Income for Year 18		($5,036,885)	$12,121,476	$11,668,337
P. E. Patient Income for Year 19			($4,848,590)	$11,668,337
P. E. Patient Income for Year 20				($4,667,335)
P. E. Patient Income for Year 21				
P. E. Patient Income for Year 22				
P. E. Patient Income for Year 23				
P. E. Patient Income for Year 24				
P. E. Patient Income for Year 25				
P. E. Patient Income for Year 26				
P. E. Patient Income for Year 27				
P. E. Patient Income for Year 28				
P. E. Patient Income for Year 29				
P. E. Patient Income for Year 30				
P. E. Patient Income for Year 31				
P. E. Patient Income for Year 32				
P. E. Patient Income for Year 33				
Grand Total	$46,808,255	$45,075,882	$43,391,428	$41,765,779
*P.E. = Present Equivalent				

Table A-6: Present Worth of Patients' Future Income Minus Expenses (Cont.)

	Year 21	Year 22	Year 23	Year 24
*P. E. Facility Cost	($227,844)	($232,722)	($213,747)	($203,753)
P. E. Patient Income for Year 3				
P. E. Patient Income for Year 4				
P. E. Patient Income for Year 5				
P. E. Patient Income for Year 6				
P. E. Patient Income for Year 7				
P. E. Patient Income for Year 8				
P E. Patient Income for Year 9				
P. E. Patient Income for Year 10				
P. E. Patient Income for Year 11				
P. E. Patient Income for Year 12				
P. E. Patient Income for Year 13				
P. E. Patient Income for Year 14				
P. E. Patient Income for Year 15				
P. E. Patient Income for Year 16				
P. E. Patient Income for Year 17	$11,232,137			
P. E. Patient Income for Year 18	$11,232,137	$10,812,244		
P. E. Patient Income for Year 19	$11,232,137	$10,812,244	$10,408,048	
P. E. Patient Income for Year 20	$11,232,137	$10,812,244	$10,408,048	$10,018,962
P. E. Patient Income for Year 21	($4,492,855)	$10,812,244	$10,408,048	$10,018,962
P. E. Patient Income for Year 22		($4,324,898)	$10,408,048	$10,018,962
P. E. Patient Income for Year 23			($4,163,219)	$10,018,962
P. E. Patient Income for Year 24				($4,007,585)
P. E. Patient Income for Year 25				
P. E. Patient Income for Year 26				
P. E. Patient Income for Year 27				
P. E. Patient Income for Year 28				
P. E. Patient Income for Year 29				
P. E. Patient Income for Year 30				
P. E. Patient Income for Year 31				
P. E. Patient Income for Year 32				
P. E. Patient Income for Year 33				
Grand Total	$40,207,849	$38,691,357	$37,255,226	$35,864,511
*P.E. = Present Equivalent				

Table A-6: Present Worth of Patients' Future Income Minus Expenses (Cont.)

	Year 25	Year 26	Year 27	Year 28
*P. E. Facility Cost	($195,638)	($180,590)	($130,957)	($116,293)
P. E. Patient Income for Year 3				
P. E. Patient Income for Year 4				
P. E. Patient Income for Year 5				
P. E. Patient Income for Year 6				
P. E. Patient Income for Year 7				
P. E. Patient Income for Year 8				
P. E. Patient Income for Year 9				
P. E. Patient Income for Year 10				
P. E. Patient Income for Year 11				
P. E. Patient Income for Year 12				
P. E. Patient Income for Year 13				
P. E. Patient Income for Year 14				
P. E. Patient Income for Year 15				
P. E. Patient Income for Year 16				
P. E. Patient Income for Year 17				
P. E. Patient Income for Year 18				
P. E. Patient Income for Year 19				
P. E. Patient Income for Year 20				
P. E. Patient Income for Year 21	$9,644,422			
P. E. Patient Income for Year 22	$9,644,422	$9,283,882		
P. E. Patient Income for Year 23	$9,644,422	$9,283,882	$8,936,821	
P. E. Patient Income for Year 24	$9,644,422	$9,283,882	$8,936,821	$8,602,735
P. E. Patient Income for Year 25	($3,857,769)	$9,283,882	$8,936,821	$8,602,735
P. E. Patient Income for Year 26		($3,713,553)	$8,936,821	$8,602,735
P. E. Patient Income for Year 27			($3,574,729)	$8,602,735
P. E. Patient Income for Year 28				($3,441,094)
P. E. Patient Income for Year 29				
P. E. Patient Income for Year 30				
P. E. Patient Income for Year 31				
P. E. Patient Income for Year 32				
P. E. Patient Income for Year 33				
Grand Total	$34,524,280	$33,241,387	$32,041,600	$30,853,552
*P.E. = Present Equivalent				

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Table A-6: Present Worth of Patients' Future Income Minus Expenses (Cont.)

	Year 29	Year 30	Year 31	Year 32	Year 33
*P. E. Facility Cost	($113,602)	($107,760)	($81,047)	($51,242)	($230,022)
P. E. Patient Income for Year 3					
P. E. Patient Income for Year 4					
P. E. Patient Income for Year 5					
P. E. Patient Income for Year 6					
P. E. Patient Income for Year 7					
P. E. Patient Income for Year 8					
P. E. Patient Income for Year 9					
P. E. Patient Income for Year 10					
P. E. Patient Income for Year 11					
P. E. Patient Income for Year 12					
P. E. Patient Income for Year 13					
P. E. Patient Income for Year 14					
P. E. Patient Income for Year 15					
P. E. Patient Income for Year 16					
P. E. Patient Income for Year 17					
P. E. Patient Income for Year 18					
P. E. Patient Income for Year 19					
P. E. Patient Income for Year 20					
P. E. Patient Income for Year 21					
P. E. Patient Income for Year 22					
P. E. Patient Income for Year 23					
P. E. Patient Income for Year 24					
P. E. Patient Income for Year 25	$8,281,137				
P. E. Patient Income for Year 26	$8,281,137	$7,971,562			
P. E. Patient Income for Year 27	$8,281,137	$7,971,562	$7,673,560		
P. E. Patient Income for Year 28	$8,281,137	$7,971,562	$7,673,560	$7,386,697	
P. E. Patient Income for Year 29	($3,312,455)	$7,971,562	$7,673,560	$7,386,697	$7,110,559
P. E. Patient Income for Year 30		($3,188,625)	$7,673,560	$7,386,697	$7,110,559
P. E. Patient Income for Year 31			($3,069,424)	$7,386,697	$7,110,559
P. E. Patient Income for Year 32				($2,954,679)	$7,110,559
P. E. Patient Income for Year 33					($2,844,224)
Grand Total	$29,698,492	$28,589,862	$27,543,768	$26,540,869	$25,367,992
*P.E. = Present Equivalent					

Table A-6: Present Worth of Patients' Future Income Minus Expenses (Cont.)

	Grand Total for Patients of All Years
P. E.* Facility Cost	($10,952,617)
P. E. Patient Income for Year 3	$72,248,662
P. E. Patient Income for Year 4	$69,547,777
P. E. Patient Income for Year 5	$66,947,860
P. E. Patient Income for Year 6	$64,445,137
P. E. Patient Income for Year 7	$62,035,973
P. E. Patient Income for Year 8	$59,716,871
P. E. Patient Income for Year 9	$57,484,465
P. E. Patient Income for Year 10	$55,335,513
P. E. Patient Income for Year 11	$53,266,895
P. E. Patient Income for Year 12	$51,275,610
P. E. Patient Income for Year 13	$49,358,764
P. E. Patient Income for Year 14	$47,513,577
P. E. Patient Income for Year 15	$45,737,368
P. E. Patient Income for Year 16	$44,027,560
P. E. Patient Income for Year 17	$42,381,670
P. E. Patient Income for Year 18	$40,797,309
P. E. Patient Income for Year 19	$39,272,176
P. E. Patient Income for Year 20	$37,804,057
P. E. Patient Income for Year 21	$36,390,821
P. E. Patient Income for Year 22	$35,030,417
P. E. Patient Income for Year 23	$33,720,868
P. E. Patient Income for Year 24	$32,460,275
P. E. Patient Income for Year 25	$31,246,807
P. E. Patient Income for Year 26	$30,078,702
P. E. Patient Income for Year 27	$28,954,264
P. E. Patient Income for Year 28	$27,871,862
P. E. Patient Income for Year 29	$26,829,923
P. E. Patient Income for Year 30	$18,982,192
P. E. Patient Income for Year 31	$11,427,833
P. E. Patient Income for Year 32	$4,155,880
P. E. Patient Income for Year 33	($2,844,224)
Grand Total	$1,262,550,247
*P.E. = Present Equivalent	

APPENDIX B
FUNCTIONAL FLOW DIAGRAM

Functional Flow
Diagram

For Radium Storage and Processing Facility

Figure 19: Cover Sheet for Functional Flow Diagram

Functional Flow
Diagram

For Radium Storage and Processing
Facility

1.0	2.0	3.0	4.0
Plan Facility	Establish Facility	Operate Facility	Decommission Facility

Legend

Function Block

Reference Block

Functional Flow Arrows

Reference Arrows

AND — Summing Gate for Parallel Functions

OR — Summing Gate for Alternative Functions

2.2.1 ◄——— **Function Number:**
Level of indenture equals
number of decimals plus one
except for numbers ending in zero.
For numbers ending in zero,
level of indenture equals number
of decimals.

Install HVAC

Figure 20: Functional Flow Diagram Showing Top Level Functions
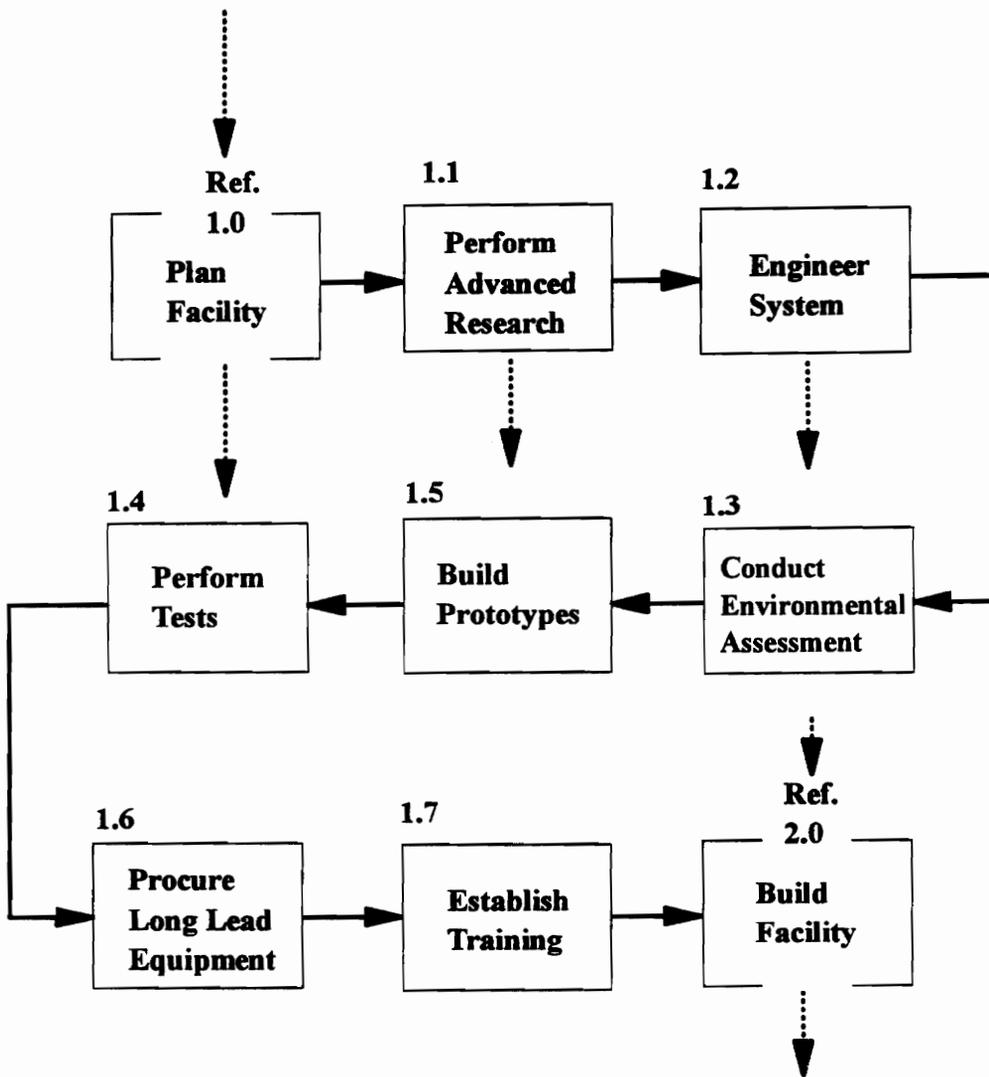
Figure 21: Subfunctions of Function 1.0

138
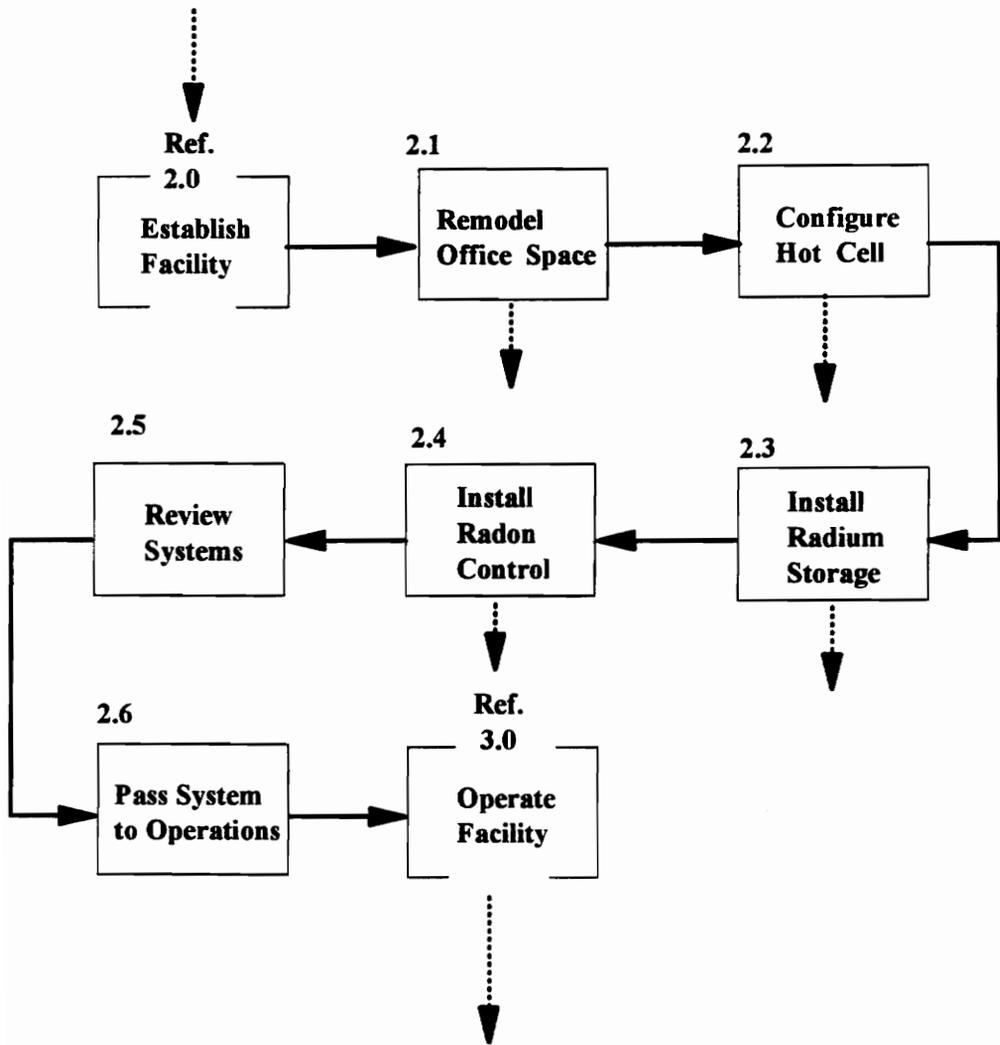
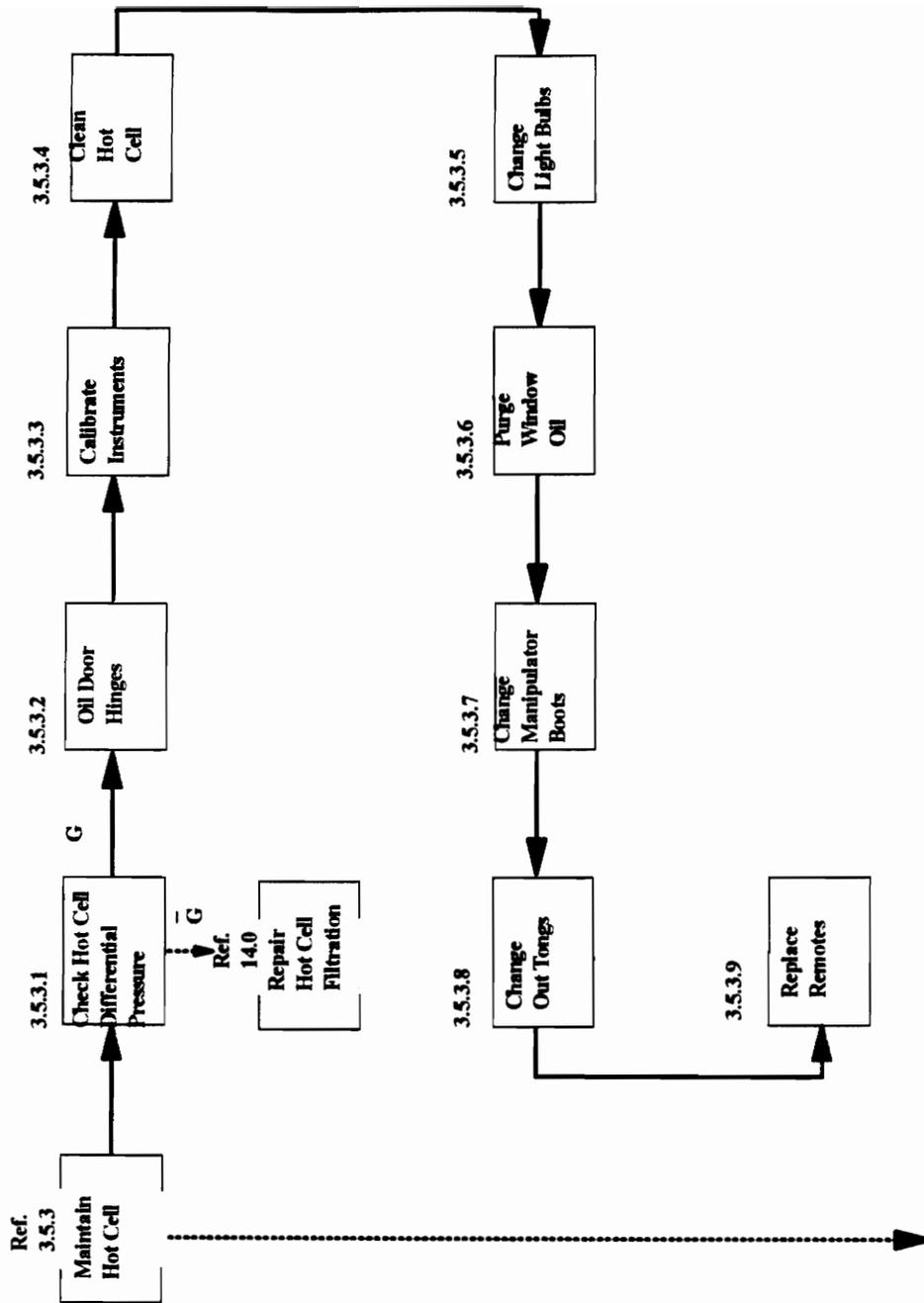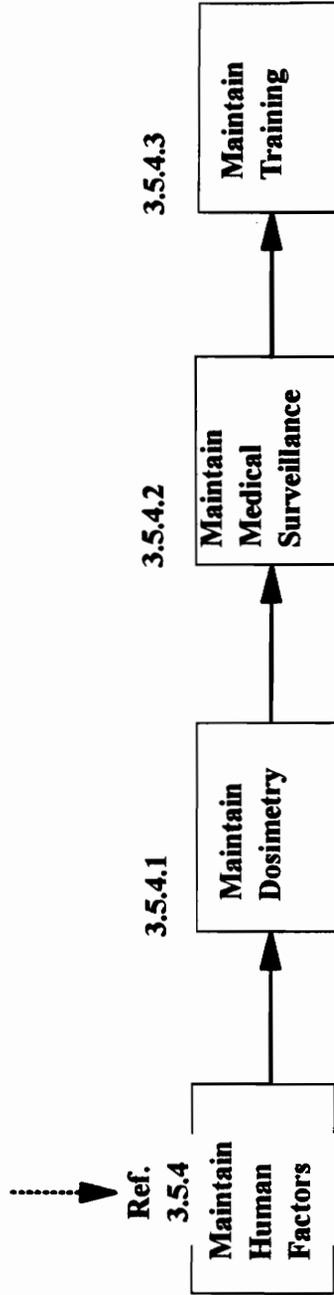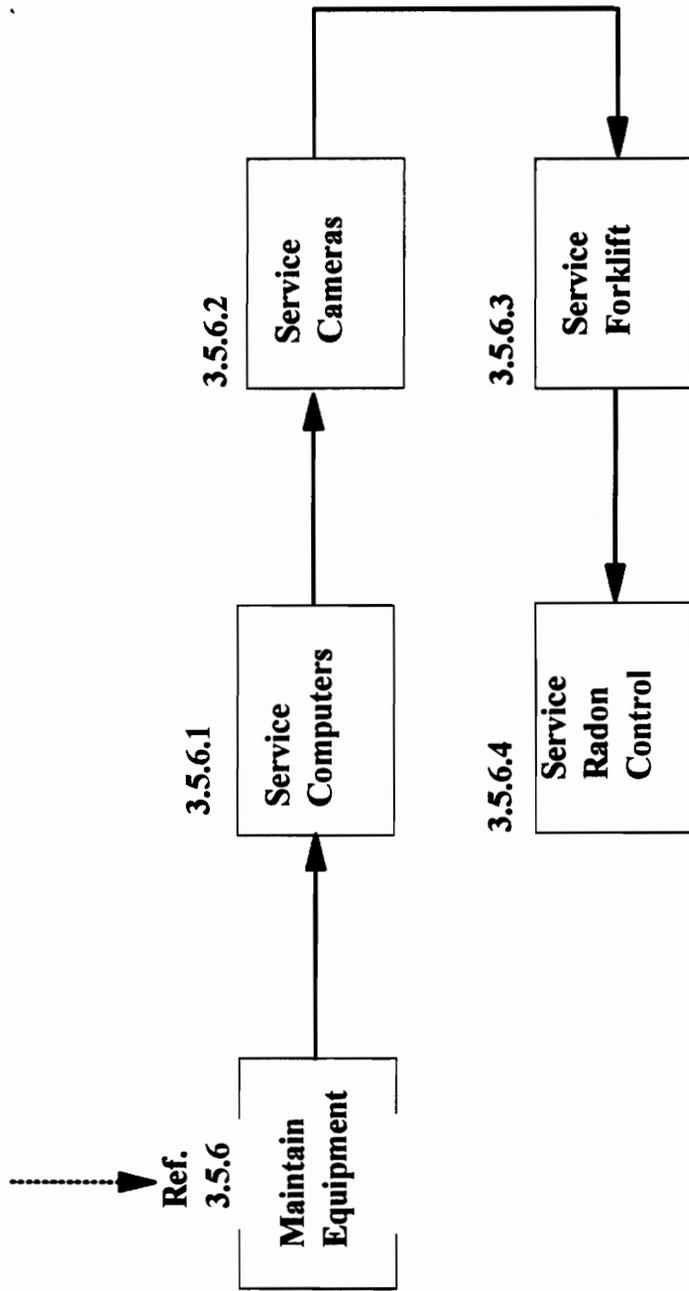**Figure 22: Subfunctions of Function 2.0**

139
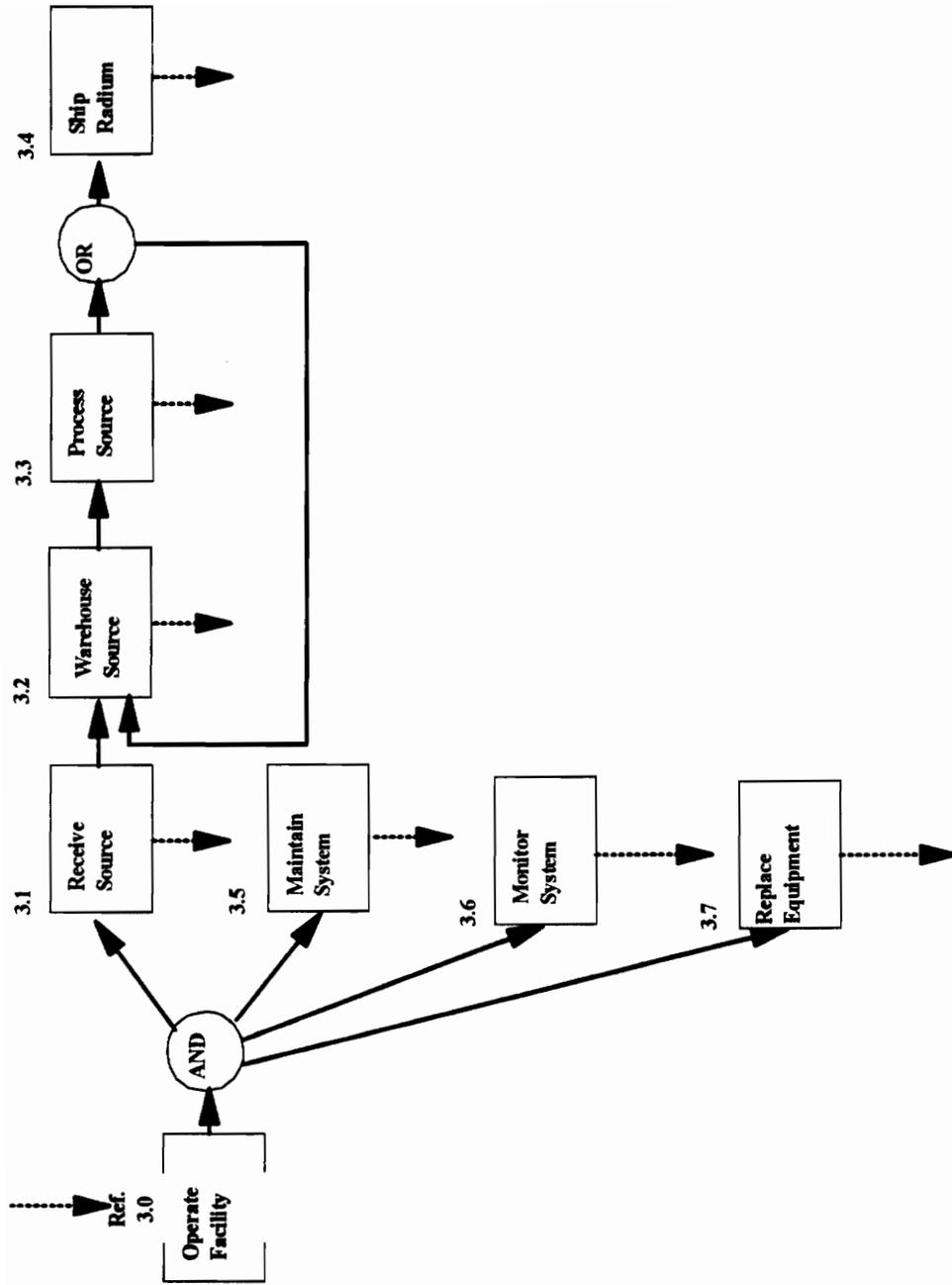
Figure 23: Subfunctions of Function 3.0

140
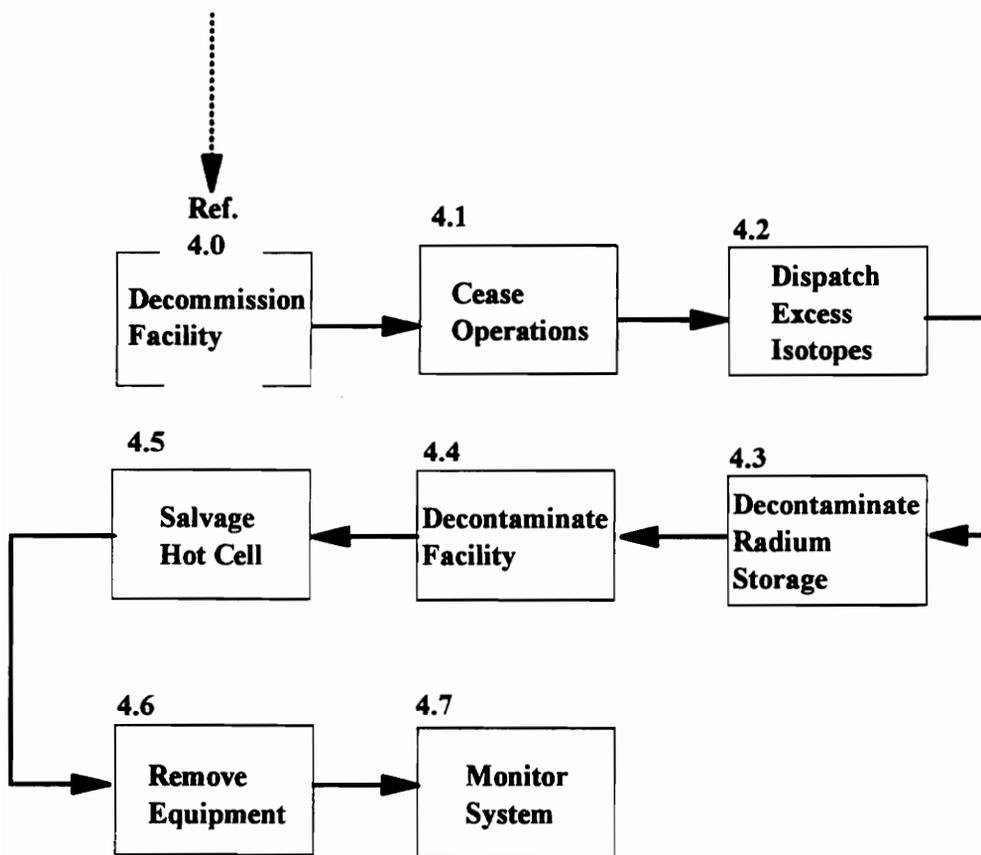
Figure 24: Subfunctions of Function 4.0

141
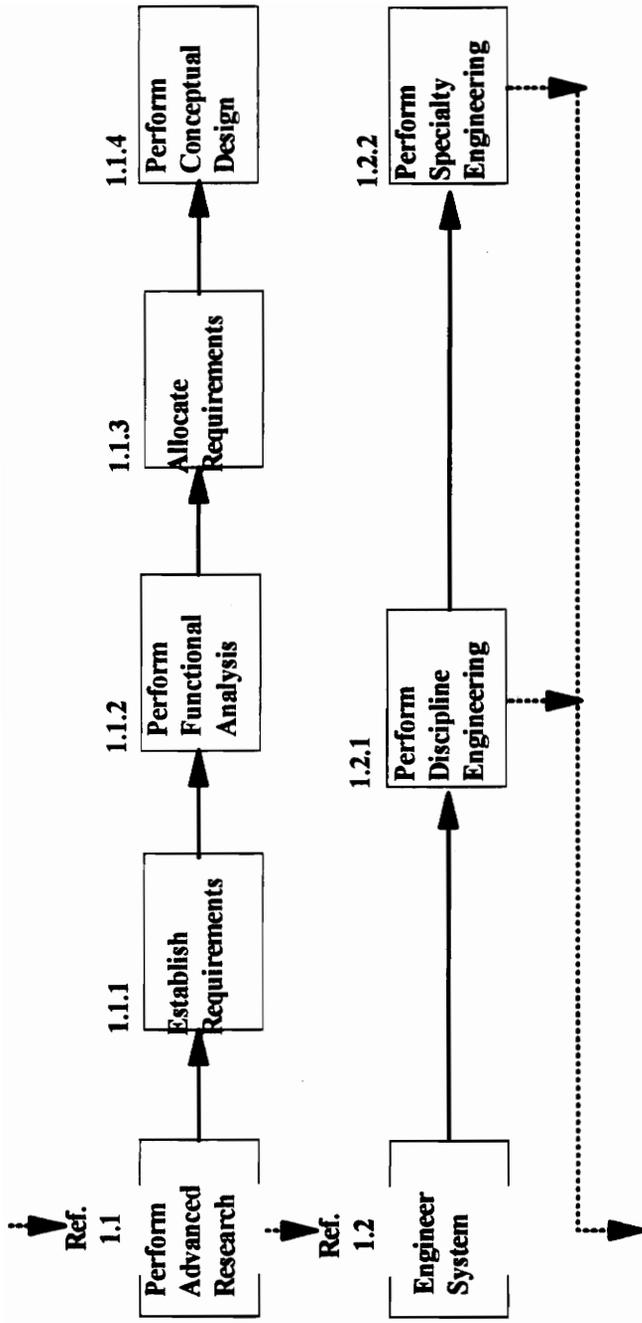
Figure 25: Subfunctions of Subfunctions 1.1 and 1.2

142
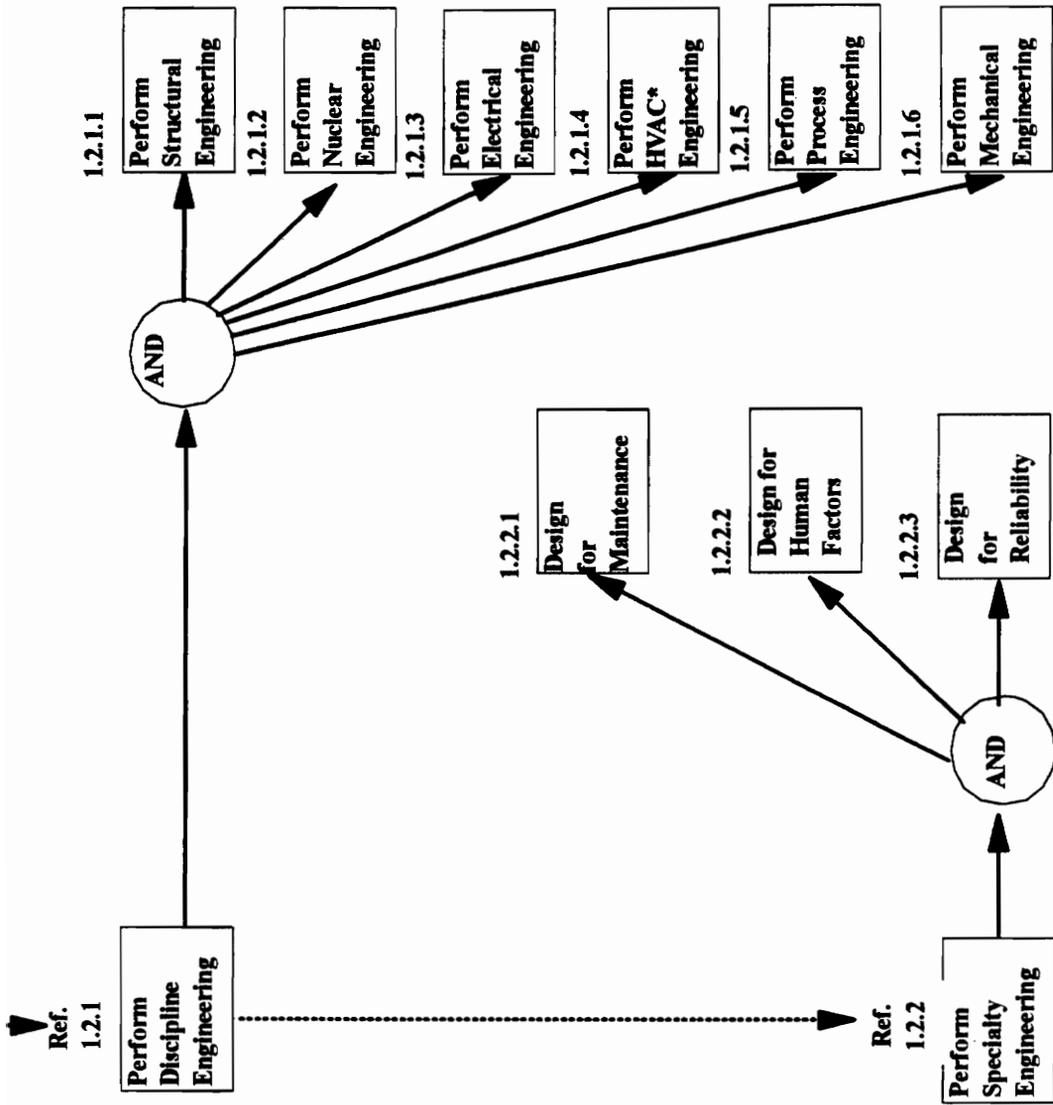
Figure 26: Subfunctions of Subfunctions 1.2.1 and 1.2.2

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Ref.
2.1

| Remodel Office Space |
| 2.1.1 Install Partitions |
| 2.1.2 Install Computers |
| 2.1.3 Install Furniture |
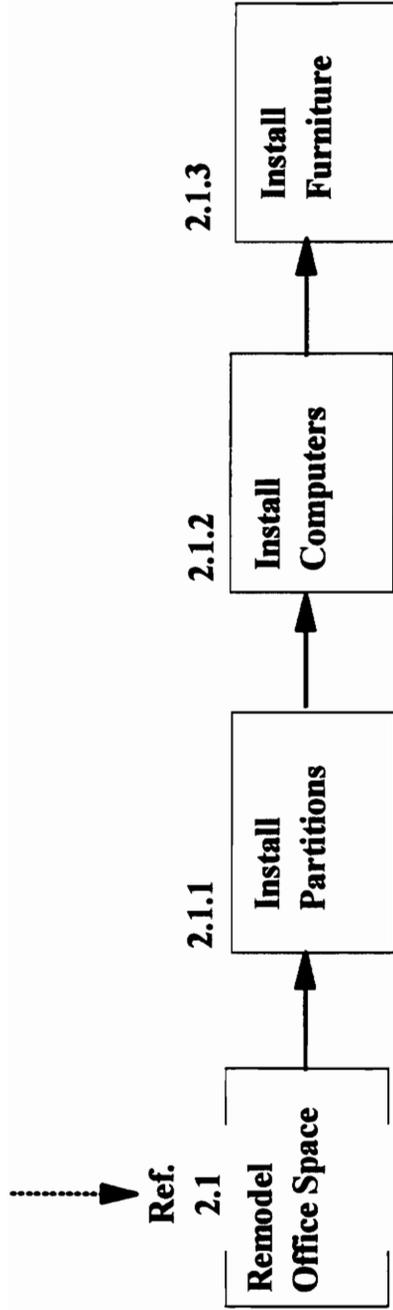
Figure 27: Subfunctions of Subfunction 2.1

144
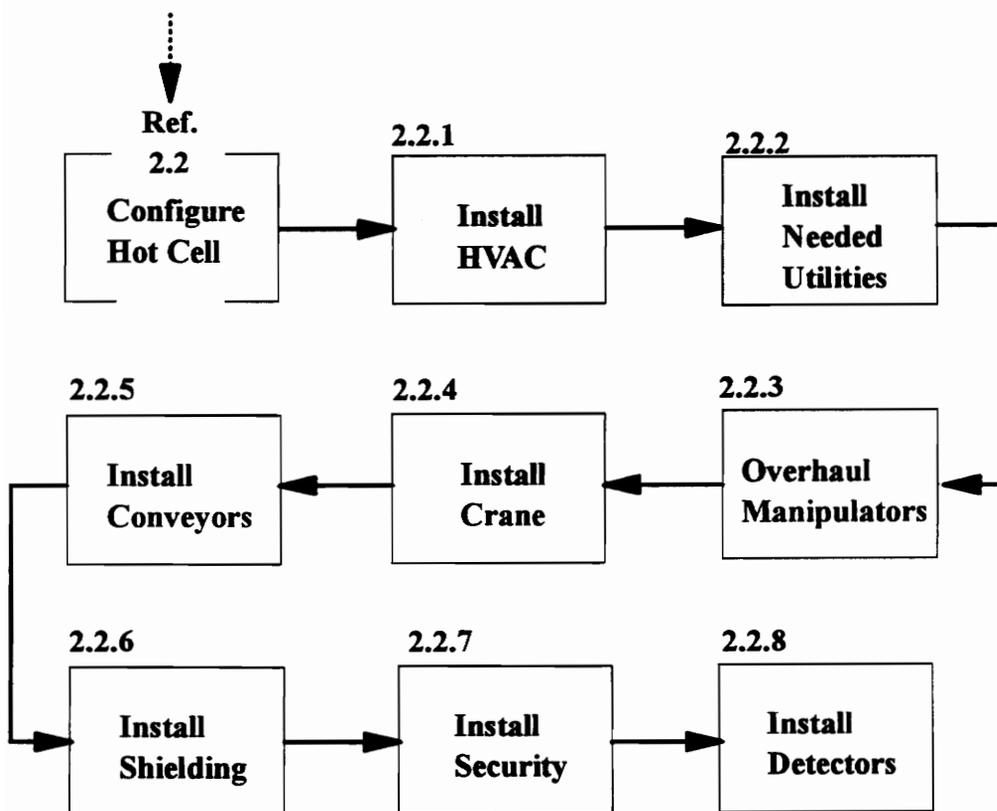
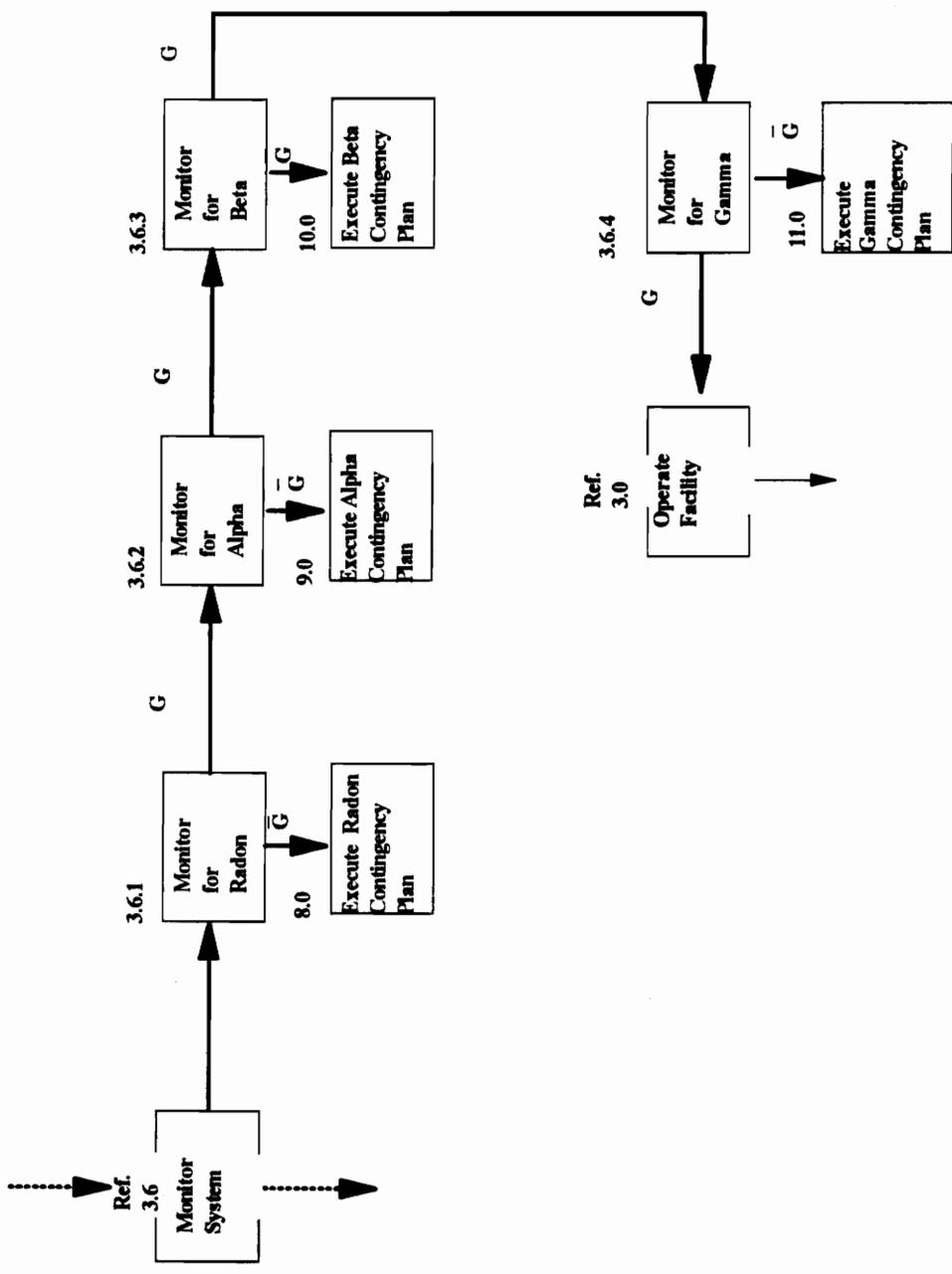**Figure 28: Subfunctions of Function 2.2**

145
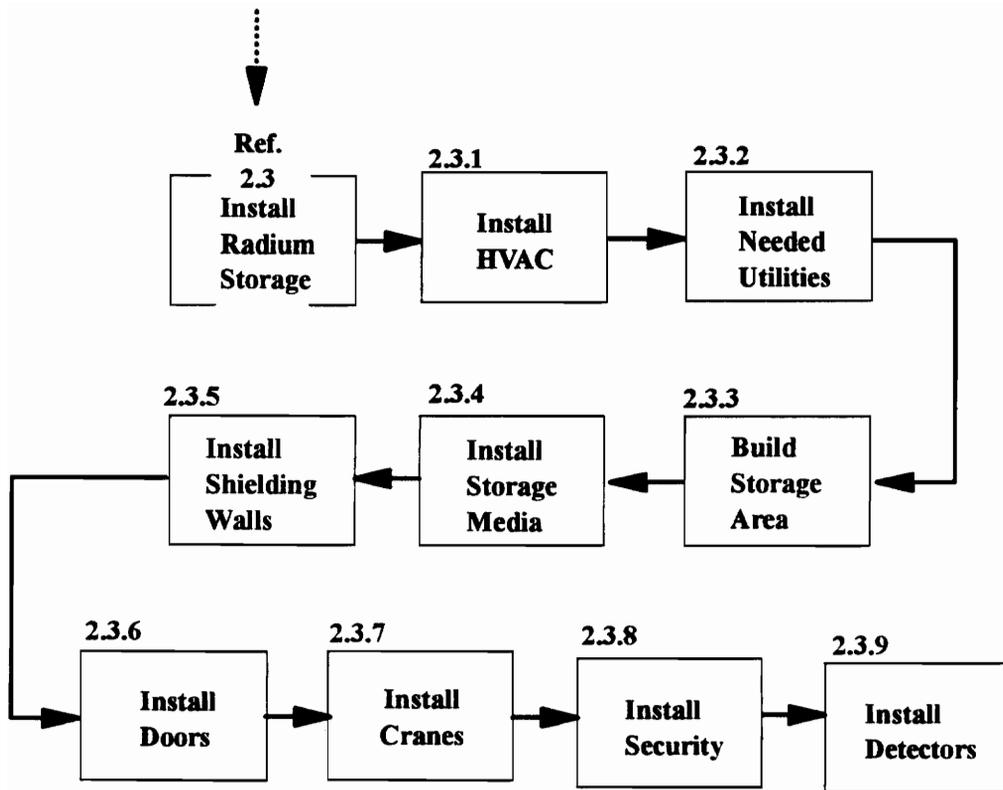
Figure 29: Subfunctions of Subfunction 2.3
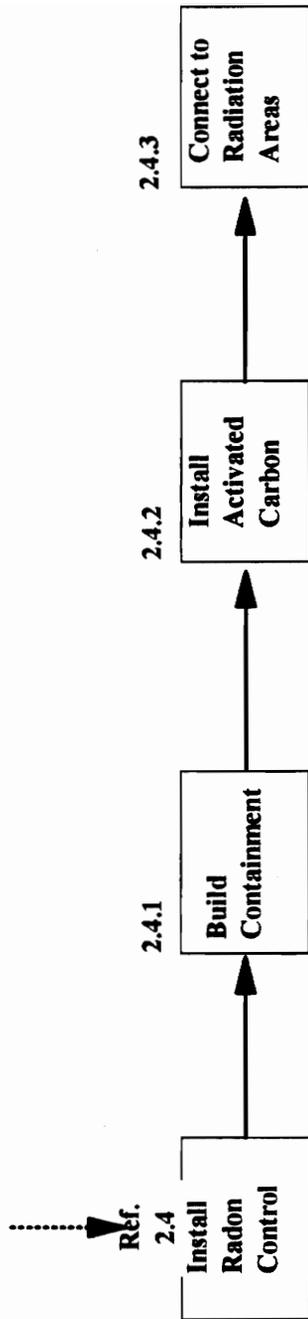
Figure 30: Subfunctions of Subfunction 2.4

147
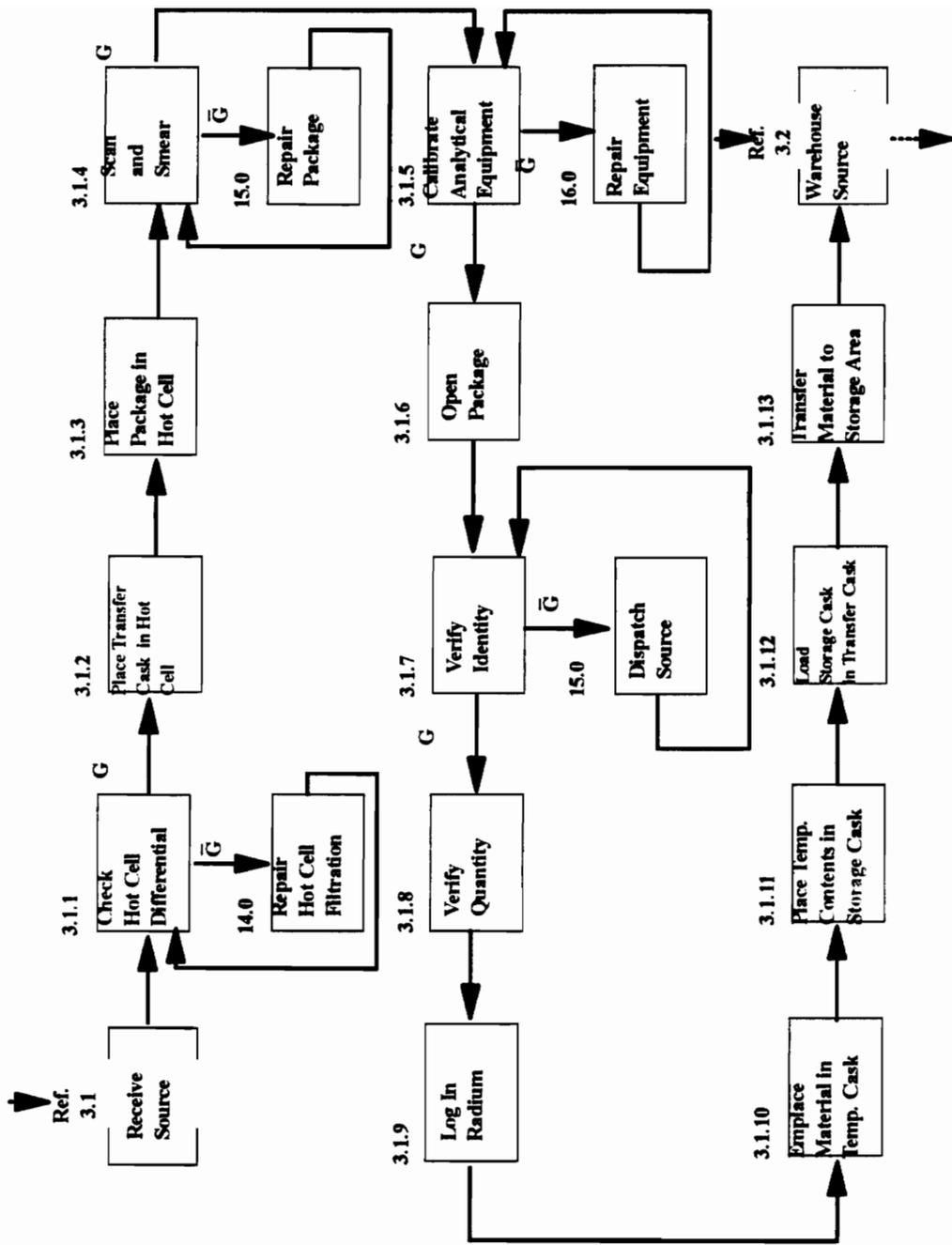
Figure 31: Subfunctions of Function 3.1

148
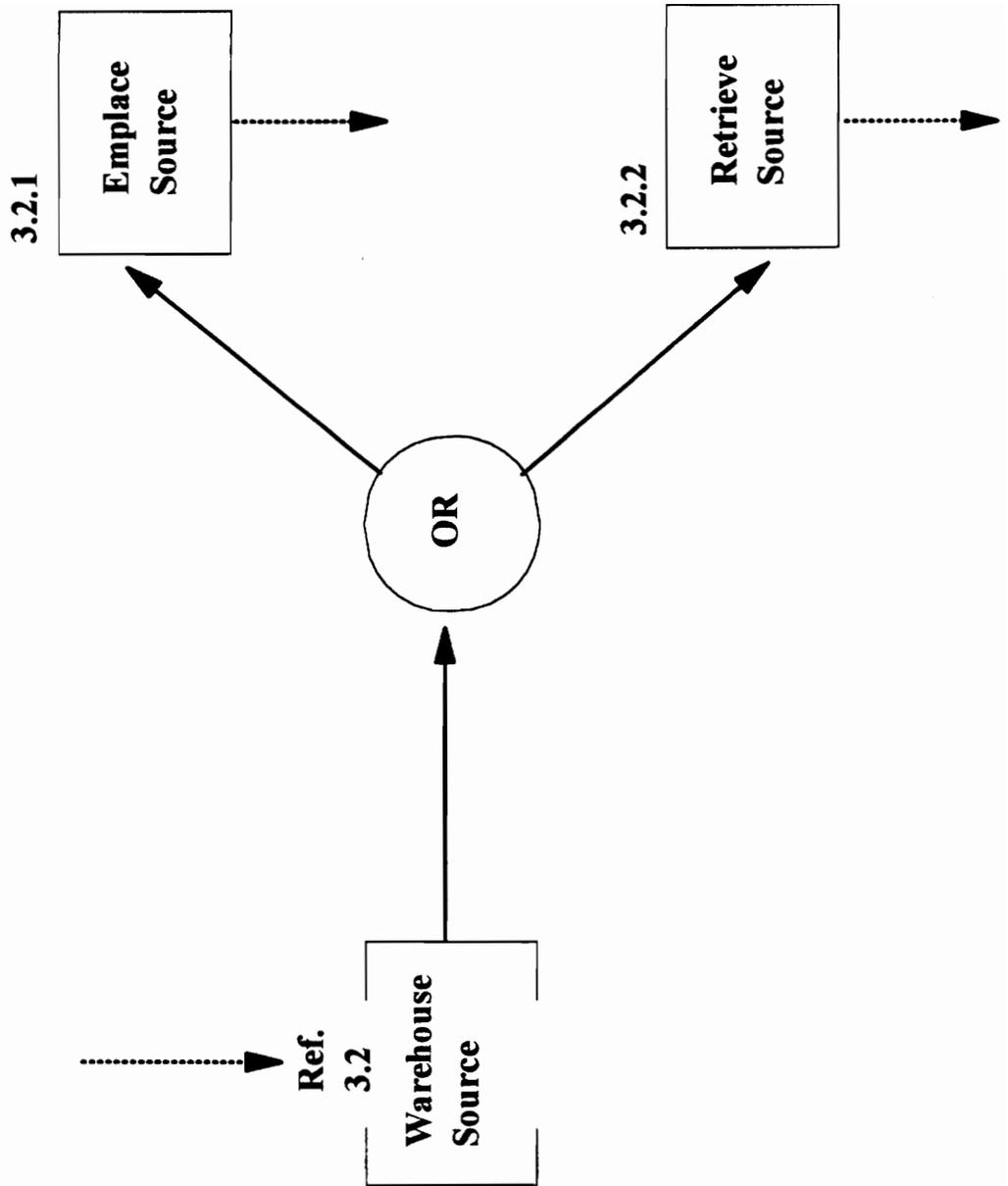
Figure 32: Subfunctions of Subfunction 3.2

149
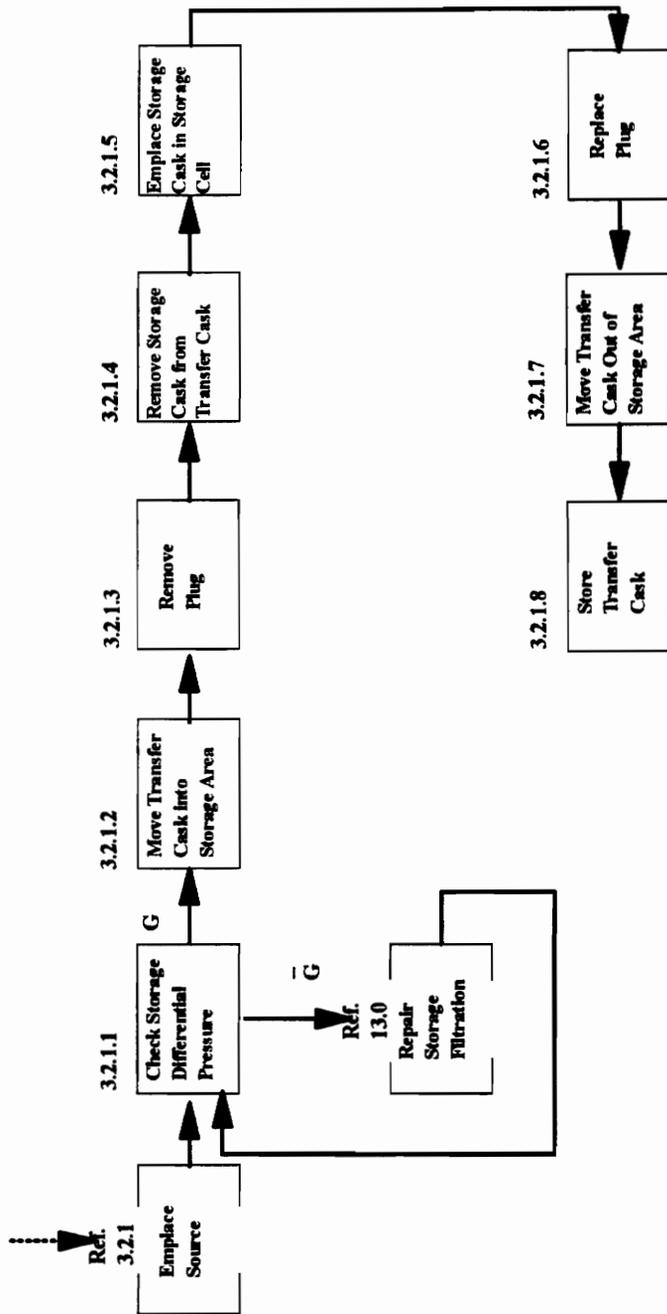
Figure 33: Subfunctions of Subfunction 3.2.1

150
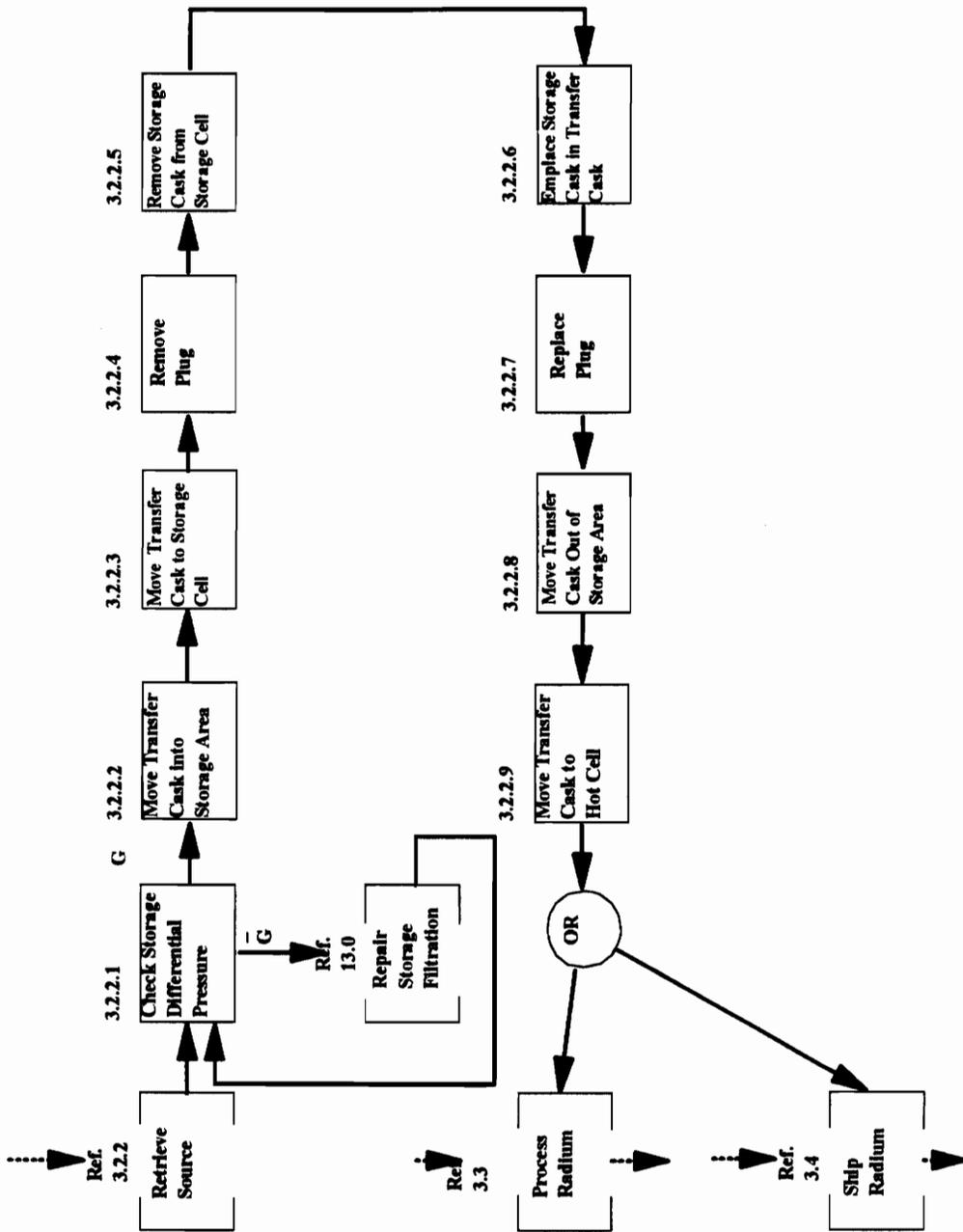
Figure 34: Subfunctions of Sufunction 3.2.2

151
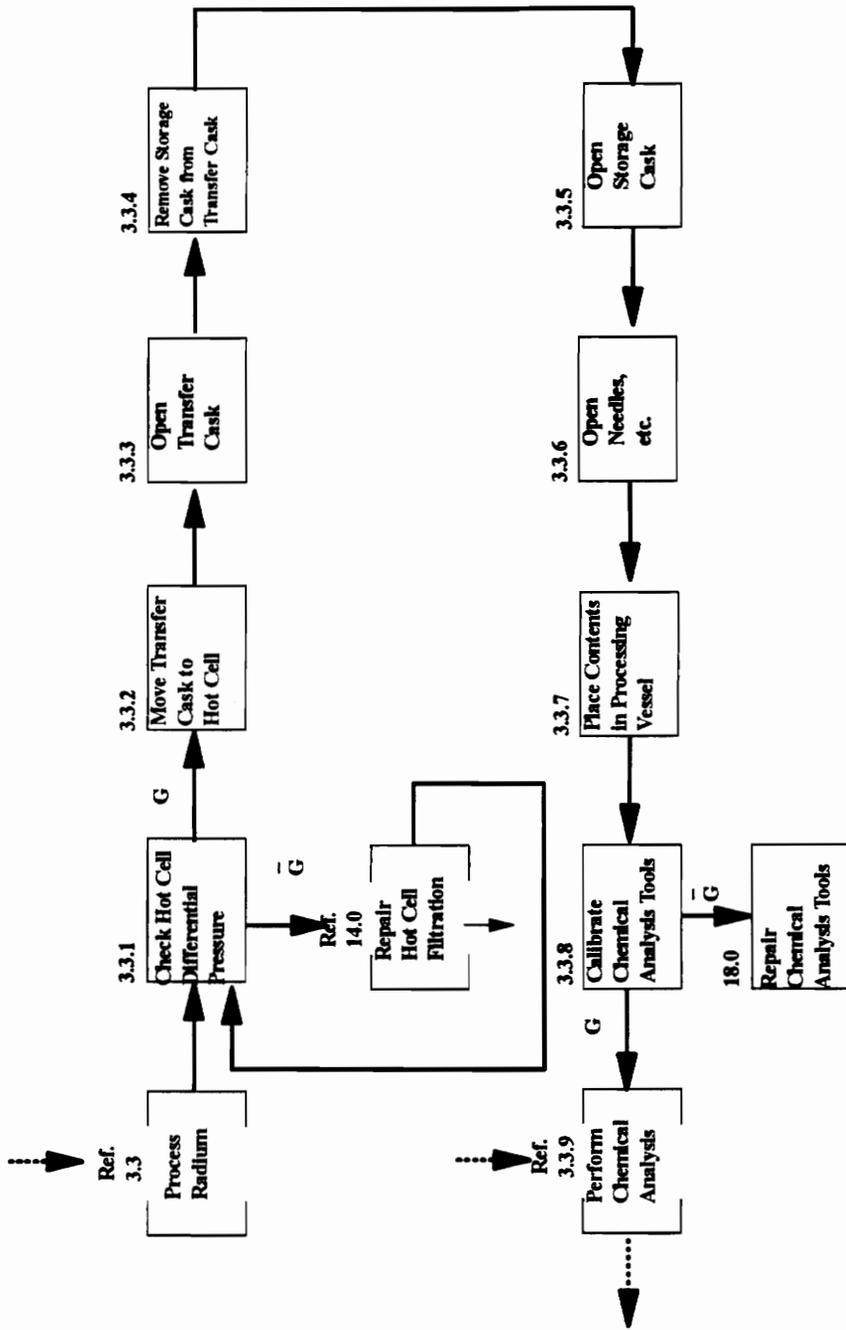
Function 35: Subfunctions of Subfunction 3.3

152
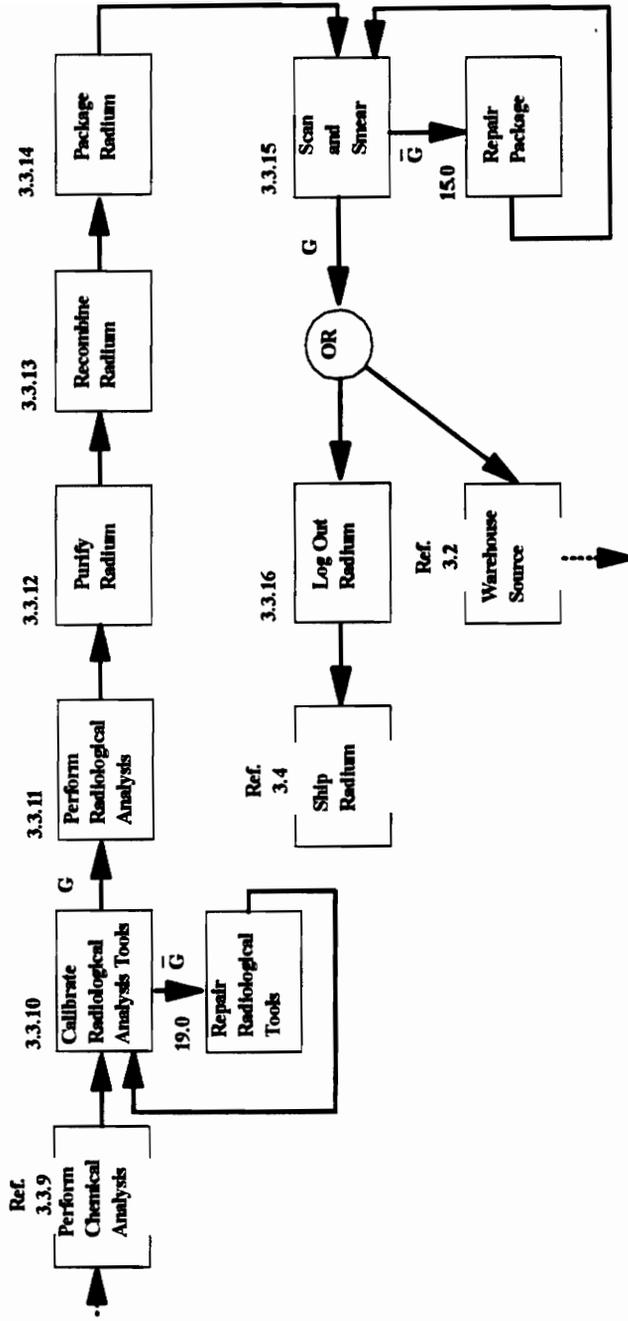
Figure 36: Subfunctions of Subfunction 3.3 (Cont.)

153
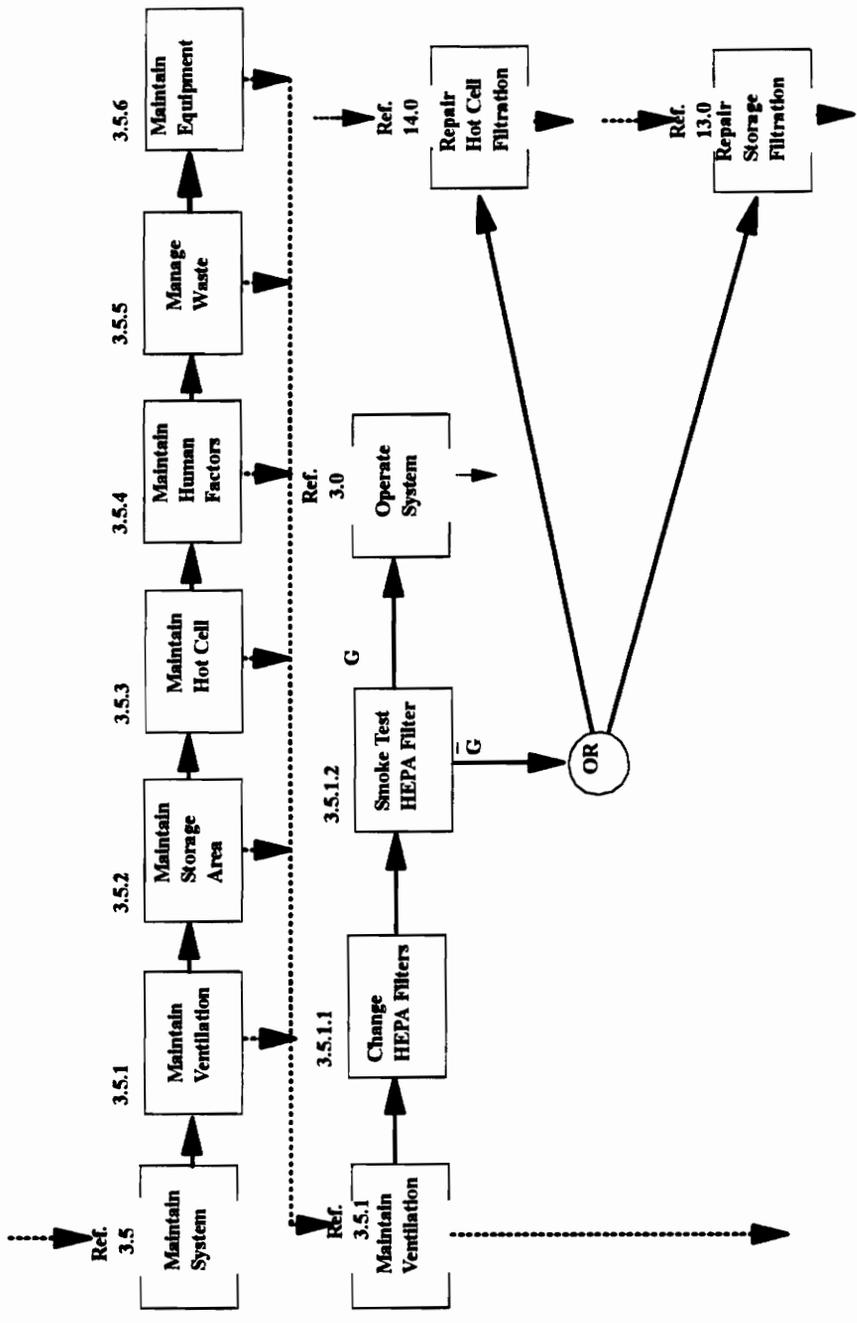
Figure 37: Subfunctions of Subfunctions 3.5 and 3.5.1

154
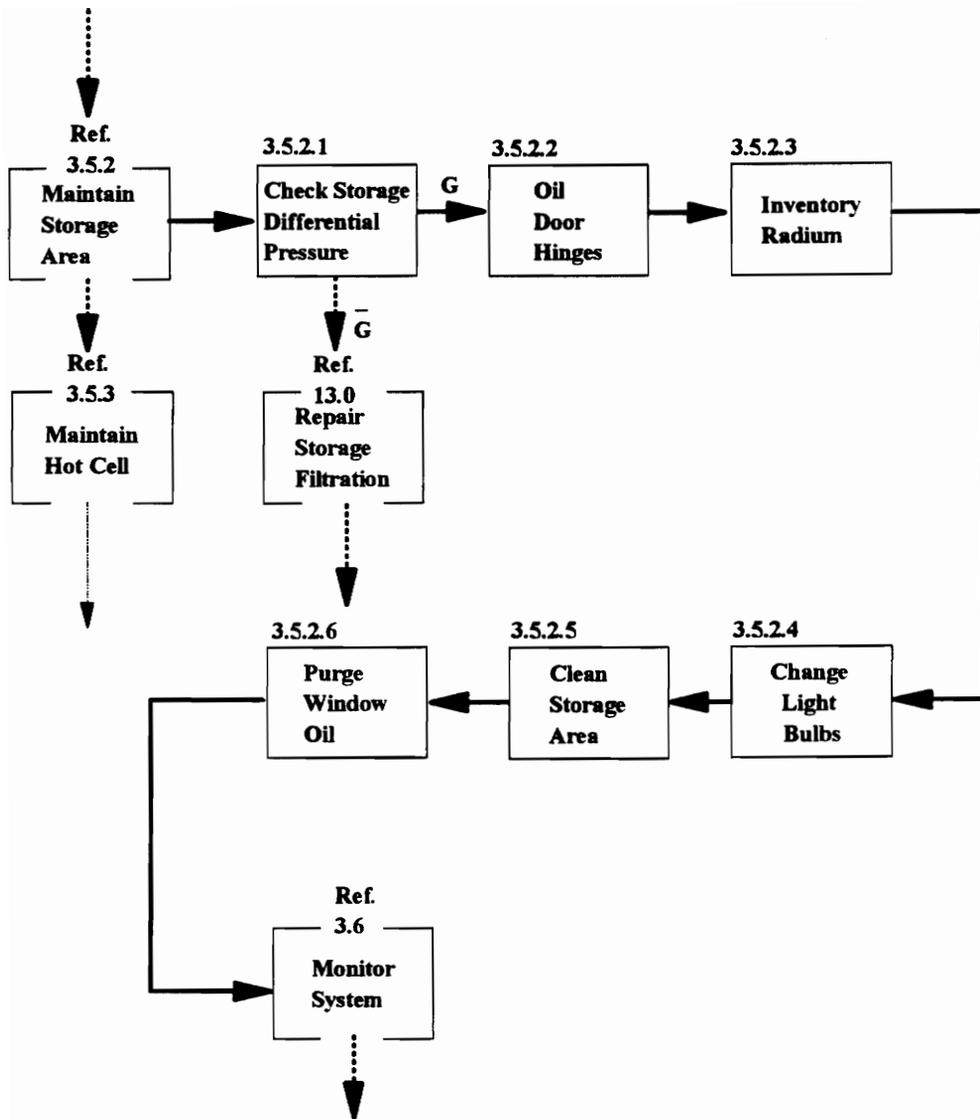
Figure 38: Subfunctions of Subfunction 3.5.2

155

Figure 39: Subfunctions of Subfunction 3.5.3

156

Figure 40: Subfunctions of Subfunction 3.5.4
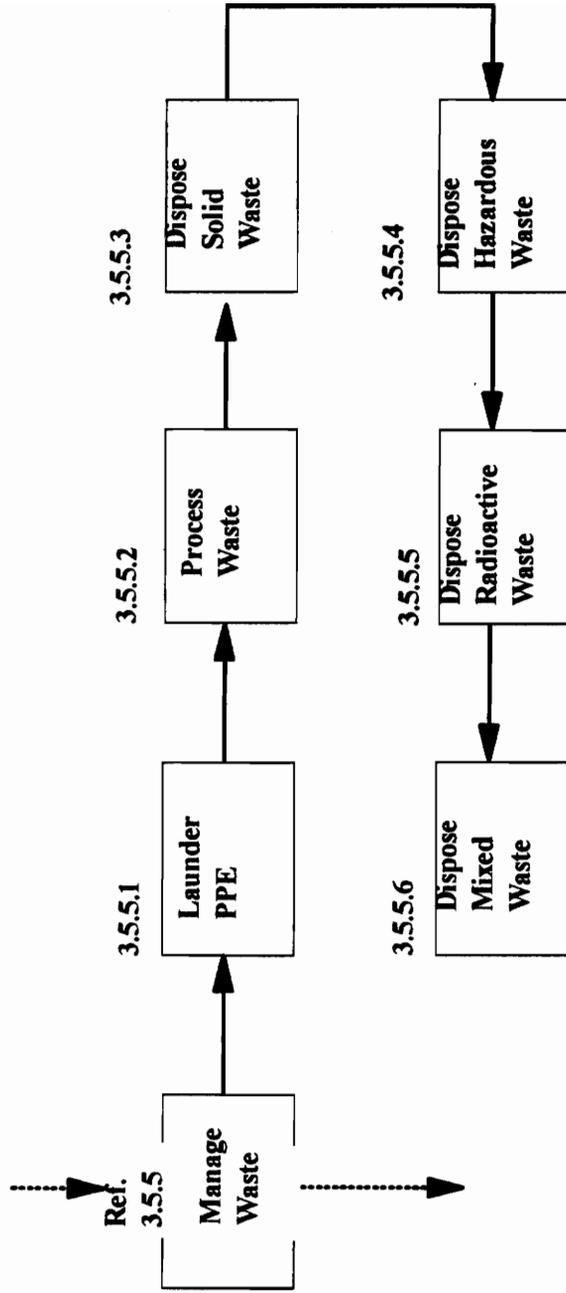
Figure 41: Subfunctions of Subfunction 3.5.5

158

Figure 42: Subfunctions of Subfunction 3.5.6

159

Figure 43: Subfunctions of Subfunction 3.6
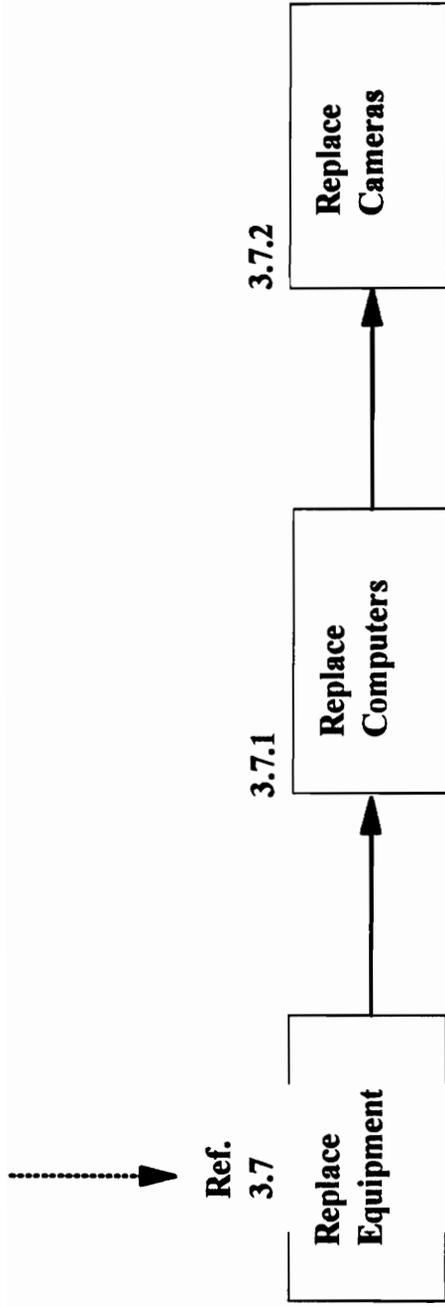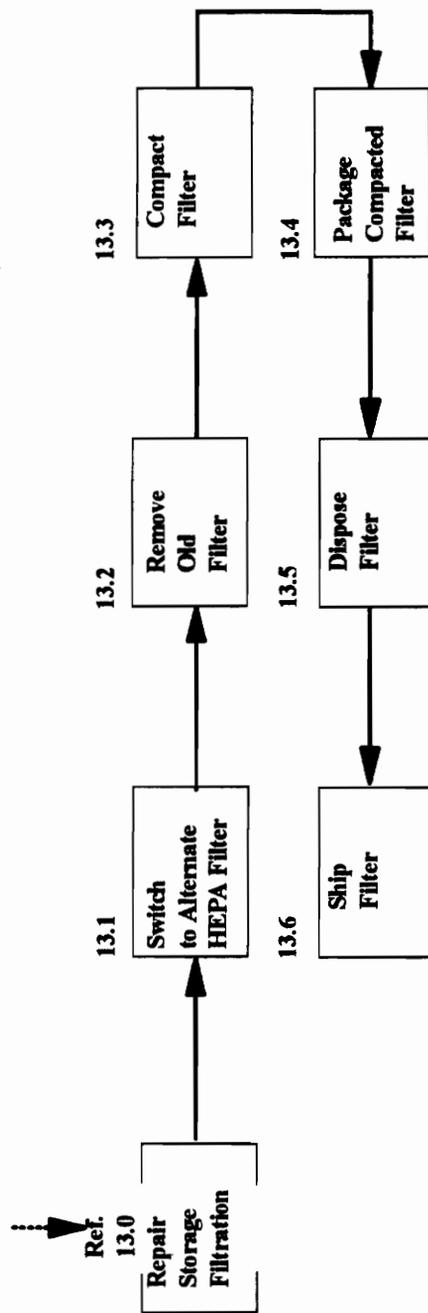
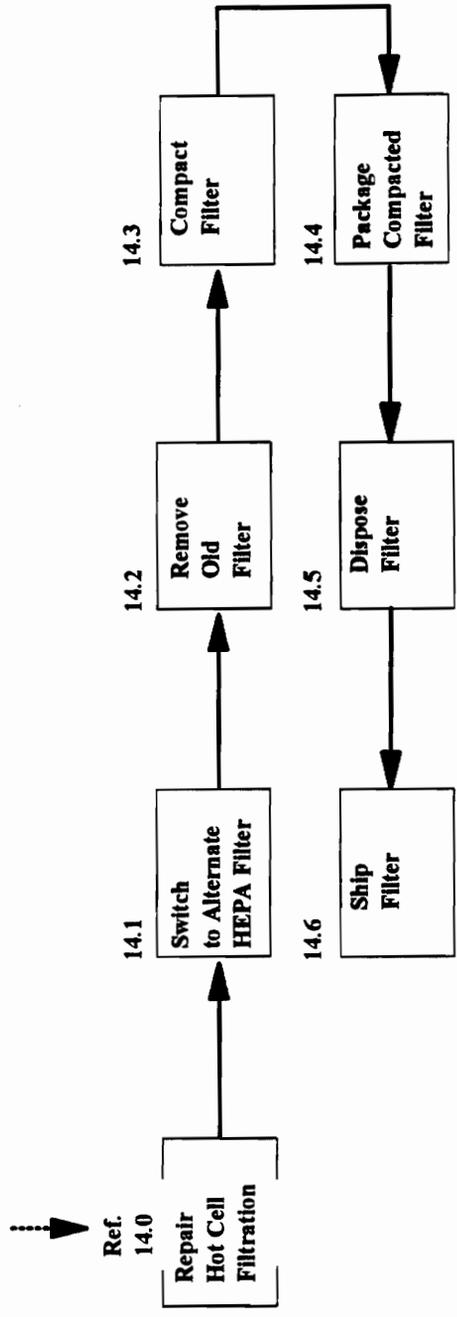**Figure 44: Subfunctions of Subfunction 3.7**

Figure 45: Subfunctions of Function 13.0

Figure 46: Subfunctions of Function 14.0

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