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# HIGH-LEVEL RADIOACTIVE WASTE DISPOSAL

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by


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## ABSTRACT

The U.S. Atomic Energy Commission (AEC) has and is developing additional plans and new methods for managing radioactive wastes generated by past, present and future operations. The objectives of these programs include plans to; (1) ensure the health and safety of the public, (2) protect our environment and ecology, and (3) use methods acceptable to the public. A brief overview is presented of the plans and current studies for disposing of high-level radioactive waste generated in commercial nuclear facilities. The methodology being developed and used to assess the merits of alternate concepts is presented. The technical areas where the physics community might contribute to improving this program are outlined.

## INTRODUCTION

The power of the atom - a self-sustained nuclear reaction - was demonstrated under the stands of Stagg Field in Chicago on December 2, 1942. Because the military implications of nuclear fission had already been recognized, the United States launched a massive effort, the Manhattan Project, to develop this energy form. This led to the construction of large nuclear reactors to produce nuclear weapons materials.

The peaceful uses of splitting the atom were also recognized and soon after World War II, the government initiated programs to realize the benefits of producing useful energy from nuclear fission. This effort led to the establishment of a commercial nuclear power industry in the 1960s.

Whether nuclear reactors are used to produce materials for military purposes or to generate electrical power, a by-product of their operation is a radioactive residue. The potential risks associated with these radioactive materials were recognized at the start. Therefore, stringent methods have been developed to limit the release of radioactivity and the consequences of any release so as to not have a significant adverse effect on workers in the plant, the public, and the environment.

Because of the military priorities applied to the initial development of nuclear fission, there was little time to consider all possible alternatives for the management of radioactive wastes. In those early days, a prudent course of action was taken: i.e., confine the most hazardous wastes in storage tanks. The current plan for managing radioactive wastes in AEC-owned facilities is documented in Reference 1.

## SUMMARY

Electrical generation planners are looking to an increased use of central nuclear power stations to meet consumer demands. Studies are being conducted to assess the merits of various methods for effectively managing the radioactive residues expected to be produced by projected growth of nuclear power. The use of a Retrievable Surface Storage Facility (RSSF) is being developed as an interim management method while numerous advanced methods for permanent disposal are being thoroughly examined. The scientific and technical community can contribute to solving this problem which is extremely technically interesting and certainly in the National interest. Certainly not all of the creative ideas for disposing of nuclear waste have been forwarded as yet. Moreover, quantitative information is needed to provide a firm technical and economic basis for evaluating concepts currently under study. Developing the best method for managing high-level wastes represents a challenge to the scientific and technical community.

## BACKGROUND

The components of the nuclear fuel cycle are shown in Figure 1, which basically represents the cycle for Light Water Power Reactors (LWRs). The logistics of fuel in this cycle starts with the mining of uranium, then on to the three processing steps to upgrade the quality of the fuel (milling, conversion, and enrichment), through the fabrication of fuel elements and utilization of these to produce electrical energy, to the reprocessing of the spent fuel and the disposal of reprocessing residues. In the process of producing fuel either from mining and refining uranium or in recycle of fissionable materials recovered in reprocessing (see Figure 1), radioactive wastes are generated. These wastes consist of such things as rags, sweepings, boxes, piping, filters, spent resins, etc., contaminated with small amounts of uranium, plutonium and fission products. The volume of this type of non-high-level waste which is generated in the various steps of the fuel cycle is several hundred times larger than the volume of high-level waste. However, the average concentration of radioactive materials in these wastes will be low.

In the process of producing nuclear power, radioisotopes other than uranium are produced. These include fission products (essentially the by-product of fissions in uranium and plutonium) and other actinide elements (by-products of neutron capture in uranium and plutonium). Spent fuel discharged from the reactor is then chemically reprocessed to recover uranium and plutonium. During this step, high-level waste is formed as an acidic aqueous stream.* This high-level waste contains most of the reactor-produced

*High-level liquid waste is defined in Appendix F, 10 CFR 50, (Reference 2), as the aqueous waste resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated waste of subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuels.

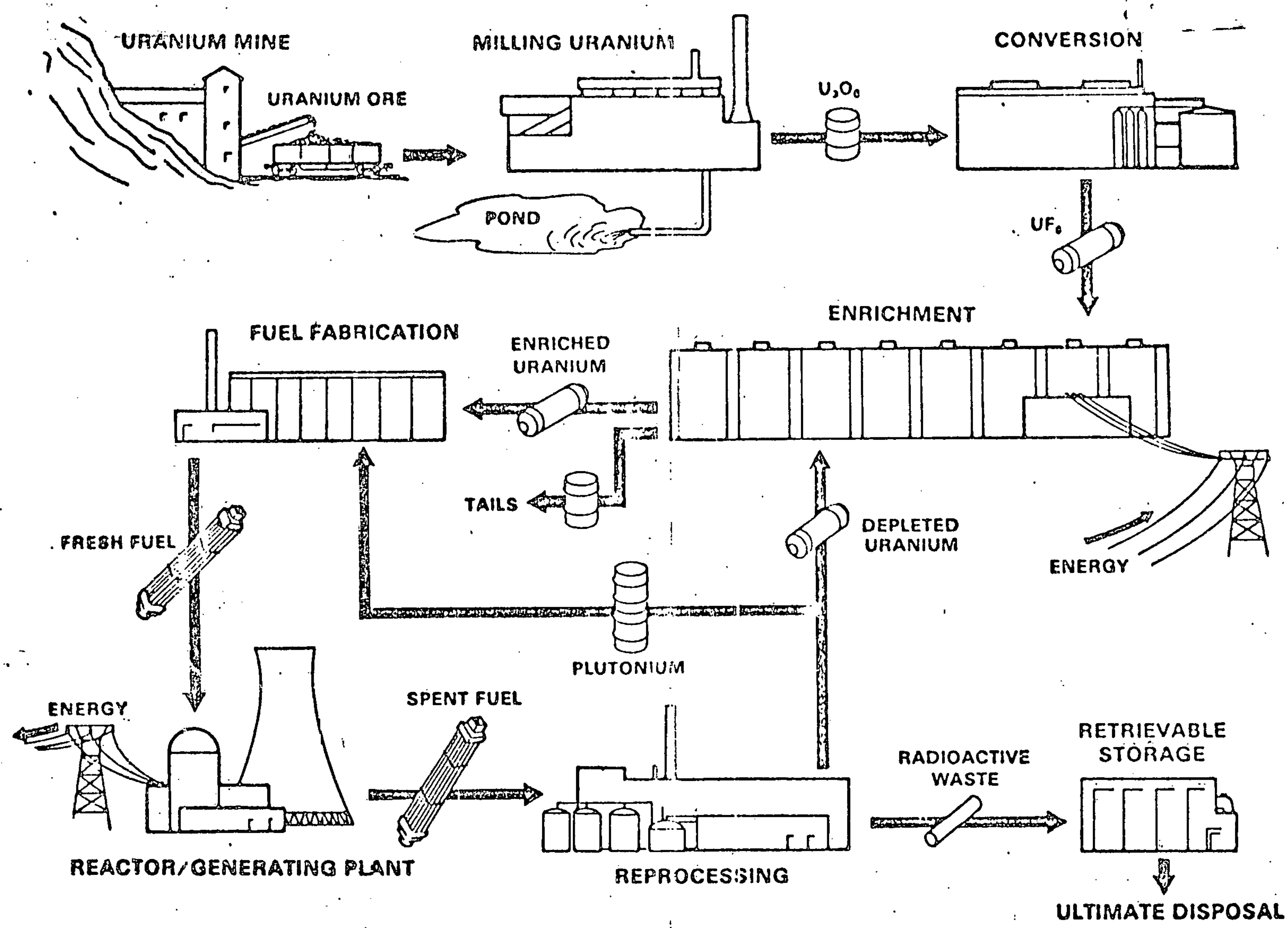


FIG. 1. NUCLEAR FUEL LOGISTICS

fission products and actinides except the uranium and plutonium that are separated during reprocessing. The high-level waste from the reprocessing of the irradiated fuels is the most significant waste material from the standpoint of hazard and difficulty of disposal since it contains essentially all of the fission products and a fraction of the fuel materials. This high-level waste generates sufficient heat to require substantial cooling. It emits large amounts of potentially hazardous ionizing radiation and it must be carefully isolated or contained for thousands of years to prevent significant quantities of the more highly toxic radionuclides from entering man's environment. High-level nuclear wastes are categorized as long-lived and short-lived. The short-lived are defined as those with half-lives of ten of years or less, whereas the long-lived are those with half-lives of thousands or more years. With reprocessing, high-level waste management begins. Under the terms of present Federal policy, liquid high-level waste from fuel reprocessing must be converted to a stable solid material within five years after separation in the fuel reprocessing step, and be encapsulated and shipped to a Federal repository within 10 years of its production for long-term management by the AEC.

## HIGH-LEVEL WASTE PROJECTIONS

Forecasts (3,4,5) of installed electrical generation capacity for the United States show an increasing dependence on nuclear power. As shown in Figure 2, installed U.S. nuclear electrical generating capacity is projected to increase from about 15,000 megawatts in 1973 to about 1,200,000 megawatts by the year 2000. The power reactors expected to be used include Light Water Reactors (LWRs), High-Temperature Gas Cooled Reactors (HTGRs) and Fast Breeder Reactors (FBRs) principally the liquid metal cooled type. The nuclear projection by reactor type is shown in Figure 3. As shown, the LWRs are the major reactor type expected to be producing power.

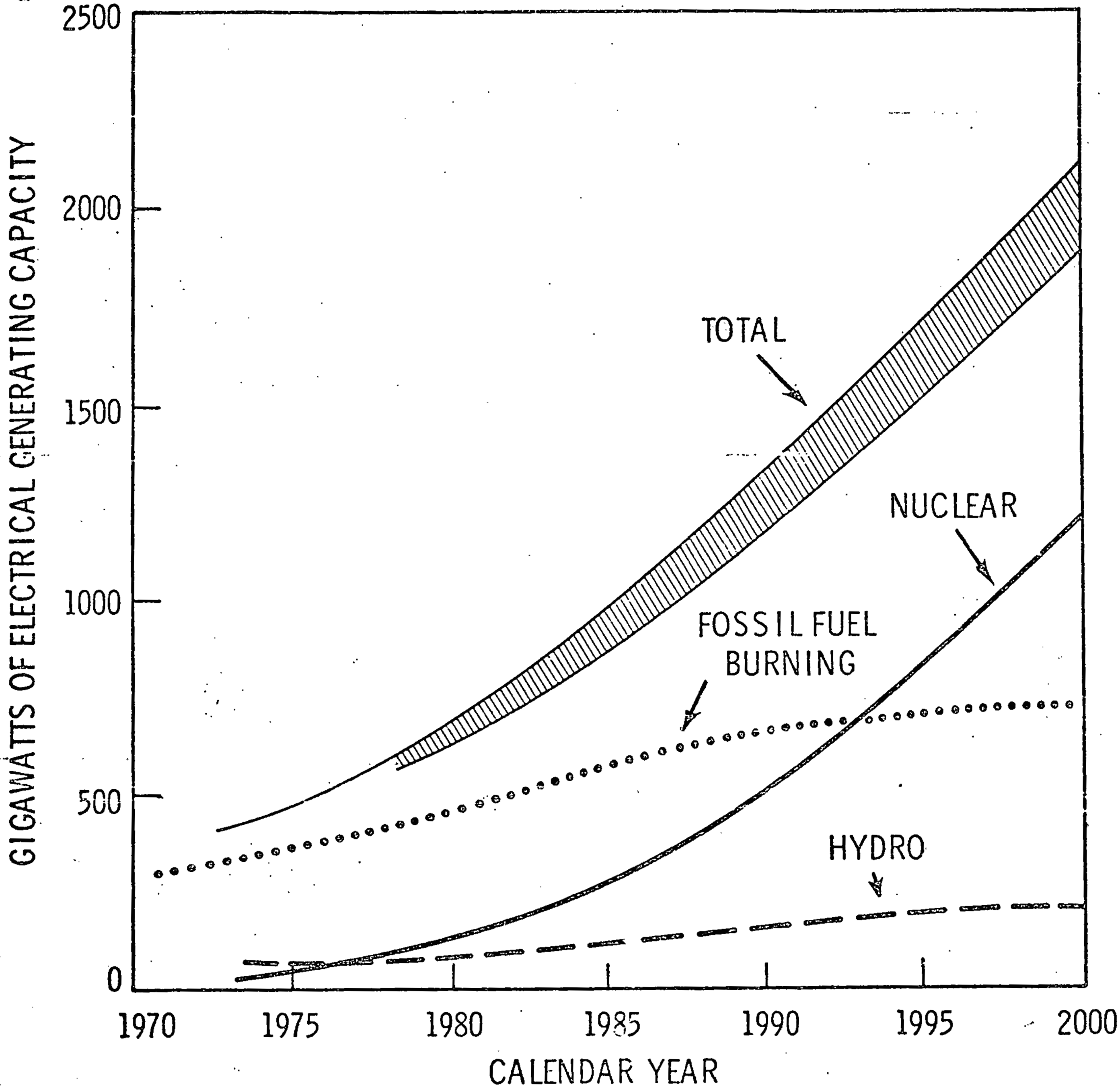


FIGURE 2. PROJECTED U.S. ELECTRICAL GENERATING CAPACITY

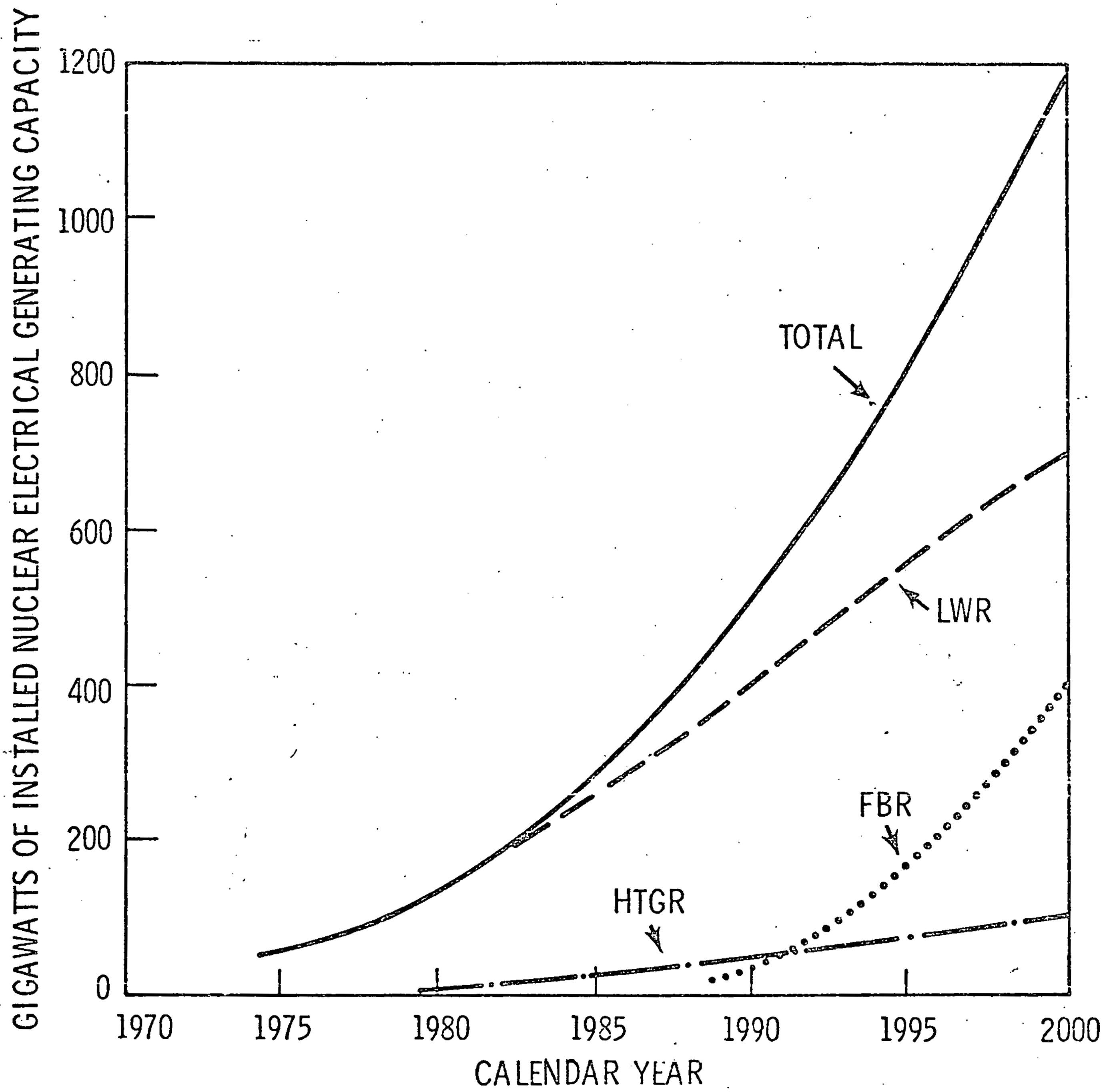


FIGURE 3. PROJECTED U.S. NUCLEAR ELECTRICAL GENERATING CAPACITY

The irradiated or "spent" fuel discharged from these reactors will be chemically processed at fuel reprocessing plants to recover the significant amount of valuable "unspent" fissile and fertile materials for recycle. As an example, irradiated enriched uranium Light Water Reactor (LWR) fuels typically contain about 30 percent of the original fissile uranium and the fissile plutonium that is produced by reactor irradiation. Typical constituents of high-level liquid wastes from the reprocessing of irradiated fuels from LWR, LMFBR, and HTGR plants are shown in Table 1. This table was developed for aqueous acidic wastes from first-cycle solvent extraction where the addition of chemicals that could be troublesome in subsequent solidification processes is minimized. Troublesome chemicals include the water soluble, volatile, or corrosive species or those that result in segregation or phase separation during solidification.

Under terms of present policy(2), this high-level waste must be solidified prior to shipment to a Federal repository. The amount of solidified waste expected to be generated is shown in Figure 4. By the year 2000, about 480,000 cubic feet of solidified high-level waste will be accumulated. This amount of material will generate approximately 600 megawatts of decay heat from some 140,000 megacuries of radioactive residue. The heat will decay to essentially insignificant levels within the first 1000 years; however, the presence of long-lived isotopes extends the safety aspects of waste management into a much longer period of time--perhaps as much as a million years.

## WASTE MANAGEMENT PLANS

The near-term waste management plan that has been adopted by the AEC for high-level waste calls for AEC receiving and managing these wastes in retrievable and monitorable storage facilities until one or more of methods for ultimate disposal is selected and developed. Permanent management methods

TABLE 1. Constituents of High-Level Liquid Wastes

| Constituent | Grams/metric ton (MT) from Reactor Type | | |
|---|---|---|---|
| | LWR[a] | HTGR[b] | LMFBR[c] |
| H | 400 | 3,800 | 1,300 |
| Fe | 1,100 | 1,500 | 26,200 |
| Ni | 100 | 400 | 3,300 |
| Cr | 200 | 300 | 6,700 |
| Si | --- | 200 | --- |
| Li | --- | 150 | --- |
| B | --- | 1,000 | --- |
| Mo | --- | 50 | --- |
| Al | --- | 6,400 | --- |
| Cu | --- | 50 | --- |
| $BO_3$ | --- | --- | 98,000 |
| $NO_3$ | 65,000 | 435,300 | 293,600 |
| $PO_4$ | 900 | --- | --- |
| $SO_4$ | --- | 1,100 | --- |
| F | --- | 1,900 | --- |
| Total (Reprocessing Chemicals and Corrosion Products | 68,500 | 452,000 | 379,300 |
| U[d][e] | 4,780 | 250 | 4,300 |
| Pu[d][e] | 50 | 1,040 | 470 |
| Th[d][e] | <.01 | 4,200 | <.01 |
| Np[d] | 480 | 1,440 | 260 |
| Am[d] | 140 | 30 | 1,250 |
| Cm[d] | 40 | 10 | 50 |
| Other Actinides[d] | <.001 | 20 | <.001 |
| | 5,500 | 7,000 | 6,300 |
| Total Fission[f] Products | 28,800 | 79,400 | 33,000 |
| Total | 102,800 | 538,400 | 418,600 |

(a) U-235 enriched PWR, using 378 liters of aqueous waste per metric ton, 33,000 MWd/MT exposure.

(b) Combined waste from separate reprocessing of "fresh" fuel and fertile particles, using 3,785 liters of aqueous waste per metric ton, 94,200 MWd/MT exposure.

(c) Mixed core and blanket, with boron as soluble poison, 10% of cladding dissolved, 1,249 liters per metric ton, 37,100 MWd/MT average equilivant exposure.

(d) At time of reprocessing.

(e) Assumes 0.5% product loss to waste.

(f) Noble gas and tritium fission products excluded.

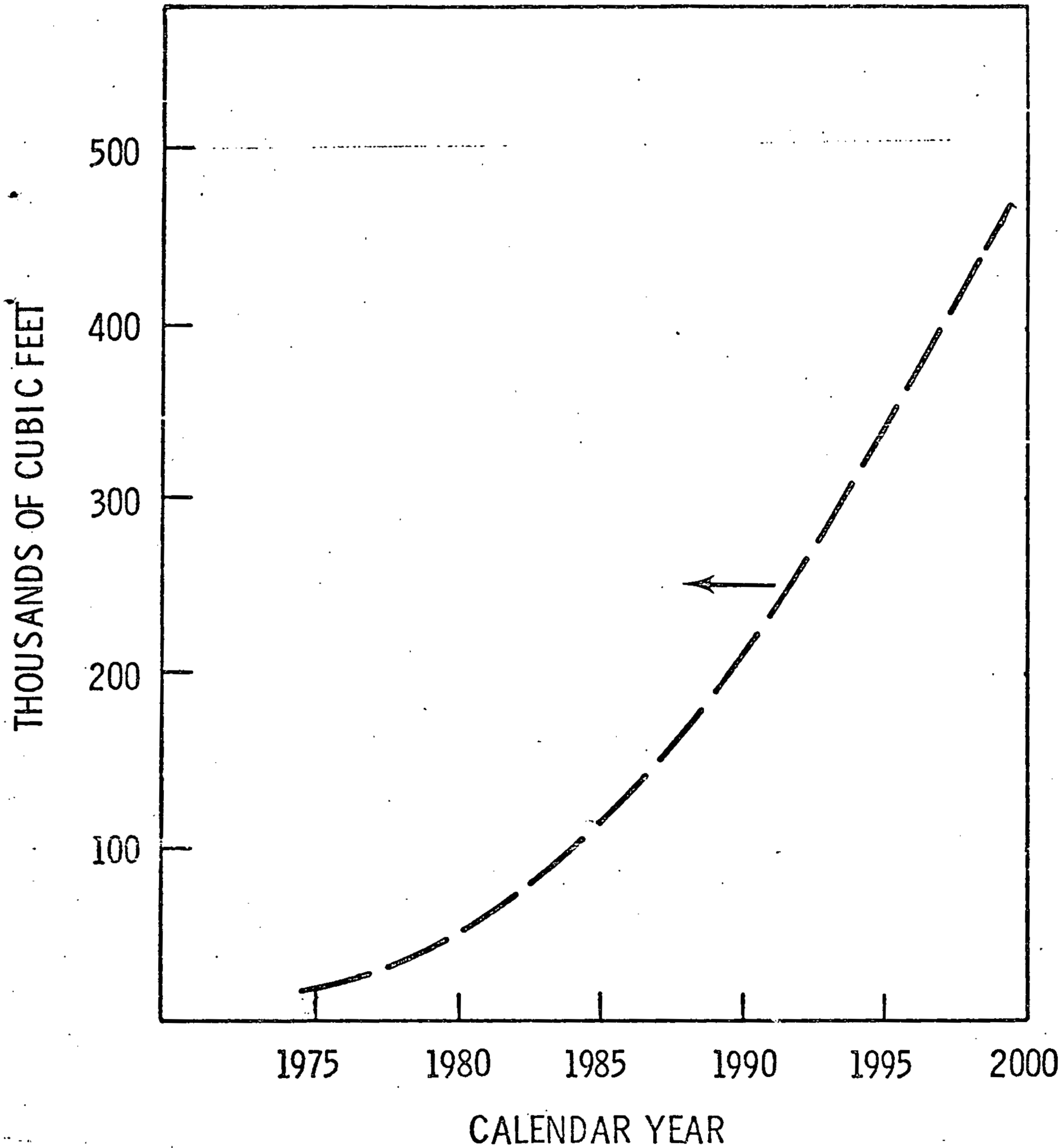


FIG 4. ACCUMULATED VOLUME OF HIGH-LEVEL WASTE

will be developed from various concepts now under study. The feasibility, technical status, safety analysis, development requirements, schedules and costs are being projected to properly assess each concept and provide data for selection of the most promising concepts. Wastes other than high-level wastes are disposed of in commercial burial grounds. In the case of cladding hulls, noble gas cylinders, and long-lived alpha-emitting plutonium and other transuranic wastes, future regulations may require storage in a Federal repository.

Partitioning prior to disposal is a key element in certain of the conceptual waste management systems. By dividing the high-level waste into two fractions, one in which the major content of radioactively toxic materials will diminish to very low levels in about a thousand years and the other, much smaller in quantity and heat generation rate, but containing long-lived materials, a substantial increase occurs in waste management options. The short-lived fractions would then decay to become radioactively non-toxic in relatively short times--times short enough to perhaps consider long-term storage such as in manmade structures. The long-lived fraction could be considered for treatment by other management systems. To produce a short-lived waste fraction which would decay to negligible radioactive toxicity in about 1,000 years would require removal of the actinide elements, samarium, technetium, tin, iodine, and nickel (radioactive nickel present due to dissolution of some non-core components.

Solidification of High-Level Waste

Present Federal regulations require that the liquid high-level waste from fuel reprocessing be converted to a solid material and be encapsulated prior to shipping to a Federal repository for long-term management by the AEC. The solidified high-level waste is assumed to be encased in steel canisters typically 12 inches (30 centimeters) in diameter and 10 feet

(300 centimeters) long, each container holding 6.3 cubic feet of solid waste. The projected and annual accumulation rates of volumes of solidified waste contained in canisters of this size are shown in Figure 5. By the year 2000, the volume of solid high-level waste in terms of the number of canisters will number about 75,000.

Four solidification processes have been developed in the United States to the point of radioactive demonstration on an engineering scale:

- Spray Solidification
- Fluidized Bed Calcination
- Pot Calcination
- Phosphate Glass Solidification

In all four processes, heat is applied to drive off volatile constituents, primarily water and nitrates, resulting in either a calcined solid or a melt that will cool to a monolithic solid.

The Waste Fixation Program* (WFP)[8] has as its chief goal to provide technology for reprocessors by developing and evaluating final waste forms and developing appropriate waste solidification technology. Developed systems will be taken all the way through a radioactive demonstration phase. Solid waste forms from these demonstrations will be studies to determine the effects of time and environment. The current emphasis of the WFP is to provide early solidification technology by working with borosilicate glass or ceramic systems. As these solids have had the greatest development effort on a worldwide basis, development of acceptable systems to produce the solids should be near-term. The borosilicate solids will offer a vast improvement in waste management safety over liquids or calcined solids. In an effort parallel to the borosilicate solid development, studies are aimed at determining and developing a waste form with even better confinement properties. An example of this

*An AEC Program in progress at the Pacific Northwest Laboratory to develop and demonstrate solidification of high-level waste.

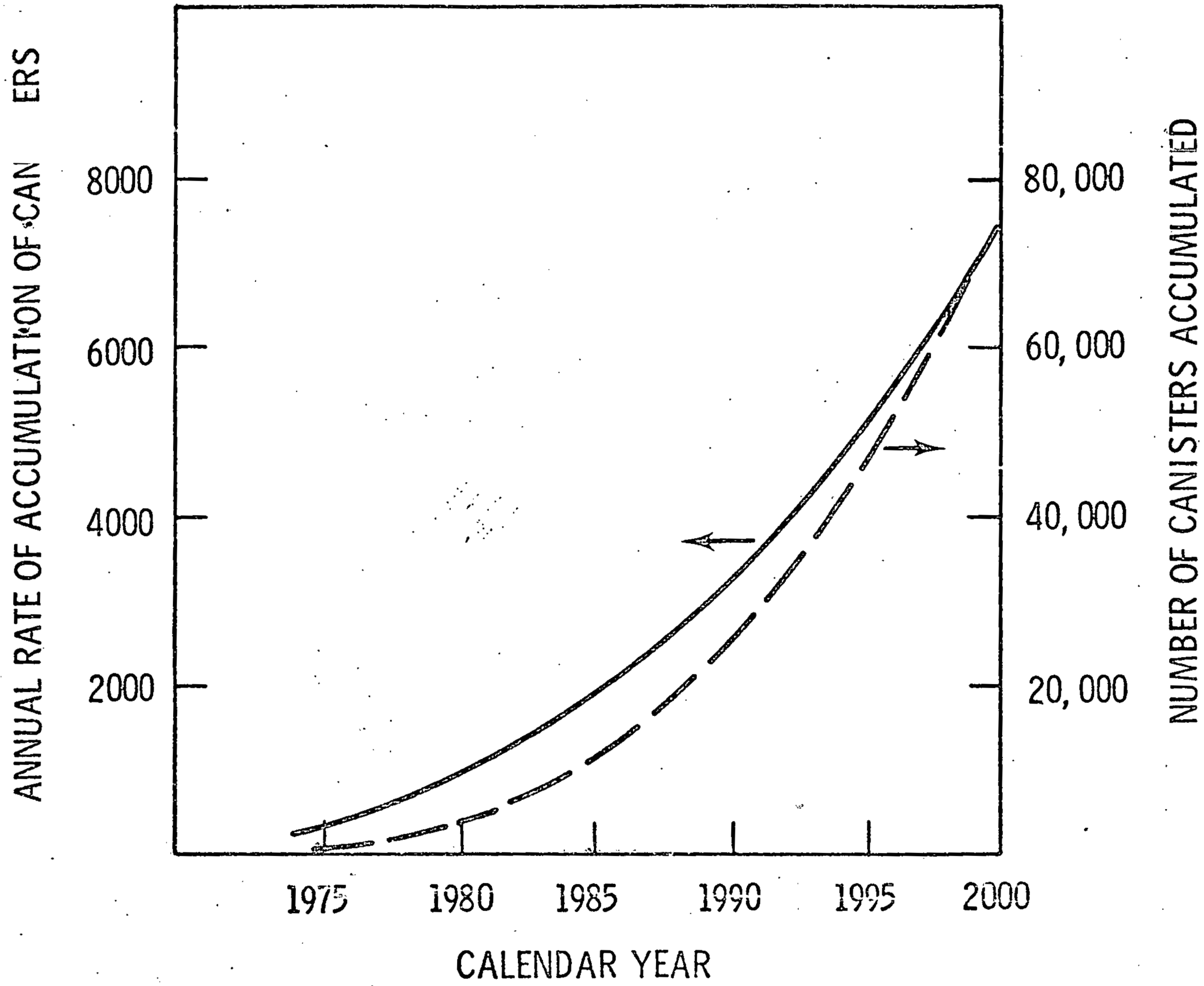


FIGURE 5. VOLUME OF SOLID HIGH-LEVEL WASTE

would be a multiple-barrier material. This could involve covering small pieces of solid waste with a protective coating. The coated solids could then be dispersed in a protective matrix. Further protection could be provided by outer wrappers.

Retrievable Surface Storage Facility (RSSF)

For retrievable and monitorable storage of solidified high-level waste in a surface facility, several alternative RSSF concepts based on the enclosed basin or vault type of storage with air or water cooling of the waste are being developed by the Atlantic Richfield Hanford Comapny for the AEC[9,10]. For sake of providing an overview of high-level waste management, a brief summary of these concepts is given here.

The Retrievable Surface Storage Facility (RSSF) will be comprised of facilities for receiving and inspecting packaged wastes from fuel processors and facilities for safely storing these wastes. The facility will be designed to hold safely, for at least 100 years if necessary, all of the commercial high-level waste produced in the United States through the year 2000.

Basically three RSSF concepts are under consideration by the AEC, the Water Basin Concept, the Sealed Cask Concept, and the Air-Cooled Vault Concept.

Water Basin RSSF. In the Water Basin Concept, the canisters are stored in water-filled stainless-steel-lined concrete basins. The concept consists of three major elements, namely: the waste receiving and handling facility; the storage facility, a series of water-filled concrete basins in which the wastes would be placed for cooling and long-term surveillance; and the heat rejection facilities. For the latter, a series of forced-draft cooling towers is associated with the basins, from which the waste heat would be dissipated to the atmosphere. As in all the concepts, there would also be support facilities and services. Figure 6 shows a conceptual layout of the water-cooled basin concept. Modular construction of the actual storage area would be planned so that the storage capacity would keep pace with the waste expected to be delivered to a Federal repository. Water in the basin would serve as a heat sink in case of temporary failure of mechanical cooling equipment and the water would provide both radiation shielding and a confinement barrier.

Sealed Storage Cask RSSF. In the sealed Storage Cask Concept, the canisters would be sealed in steel casks which would be stored outdoors on concrete pads inside concrete neutron shields as shown in Figure 7 for the thick wall storage unit and in Figure 8 for the medium wall storage unit. Heat would be dissipated from the casks by natural convection air flow through the annulus between the cask and the neutron shield. The three major elements of the concept are the waste receiving and handling facility; the storage cask welding and testing facility; and the outdoor waste cask storage areas. The storage area would be surfaced with crushed rock as required to prevent wind erosion and provide access for the transport vehicle to all the storage cask locations. Area monitors and samplers would be provided to detect any radioactivity above the normal background level. A security fence would enclose the area to provide isolation and prevent inadvertent entry by personnel.

Air-Cooled Vault RSSF. In the air-cooled vault concept, the waste canisters would be sealed by welding them inside of another carbon steel container. This assembly is then placed inside concrete vaults to be cooled by natural draft convection as illustrated in Figure 9. The three major elements of the concept are the waste receiving and handling facility; the welding and testing facilities, and the canister storage cells. Expansion of facilities for handling and encapsulating (overpack) would be required

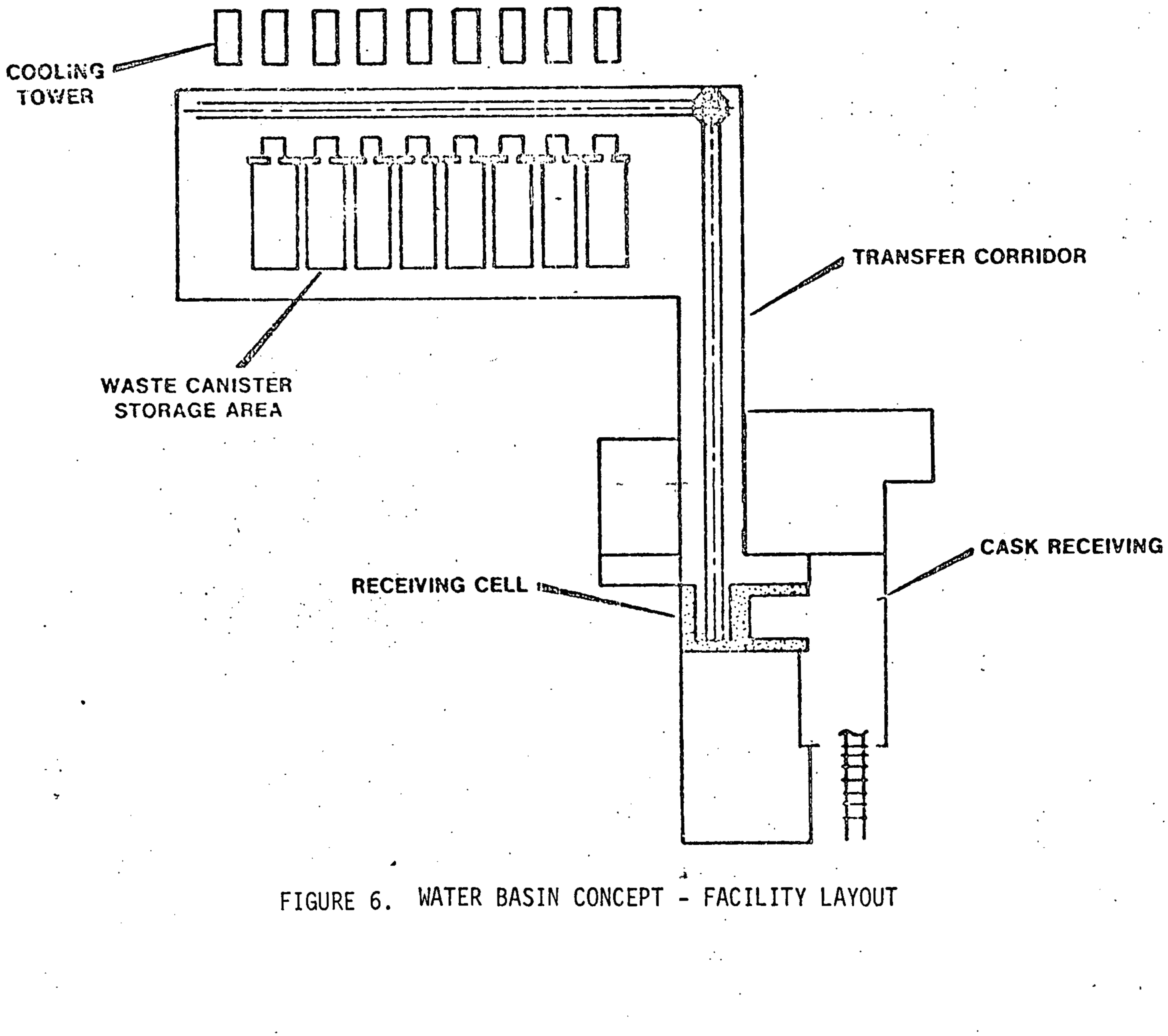


FIGURE 6. WATER BASIN CONCEPT - FACILITY LAYOUT

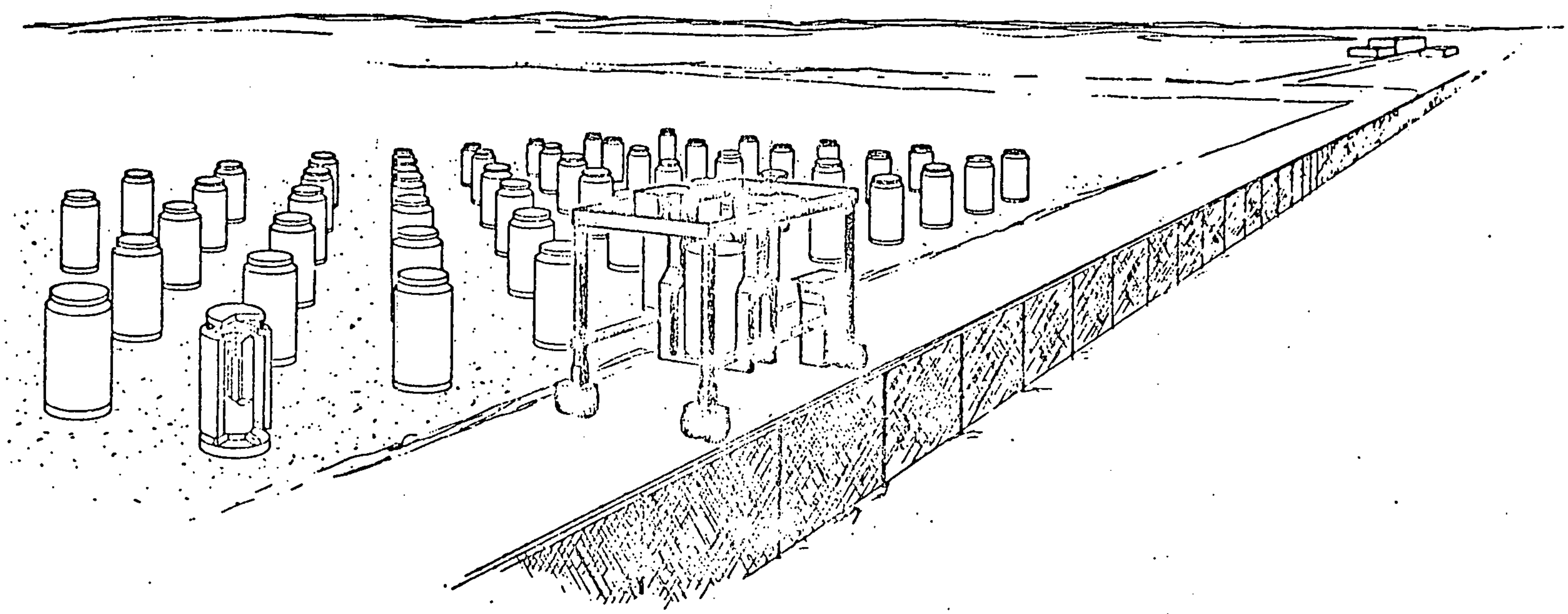

FIGURE 7. STORAGE AREA - THICK WALL SEALED STORAGE CASK CONCEPT

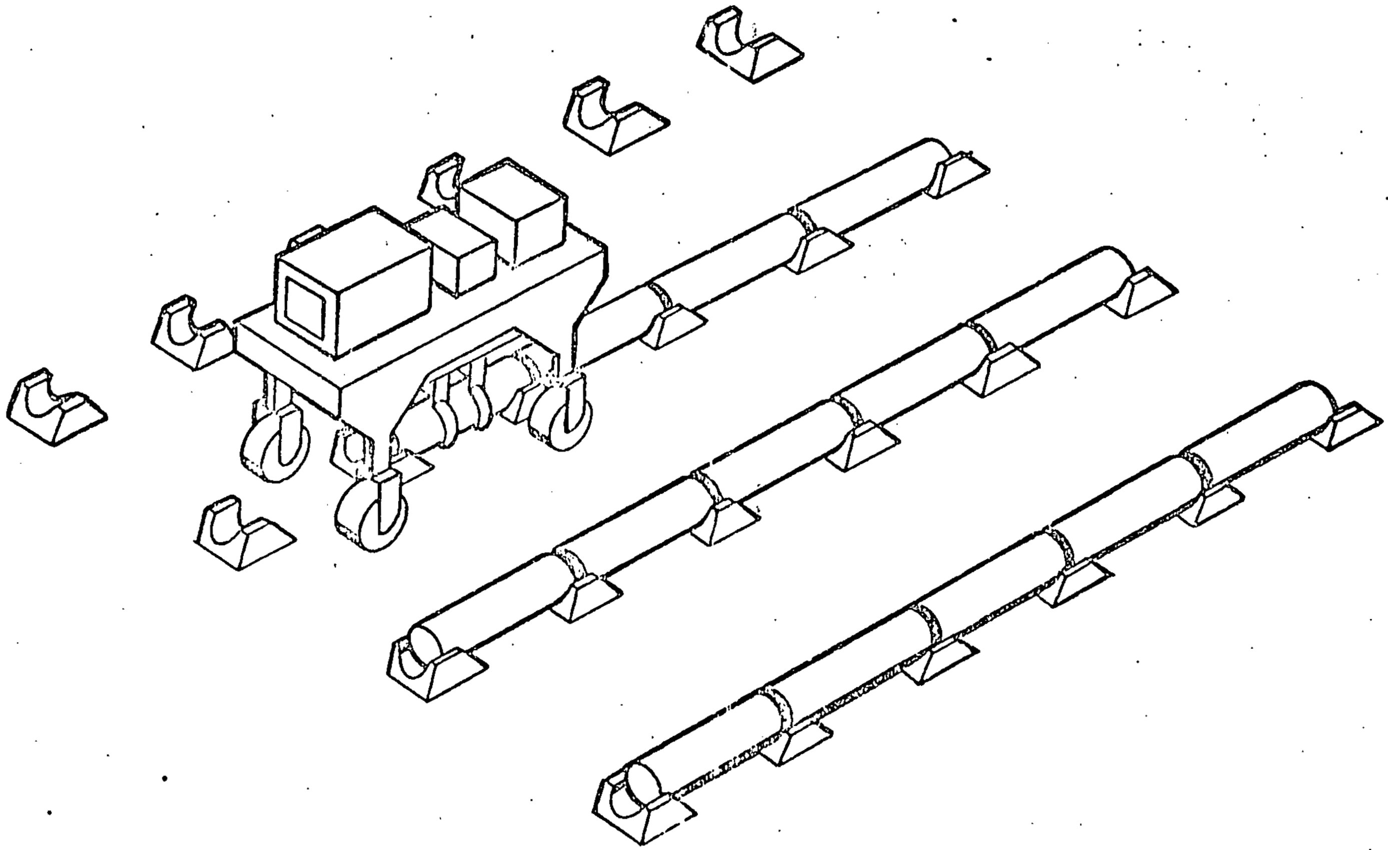

FIGURE 8. STORAGE AREA - MEDIUM WALL SEALED STORAGE CASK CONCEPT

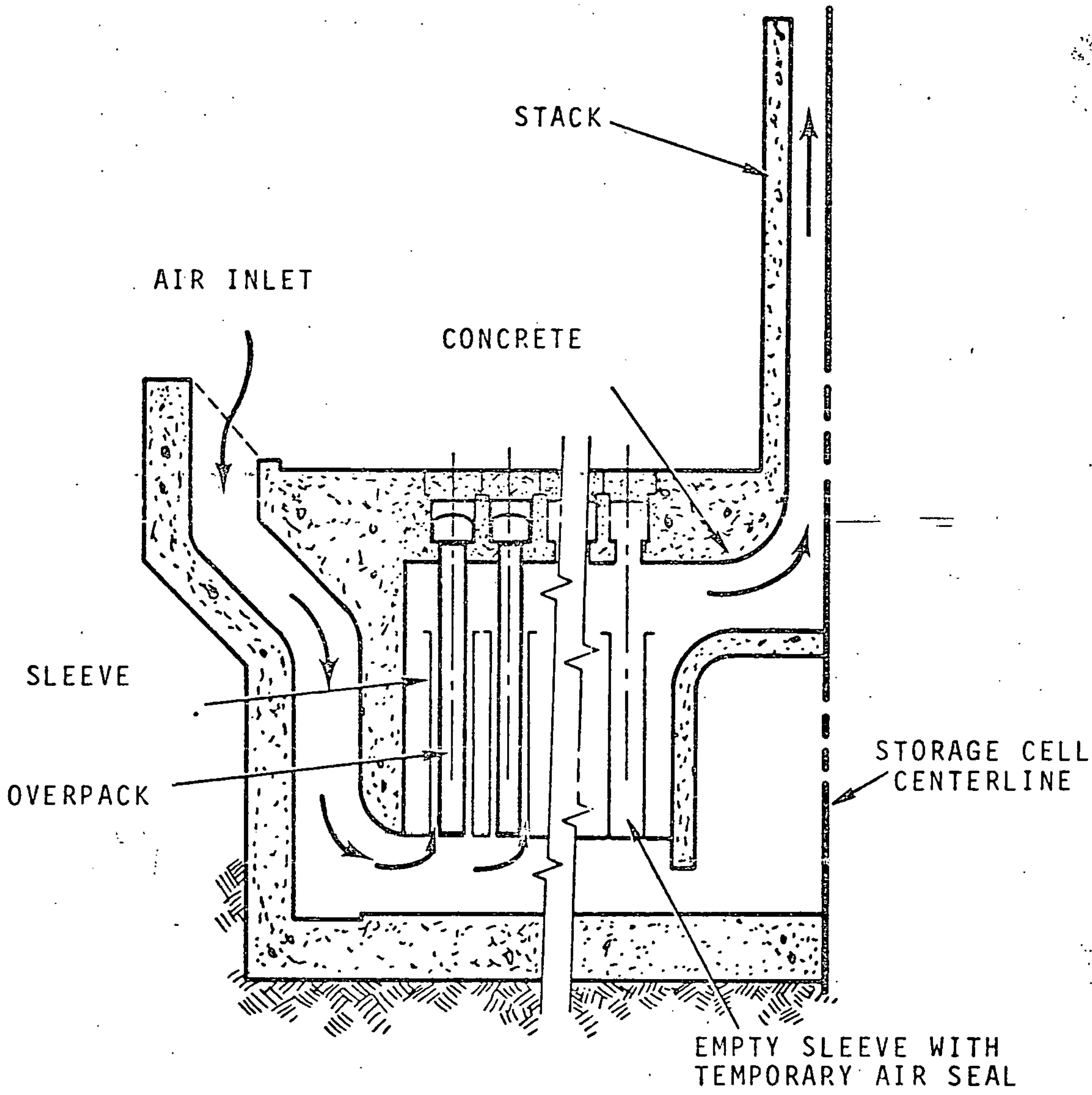


FIGURE 9. AIR-COOLED VAULT CONCEPT

periodically. The receiving and welding stations could be expanded in modular components. No continuous mechanical cooling systems or emergency backup facilities would have to be provided.

Potential Future Alternatives

When the AEC made its decision to use the RSSF technique for managing the commercial high-level radioactive waste, it recognized that while this approach is simple, straightforward and safe, it does impose a long-term requirement for human surveillance and maintenance. The AEC feels that if management techniques can be developed which are equally safe and which would eliminate, or at least minimize, this human action requirement, they should be used. For this reason, the AEC undertook a rather extensive program to identify, evaluate and possibly demonstrate feasible alternative disposal techniques for later use. Studies of disposal in bedded salt formations have been and are being conducted by Oak Ridge National Laboratory for the AEC[11,12] and studies of other alternatives for managing high-level waste are being studied by Battelle Pacific Northwest Laboratories (Battelle-Northwest) for the AEC[13]. A brief description of the bedded salt concept is given here to aid in the overview of high-level waste disposal. In the next section the advanced waste studies being conducted by Battelle-Northwest are reviewed.

As shown in Figure 10, there are fairly large deposits of rock salt in the U.S. The bedded salt concept is based upon the principle of isolating the high-level wastes in a stable underground salt formation. The handling process and emplacement operations envisioned is shown in Figure 11. Studies are underway to evaluate and demonstrate safe, competent, receiving, handling, emplacement, and retrieval operations as well as providing means to demonstrate the adequacy of analytical techniques used to predict the long-term stability of salt beds when they contain heat-producing waste.

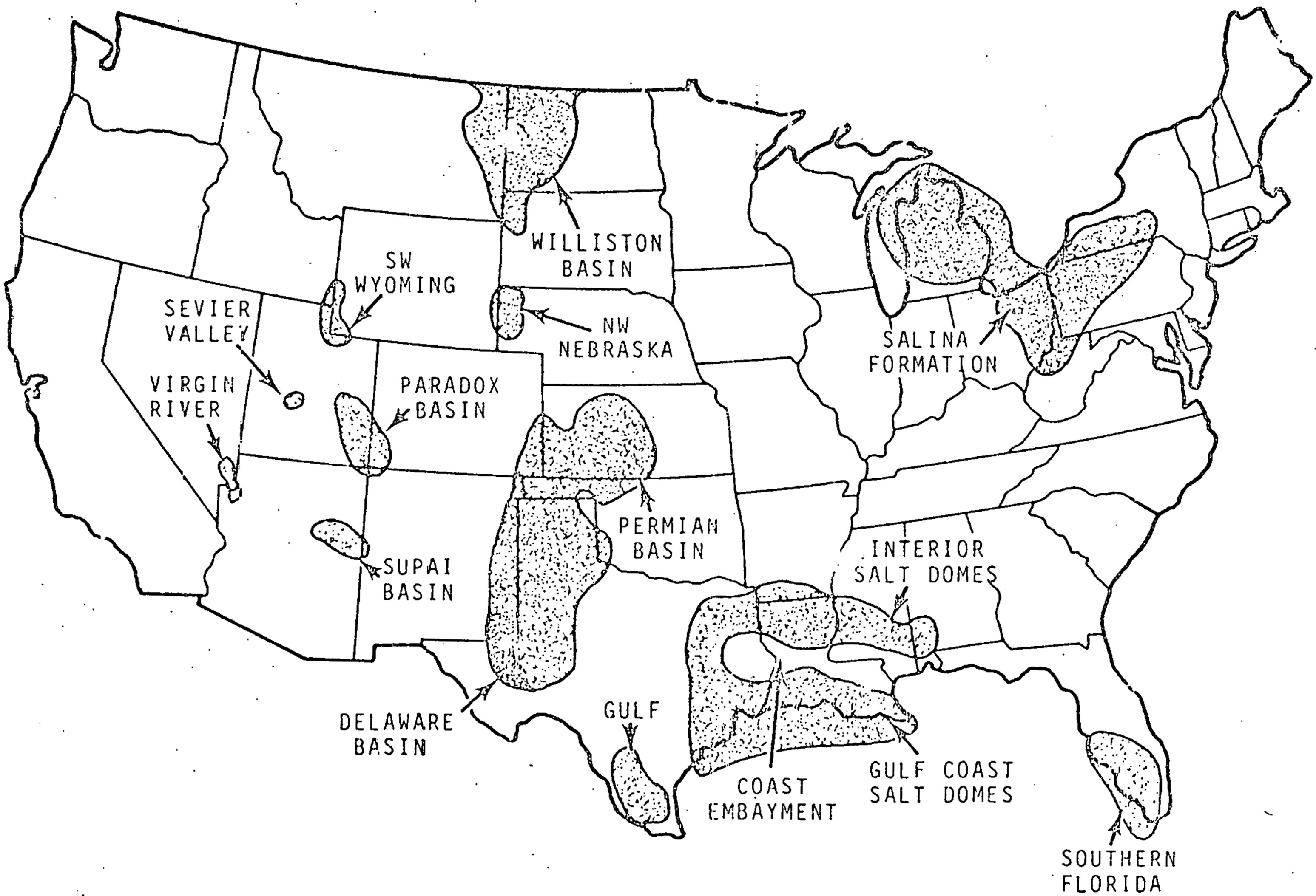


FIGURE 10. ROCK SALT DEPOSITS IN THE UNITED STATES (AFTER PIERCE AND RICH, U.S.G.S. BULL. 1148)

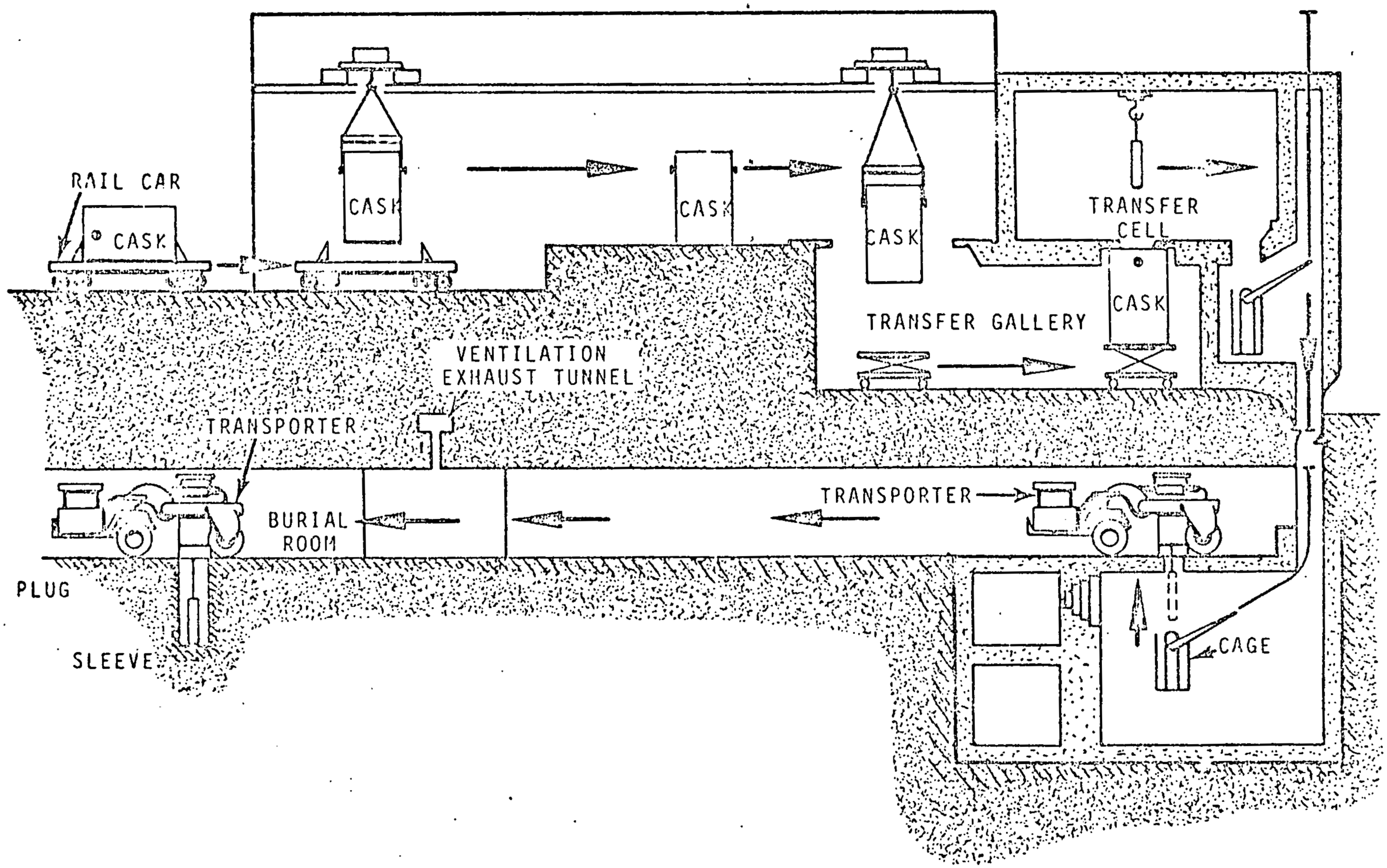


FIGURE 11. HANDLING PROCESS IN BEDDED-SALT DISPOSAL

Advanced Waste Studies Conducted by Battelle-Northwest

In addition to the RSSF and bedded salt disposal programs, the AEC has commissioned Battelle-Northwest to make an evaluation of all other potentially attractive disposal concepts. The purpose of this evaluation is to identify feasible and potentially feasible long-term waste management systems and their components, evaluate the safety of these systems, identify the research and development necessary for their establishment, and estimate the schedule and costs associated with selected systems. A synopsis of this work has been published previously(14) and details of these studies will be published in topical reports to be issued later this year(15).

Three basic types of waste management concepts are under study: (1) disposal on earth, (2) conversion by nuclear processes called transmutation, and (3) disposal in space. The earth disposal concepts involve use of geologic formations, ice sheets and the seabed. The space disposal concept involves transporting waste to various orbits or trajectories in space. Transmutation involves elimination of some of the more offensive waste nuclides by nuclear transition. Alternatives within these categories are listed in Table 2.

Study Methodology - Briefly presented here is the overall analytical system methodology by which each disposal concept and its waste management system elements are being studied. The factors upon which the evaluations are being made is graphically illustrated in Figure 12.

The technical feasibility of the potential disposal concepts is being determined in this study by answering the following questions:

1) Can the disposal concept be implemented using today's technology? (This does not imply that additional development is not necessary to adapt existing scientific and engineering technology to these disposal concepts.)

2) Can the disposal concept be implemented with future technology based upon current theory? (Is it theoretically possible?)

3) Will the disposal concept provide adequate safety for the time period of concern? (Truly quantified answers to this point require very extensive study, and only qualitative indications are being developed for this study using currently available data.)

4) Does the concept have a favorable energy balance? (Is the energy consumed in the implementation of the disposal concept sufficiently less than the electrical energy obtained from the nuclear fuel represented by the waste?)

Estimates are being made of the research and development time and expenditures necessary for solution of the technology needs. The date by which the concept could be in operation is also being estimated.

Capital and operating costs are being estimated, using the basic assumption that the necessary research and development had been successfully completed. Major legal constraints (i.e., policy conflicts) and expected or potential major environmental impacts are also identified. Social psychologists are developing techniques to measure the public's perception of the safety elements of (i.e., risk) the various concepts.

The evaluation proceeds as follows. Since the results of these elements are calculated in completely different units, simply adding up the performance level by element does not necessarily lead to consistent information. Recognizing this, the technique being used is simply one of overcoming obstacles to performance. For instance, the technical feasibility obstacle would be of the "yes-no" type. Here "yes" is required before analysis of R&D requirements would be undertaken. In this way the timing for availability of a given technology could be ascertained. Once the feasibility of the technology is established, a preliminary analysis

TABLE 2. Concepts Under Study for High-Level Radioactive Waste Management

## DISPOSAL

### Geologic Formations

- Mined Cavity
- Nuclear Cavity
- Deep Hole
- Drilled Hole Matrix
- Manmade Structures in Geologic Formations

### Seabed

- Stable Deep Sea Floor
- Tectonic Subsidence Areas
- Deep Trenches Other Than Subsidence Areas
- Rapid Sedimentation Burial

### Ice Sheet

- Ice Burial - Free Flow
- Ice Burial - Anchored
- Ice Surface Facility

### Extraterrestrial

- Solar Impact
- Orbiting
- Solar Escape to Deep Space

## ELIMINATION

### Transmutation

- Accelerator
- Fission Reactor
- Fission & Thermonuclear Explosives
- Controlled Thermonuclear Reactor (Fusion Reactor)

## PROCESSING

Partitioning

# EVALUATION FACTORS

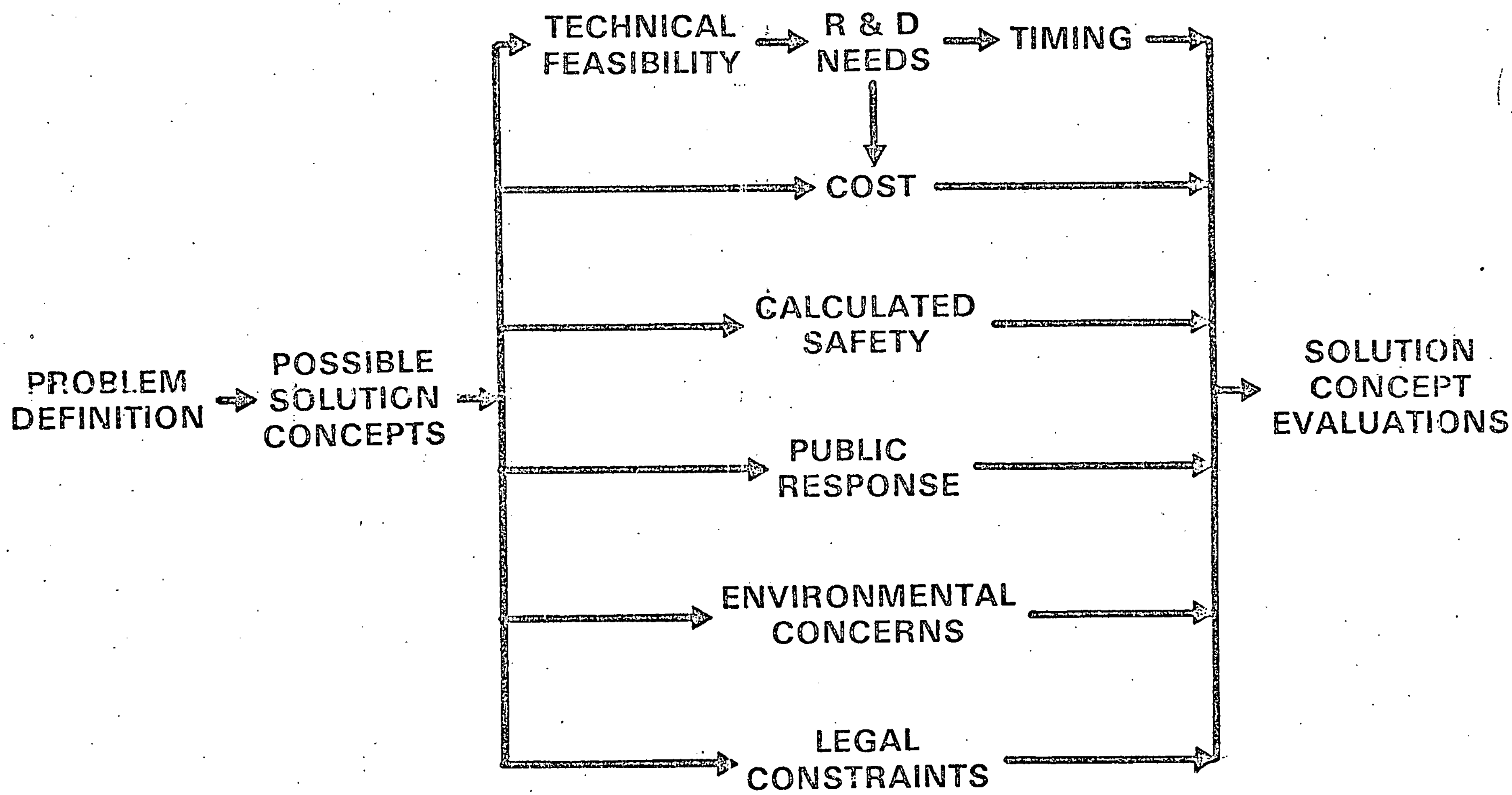


FIGURE 12. EVALUATION FACTORS

of system safety is made using the model outlined in Figure 13. Safety is, and has to be, a major consideration in decisions on the use of any potential disposal scheme. An acceptable option must provide adequate protection during operational phases and provide the necessary isolation during the disposal phase. For this study "safety" is equated directly to the potential risk to man that could result if the disposal option was implemented.

As shown in Figure 13, the overall matrix starts with defining the general characteristics of the disposal concept. The next step is evaluation of the most likely sequences of failure events leading to release of radioactive materials to man's environment and determination of the probability of these sequences taking place. The next step follows the most likely sequences through the physical and chemical processes required to release the waste constituents into man's immediate environment. The characteristics of the waste must be dealt with parametrically at the time the critical event takes place. The generic site defines the media (granite, salt, shale, soil, air, water, etc.) through which radionuclides must move. Finally, based on the population as indicated for the generic site and the calculated release rate, the dose to the surrounding population can be estimated.

The probabilistic risk to man can be determined by multiplying the probability of the event taking place times the radiological dose if the event happened. By comparing each of these doses with appropriate criteria, it can be determined whether or not the risk to man exceeds acceptable criteria. If the risk level is unacceptably high, changes could be made in the concept to improve the level of risk. If the risk for a concept meets all criteria, the concept will be considered to have met the safety requirements.

Analysis of system cost being made for this study considers such costs important only if they would result in major changes in the nuclear fuel cycle and hence alter the nuclear waste management system.

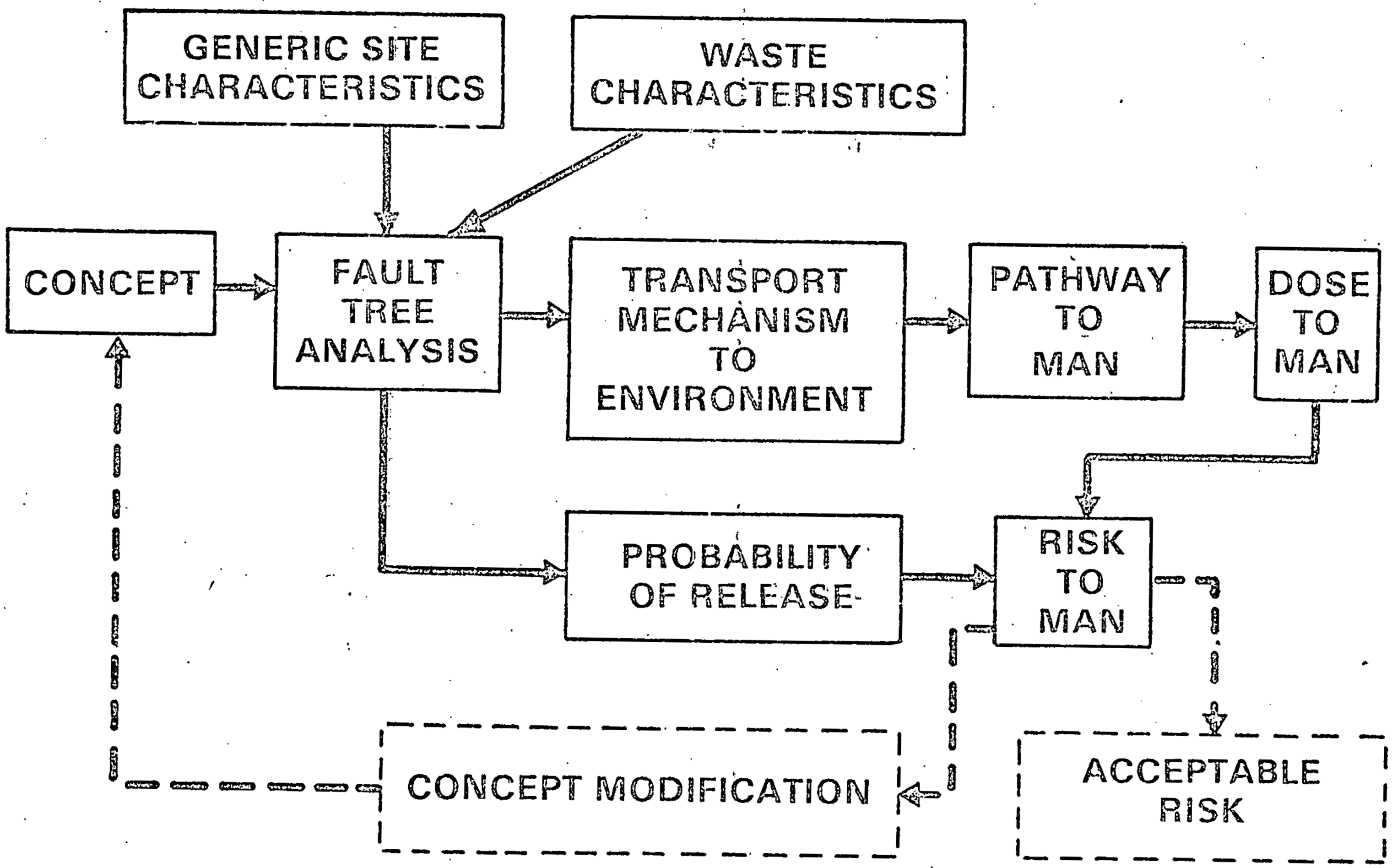


FIGURE 13. SYSTEM SAFETY EVALUATION MODEL

Implementation of some of the considered concepts would conflict with present policies--such as disposal of radioactive materials in the ocean. This policy and similar ones which are either parts of the Federal Code of Regulations or of international agreements are identified so that problems involved with policy changes can be weighed against the safety and economic potentials of a particular waste management concept. The environmental impacts, aside from the potential release of radioactive materials, are not expected to control concept selection but will be important factors in detailed site selection. General impacts, such as land, sea or water use, are listed for evaluation.

The final area for evaluation is the potential public response to a chosen waste management scheme. Obviously this is a nontechnical subject and most difficult to evaluate. An initial study of methodology is being designed to identify those aspects of the waste management systems that might be deemed most important by the general public. After such analysis, adequate information could be made available on these points so that the public could better understand and state it's opinions on overall implications of the alternative waste management concepts. The public's acceptance of a technically sound waste management system is a most important goal.

Class 1 - Geologic Disposal Concepts - Disposal of radioactive waste in geologic formations has the potential of isolating the waste from man's environment for extended time periods (millions of years). Geologic environments exist which have been physically and chemically stable for millions of years, are isolated from man's environment, and can potentially provide effective barriers between waste and man's environment for the time periods required. The basic requirement for any geologic environment to be suitable for disposal of radioactive waste is the capability to safely contain the emplaced radioactive material until decay has reduced the radioactivity to nonhazardous levels. The geologic environment should (a) be adequately far removed from man's environment, (b) not permit waste transport readily, (c) remain relatively stable over geologic time periods, and (d) adequately contain a highly immobile waste form.

There are several ways a geologic formation can be penetrated and altered to provide a suitable cavity for waste emplacement purposes. The present study is considering the use of drilling, mining (mechanical and dissolution), hydraulic fracturing, and nuclear cavity formation. All of these methods become more difficult with increasing depth. At depths up to about 10,000 feet, any of the methods may be used. Drilling has the potential of going to great depths; the present record is around 30,000 feet (about 5.6 miles).

The geologic disposal studies involve evaluation of concepts other than the bedded salt disposal concept. The methods under consideration for disposal of radioactive waste in a given geologic formation include:

(1) Placing solidified waste directly into a geologic formation.

(2) Placing solidified waste in man-made containment barriers within a geologic formation.

(3) Placing solidified waste in a geologic formation in a configuration to allow the waste to melt and form a rock-waste matrix.

Each of these basic concepts has a number of variations.

Disposal of previously solidified waste in a conventionally mined cavity, shown in Figure 14, is one of the more basic concepts under study and is used here to illustrate a geologic disposal alternative. It would use a building above ground to receive the waste canisters and transfer them down into the underground area. The waste canisters are placed in storage pods located in lined tunnels. The storage pods are air-cooled, though other means of cooling appear feasible. After an appropriate time period (generally tens of years), the cooling system can be shut down and the repository permanently sealed.

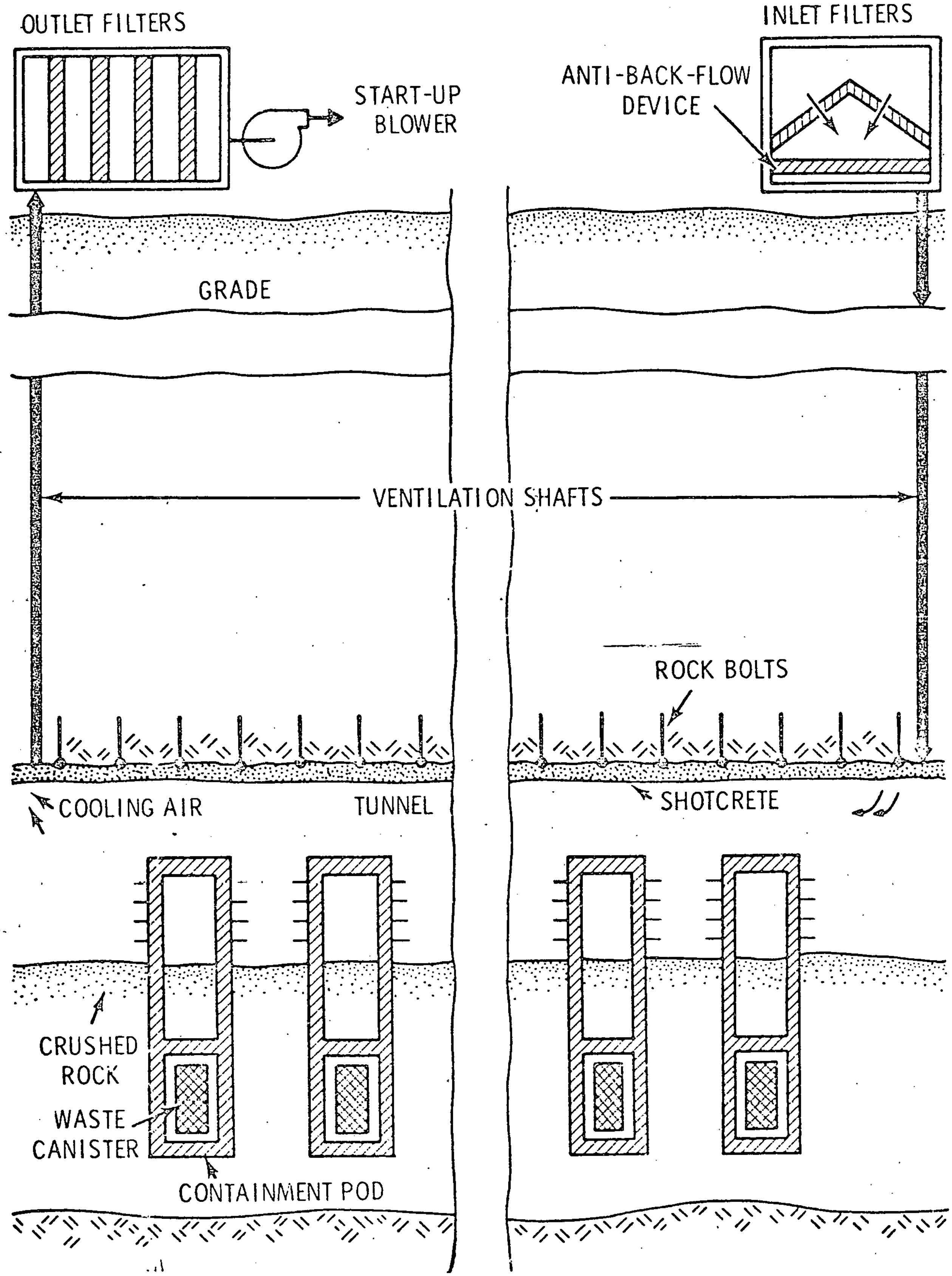


FIGURE 14. Concept for Solid Waste Emplacement in a Mined Tunnel with Natural Convection Air Cooling

Seabed Disposal Concepts

Disposal of high-level waste within the floors of the world's oceans offers another possibility for permanent isolation of the waste from man's environment. The depth to the floor or seabed would provide isolation and safety from natural disasters such as storms, as well as from sabotage or accidental disturbance. The large volume of seawater could help cool the waste and effectively dilute any material that escaped from the disposal site. The known high ion exchange capacity of the seabed sediments would aid in immobilizing waste material if any waste escape should occur.

A number of seabed disposal concepts are being evaluated but all are basically the same except for the site. The following geologically distinct types of sites on the seabed are being considered.

(1) Stable Deep Sea Floor--areas such as deep sea basins and abyssal plains and hills, which are considered geologically stable. The waste would be placed in the seabed below the unconsolidated sedimentary cover.

(2) Subduction Zones--areas where, according to crustal plate tectonics theory, one edge of certain crustal plates is moving under other crustal plates and down into the earth's mantle. The waste would be placed in these areas to be carried down, or subducted, into the earth's mantle with the crustal plate.

(3) Deep Sea Trenches other than Subduction Zones--areas where deep trenches occur in the sea floor. The waste would be placed in the dense seabed at the bottom of these trenches.

(4) High Sedimentation Rate Areas--areas where major rivers are building deltas into the ocean. The waste would be placed in the seabed below the accumulating deltaic sediments.

The radioactive waste would be in a solid form and enclosed in a durable sealed canister. To further isolate wastes, the canisters would be placed in prepared holes in the seabed, after which the holes would be sealed. The depth of the prepared holes would depend on the nature of the seabed at the disposal site.

A schematic description of the seabed concept is shown in Figure 15. The previously solidified and canned bulk waste from the reprocessing plant would be transported in protective casks to special ports of embarkation for inspection and possible short-term storage. The waste would then be transported in protective casks by ships to the disposal site where a number of waste canisters would be placed in each pre-drilled hole in the basement rock from a special drilling platform and the upper section of each hold would be filled with a sealant.

Implementation of the seabed disposal concepts in the stable deep sea areas and in the areas of rapid sedimentation could be attained with today's technology but a number of years would be required for development to prove the safety of the concept. Significant development of drilling and emplacement technology would be required to implement disposal in the very deep sea areas of the trenches and the subduction zones. Final sealing of the disposal holes to maintain isolation for the long time periods of concern would need to be tested (and improved if necessary) for radioactive waste disposal.

Disposal of radioactive waste in the seabed has the potential for isolating waste from man's environment for periods in the order of millions of years, depending upon confirmation of inferred knowledge by future seabed exploration.

Ice Sheet Disposal Concepts

Alternative concepts for radioactive waste disposal in the major ice sheets of the world (Greenland and Antarctica) are being evaluated. Potential

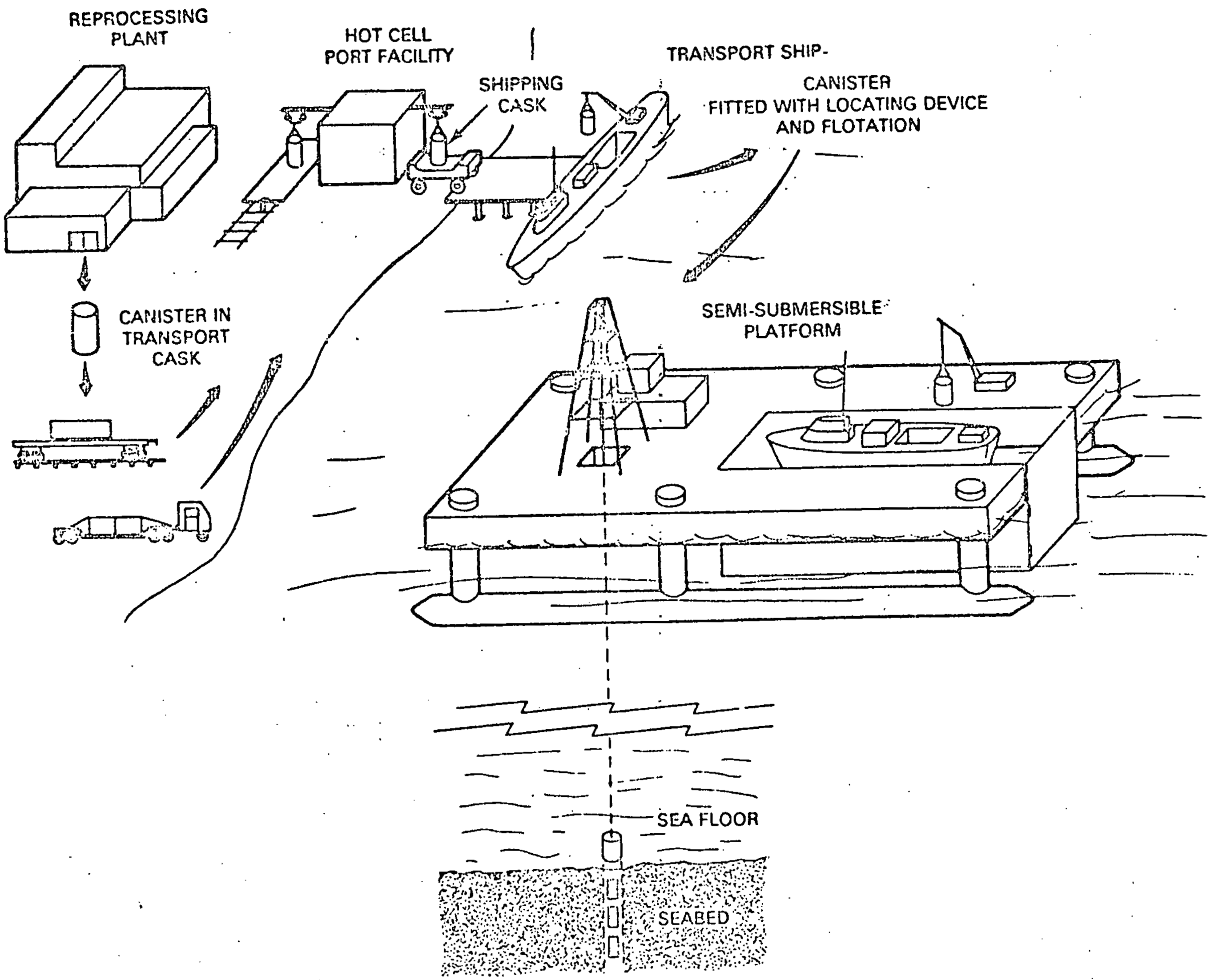


FIGURE 15. CONCEPT FOR SEABED DISPOSAL OF SOLIDIFIED WASTE

advantages are great thicknesses of ice, remoteness from man's activities, and low likelihood for future development. The ice could provide effective direct cooling for the waste and, at the same time, maintain isolation from man's environment.

Three potential disposal concepts are being evaluated for the ice sheet areas such as Antarctica or Greenland.

(1) Meltdown or Free Flow--the waste canister would be placed in an individual shallow drilled hole in the ice and allowed to melt down through the ice sheet to bedrock.

(2) Anchored Emplacement--the waste canister would be placed in an individual shallow drilled hole in the ice but connected to surface anchors by cables or chains, which stop its descent and maintain its position (500 to 1500 feet below the ice surface) for up to about 100 years.

(3) Surface Storage/Disposal--the waste canister would be placed in a temporary hot cell type of storage facility with jack-up piers on the ice sheet surface. After about 50 years, the facility would be allowed to become covered by accumulating snow and would be eventually buried in the ice sheet for final disposal.

A schematic description of the ice sheet concept is shown in Figure 16. It consists of transporting previously solidified and canned bulk waste in protective casks from the reprocessing plant to special embarkation ports. The waste would then be transported in protective casks by ships to the edge of the ice sheet when the waste canisters and casks would be off loaded to a debarkation facility near the edge of the continent. Surface vehicles would provide over-ice transport to the disposal site.

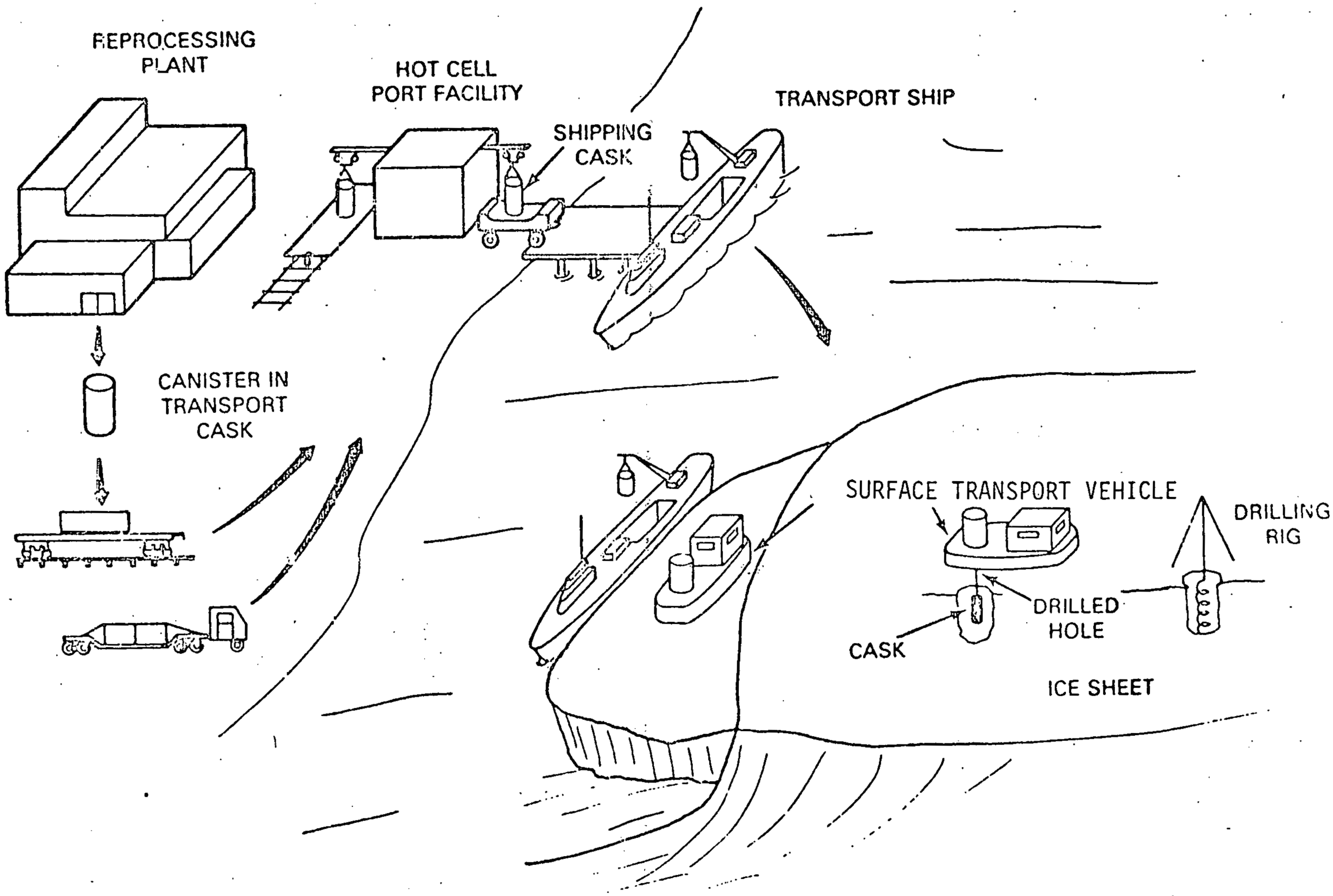


FIGURE 16. CONCEPT FOR ICE SHEET DISPOSAL OF SOLIDIFIED WASTE

The implementation of all ice sheet disposal concepts could be done with today's technology, but a number of years would be required for development to prove out the safety of any concept. The disposal system aspects of containerization, transportation, and emplacement could all be accomplished by modification of technology. Final sealing of the waste could be performed by natural refreezing of the water around the waste in all concepts.

Disposal of radioactive waste in ice sheets is considered to have an uncertain potential for isolating waste from man's environment, depending largely on long-term ice stability.

Extraterrestrial Disposal Concepts

Disposal of radioactive waste by removing it from the earth with rockets is another disposal concept being evaluated. If a stable non-earth intercept trajectory or orbit can be guaranteed, extraterrestrial disposal offers a method for the complete removal of long-lived nuclear waste constituents from the earth. The primary unfavorable features are that the concept deals with only part of the waste, there are possible launch safety problems, retrievability and monitoring are difficult, and there is possibility for international disagreement.

Extraterrestrial disposal of the total waste constituents and of only the actinides are both considered. However, primarily because of the high space transport cost per unit of weight, space disposal of just the actinides is believed to be the most practical scheme. The remaining waste would have to be disposed of by some other means.

The launch deployment sequence using a shuttle and a tug is shown in Figure 17. Typically, the shuttle would be launched into a low circular earth orbit. From this orbit, the tugs or upper stage(s) would be launched to carry the waste package to its final destination.

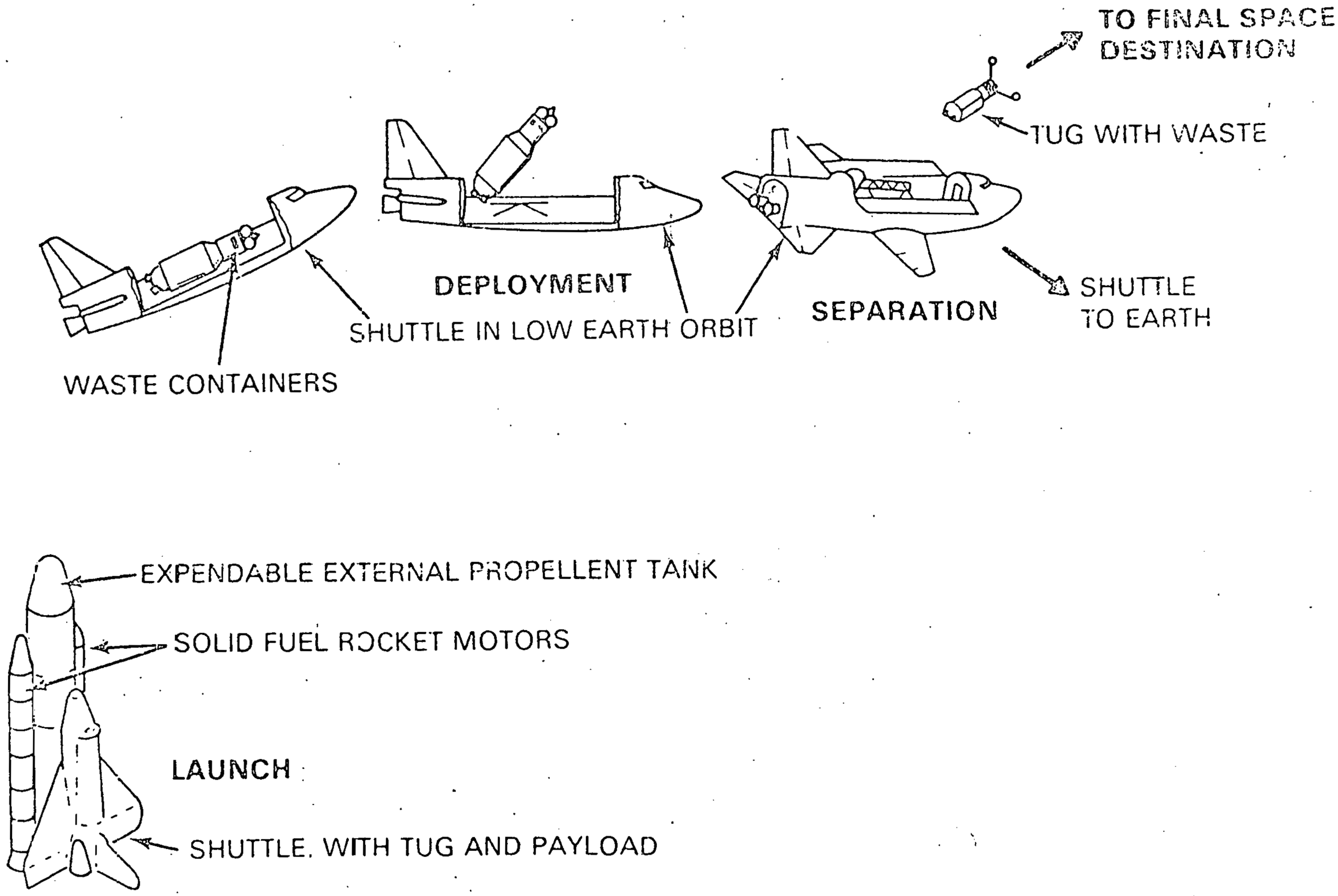


FIGURE 17. CONCEPT FOR EXTRATERRESTRIAL DISPOSAL OF SOLIDIFIED WASTE

The implementation of space disposal of actinide waste could be acheived with current technology, but the safety of the concept cannot yet be established. This technology is considered to include the space shuttle (with separately retrievable and reusable lift-off-assist rockets) and the space tug, which are advanced vehicles but which will use existing engineering technology.

Extraterrestrial disposal has the potential for permanent removal of radioactive waste constituents from the earth, depending largely on incentives and improved knowledge of deep space travel.

Transmutation Concepts

Another possible approach to the management of radioactive waste is the use of nuclear processes themselves to change (transmute) the hazardous long-lived radioactive waste constituents into short-lived radioactive waste or nonradioactive isotopes. Transmutation is generally defined as any process whereby a nuclide absorbs or emits radiation and is thereby transformed into another nuclide. Ideally transmutation of radioactive constituents in waste to shorter-lived or nonradioactive isotopes could completely eliminate the noxious isotopes. It is theoretically possible through use of nuclear processes themselves to achieve the transmutation.

To establish the relative merits and specific technical feasibility of the transmutation approaches, special criteria were developed and applied which are unique to transmutation. These include: overall waste balance, specific transmutation rate, and total transmutation rate.

The results of the evaluation for the various transmutation alternatives are summarized in Table 3. The accelerator devices failed to meet the criteria for transmutation for essentially all categories of radioactive waste. The only possible exception is the use of a spallation neutron source for transmutation of long-lived fission products. Likewise, use of neutrons from a thermonuclear

TABLE 3. Summary of Transmutation Device Feasibility

| Device | Technically Feasible for Transmutation | | | |
|---|---|---|---|---|
| | Fission Products | | | Actinides |
| | Category 3* | Category 2* | Category 1* | Category 1 |
| Accelerators | | | | |
| • Electron Accelerator | No | No | No | No |
| • Proton Accelerator | No | No | No | No |
| • Spallation Accelerator | No | No | Possibly | No |
| Thermonuclear Explosives | No | No | No | No |
| Fission Reactors | No | No | No | Yes |
| Fusion Reactors | No | Possibly | Yes | Yes |

*Category 1: Storage required for >1000 years

Category 2: Storage required for 100-1000 years

Category 3: Storage required for <100 years explosion does not appear technically feasible. The Use of fission and fusion reactors met the selection criteria for transmutation of actinides. Fusion reactors also may transmute selected fission products.

The transmutation concept of continual recycle of actinides in fission reactors appears to be particularly attractive. Calculations by Claiborne(16) at Oak Ridge National Laboratory, by Kubo(17) and Kubo and Rose(18) at the Massachusetts Institute of Technology, and at Battelle-Northwest indicate that significant reductions are possible in the cumulative toxicity index* of actinides. The calculations indicate that using existing separations efficiencies with recycling of actinides in light water power reactors could achieve an order of magnitude decrease in the short-term actinide toxicity indices and about a factor of fifty decrease in the long-term toxicity index. These reduction factors may be significantly improved by achieving higher separations efficiencies, better optimization of the reactor irradiation, or by recycling in LMFBRs.

The PNL studies of the neutron-induced transmutation of actinides and fission products in the blankets of hypothetical Controlled Thermonuclear Fusion Reactors (CTRs)(19) have demonstrated that reductions of cumulative toxicity index of actinides by a factor of 10 or more below that achievable in fission reactors could be obtained in the high neutron flux levels proposed for CTRs. These studies have also shown that large reductions in the respective toxicity indices are possible for some fission product elements. For others, notably strontium and cesium, the degree of toxicity reduction is minimal, but the calculated values are uncertain by a factor of about two because of uncertainty in nuclear reaction data for these elements. All considerations of radionuclide transmutation in CTRs, of course, presuppose the successful

*Toxicity index is defined as the amount of air or water required to dilute the present amount of a given isotope to levels defined in the Code of Federal Regulations (10 CFR - Part 20).

accomplishment of controlled thermonuclear fusion.

Since it is technically feasible to transmute actinides in fission reactors and CTRs and certain fission products in CTRs, these two reactor technologies combine to form a potentially viable long-term (year 2000 or 2010), the actinides separated from the rest of the waste would continue to be recycled in fission reactors with the fission products stored in a retrievable facility. In the long-term, with the advent of CTRs, the fission products would be retrieved from storage and recycled along with the actinides in the CTR. In either strategy, some of the fission products and whatever "heel" of untransmuted waste at the end of this era must be disposed of by other means.

Summary of Advanced High-Level Waste Studies - The overall objective of this study is to prepare a comprehensive overview compendium of information pertinent to the various potential waste disposal techniques. The disposal concepts are being studied on a systematic, generic basis and are developed only to the extent necessary to perform the overall evaluations.

Initial evaluations of technical (or theoretical) feasibility for these advanced waste management concepts show that in the broad category, (i.e., geologic, seabed, ice sheet, extraterrestrial, and transmutation) all meet the criteria for judging feasibility, though certain alternatives within these categories do not (i.e., use of accelerators for transmutation).

Preliminary cost estimates have also been developed for all the principal waste management alternatives being evaluated. The results show that, although many millions of dollars may be required, the cost for even the most exotic concepts are small relative to the total cost of electric power generation. For example, the cost estimates for the disposal on earth concepts are less than 1% of total generating costs. The cost for actinide transmutation is estimated at around 1% of generation costs, while actinide element disposal in space is less than 5% of generating costs.

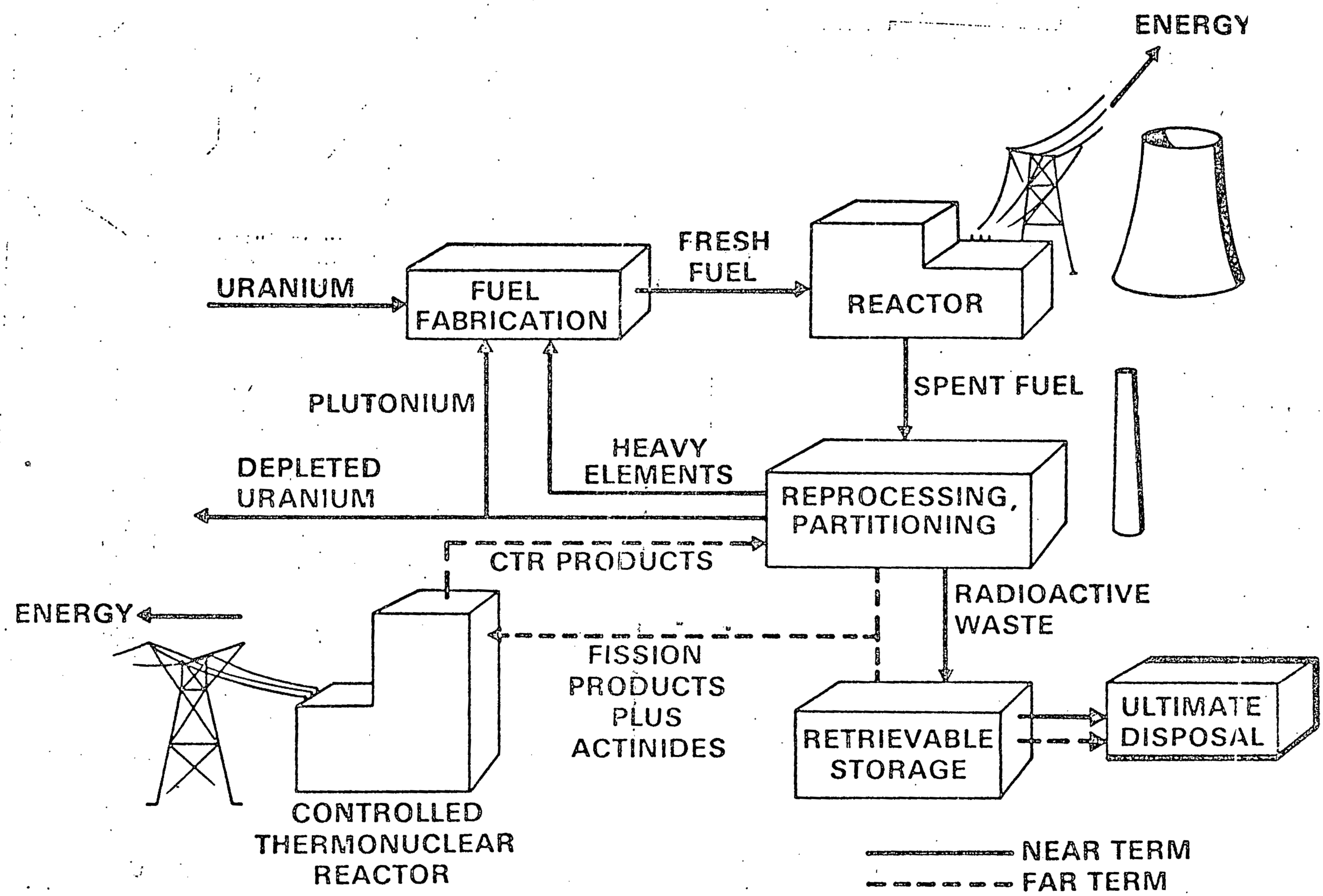


FIGURE 18. CONCEPTION OF TRANSMUTATION ELIMINATION

Thus neither technical feasibility nor cost seems to be no-go factors in selecting a waste management system. The seabed, ice sheet, and space disposal concepts face legal constraints (i.e., international policies). The information being developed in safety, environmental concern, and public response will be important factors in determining which concepts appear most promising for further development.

## CONTRIBUTIONS THE SCIENTIFIC COMMUNITY CAN MAKE

Assessment of waste disposal alternatives and selection of the most effective means of long-term management of high-level wastes requires a quantitative determination of all the evaluation factors outlined above. A quantitative assessment requires the best thinking and methodology that science and engineering can bear on this subject. To illustrate, we would like to use the safety methodology as outlined in Figure 13.

The box shown as acceptable risk precludes determining what the public's response is in relation to waste disposal options. This means that the social scientist must work in concert with the physical scientist to bring the message of the physical scientist to the public in terms of language that our society can understand and to properly evaluate the laities response. If this response is negative, then either the concept must be modified to bring it into line with the public's views or the concept must be rejected since it is an unacceptable method to the public. The social scientist is responsible for providing the tools which can be used to accurately assess the concensus view of the public and not merely the view of a vocal minority or an uninformed public.

The consequences of a release of radioactivity involves many facets which the scientific community can contribute to improving the present knowledge and understanding of. The dose to man involves the interpretation of the health effects of ionizing radiation to man. The physical chemist, the biophysicist, and the health physicist can make important contributions to the present understanding of the impact of various radiation sources on man's health. In disposal of radioactive waste, a spectrum of ionizing radiation sources exist, ranging from isotopes in the actinide element series to the species of fission products. It is important, that the mechanisms of transport, pathways to the environment and man, and the impact on man's health be thoroughly understood to assure public health and safety.

The nuclear physicist, reactor physicist, and physical chemist can contribute to improving the understanding of knowledge of the radiation characteristics of nuclear waste. The nuclear physicist is called upon to provide the best estimate of the nuclear data. He must provide the nuclear chemist the data needed to determine whether chemical and/or physical forms of high-level waste can be maintained for long periods of time. The reactor physicist,working in conjunction with the nuclear physicist,must provide the best estimates of the volumes and characteristics of wastes produced in generating electrical power with nuclear reactors.

Depending upon the concept, experts in the physical and engineering sciences must contribute to improving the knowledge of previously outlined concepts, the characteristics of the site(s) which the concept emcompasses, and the known and potential modes of failure of such systems. As examples, the geophysicist must provide the most accurate information of geologic disposal sites, be they formations on land, in the seabed or in ice sheets. Moreover, the geophysicist will be required to provide accurate predictions of the behavior of these potential terrestrial disposal formations for thousands of centuries into the future. By the same token, the physicist working on extra-terrestrial deployment of vehicles must provide the best estimates of the time-dependent behavior of vehicles carrying high-level waste into space.

All of science and engineering can contribute by offering ideas or methods for managing high-level waste. Central to assessment of these ideas is determining the advantages and disadvantages of proposed concepts. The fault tree (or failure mode) analysis is an important part of determining the potential advantages and disadvantages. This segment of the analysis requires the input of all kinds of experts, in science and technology, to make an overall adequate assessment.

The management of high-level radioactive waste produced by the nuclear power industry is a problem which is amenable to solution. To assure achieving the optimal solution, the science and engineering community must: 1) become aware of the problem, 2) become involved in developing and evaluating conceptual schemes for disposal, and 3) assist in carrying on dialogue with the public at large.

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