Program on Nuclear Power Plant Innovation

DESIGN OF A HIGH–LEVEL WASTE REPOSITORY SYSTEM FOR THE UNITED STATES

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22.033, Nuclear Systems Design
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ABSTRACT

This report presents a conceptual design for a High Level Waste disposal system for fuel discharged by U.S. commercial power reactors, using the Yucca Mountain repository site recently designated by federal legislation. It represents the results of approximately 2000 person–hours of work by students enrolled in the combined undergraduate and graduate design subjects 22.033/22.33 of the M.I.T. Nuclear Engineering Department during Spring Term 1988.

Principal features of the resulting conceptual design include :

- use of unit trains (including piggyback cars for truck cask transporters where required) for periodic (once every ten years at each reactor) removal of old (cooled ≥ 10 yrs.) spent fuel from at–reactor storage facilities
- buffer storage at the repository site using dual purpose transportation/storage casks of the CASTOR V/21 type
- repackaging of the spent fuel from the dual purpose transportation/storage casks directly into special–alloy disposal canisters as intact fuel assemblies, without rod consolidation
- emplacement into a repository of modular design having a maximum total capacity of 150,000 MT and an annual handling capability of 4000 MT/yr
- use of excavation techniques that minimize disturbance, both mechanical and chemical, to the geologic environment
- Incoloy 825 waste canisters arrayed to provide 57 kW/acre thermal loading optimized to the projected inventories
- include a unit rail mounted vehicle for both the transportation and emplacement of the canister from the surface facilities to the underground repository
- cost–effectiveness of the Yucca Mountain Site Criteria was studied via: a computer model, "WADCOM–II — Waste Disposal Cost Model II"; and an independent cost evaluation by the members of the design team. The total system cost (in constant 1988 dollars) was 1.9 billion dollars by WADCOM–II, and 5.3 billion dollars from the independent cost evaluation, resulting in a levelized disposal cost of 0.2 mills/kW–hr by WADCOM–II and 0.55 mills/kW–hr by the independent cost evaluation.

ACKNOWLEDGEMENTS

The work reported herein is solely that of the (three) undergraduate and (six) graduate students identified on the title page. However, significant contributions were also made by several individuals consulted in the course of this effort, the following in particular: Prof. R.G. Ballinger and R.K. Lester of the M.I.T. Nuclear Engineering Department; Dwight Shelor of the Office of Civilian Radioactive Waste Management Headquarters in Washington, D.C.; Spyridon Tzeros of Battelle Columbus Laboratories from whom WADCOM–II was obtained; Rachel Morton, a computer consultant for the M.I.T. Nuclear Engineering Department, who helped get WADCOM–II running; Anne Hudson of the Nuclear Engineering Department for her tremendous secretarial support; and Prof. M.J. Driscoll of the Nuclear Engineering Department for his many efforts in assisting with the development and completion of this report.

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CHAPTER 1

INTRODUCTION

1.1 Foreword

Each year the combined undergraduate/graduate design subjects in the Nuclear Engineering Department at MIT are assigned a comprehensive systems design project relevant to contemporary issues. This spring (1988) the task of developing and evaluating a conceptual design for a HLW repository was considered to be particuarly timely in view of the recent designation by the federal government of Yucca Mountain, Nevada, as the sole site for the U.S. repository. An even more compelling motivation was the fact that in the view of the general public, the presumed lack of a means to dispose of spent nuclear fuel is the most important barrier to further (or even continued) use of nuclear power.

In view of the wide–ranging scope of the problem, considerable attention was paid at the outset to negotiation of a well–defined set of assumptions and boundary conditions on the assignment at hand. The results are summarized in Table 1.1. Location, customers served, and time frame are the most important entries. While overall cost optimization is, as usual, the principal goal, it is tempered in the present instance by the hard–to–quantify considerations of risk aversion by the public, and an underlying faith in simplification of design and operations as a means towards realization of a successful concept. Time constraints also limited the degree of optimization achievable.

Table 1.1. Ground Rules

- Location: Yucca Mountain, Nevada
- Target Date for Operation: 2005
- Steady State Handling Capability: 4000 MT/yr
- Total Capacity $\geq$ 70,000 MT
- No special effort to insure retrievability
- No requirement for an independently located MRS
- All applicable NRC, EPA, DOT, and other regulations are to be met
- Design focus on spent LWR fuel assemblies (PWR, BWR); but vitrified wastes (both commercial and defense) and advanced reactor (LMR, MHTGR) fuel or reprocessed wastes are also acceptable
- Concurrent use of repository for defense HLW was not examined, but was not specifically precluded
- Goal was to minimize overall levelized cost of waste disposal to nuclear–generated electricity (mills/kwhre) ratio
- To the extent practicable, the waste container and overpack are to be less hazardous than the contained waste

1.2 Background

The problems associated with waste disposal from commercial nuclear power reactors have become an issue of concern for several reasons. First, radioactive wastes are extremely hazardous and present a potential danger for many thousands of years. Second, high level waste in the form of spent nuclear fuel assemblies have been piling up at reactor sites across the country for over two decades. Third, the storage capacity designed and constructed at these facilities is rapidly being exhausted. Finally, neither the federal government nor any other body had set up a mechanism to address and solve the problems of high level radioactive wastes until only six years ago. In 1982, the President of the United States signed into law the Nuclear Waste Policy Act of 1982. The Act specified that high level radioactive wastes would be disposed of in underground repositories. The first site was to be selected by a process which narrowed a list of nine original sites first down to five, then three, and finally one site. The sites were reduced down to three sites partially by the use of a multi–attribute utility analysis to assess the problem. In going from three sites down to the final site, however, the process became embroiled in debate and slowed to a standstill. To remedy this, the Congress of the United States passed an amendment to the original Nuclear Waste Policy Act which made the Yucca Mountain Tuff site in Nevada the first choice for the site of the nation's first high level waste repository, unless evidence precluding this choice is found. Addressing the problems related to radioactive waste disposal in the light of a confirmed repository site is the motivation for this project, which uses the Yucca Mountain site as the basis for a "Design of a High Level Waste Repository System for the United States."

1.3 Report Organization

The effort reported here quite naturally falls under two major catagories: above–ground and below–ground, from both a technical and an economic standpoint (e.g., overall cost is roughly evenly divided between these activities).

Chapter 2 is devoted to surface facilities and operations, including at–reactor operations, transportation, and at–repository surface facilities (buffer storage, repackaging, and canister handling.)

Chapter 3 focuses on the underground repository, including engineered barriers, geological characterization, repository construction, and emplacement operations.

Since the objective of this effort was to devise a comprehensive, cost–effective overall system, Chapter 4 addresses system economics, with heavy reliance on the WADCOM–II computer program, in addition to independently–derived subsystem costs estimated by the members of the design team.

Finally, Chapter 5 summarizes the principal findings of the report and identifies priority items for future work.

1.4 Repository Startup Date

The planned date for beginning repository operation is in the year 2005, with spent fuel initially being accepted beginning in the year 2003. These dates are based on conservative estimates of the time required for: geologic testing; system design; system licensing; politics and congressional approval; construction; and pre–operational testing. The time estimates for each of these items are given in the table below:

Geologic Testing and System Design	5 years
Licensing – NRC	3 years
Politics and Congressional Approval	2 years
Construction	6 years
Pre–Operational Testing	1 year
TOTAL	= 17 years

1988 + 17 years = 2005

Thus, the repository opening date is conservatively estimated to be in 2005, and in order to have a sufficient supply of spent fuel to begin operations, the surface facility will begin transporting and storing spent fuel starting in 2003.

If the repository opening is delayed beyond 2005, the surface facility will still begin accepting fuel starting in 2003, and the surface facility buffer storage capacity will be increased as needed. If the surface facility spent fuel storage capacity is projected to exceed 10,000 MTU of spent fuel, a license submittal will be made to the NRC to license the facility as a federal interim storage facility before any spent fuel in excess of 10,000 MTU will be accepted.

CHAPTER 2

SURFACE FACILITIES AND OPERATIONS

2.1 Introduction

The Surface Facilities and Operations chapter encompasses all of the activities from the reactor, where the spent fuel is picked up, to the underground repository interface, where the sealed disposal canisters are transferred to the underground repository facility. This chapter discusses spent fuel handling, transportation, storage, and finally repackaging into repository specific disposal canisters.

The following is a synopsis of the reactor to repository system design. The system uses nodular cast iron Castor V/21 type spent fuel casks for both transportation to and storage at the repository. The system does not include a Monitored Retrievable Storage (MRS) facility. Instead, handling and repackaging operations are done at the repository site, and a small buffer storage facility is included at the repository surface. Transportation from the reactor to the repository is by dedicated unit trains, which will pick up a full load of spent fuel from any given reactor site once every ten years. The unit trains will be purchased as part of the overall repository system, and therefore their cost is explicitly included in the estimated costs of the repository system design. The repackaging operation at the repository site deals entirely with intact spent fuel. No rod consolidation is done, and the intact fuel assemblies are loaded directly into the disposal canisters. The entire reactor to repository system is designed to process an average of 4,000 MTU of spent fuel per year, using only fuel which has been cooled out of reactor for ten years or more.

Several critical decisions were made during the design process in order to come up with this reference system design. The most important of these decisions are discussed in the following paragraphs.

The Dual Purpose Cask Decision

The reference system uses a nodular cast iron cask for both transportation from the reactor to the repository, and buffer storage at the repository site. This design concept was selected to limit the amount of required handling of the spent fuel in order to limit radiation exposures, accidental release probabilities, and handling costs. The major assumption of this decision was that a suitable dual purpose storage and transportation cask will be available by the time the system begins accepting spent fuel in 2003. The reference cask design selected is the Castor V/21 cask made by GNS of the Federal Republic of Germany. Although this cask has not been licensed as a dual purpose cask in the United States, it is licensed for spent fuel storage in the United States, and similar GNS casks are licensed and routinely used for spent fuel transportation in Europe.

The Monitored Retrievable Storage (MRS) Decision

The system design does not include an independently located MRS facility. The decision to not include an MRS was made for several reasons. First and foremost, all of the handling and repackaging operations done at an MRS can just as easily be done at a facility at the repository site. Second, it was viewed as beneficial to have the repackaging operation co–located with the repository, which leaves no potential for a transportation bottleneck that would leave repackaged fuel stranded and unable to be placed in the underground repository. Third, the moderately sized (4,000 MTU maximum capacity) buffer storage facility at the repository site provides the same system flexibility as the MRS storage facility, without requiring a substantially larger storage facility (MRS capacity is 15,000 MTU) located somewhere else in the country. Finally, performing the repackaging at the repository site, instead of at an independently located MRS facility, means that the Department of Energy and the United States Congress will not be required to wade through another long and complicated process to site another domestic high level radioactive waste facility.

The Unit Train Decision

The reference system design includes dedicated unit trains that will pick up a full trainload of spent fuel from one reactor at a time, and pick up at each domestic reactor will be done once every ten years. This system design was selected for several reasons. First, unit train shipments are much easier to monitor and protect than are a larger number of smaller shipments by regular cargo trains. Second, using large unit trains to visit each reactor infrequently reduces the total number of shipments made, and therefore the number and frequency of shipments passing through specific states and geographic regions of the country. This is a great public policy and relations advantage of the design. Finally, visiting each reactor only once every ten years greatly reduces the inconvenience to power operations at the reactor.

The System Throughput Decision

It was decided that the entire reactor to repository system will process 4,000 MTU of spent fuel per year, and that only spent fuel that has been cooled out of reactor for ten years or more will be accepted. The throughput rate of 4,000 MTU per year was selected because it is the best estimate of the eventual steady–state annual spent fuel discharge rate from all of the power reactors in the United States. The system design could easily be modified for a higher throughput rate, but it is impractical to receive more spent fuel per year than is being generated, which would eventually lead to a time when the repository would have to shut down for a period of years in order to wait for more spent fuel to be generated. With an annual throughput rate of 4,000 MTU per year and a 2003 initial spent fuel acceptance date, it was found that if a policy of "oldest fuel first" is used when picking up spent fuel from the reactors, then the criteria of accepting only fuel cooled out of reactor for ten years or more follows naturally, and places no unnecessary constraints anywhere in the system.

The Consolidation Decision

A decision was made to dispose of the spent fuel as intact spent fuel assemblies, and that no rod consolidation will be done. This critical decision was made after several long discussions in which the advantages and disadvantages of rod consolidation were listed and compared. There are several disadvantages to performing rod consolidation. First, rod consolidation requires a high degree of technical sophistication: the equipment is in a harsh radiation environment; robotics are required which are beyond the present state of the art; and elaborate computer systems and artificial intelligence that would be at the very cutting edge of today's technology are required. Second, the rod consolidation process is arguably the most dangerous step in the entire waste disposal process: it has the greatest potential for releases of radioactivity of any operation in the entire system; the potential exists for in–cell fires due to the ignition of pyrophoric zirconium fines generated in the process; and there is the problem of criticality any time there is a large number of unconstrained fuel assemblies. Third, the rod consolidation process has the potential to be a severe system bottleneck: the technology of rod consolidation is untested and the current evolutionary design process will not produce a testable system for close to ten years; if the rod consolidation system breaks down it is on the critical flow path and will force the whole system to shut down; and the rod consolidation equipment will be optimized for one type of waste package and any package changes may force a extensive redesign of the equipment. The potental advantages of rod consolidation are few, but may be quite important. First, if heat transfer within the canister is a problem, the consolidated fuel provides a better heat transfer mechanism than does intact fuel. This possibility was investigated (see 3.2.2.3), and it was found that peak canister temperatures were not a problem for either consolidated or intact spent fuel. Second, intact spent fuel may present a criticality problem due to its highly reactive geometry as opposed to the highly undermoderated geometry of consolidated spent fuel. For the small amount of spent fuel contained in each of the reference design canisters, criticality was judged not to be a problem. The final possible advantage of rod consolidation is the potential savings in disposal cost due to the use of fewer canisters. This was investigated, and it was found that the additional number of canisters required in combination with the relatively low cost of the design disposal canisters resulted in no substantial cost savings for this design, particularly when the additional cost of design, fabrication, and operation of the rod consolidation equipment is considered. In summary, the clear disadvantages of rod consolidation for this design were viewed to far outweigh the somewhat nebulous advantages, and therefore rod consolidation was not included in the system design.

2.2 At–Reactor Operations

2.2.1 Introduction

The at–reactor operations consist of loading the spent fuel assemblies into a transport cask and then loading the cask onto a train or truck for transportation. A "unit train" concept is used because it was determined to be the safest and most efficient mode of transportation to the repository. The facilities at the reactors that are used for the preparation of the spent fuel are supplied by the repository. By supplying the necessary extra equipment to the reactors, the at–reactor operations are kept as inexpensive and uniform as possible.

2.2.2 Unit Train Concept

The transportation of spent nuclear fuel can be accomplished through the use of trucks, railroads, and/or barges. In assessing the optimal modal mix for the present situation, four broad areas need to be considered: public acceptance, safety, environmental impact, and economics. The design philosophy of the transportation phase of the waste disposal system has been to make decisions based on these criteria in this order of priority. Because the cost of transporting nuclear wastes is relatively small compared to the other phases of the disposal process, and because transportation involves the greatest degree of contact with the general public, it is prudent to choose the mode of transport which is safest and most acceptable to the public even if this results in an increased cost. The modal mix which best fits this philosophy is the unit train concept, with truck and barge transport to be used only cases where rail access to a site can not realistically be achieved. Special dedicated trains will be set up specifically for this purpose which will allow them to run with less frequency and with greater ease of coordination and security control. More details concerning regulations, operations, routing, shipment frequency, and security can be found in Section 2.3.3.

2.2.3 Storage/Transportation Cask

Two types of transport casks will be used in the repository operations. Reactors with rail spurs will use the Castor–V/21 cask. Since the Castor cask cannot be transported by truck, reactors without rail spurs will be forced to use standard truck casks. The advantage of the Castor–V/21 spent fuel cask is its dual purpose nature; this cask can be used as a storage cask as well as a transport cask. Although the Castor–V/21 is presently awaiting transportation licensing, the cask will most likely have its license by the time the repository begins collecting spent fuel.

Repository operations will be simplified considerably by using a transport cask that doubles as a storage cask. The Castor cask would save the time and expense of reloading incoming spent fuel from transport casks to storage casks. Although several other cask vendors are also awaiting transportation licensing of their casks, the Castor cask was chosen because of the abundance of available technical data and the decision of Surry Power Station to purchase five Castor–V/21 casks for their new dry storage facility.

Designed by Gelleschaft fur Nuclear Service of the Federal Republic of Germany, the Castor–V/21 cask is constructed from nodular cast iron. With an outside diameter of 8 feet and an axial length of 15 feet, the cask is designed to hold 45 intact BWR fuel assemblies or 21 intact PWR assemblies with enrichments less than 3.5 percent (Figs. 2.1 and 2.2). The assemblies must be aged more than 5 years, have burnups less than 35,000 MWD/MT, and have decay power less than 1 kW per PWR assembly. These limitations may require the use of an alternative cask with higher specifications in the future for fuels with higher burnups. The cask's neutron shielding is accomplished by moderator rods that are placed into axially drilled holes in the iron wall. The gamma shielding of the cast iron lowers the dose rate to approximately 50 mrem/hr on the sides although there is a higher dose on the top due to the lighter shielding (Figure 2.3). This massive shielding explains the cask's unloaded weight of approximately 100 tonnes. Two stainless steel lids with metallic seals

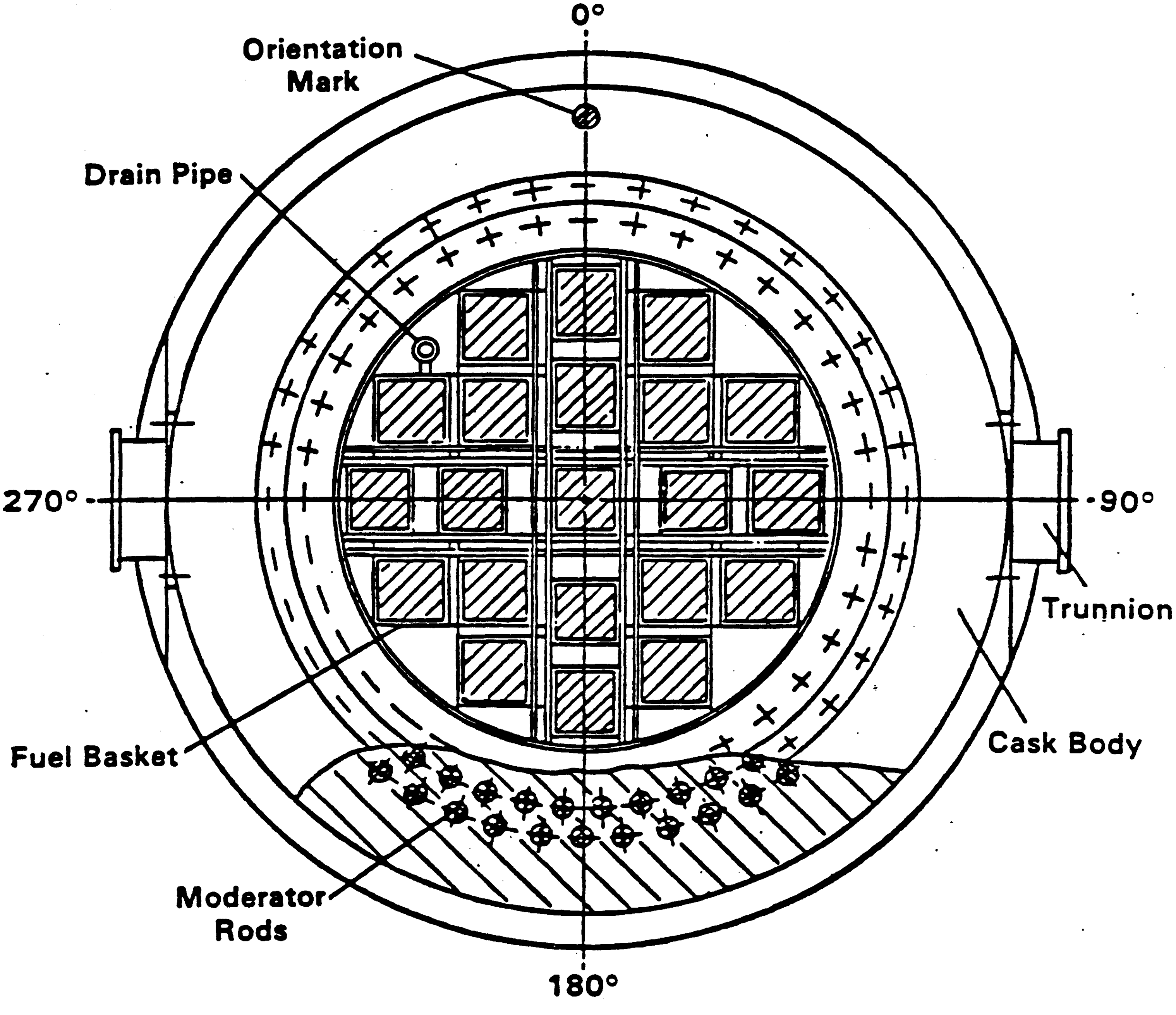


Figure 2.1: Castor Cask Cross Section

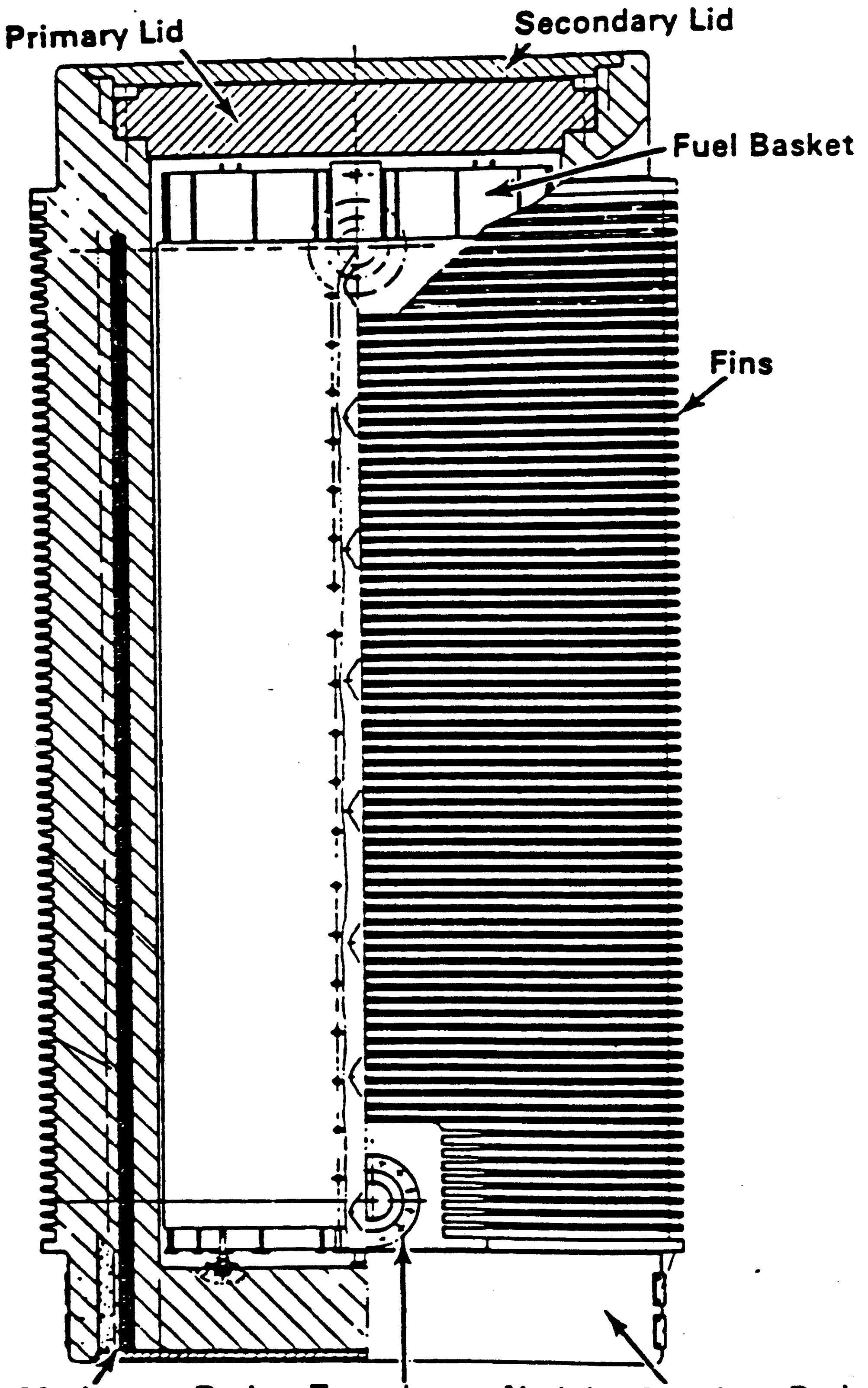
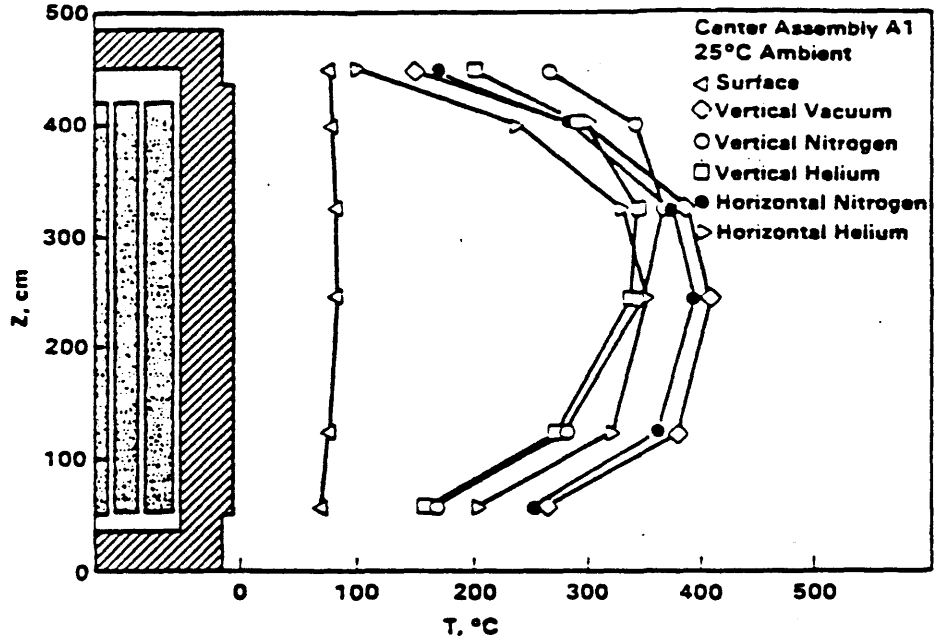
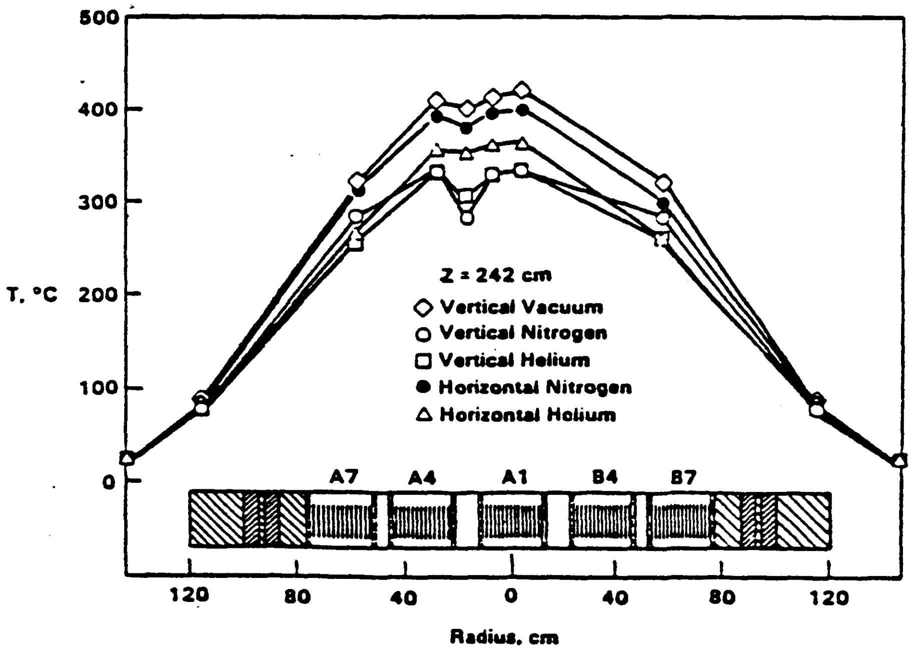


Figure 2.2: Castor Cask Dry Storage Cask



CASTOR-V/21 Axial Temperature Profiles



CASTOR-V/21 Radial Temperature Profiles

Figure 2.3: Castor Cask Dose Rates

are used to retain the helium cover gas at a pressure of 800 mbar. The helium backfill maintains a peak clad temperature of less than 380 C (Figure 2.4). A built–in leak detection circuit is also included to facilitate inspections and monitoring.

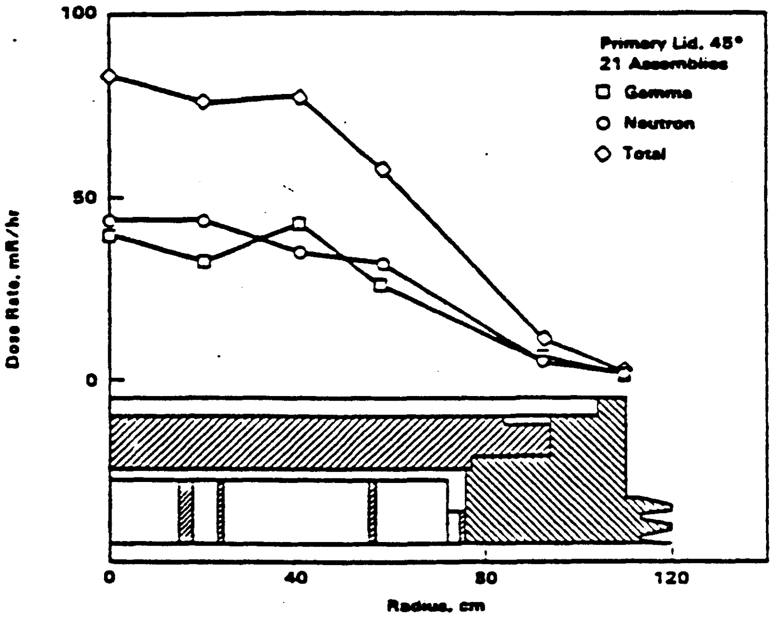
The truck casks used by the reactors without rail spurs are much smaller than the Castor cask. These casks are available in sizes large enough to carry almost 10 tonnes of spent fuel. A typical example is the CNS 14–190H Transport Cask, marketed by Chem–Nuclear Systems, Inc. This large volume Type A cask accepts up to a 20,000 pound (9.1 tonne) payload.

2.2.4 Facilities and Operations

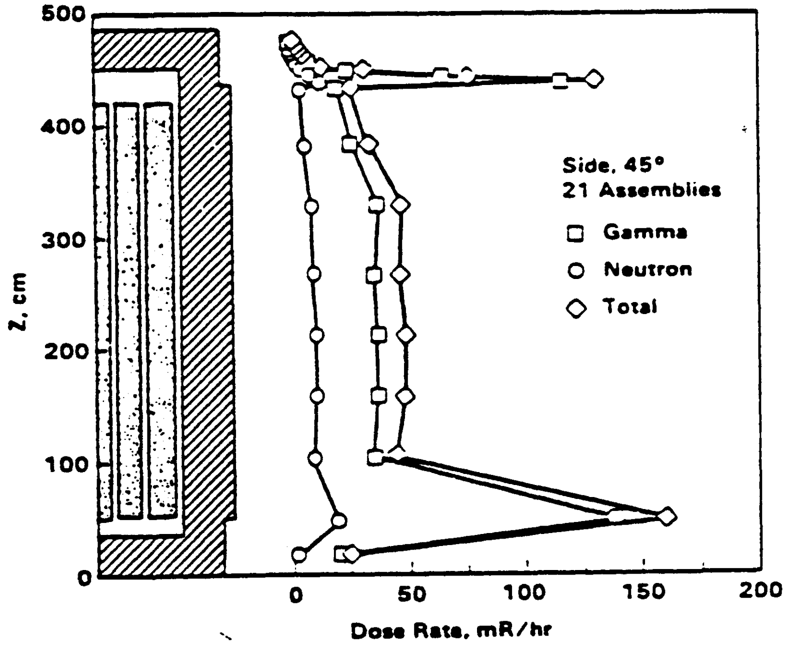
Every ten years, a shiptment of thirty empty casks is delivered to a reactor facility. The facility is responsible for loading the oldest spur. Once at the rail spur, the repository transportation staff oversees the loading of the casks onto the unit train. Each unit train carries a mobile crane for this purpose. Plants that do nto have access to nearby rail spurs load their spent fuel into smaller truck casks and transport them to their assigned location by truck. The trailers and casks are then loaded onto the train together as in a conventional "piggyback" operation and transported to the repository site (see Fig. 2.5).

The reactors that have access to a rail spur utilize a larger cask that is placed directly on a rail car (see Fig. 2.6) and are the cask transporter that is supplied by the repository. The task of loading the casks onto the unit train is the repository's responsibility and is done with the aid of the crane on the unit train.

The process of loading the casks with the spent fuel assemblies is a relatively simple one. The cylindrical casks arrive at the reactor site unassembled (i.e., the lid will not be attached) and are immersed into the spent fuel pool. The fuel is placed into the cask, the water is drained out of the cask and the lid is welded on. The cask is sealed and is checked for leaks.



GAMMA AND NEUTRON DOSE RATES ON CASTOR-V/21 PRIMARY LID



GAMMA AND NEUTRON DOSE RATES ON CASTOR-V/21 SIDE

Figure 2.4: Castor Cask Temperature Profiles

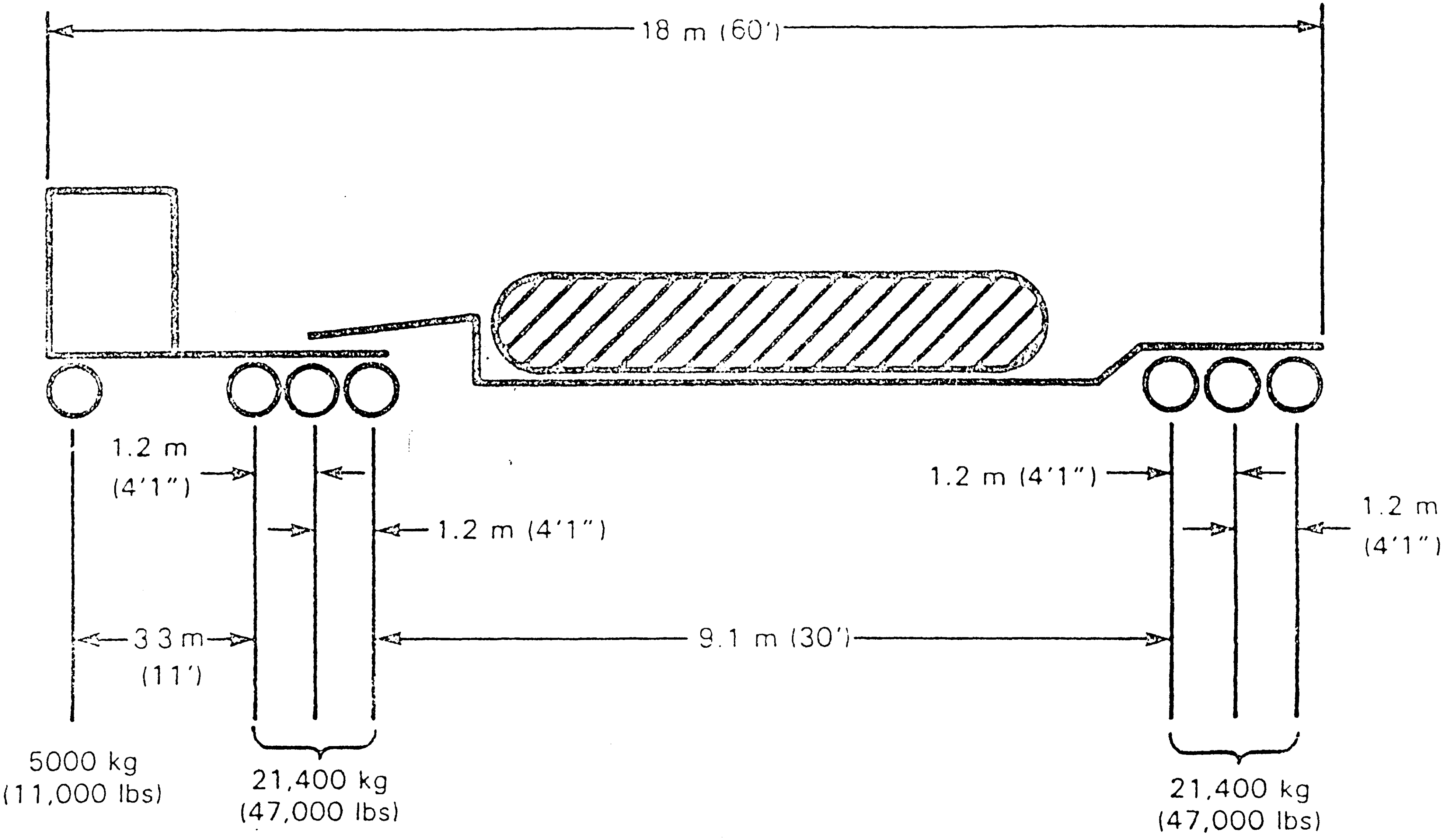


FIG 2.5 Overweight Truck Design Envelope

2.2.5 Flat Car Design

There are two types of rail cars that will be used in the transportation of the casks to the repository site. For the reactors with access to a rail spur, a flat–car capable of transporting the Castor cask will be used. For the reactors without rail access, a flat–car capable of carrying truck trailers in the conventional "piggy–back" style will be used.

The rail car designed for carrying the larger Castor cask is capable of holding as much as 200 tonnes of gross vehicle weight. The rail car is 27 m (90 ft) in length and has double trucks at each end of the rail car (see Fig. 2.6).

The rail car that will be used in the "piggy–back" operation is of a conventional type. The truck trailer, however, is an overweight design and will require overweight permits. The permits are not difficult to obtain and should not be the limiting factor as long as the weight restriction of 50 tonnes gross vehicle weight is followed. This weight will be distributed over seven axles (see figure 2.5) and is in common usage today.

2.2.6 Reactors Without Rail Spurs

Forty–two commercial nuclear reactor sites in the United States do not currently have rail access [2–1]. In addition, some rail right–of–ways will require upgrading to handle overweight rail casks. To the greatest extent possible, these sites will have rail spurs laid or upgrading done so that use can be made of more economical, safer, and more publicly acceptable rail transport.

In the cases where this can not be accomplished, two options are available. If the site is accessible by ocean waterways, barge transport can be used to convey rail casks to the nearest railroad branch. Alternatively, fuel can be placed in truck casks and transported by highway routes to a railroad branch, in which case the trucks will be transported piggy–back style to the repository site as part of the unit train.

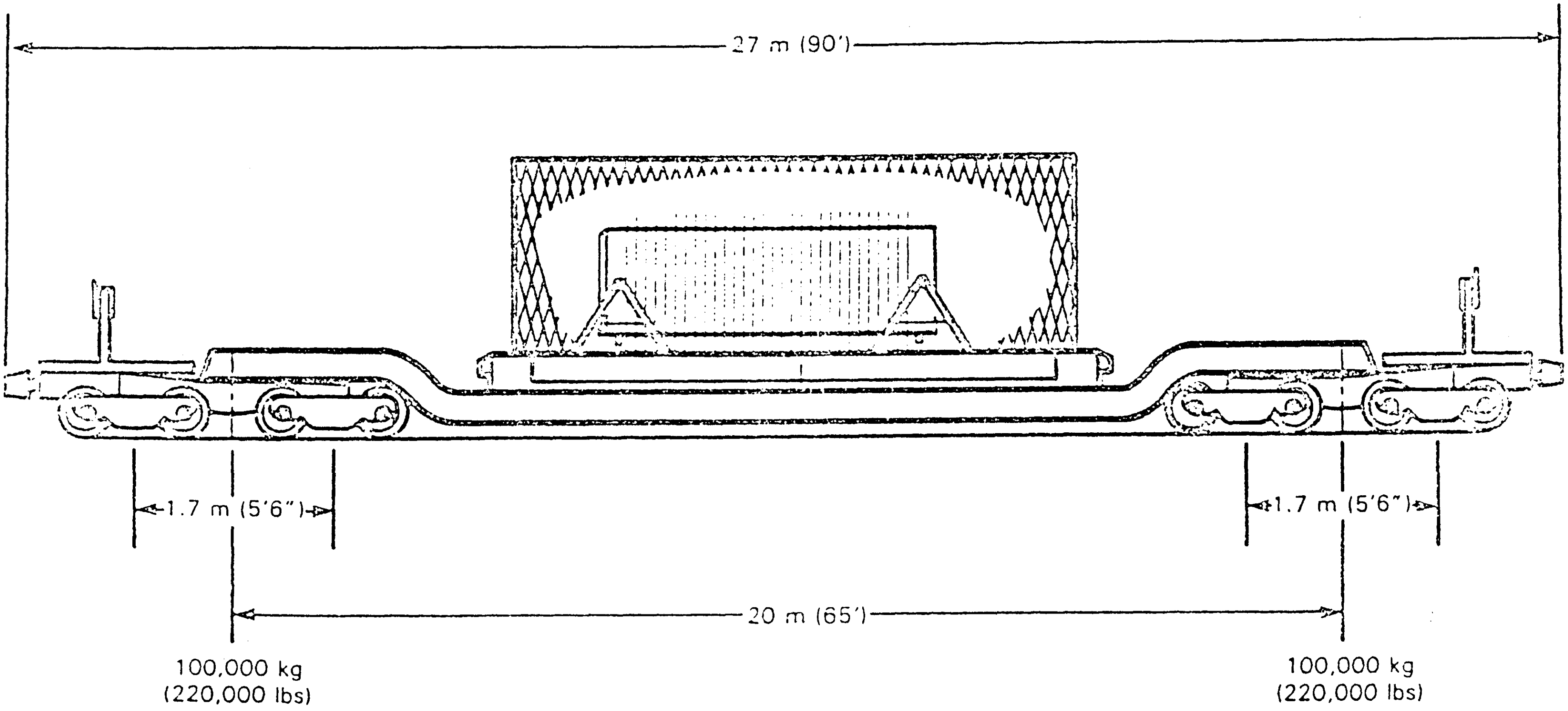


FIG 2.6 Heavy Railcar Design Envelope

2.2.7 Off–Normal Events

During the process of transporting and loading the casks, certain problems could arise. There is always the chance that the cask could be dropped when being transported from the fuel pool to the storage pad since the cask is lifted off the ground. If the cask is dropped, it will immediately be inspected for leaks and cracks in the weld. If any are detected, the cask will be resealed. If the cask is beyond repair, the fuel assemblies will be reloaded into a different cask and sealed in the same manner as before.

If, immediately after a cask has been welded shut, a leak is detected, the cask must be opened and rewelded shut before it can be transported. The casks are routinely monitored for any leaks that may develop throughout the operation.

Since the cask serves the dual purpose of both a storage and transportation medium, no significant problems arise if a unit train fails to pick up the casks. The storage pads at the reactors have enough space to store the casks until the behind–schedule train can be serviced and/or replaced.

2.3 Transportation

2.3.1 Introduction

Transportation is an integral and essential part of the projected waste management system. The United States has a long history of transporting radioactive material. Commercial spent fuel has been shipped for over 20 years and high–level waste from defense activities for an even longer period. These shipments have been conducted without any accidents causing death or environmental damage due to the radiological nature of the cargo. The DOE is taking measures to ensure that this safety record continues. An extensive program is under way to develop equipment and procedures that can accommodate the expected increase in the number of shipments when Nuclear Waste Policy Act (NWPA) facilities begin operating. Under the NWPA, the Office of Civilian Radioactive Waste Management (OCRWM) will accept commercial waste at reactor sites or point of origin for transport to the repository. Spent fuel shipments will be in compliance with all applicable Federal regulations and OCRWM procedures in effect at the time of transfer to the repository. In addition, State, Tribal, and local requirements that are consistent with Federal Law will be followed. In implementing the DOE's mandate under the NWPA, the OCRWM will develop and operate a transportation system to move waste from the commercial reactors where it is generated and currently stored to the repository at Yucca Mountain, Nevada. This system requires development of the physical equipment and transportation services to transport the waste as well as an institutional framework that will act to facilitate the effective development and operation of the system. The projected physical transportation system will consist of shipping casks, carriage equipment, and associated ancillary equipment. The services required will include the carriage of the fuel by commercial transport companies, the maintenance of the casks and other equipment, and the training of system operators such as drivers, maintenance personnel, and inspectors. In accordance with the NWPA, the OCRWM "... shall utilize by contract private industry to the fullest extent possible..." to develop and operate this system.

A successful transportation system must not only be safe and efficient but also widely acceptable. To achieve the necessary public understanding, a number of questions and issues regarding the establishment and operation of the transportation system must be addressed. Since the transportation phase of the waste disposal system involves the greatest degree of contact with the public, it is here that steps must be taken to minimize any accidents or problems that occur, and to prevent such complications to the greatest extent possible. An extensive public relations plan that points out these safety measures and emphasizes the excellent safety record of radioactive materials transport relative to other dangerous materials will be an important part of the transportation system. While public policy is complicated by the differing interests of the parties involved, it is an important key to program implementation.

2.3.2 At–Reactor Operations

At each reactor, there is a "reactor–repository interface team" of approximately five people that is responsible for supervising the preparation and loading of the spent fuel assemblies into the transportation casks. When the transportation casks are delivered to the reactor site, a cask transporter will also be unloaded to facilitate the cask movements. The casks are then transported to the spent fuel pools and loaded with the oldest fuel assemblies first. The loading process will not require a significant amount of extra equipment at the reactor since the cask loading operation is similar to the loading of the assemblies into the spent fuel pool. Once the assemblies have been loaded, the cask is backfilled, sealed, leak checked, and transported to the holding pad to await transportation.

Although each reactor may have its own special needs, the basic operation will follow one of two paths. If the reactor does not have a nearby rail spur or access to a rail line, then the reactor is responsible for transporting the truck casks from the designated drop–off point to the reactor site. If the reactor has access to a local rail spur, then the full size casks and cask transporter are delivered to the holding pad at the reactor.

The casks are transported to the spent fuel pools and loaded with the spent fuel. The process involves the lifting of the cask and placing it in the pool using a crane which has been upgraded to lift the cask. Most reactors' cranes are designed to lift maximum weights comparable to that of fuel assemblies. The repository has the responsibility of upgrading the cranes to accommodate the extra weight of the transportation casks if the reactor has a rail spur and uses the larger cask.

When the casks are loaded with the spent fuel assemblies, the oldest fuel is loaded first for safety reasons. During the initial operational period, it is a good idea to transport the fuel that is not as hot in case some unforeseen problems arise. There is also the common sense reason that the first in should be the first out. This method prevents the accumulation of extremely old fuel assemblies in the spent fuel pools. Once the transportation system has been completely tested and shown to be safe, the repository, if necessary, can dictate what heat load of spent fuel should be transported to the repository. By doing so, the repository is able to utilize as much of the underground space as efficiently as possible.

2.3.3 Reactor to Repository Transport

2.3.3.1 Regulations

Inspection and enforcement activities for the transportation of radioactive materials are shared by Federal and State agencies. The responsibilities of various agencies are reviewed below.

The Nuclear Regulatory Commission (NRC) maintains an active inspection and enforcement program to ensure that its regulations and control procedures are met by licensees. The NRC is responsible for review of: procedures for preparing empty casks for transportation, procedures for loading shipping casks on transport vehicles, cask–maintenance programs (periodic cask testing, inspection, and adherence to replacement schedules), physical protection plans and procedures, and radiation monitoring. Enforcement mechanisms for violations of NRC requirements include written citations and monetary penalties.

The Department of Transportation (DOT) inspects radioactive waste shipments to monitor compliance with regulatory requirements. DOT inspectors are provided by the Office of Research and Special Programs Administration, the Federal Highway Administration, and the Federal Railroad Administration. Inspections monitor compliance with in areas such as package marking and labeling, placarding, shipping papers, and radiation dose rates. In addition, inspections vehicle safety and route plans, track safety, power and equipment, operating practices, and signal and train controls. There are written citations and monetary penalties in use to enforce DOT requirements.

The Department of Energy (DOE) is also responsible for the inspection of casks and transportation vehicles used in the shipment of radioactive waste. The DOE reviews areas such as: preparation of casks for transport, vehicle loading and safety, marking and labeling, placarding, physical protection plans, and radiation emissions from the casks. The enforcement procedures used by the DOE are specified in contractor agreements, and include the suspension and termination of contracts as penalties for noncompliance.

States wishing to implement and enforce Federal regulations governing the transportation of radioactive materials are required to train and certify personnel and conduct State inspection and enforcement activities in a manner consistent with Federally established procedures. The Motor Carrier Safety Assistance Program is provided to States to assist in the development of safety regulations for commercial motor vehicles.

The Federal Railroad Administration supports programs to assist in the development of regulations for rail transport.

2.3.3.2 Transportation Operations

All shipment operations to be performed by transportation service contractors are included in a Transportation Operations Procedure Manual. This manual standardizes procedures across the transportation system to insure smooth operation and compliance with governing regulations.

Operational Scheduling is the first stage of the transportation process. A precise schedule of activities is necessary to insure that all events take place as required without delays or interruption. The first event in this category is the arrival of the casks and transporter at the reactor site and the loading of the shipment as described in Section 2.2.4.

Shipment checkout procedures are required to insure compliance with all relevant regulations prior to the dispatch of the shipment. After a physical inspection of the shipment and equipment, shipping papers and title must be prepared and accepted. After the actual dispatch of the shipment, notification of appropriate authorities must take place.

While the shipment is in transit, continuous attention to routing (as described in Section 2.3.3.3) and security procedures (as described in Section 2.3.3.5) must be maintained. A special truck or rail car will be travelling at the front of the shipment convoy to monitor upcoming road or track conditions and to notify the rest of the convoy as well as the appropriate authorities in the event that emergency procedures need to be implemented (as described in Section 2.3.3.5).

The final stage of the transportation process, shipment receipt, also requires careful scheduling well in advance to insure the availability of the necessary equipment to transfer the shipment casks to the buffer storage area (as described in Section 2.4.3.4) in an efficient manner. After a final inspection has taken place, the casks can be unloaded and the decontamination check–out procedure can be completed, at which point release of equipment takes place and the transportation phase has ended for this shipment.

Provision will also be made for scheduled and unscheduled maintenance and repair of the casks and transport equipment, as well as inspections by State and Federal authorities.

2.3.3.3 Highway/Rail/Barge Routing

As discussed in Section 2.2.2, the Unit Train Concept was determined to be the optimal method of waste transportation when safety, economics and public policy are econsidered together. Consequently both highway and barge transport will be us d only in cases where rail access to a reactor site is not available. In these cases, the routing used will presumably be the most direct route from the reactor to the nearest rail spur, with necessary detours around population centers or possible trouble sites. Since rail transportation offers fewer routing alternatives than does highway transportation, due to a smaller number of alternate routes and the condition of rail tracks, it will be somewhat easier and less expensive to conduct optimization studies for rail routing. The route planning criteria established by the OCRWM require the selection of rail routes that limit shipping costs and transit times, avoid population centers (where possible), and avoid adverse weather conditions. Within these guidelines, private industry will be utilized to the greatest extent possible to develop and maintain routing plans for each reactor.

2.3.3.4 Shipment Frequency

The average amount of fuel that comes into the repository is 4,000 MTU per year. This number was chosen to keep pace with the reactor output each year. In order to achieve this rate, a unit train must pickup spent fuel from each of the 126 reactor sites once every ten years. Each unit train has 100 rail cars, 60 that are designed to carry the Castor casks, and 40 that carry the truck casks. Since each reactor loads 300 MTU into the thirty casks it receives, the unit train is able to visit three reactors at a time. With this knowledge, a train must make approximately five trips a year between the repository and the reactors in order to deliver 4,000MTU per year.

Due to the time involved with unloading, loading and filling the casks, a train is only able to make two trips per year which results in the need for three unit trains. This estimate is a conservative one and may change as the operations become more familiar to the personnel involved.

2.3.3.5 Security

Federal regulations for the protection of commercial spent fuel shipments from acts of theft and sabotage are specified in 10 CFR 73.37 (NRC), 49 CFR 173.22 (DOT) and DOE Order No. 5632.2. The actions required under these regulation are summarized below.

1) NRC approval of the route in advance of shipment.
2) The development of specified procedures for coping with circumstances that threaten deliberate damage to the spent fuel shipment.
3) Provision of at least one escort to maintain visual surveillance of the shipment during stops.
4) Use of a commercial center at a designated location to monitor the progress of the shipment.
5) Calls made to the communication center by shipment escorts at least every two hours to relay the status of the shipment.
6) Shipment planning to avoid intermediate stops to the extent possible.
7) Advance arrangement with local law enforcement agencies along the route to assist in their response to and emergency.
8) The use of one escort to accompany a driver in a transport vehicle or the use of a second vehicle occupied by two escorts.

9) The use of some form of vehicle locating device to assist in response in the event of an emergency incident.

10) Inspection before shipment for evidence of sabotage attempts. The utilization of these procedures will help to reduce the possibility of an emergency incident and will facilitate a response in the unlikely event that an emergency arises which cannot be handled by personnel present in the transport convoy. In case such an emergency does arise, assistance will be provided by State and local governments and the Federal Emergency Management Agency.

2.3.4 At–Repository Operations

When the unit train reaches its final destination at the repository in Yucca Mountain, Nevada, the transportation phase of the operation has ended. Once the train has stopped on the siding near the buffer storage area and the necessary security and regulatory procedures have been completed, the casks will be transferred to the buffer storage area as described in Section 2.4.3.4.

2.3.5 Public Policy Issues

Public policy issues are extremely important to consider at an early stage in the development of a nuclear waste management program because there already is a great deal of opposition to nuclear power (even if much of it is purely political in nature), and nuclear wastes are often cited by critics as a serious problem that must be dealt with before any more nuclear plants are built. Since the transportation phase of waste disposal involves the greatest degree of contact with the general public, it is especially important to include an educational program as part of the repository design report. An examination of the history of radioactive materials transportation shows an excellent safety record. In shipping about 5000 spent fuel elements over the past 20 years, there have been only two transportation accidents of any kind and none involved any release of radiation or injury to the public [2–2]. The main reason for this is the high standards set for the design of transportation casks as described in Section 2.2.3. The worst type of accident that could occur during transportation is considered to be a terrorist attack with explosives. A test performed at Sandia National Laboratories simulated such an attack on a cask containing a fuel bundle [2–3]. They found that the amount of radioactive material released under those circumstances would cause no immediate injuries or fatalities and at most one cancer fatality many years later. In another set of tests, casks were crashed into a cement wall at 80 mph, hit by a 120 ton locomotive at 80 mph, dropped to the earth from a height of 2000 feet, and submitted to fire conditions six times as severe as required by regulations; in each of these cases, the casks survived without severe damage or release of significant radioactivity [2–4]. These facts are a good illustration of the principle that risk is easier to reduce when danger is concentrated. The amount of spent fuel transported in the United States is minuscule when compared to the huge volumes of other types of hazardous wastes produced every year such as 9 million tons of chlorine, 16 million tons of ammonia, and 32 million tons of sulfuric acid. It would obviously be impossible to transport this amount of material in spent fuel transport casks. In fact, no other hazardous materials are required by regulation to be shipped in accident–resistant containers [2–5]. This explains why accidents involved with gasoline transport caused 480 deaths from 1976–1980 [2–6], and why coal transport causes between 700 and 1300 public fatalities per year [2–7]. When presented with this information, many critics will say that there is still no justification for adding to the already existing dangers with more nuclear power. But it is important to note that replacing some of the large percentage of US energy generated by coal with nuclear power, those dangers can be reduced. A 1000 MW coal plant produces solid wastes at the rate of 30 pounds per second [2–8]. They include 19 toxic metals (such as arsenic), carcinogens (such as benzopyrene), mutagens, and are more radioactive than the routine emissions of a nuclear plant. Even worse health hazards are presented by the stack wastes which include 600 pounds of carbon dioxide and 30 pounds of sulfur dioxide per second, 18 pounds of particulates per minute, and as many nitrous oxides as 200,000 automobiles running simultaneously. Considering the great superiority of nuclear power in the areas of waste transportation and disposal, it seems clear that much of the vocal opposition that still exists today should be looked at with some suspicion. Too many scientifically valid nuclear ventures have been delayed or cancelled due to a lack of public acceptance. It may be possible to avoid such complications with a nuclear waste disposal facility by making public education a part of the program at an early stage.

2.3.6 Estimated Costs

The estimated costs of the whole transportation system are presented below in constant 1988 dollars:

	COST ELEMENT (MILLIONS)
Construction:	354.2
Operation:	101.3
TOTAL:	455.5

2.4 Repository Surface Facilities

2.4.1 Introduction

The repository consists of two sites; the primary facilities are sited on a plain near the base of Yucca Mountain, while the secondary facilities are located near the peak of the mountain (Figure 2.7). The repackaging and buffer storage will be performed at the primary facility, located at the entrance to the waste tunnel, through which the spent is transported to the underground section of the repository. The secondary facilities, consisting of the ventilation shafts for the repository, the man–and–materials area, and the tuft excavation area are all located farther up Yucca Mountain.

2.4.2 Facility Siting and Layout

2.4.2.1 Primary Surface Facility

The primary facility consists of the rail stop, loading area, buffer storage, Repackaging and Handling (R&H) facility, the above ground tracks of the transportation rail vehicle, administration and operations offices, and a visitor's center with the associated security (Fig. 2.8).

The rail stop is just an extension of an existing rail line to the repository. A train, loaded with approximately 100 cars of spent fuel, will arrive at the loading area of the repository every ninety days.

The loading area is a concrete pad that is 50 feet wide and 300 feet long to accommodate three heavy–rail flat cars. The crane provided by the train replaces the loaded storage casks on each flat car with empty casks for the next reactors. The cask transporters then carry the casks from the loading area to the buffer storage pads.

The buffer storage area consists of a set of reinforced concrete pads, on which the loaded fuel casks await repackaging. The modular design allows future additions when required due to delays in the repackaging procedure.

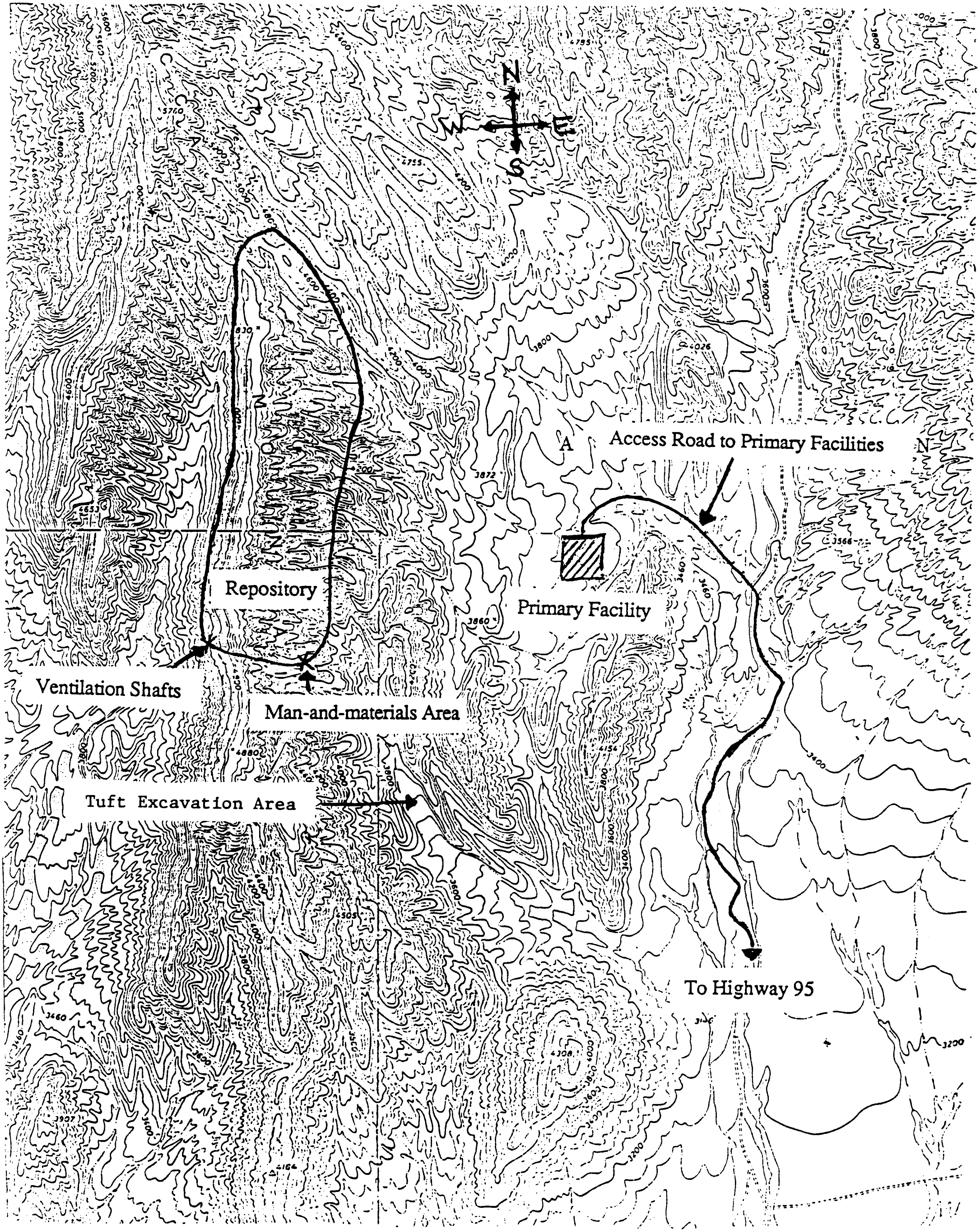


Figure 2.7: Repository Site Layout

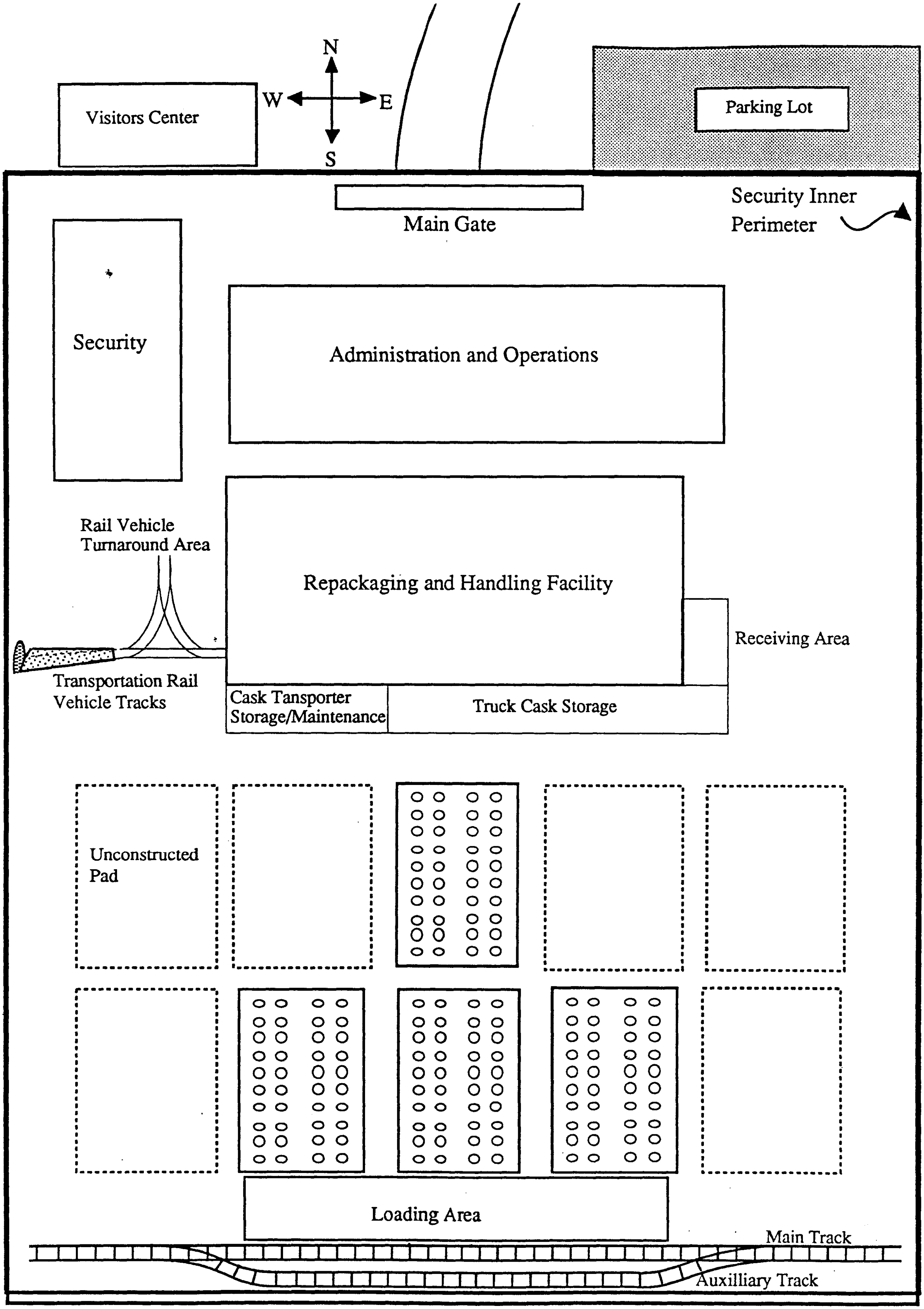


Figure 2.8: Primary Facility Layout

The spent fuel is removed from the transport casks in the Repackaging and Handling facility and transferred into the emplacement canisters which are designed for ultimate disposal. The R&H facility decides which transport casks to unpack from the burnup data compiled in the computer inventory of the contents of each transport cask. The entire repackaging procedure is conducted in large hot cells by remote manipulators, controlled by operators using closed circuit television. The repackaged waste is then stored for pickup by the transportation rail vehicle.

The transportation rail vehicle backs up to the loading deck of the R&H facility, where a crane loads the emplacement canister into the shielded bay of the rail vehicle. This vehicle then departs the repository along the surface tracks and descends down to the underground level of the repository.

2.4.2.2 Secondary Surface Facilities

The secondary surface facilities are each sited at different entrances to the underground level of the repository.

The man–and–materials area is located on a small plain near the peak of Yucca Mountain, as seen in Fig. 2.7. The area contains an operations building and the shaft house, which contains the hoist to the lower level of the repository. Miners and machinery use this entrance to the repository. The area is accessed by a winding road leading up Yucca Mountain.

The ventilation shafts are located very near the peak of Yucca Mountain and contains the air inlet and outlet shafts with the associated fans, radiation detectors, and HEPA (High Efficiency Particulate) filters. This facility's remote location requires it to be low–maintenance. Power lines to drive the fans follow a small access road to the ventilation shafts. This road provides means for a weekly inspection.

The tuft excavation area is located at the exit of the tuft conveyor. As the tunnels are mined the crushed tuff is removed from the repository by conveyor belt and deposited in the excavation area. The crushed rock is then managed by a team of bulldozers.

2.4.3 Buffer Storage Facility

2.4.3.1 Introduction

The buffer storage facility is an integral part of the repository. In the event of a delay in the repackaging or the underground operations, the incoming spent fuel will accumulate on the buffer storage pads so that the reactor pickup schedule will not be affected. At a receipt rate of 4,000 tonnes of spent fuel per year, the maximum capacity of the buffer storage facility was chosen to be 400 loaded casks, implying a maximum total delay in the remote handling and emplacement operations of one year. The current operating reactor proportions indicate that 68% of the casks should have PWR baskets with the remainder BWR baskets.

2.4.3.2 Facility Layout

The buffer storage facility will use a modular layout of 10 pads with 40 casks per pad (Fig. 2.9). The pads will be 175 feet long and 110 feet wide and hold 4 rows of casks with 10 casks per row. This arrangement is a just an enlargement of the layout used at the Surry Power Station. Like the Surry layout, the pads will be constructed of reinforced concrete to a depth of 3 feet. The transporters will have easy access to any cask in this arrangement.

Four pads and 160 Castor casks are included in the initial capital outlay along with site preparation for the other 6 pads. An initial buffer storage capacity of 1600 tonnes of spent fuel is included due to the greater probability of delays in the early years of the repackaging facility and underground operations. Casks will be purchased in sets of twenty as required for future buffer storage. The buffer storage facility will always maintain a minimum of ninety empty casks, enough for a full–train reload. If the number of empty casks drops below the minimum, the cask inventory will be enlarged by either the purchase

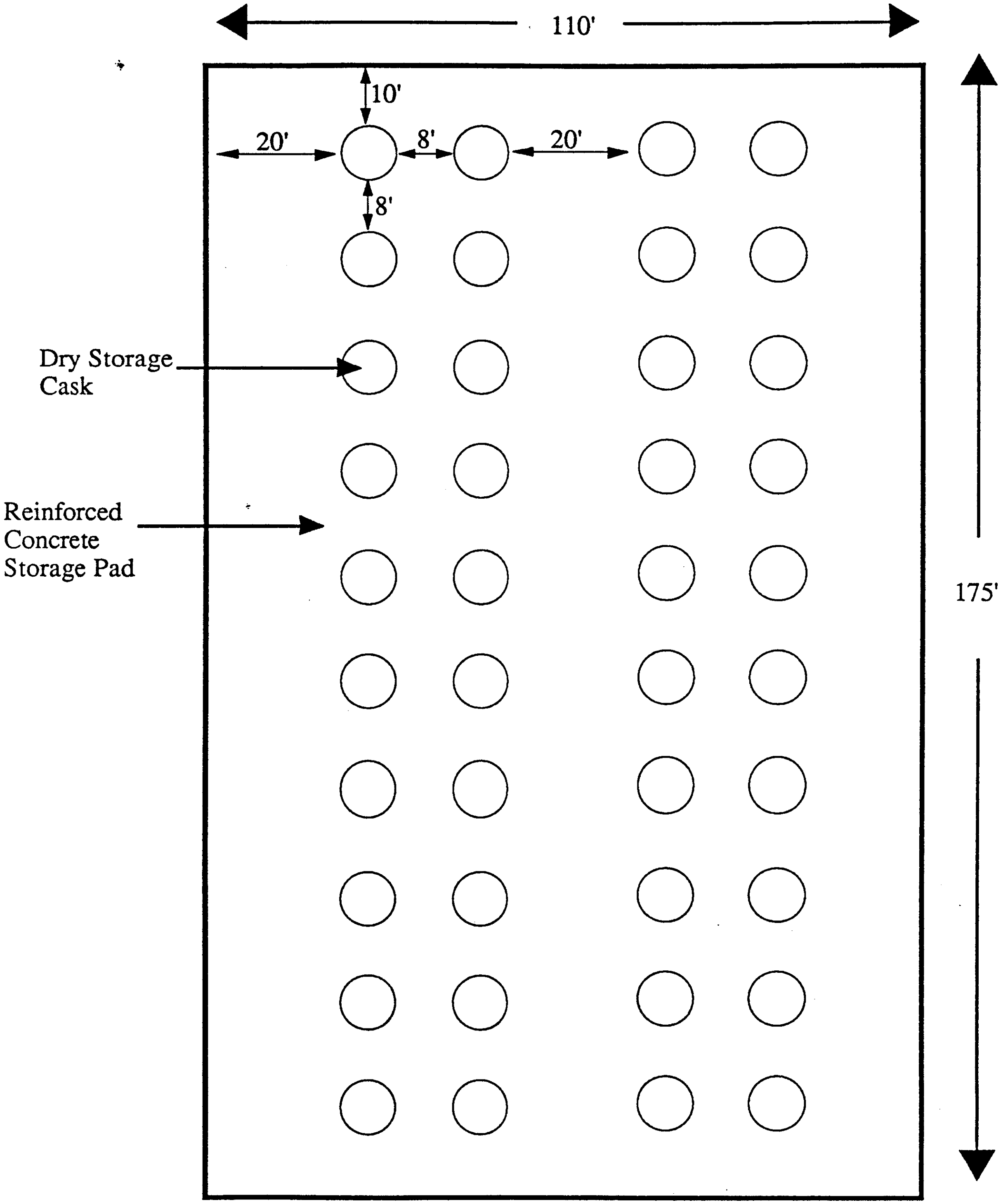


Figure 2.9: Buffer Storage Facility Layout

of twenty additional casks and the construction of a new storage pad if required for the new casks.

A small covered storage area for the truck casks is provided next to the remote handling facility. Since the truck casks are not designed for long–term storage, the spent fuel in the truck casks has a higher priority for repackaging than the fuel in the Castor casks.

2.4.3.3 Transporters

The loaded and unloaded casks are transported by large cask transporters (Fig. 2–10) designed to carry loads of greater than 100 tonnes. These transporters move at low speed and carry the casks only a few inches off the ground. The repository requires five of these cask transporters for efficient operation.

2.4.3.3 Operations

Since a shipment arrives once every three months, the preparation for the next train begins before the train arrives. The empty casks for the next scheduled reactors are placed onto the loading area so that time will not be wasted for their retrieval when the train is at the repository.

When the train arrives, the loaded casks are promptly unloaded and checked for leaks or damage that may have occurred during transport using the leak detection system built into the cask. A cask transporter is then used to move the cask to the buffer storage area. A fork lift moves the truck casks to the truck cask storage facility. The spot in the buffer storage area is recorded in the computer inventory of the spent fuel for each cask and the transporter returns to the loading area for another cask. A covered area for the transporters is provided for transporter storage and maintenance. Turnaround time for a fully–loaded train with one hundred casks is approximately one week. Once all the casks are off–loaded and positioned in the buffer storage facility, the inventory is taken to the Repackaging and Handling facility.

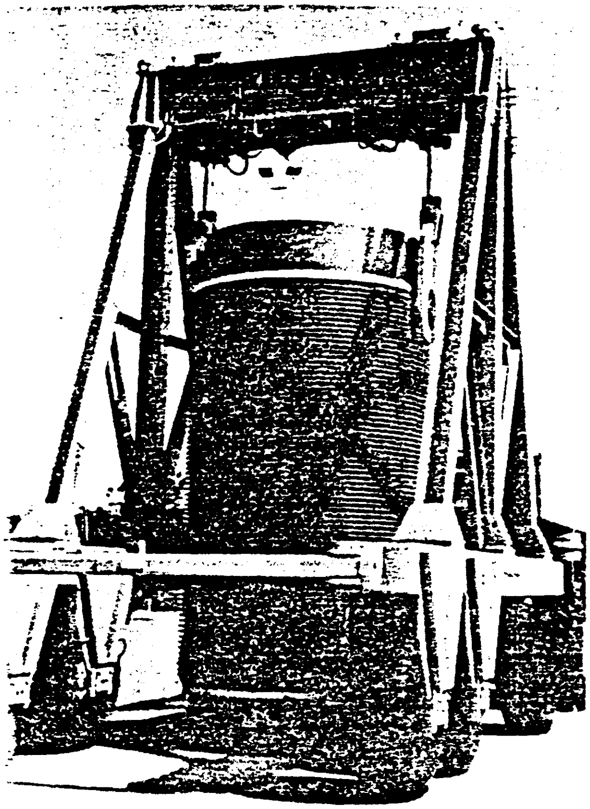


Figure 2.10: Cask Transporter

The R&H facility then calls for the retrieval of certain casks based on the information provided by the inventory. Three casks (2 PWR and 1 BWR) every other day are delivered to the receiving area of the R&H facility. The previous three casks, that have been decontaminated after the removal of the spent fuel, are picked up at the receiving area and transported back to the buffer storage pad for re–use.

2.4.3.5 Off–Normal Events

There are several off–normal events that can occur in the cask–handling process. If the post–unloading inspection or the continuous monitoring system reveals a leak in a cask, the defective cask will immediately be taken to the cask–resealing section of the R&H facility. This hot cell is devoted to resealing casks that are found to be leaking. If a casks is dropped in the unloading or transporting process, the cask will be checked for leakage, the damage will be noted, and repairs will be scheduled.

2.4.3.6 Estimated Costs

The estimated costs of the buffer storage facility were obtained from "A Preliminary Assessment of Alternative Dry Storage Methods for the Storage of Commercial Spent Nuclear Fuel", prepared by E.R. Johnson Associates under DOE Contract Number DOE–AC09–80ET47929, September 1981. Press releases from Surry indicate that the price of the Castor cask is $800,000 per delivered cask, and the transporters are $250,000 each. A contingency allowance of 20% and a social discount factor of 10% are factored into the following cost estimates. The initial outlay consists of site preparation for 10 pads, construction of 4 pads, and 400 Castor casks (160 for the buffer storage and 240 in continuous transit).

BUFFER STORAGE COSTS

MILLIONS OF CONSTANT 1988 DOLLARS

Design	3.4
Site Preparation	0.2
Concrete Base	0.4
Transporters	3.0
Casks	325.0
Support Facilities	3.0
Decommissioning	24.7
TOTAL BUFFER STORAGE CAPITAL COSTS	359.7

The cost estimates indicate that the overwhelming factor in the cost of the buffer storage facility is the cost of the 400 casks.

The annual operating costs of the buffer storage facility are relatively small, compared to the capital costs. Insurance and taxes amount to $7500 per cask and maintenance supplies total $1,000 per cask. Including the cost of cask and pad additions and operating personnel, the annual operating expenses of the buffer storage facility are listed below.

ANNUAL OPERATING COSTS

MILLIONS OF CONSTANT 1988 DOLLARS/YEAR

Casks and additions	14.6
Taxes, Ins. and Maint. Supplies	5.6
Personnel	0.7
TOTAL OPERATING EXPENSES	20.9

Estimated Costs for Program Management are presented in the summary of overall costs in Section 2.5.

2.4.4 Repackaging and Handling Facility

2.4.4.1 Introduction

The Repackaging and Handling (R&H) facility takes the intact spent fuel elements contained in the storage casks and repackages them into repository specific special–alloy disposal canisters. An overview of the R&H facility is shown in Fig. 2.11. As discussed in Section 2.1., the spent fuel is not consolidated, and hence, the intact spent fuel elements are loaded directly into the disposal canisters. The disposal canister holds three intact PWR assemblies and four intact BWR assemblies as shown in Figure 2.16. The filled canisters are welded closed and then backfilled with helium gas. The helium backfill has a very high thermal conductivity, for a gas, which results in a much lower peak canister temperature. The helium also provides a simple and effective means of inspecting the seal quality of the weld between the canister body and lid. After being sealed, the canisters are then individually decontaminated by a freon spray wash system, after which the canisters are sent to the pre–emplacement lag storage cell. The R&H facility is equipped with a small lag storage capacity in order to provide additional system flexibility between the surface facility and the underground facility. The canisters are oriented vertically in the lag storage cell, and have to be downended into a horizontal orientation to be transferred into the emplacement cask for transport to the underground facility. The contaminated areas of the R&H facility are maintained at a lower than atmospheric pressure in order to prevent leakage of contamination out of the contaminated areas in the event of a breach in the containment walls or penetrations. The low pressure contaminated areas of the facility are separated from the clean areas of the facility by air locks in order to maintain the specified pressure differential.

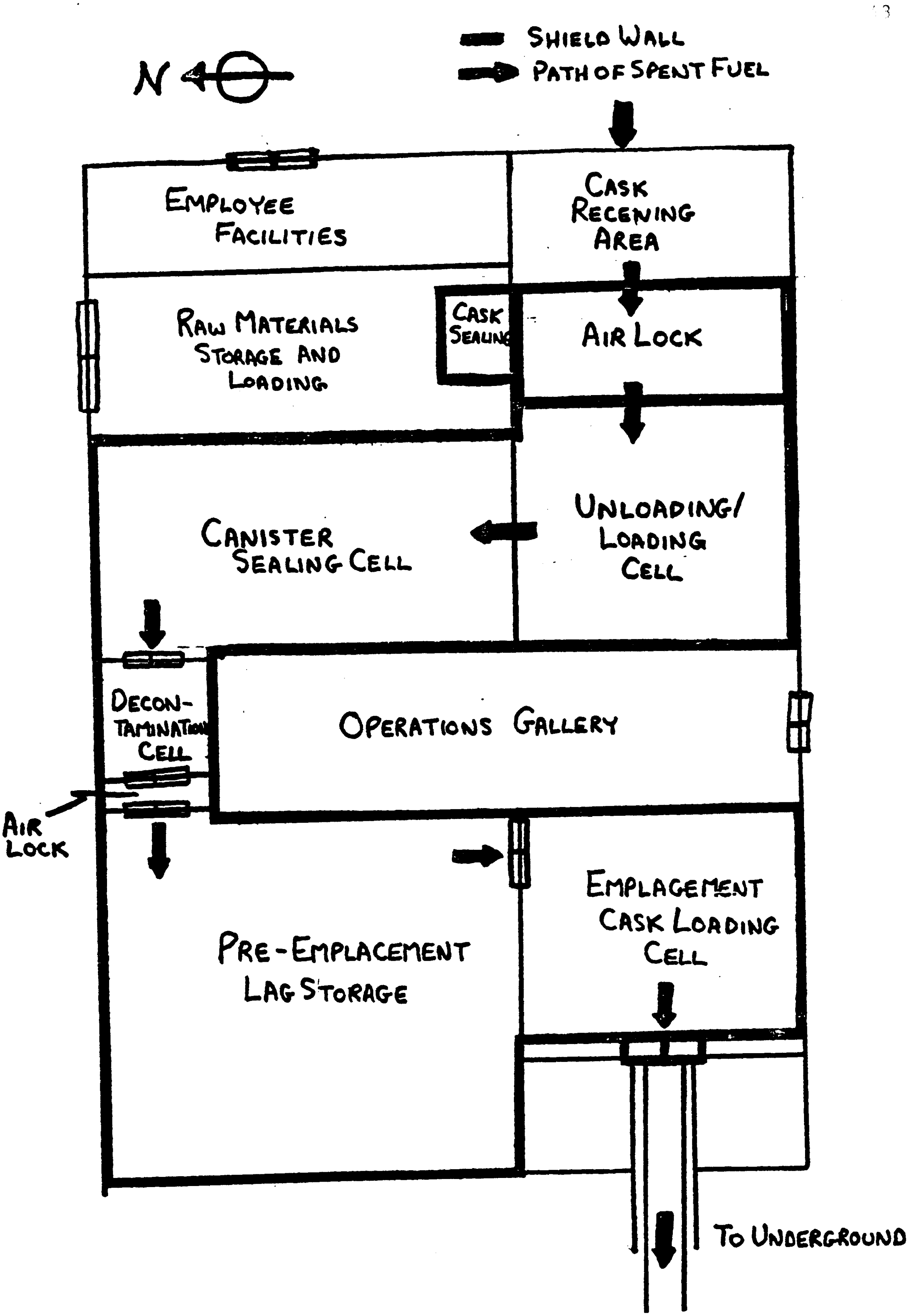


Figure 2.11 - Repackaging and Handling Facility Overview

The R&H facility will process an average of 4,000 MTU of spent fuel per year. Each canister holds 2.13 MTU of spent fuel (3 PWR assy.× 0.462 MTU/assy. + 4 BWR assy.× 0.186 MTU/assy.), and hence the R&H facility will process 1880 canisters per year; or 36 canisters per week. The R&H facility will operate five days a week with two shifts a day, processing an average of eight canisters per day. Operating at full capacity, the facility can turn out a maximum of twenty canisters per day. This throughput rate can be used if the facility falls behind schedule due to planned maintenance and forced outages. Areas of the facility which interface with the storage operations or the underground operations, such as the emplacement cask loading cell, will operate on a different time scale to accomodate that of the facility they interface with.

Each of the major systems within the R&H facility, as well as any expected off–normal events are discussed in more detail in the following sections. The final section gives an explicit breakdown of the estimated costs associated with the R&H facility.

2.4.4.2 Cask Receiving and Preparation

The casks are brought into the receiving area of the Repackaging and Handling facility in a transporter cart. Once the cask coming from the buffer storage has arrived, it is inspected and placed vertically on a cask transfer cart using a crane. From the receiving area, the cart moves by rail to the air lock and decontamination room, where gas samples are taken, the outer cask lid is removed, and other preparatory tasks are completed for unloading. From the Handling and Decontamination room, the cart moves to the unloading/loading room and underneath the hot cell port. A picture of the process is shown in Fig. 2.1.2.

2.4.4.2.1 Receiving Area

The Receiving area is designed for the transfer of the loaded cask from the

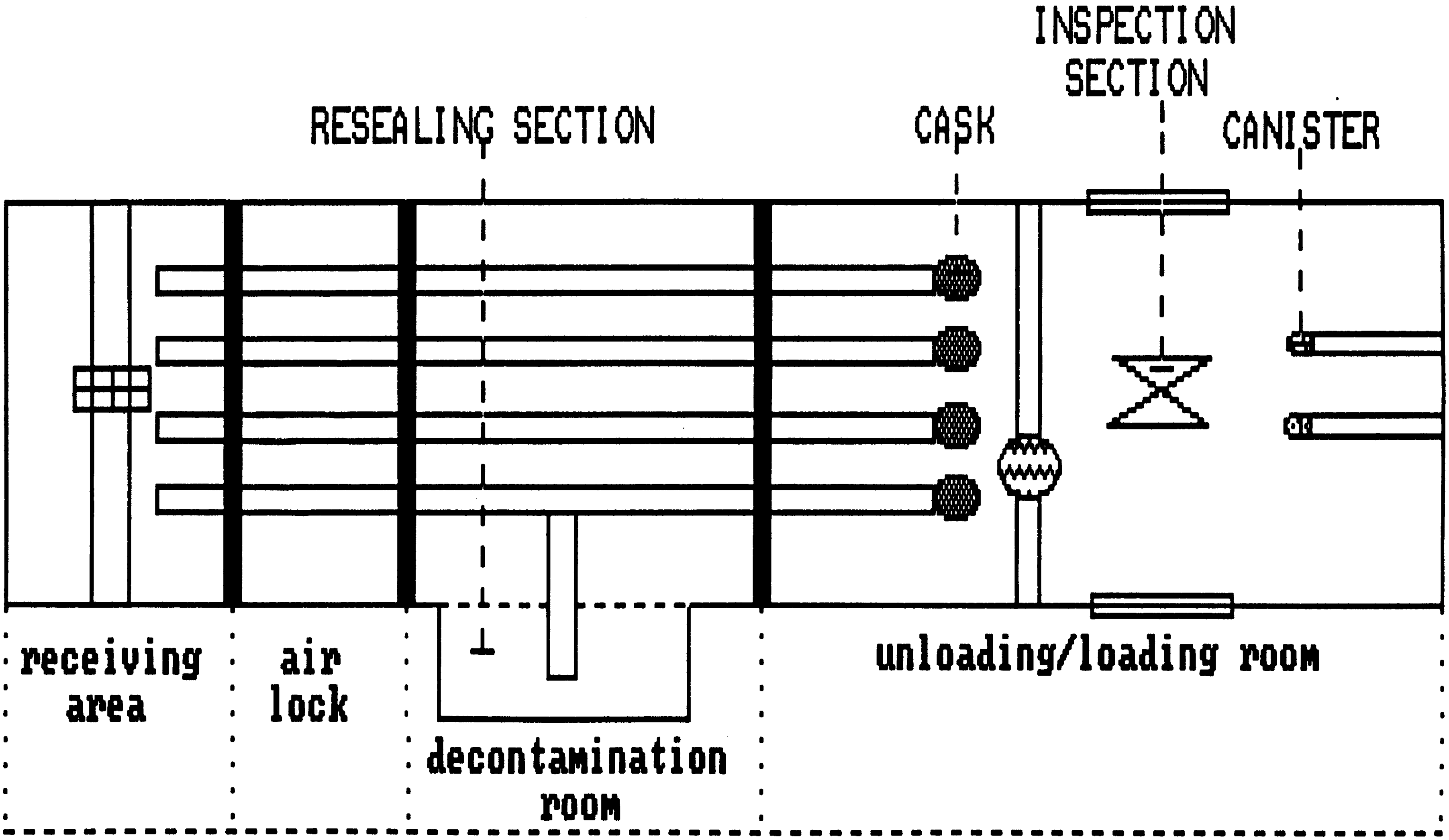


FIGURE 2.12 GENERAL PROCESS DESCRIPTION

transport vehicle to a cask transport cart. The cart is electrically propelled, sits on rail tracks and moves through the plant by rail. There are two independent rail tracks per line, allowing for use of the area, should there be problems with casks that have arrived earlier. The cask is lifted using a bridge crane designed to unload weights of approximately 150 tons. The cask is lifted to a vertical position over the cart, and placed on the cart. Personnel working in this area then secure the cask. The loaded cart is then moved by rail to the cask handling and decontamination room.

Once the cask has been unloaded and decontaminated, it is returned to the receiving area to be lifted off the cart and placed on a transporter cart to be dispatched for another load.

2.4.4.2.2 Air Lock and Decontamination Room

Once the cart has left the receiving area, it is moved through the air–lock into the decontamination room. In this area, preparations are made for the automated removal of the spent fuel. Samples of gases are taken and the outer cask lid is removed. The samples will be sent to a remote laboratory by a pneumatic transfer system. These procedures, and other preparatory activities employ robotics.

Another important function carried out in this area is the decontamination, if needed, of the interior of the empty cask to prepare it for another load of spent fuel. Tests are performed to establish the nature and extent of contamination of the casks during shipment and storage in the facility. If necessary, procedures are then employed to clean the interior of the casks before they are released. The outer lid is then replaced. Once the casks have been returned to the receiving area, the room is inspected and decontaminated. The doors on both sides (receiving and unloading area) are closed and sealed during operation.

If one cask in the buffer storage facility has been found leaking, it is sent immediately to the R & H facility. In this case, the decontamination room has been provided with a special room for resealing the cask. Maximum precautions in the handling have to be taken for these procedures.

2.4.4.3 Canister Loading

In the Unloading/Loading room, the assemblies of spent fuel are individually unloaded from the cask and loaded into in the canister for final disposal. During the entire process from the reactor site boundary to the final repository, this is the only place where the fuel is exposed outside a sealed, shielded protection. Therefore, eliminating contact with the unshielded canister by utilizing remote systems significantly minimized exposure and exercises the ALARA (As Low As Reasonably Achievable) principle. The description of the design, its shielding, criticality prevention, equipment and operations are discussed in the following subsections.

2.4.4.3.1 Design Description

The mission of the hot cells is to ensure safe, timely, and cost–effective remote handling, processing, examination, data collection, and short interim storage of spent nuclear fuels and other nuclear materials. The cask unloading/loading room (refer to Fig. 2.13) is designed to operate with two independent lines inside the room (each line with a BWR cask and with a PWR cask). This design with two independent lines allows that if one cask is unloaded, it is not necessary to stop the process, waiting for another cask of the same type to continue with the canister loading. The room is completely shielded. It has one cell fuel input port per cask where the cask is mated for the next operations. After that the cask is protected with a special cover (skirt) that is lowered over the cask in order to provide contamination control during the fuel unloading operation. From inside the hot cell, using the remotely operated crane,a plug is removed from the hot cell floor directly above the shipping cask. The hot cell crane and the remotely operated grapple are then used to lift off the shield lid of the shipping cask and then to grapple and lift the assemblies (one at a time) from the shipping cask into the hot cell.

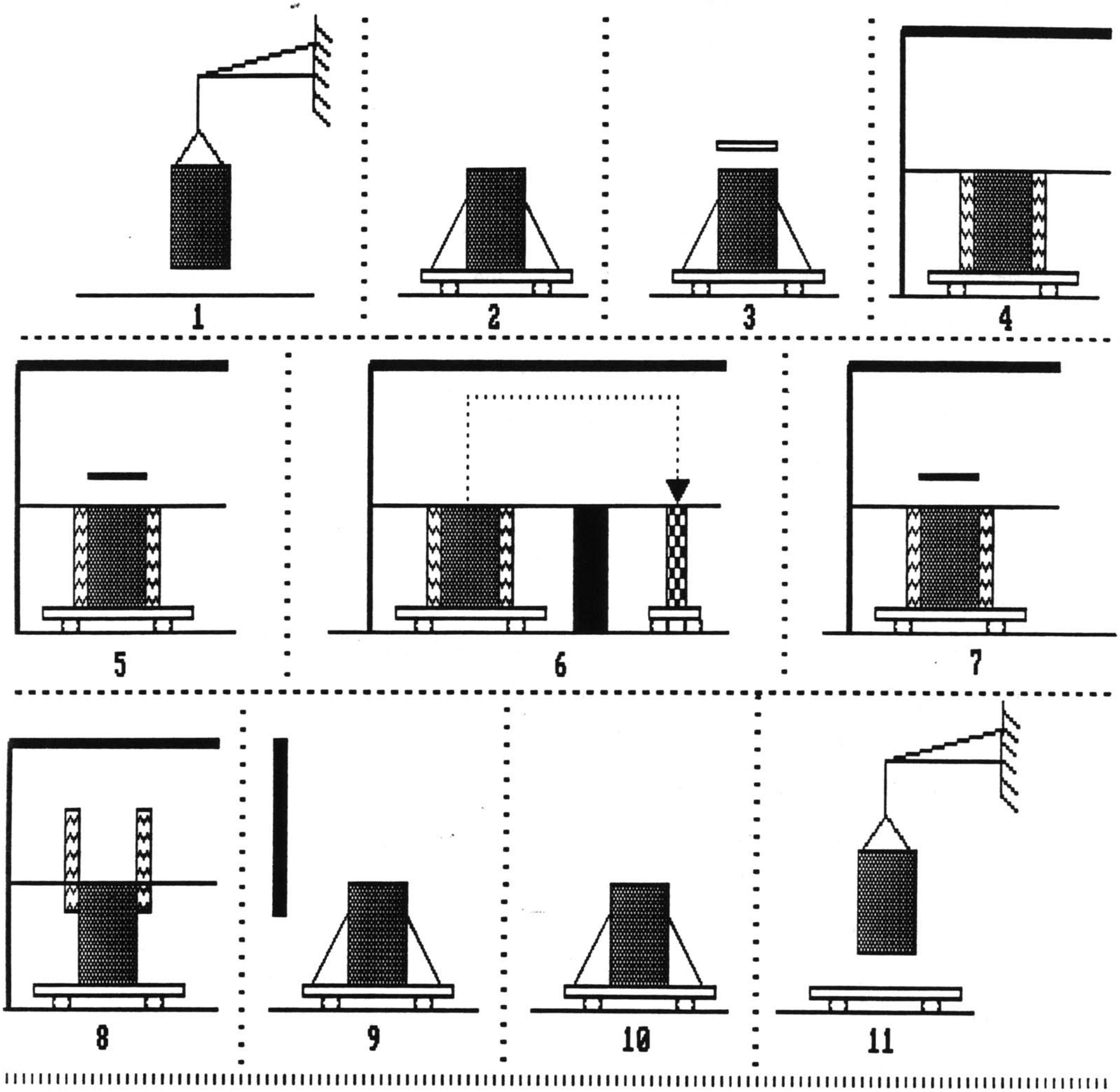


FIGURE 2.13 GENERAL CASK UNLOADING/LOADING DESIGN DESCRIPTION

(NOT TO SCALE)

From inside the hot cell, the assembly is moved to an inspection station directly in front of a shielded viewing window. The assembly is inspected for any shipping damage and swipes for surface radioactive contamination are made using through-the-wall master/slave manipulators, or an in–cell bridge–mounted manipulator. Closed–circuit television is available to provide aditional viewing. If damage and/or excessive surface contamination of the assembly exist, capability exists inside the hot cell to overpack the assembly at an overpack station. The overpack is then handled just like a normal waste assembly.

After unloading is completed, the inner cask lid is replaced and sealed and the port cover is replaced. The cask is disengaged from the cask unloading port once the cover is withdrawn. The cask is then transferred to the cask air lock and decontamination room where operations described in the last section are performed.

Once the cannister is loaded with 3 PWR and 4 BWR assemblies, it is covered and sent to the welding stations. Each cannister is filled with 2.13 MTU spent fuel (3 PWR assemblies * 0.462 MTU/PWR assembly + 4 BWR assemblies * 0.186 MTU/BWR assembly).

Primary viewing for remote operations is intended to be shielding windows. Closed–circuit television will be provided for suplemental viewing in the cell. Shield windows will be of oil–filled, cold–side serviceable design with removable alpha shields on the hot side.

This room has a constant air flow through the cell, because of the high temperatures of the spent fuel assemblies. The air is driven from and discharged to ambient, after passed through HEPA filters. The bag–in/bag–out (HEPA) filter are used routinely to isolate contaminated filters from maintenance personnel. Remotely operated HEPA filtration for hot cell application are described more detailed by Russel E. Krainiak (Charcoal Svc Corp).

2.4.4.3.2 Shielding

In this room shielding is considered necessary due to the exposure of the fuel assembly during the unloading/loading process. The hot cells have to be constructed of 0.73 m thick concrete walls (refer to section 3.2.2.4.) for shielding and single leaded glass/mineral oil shield window for viewing operation. Remote television cameras have also been installed to aid in the operation of the system. Therefore, the remote capabilities have successfully allowed radiation exposures to personnel to meet the as–low–as–reasonably–achievable goals. The operating environment is severe and it would be necessary to reduce any possible risk to very lower values.

An alternative, if necessary, is that the concrete cells and some of the lead–shielded cells can be made inert with nitrogen.

2.4.4.3.4 Equipment

The equipment used in the Unloading/Loading room must be of high technology and precision. The most important concepts for the execution of the tasks asigned are precision and safety. In order to maximize both concepts the equipment in the hot cell are basically, remote equipment and protection equipment.

Remote equipment includes the use of cranes, manipulators, robotic arms, cameras, closed–circuit television, and in general all the tools necessary to do the work from unloading the cask to loading the canister for final disposal. Protection equipment is all the equipment necessary to avoid operations inside the hot cell that can hurt to the operations personnel. It includes viewing windows, shielding, special clothes if necessary, etc.

In this subsection the different equipment and its important characteristics will be presented. Figure 2.1.4 presents a schematic representation and location of this equipment.

The remotely operated bridge crane is designed to unload the assemblies from the

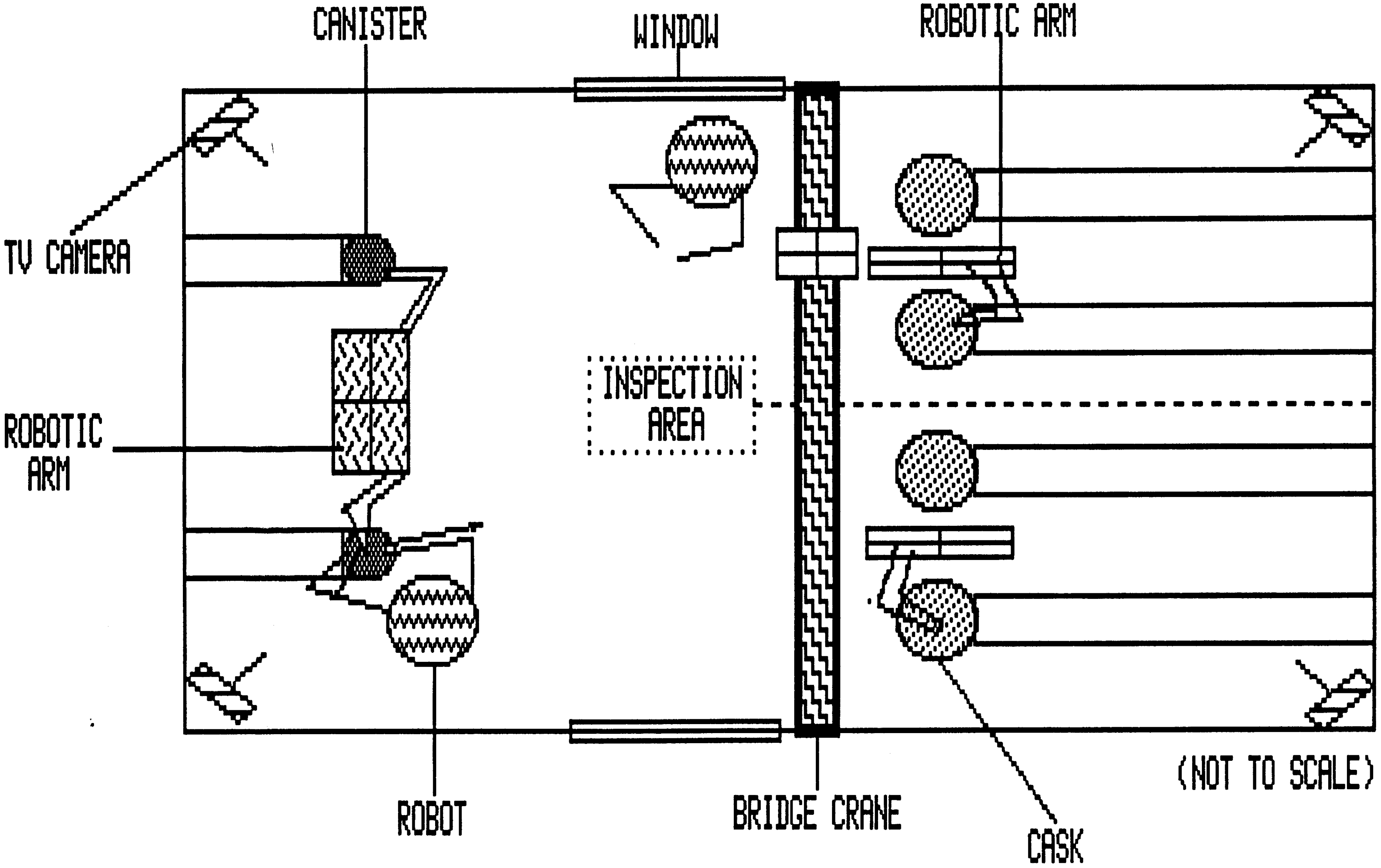


FIGURE 2.14 SCHEMATIC REPRESENTATION OF UNLOADING/LOADING ROOM EQUIPMENT

cask and to move them through the cell to its final position in the waste disposal canister. This crane is operated in connection with TV cameras located inside the cell. The crane is designed to have a 15 ton maximum lift capacity. It moves around the cell picking up just one assembly per cycle.

Robotic systems make it possible to minimize overall personnel exposure and the time required to complete the turnaround work. Robotic systems capable of safe, reliable, unattended operation can be developed. A robot can perform the swiping operation in a consistent manner because a robot's motions are repeatable, ensuring consistency in the results. Robots used for these activities must themselves, however be designed and manufactured to be highly resistant to processes and substances that present health hazards to human personnel. The components used to construct the robot must be chosen specifically for their ability to withstand the exposure to a wide variety of hazardous materials.

Robots are considered for checking and monitoring the different maneuvers inside the hot cell. Also, the design of the robot must be developed to get good performances in cases of dropped fuel assemblies.

Robots using closed–circuit television and computer control can be used. A robotic system under development is studied at Sandia National Laboratories (SNL) to perform remote radiation and analysis of nuclear waste, therefore reducing dramatically the personnel radiation exposure. One of the major developments has been the integration of advanced sensors into the robotic system as mentioned before.

The utilization of TV as the primary viewing medium has taken a relatively long time to become established in remote control technology. In windowed areas like the inspection section, TV is used to provide viewing in spaces where in–line viewing is blocked or is difficult. The basic design concept is for a system that allows the examination of a complete assembly under fully remote operating conditions. The application of tele–operated, force reflection servo–manipulators with television viewing could be a major aid in waste handling facility design.

The off–gas filters, required to clean up the gases coming from inside the canisters, are designed for remote inspection, replacement, and maintenance.

The maintenance area above the cells will be equipped with a 50–ton crane and a bridge–mounted manipulator. Access to the cells from this area will be through removable floor plugs which allow entry into the hot cells below. This access allows much of the equipment to be remotely transferred directly from its location by the in–cell crane and hoist to the decontamination room. The equipment can then be decontaminated remotely to a very low radiation level and then repaired by direct means.

This philosophy emphasizes the total system approach, which has led to synergism between the capabilities of the remote handling systems, compatibility of the in–cell equipment with these capabilities, and optimization of the facility from the initial component and facility designs.

2.4.4.3.4 Criticality

The criticality considerations showed below are based in the Report # MRS 13 "Criticality Safety Considerations" prepared for DOE by the Ralph M. Parsons Company of Delaware in September 1986. The criticality concerns are related to the design features of the facility, the safety, and the analysis of both normal operations and hypothetical off–normal operations. The analysis showed that in the absence of water or completely flooded, the array of canisters is safely subcritical.

The basic assumptions made for the criticality analysis were that fresh (unirradiated) PWR fuel was used for the calculations and dry air with less than 0.1% water by volume and 20% of relative humidity at 80°F. PWR fuel was used because it is the most reactive fuel. The Monte Carlo code KENO system was utilized for the criticality assessment calculations. Criticality calculations were performed with a maximum of six inches of water in the room.

The results shown that under operating conditions k (eff) = 0.66 and under hypothetical off–normal conditions k (eff) = 0.66, assuming that there is no change of k (eff) with a water concrete content of 5.6% by weight.

The prevention of criticality is accomplished by providing some features which ensure that neutrons are allowed to escape (leakage) without causing additional fissions in adjacent nuclear materials. More than two independent failures must occur to result in a criticality situation. To prevent this occurence all potential moderators and sources, water,are kept away from nuclear materials.

In order to prevent criticality the following features must be incorporated into the design of the R & H building:

a) Preclusion of water. This means no liquid lines except for decontamination, exclusion of water sprinkler systems for fire control, removable piping spools in all decontamination fluid lines, drains in the floors and operations with handling spent fuel and canisters at 20 feet above the PMF (Probable Maximum Flood).

b) Canisters and casks are designed to remain intact under all operational, hypothetical off–normal conditions.

c) The bottom of the spent fuel canisters are moved at no more than 10 cm above the floor.

d) Remote viewing of canister interior prior loading it and cask interior before sending it to the decontamination room.

2.4.4.3.5 Operations

The operations performed in the U/L room are completely remote because of the precision of robot arms to within the thousandths of an inch, which is required for mechanical assembly tasks. These procedures are checked with the use of special cameras. Robots with cameras are also used in this room. These additions are capable of increasing the productivity of the facility, reducing the radiation exposure of personnel, providing means to modify and upgrade complete operations, and serving as a major tool in the execution of the basic task of unloading from the cask and loading in the disposal canister.

The operations in the U/L room consist of unloading assemblies from the PWR and BWR casks and placing them in one of the four canisters designed for disposal. Each canister is filled with 3 PWR and 4 BWR assemblies. This procedure is shown in Figure 2.15. If one cask contains 21 PWR assemblies, the loading of 7 canisters can be filled. If one cask contains 64 BWR assemblies, 16 canisters are necessary for the unloading of each BWR cask. Since 8 canisters are filled per day, one BWR cask must be sent to the R & H facility every two days and at least two PWR casks every day.

The room is completely closed and sealed before the arrival of the cask. The canister for the loading of spent fuel is mated under the floor. There are positions for four canisters that can be loaded at the same time but restricted to the capability of only one remote crane.

The cask is put under the input port and the cover (skirt) is placed around the cask to minimize the contamination of other rooms (under the R & H room). Once the cask is completely mated to the hole under the input port, from inside the hot cell, using the remotely operated crane, the cover cell port is removed from the hot cell floor directly above the shipping cask. The hot cell crane and the remotely–operated

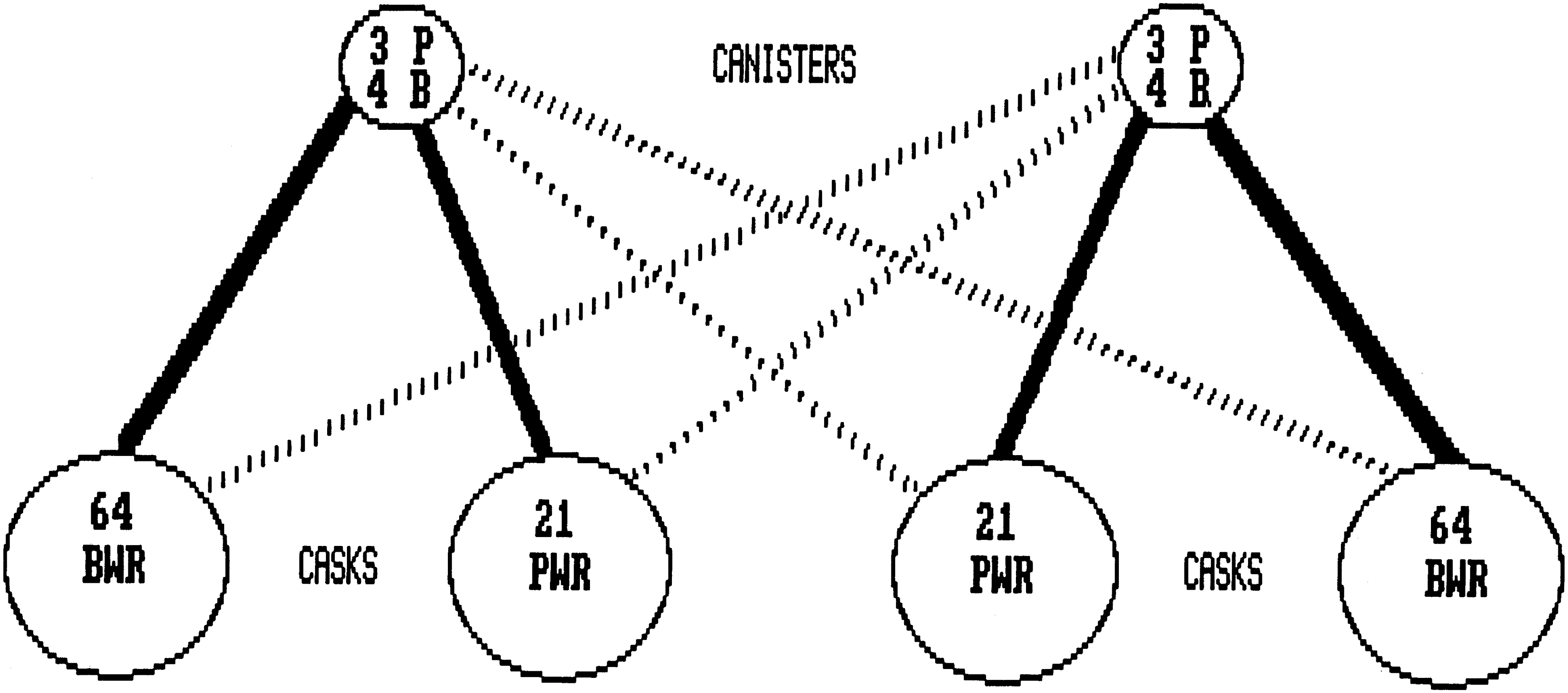


FIGURE 2.15 LOADING CANISTER PROCEDURE

(NOT TO SCALE)

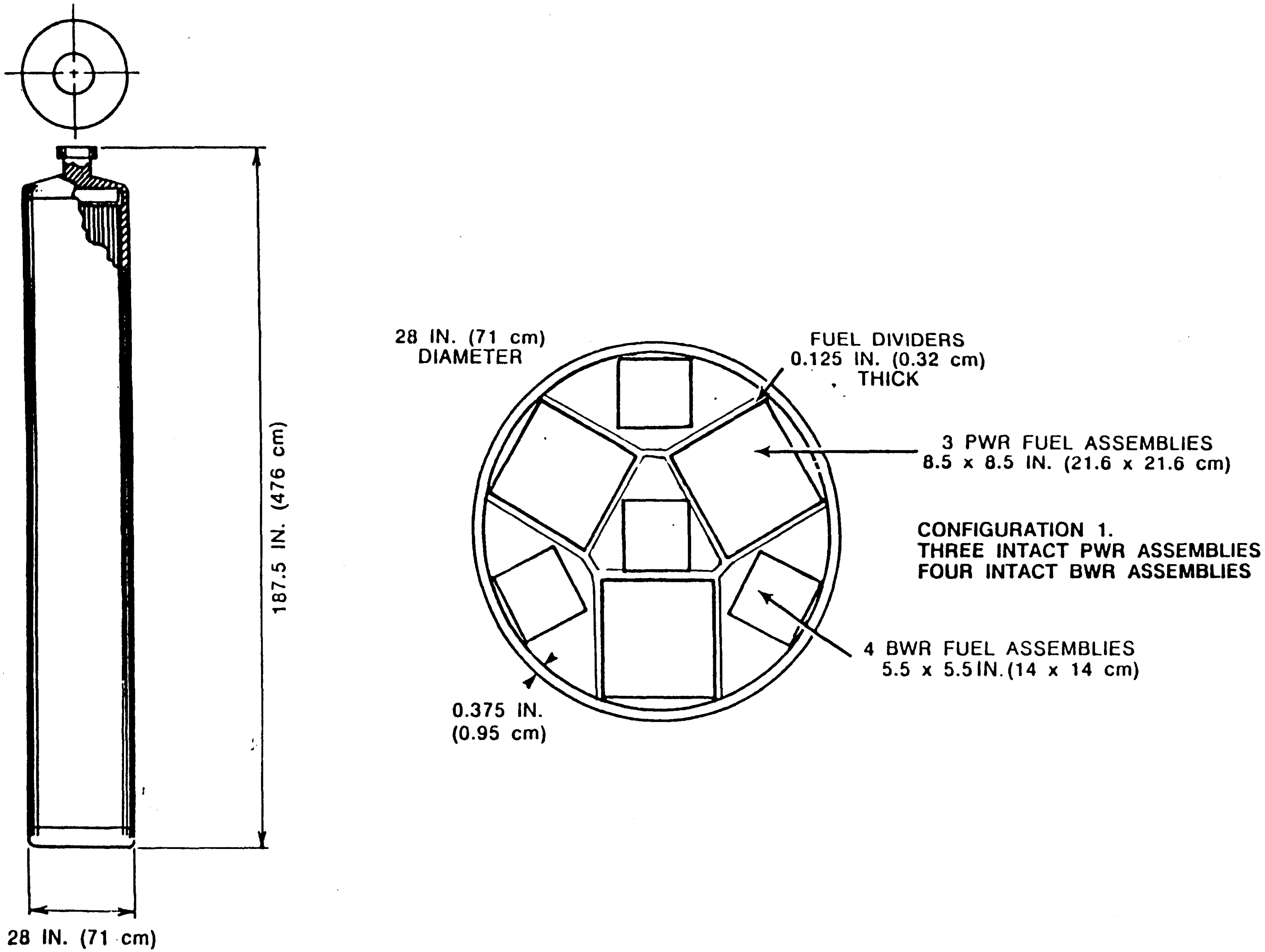


Figure 2.16 - Repository Specific Disposal Canister

grapple are then used to lift off the inner shielded lid of the shipping cask and lift the assemblies (once at a time) from the shipping cask into the hot cell. The movements and precision of this operation must be done with the use of cameras watching that the assembly does not bend or any other situation which result in the breaking of the assembly.

From inside the hot cell, the assembly is moved to an inspection station directly in front of a shielded viewing window. The assembly is then inspected for any shipping damage and a general visual inspection is made. Closed–circuit television is available to provide aditional viewing. If damage is observed, capability exists inside the hot cell to overpack the assembly (if necessary) at an overpack station. The overpack is then handled just like a normal waste assembly.

After the inspection the assembly is moved and loaded into the canister. This maneuver requires the maximum precision in order to avoid that the assembly, when lifted down, does not get inside a space filled with another assembly. Remote cameras are used in this operation.

The repetition of all the process described before must be done until one canister is completely loaded. Once the canister is loaded a robotic arm places the inner lid. The cell port is replaced and the canister is transferred to the adjacent welding station.

Once the cask is completely unloaded, the inner cask lid and then the cell port are replaced. The cover is taken out and the cask is decontaminated (if necessary). The cask is sent to the decontamination room where operations described in Section 2.4.4.2.2. are performed.

When the major repair is required, the processing frame will be decoupled by the robot and moved to the decontamination room and maintenance area by a conventional overhead bridge crane.

Experience has shown that no matter how detailed the failure analysis is, the actual operating experience will produce events that have not been planned. The availability of manipulators that closely parallel human capabilities is of major importance in responding to these unplanned events.

2.4.4.4 Canister Sealing

2.4.4.4.1 Design Description

Once the canister loading operation is complete, the canisters are then moved by rail car into the canister sealing cell. An overview of the canister sealing cell is shown in Figure 2.17. The rail car, which holds both of the filled canisters, is first moved so that the lead canister is positioned at the welding station. At this station a lid is placed on the canister and held in position by a computer controlled robotic arm, while a second robotic arm equipped with a welding tip is used to weld the lid to the canister body. The rail car is then moved forward so that the lead canister is aligned with the backfilling/leak testing station. The rail car is designed dimensionally so that the second canister is simultaneously aligned with the welding station. The first canister is then backfilled with helium gas, and then the canister lid to body weld is inspected by passing a helium sniffer around the welded seam. If the weld is found to be satisfactory, the tap valve used in the backfilling operation is then welded permanently closed. Once both canisters have been welded and leak tested, the rail car moves them to the unloading station of the cell where the canisters are taken one at a time by overhead crane to the decontamination cell, which is discussed in Section 2.4.4.5.

After the two canisters have been removed from the rail car, the rail car is then moved along the other leg of the rail circuit to the empty canister loading station. Here the rail car is reloaded with two empty canisters by another overhead crane. Another overhead crane is also used to move items in and out of the cell through the equipment hatch. An off–normal station is included to service any possible off–normal events such as

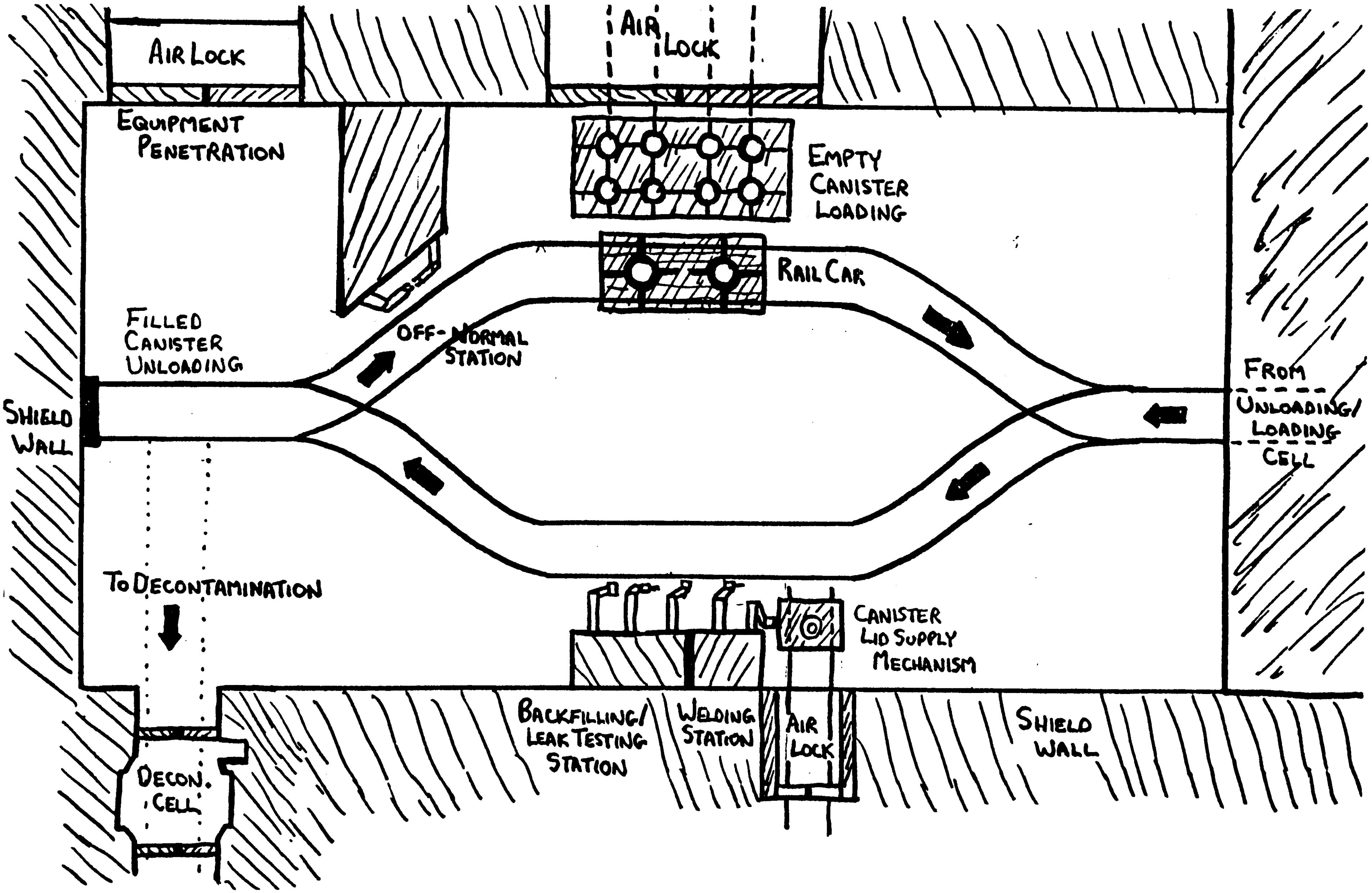


Figure 2.17 - Canister Sealing Cell

faulty canister welds. Several peripheral operations are performed within the cell during the third shift of the day when the cell is not in use, such as restocking the supply of canisters and lids, and performing routine maintenance on equipment within the cell.

2.4.4.4.2 Welding Station

A close–up view of the welding station is shown in Figure 2.18. The major components of the welding station are the two robotic arms and the canister lid supply mechanism. The first robotic arm is programmed to remove a lid from the supply stack, place it on the adjacent canister, and hold the lid in place while it is welded on. The canister lid supply mechanism holds a stack of canister lids resting on a spring loaded lifting mechanism. The lifting mechanism is designed to keep the uppermost lid of the stack at a constant elevation. The whole lid supply mechanism is mounted on rails which allows it to be moved in and out of the canister sealing cell in order to be reloaded. The second robotic arm is equipped with a weding tip which is used to make an air–tight weld between the canister lid and body. The welding is done by a TIG inert gas welding process in which the environment located immediately about the weld point is an inert gas in order to provide weld impurity and properties control. Both robotic arms are computer controlled, but can be manually overridden if necessary. The welding station equipment is designed so that only the robotic arms and their attendant wiring are in the cell environment, while the remainder of the equipment is located through the shield wall where it can be easily and routinely maintained.

2.4.4.4.3 Backfilling/Leak Testing Station

After a canister has been welded closed, it is then moved to the backfilling/leak testing station shown in Figure 2.18. The canister lid is equipped with a tap valve which is used in the backfilling operation. The first robotic arm at the station has a flange which is mated to the lid tap valve. Once the mating is completed, all air is evacuated from the canister and then the canister is filled with helium gas. The helium backfill gas provides

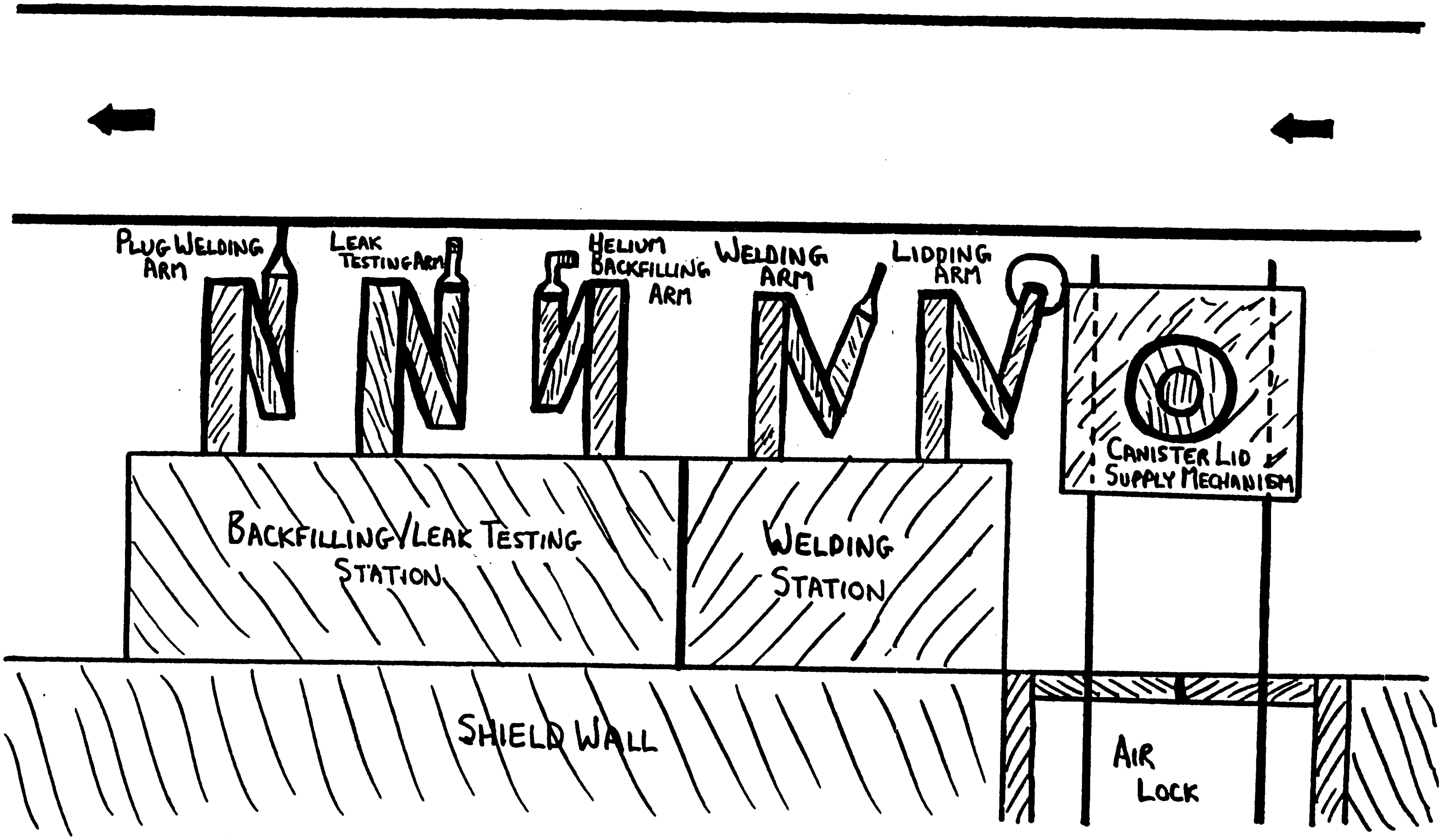


Figure 2.18 - Welding and Backfilling/Leak Testing Stations

both excellent thermal conductivity and ease of weld inspection. After the backfilling is completed and the flange is removed, the canister lid to body weld seam is then checked by a helium sniffing tip attached to the end of a robotic arm. If the helium sniffer discovers helium near the weld in an amount far in excess of the local background concentration, the weld is considered to be faulty; if not, the weld passes inspection. A faulty canister is first returned to the welding station for another attempt at welding, followed by a second backfilling and leak testing. If the weld is still found to be faulty it is treated as an off–normal event and dealt with as discussed in Section 2.4.4.4.5. If the weld passes inspection, a third robotic arm equipped with a welding tip is used to permanently seal off the lid tap valve. Once both canisters have been backfilled and leak tested, they are moved by rail car to the unloading station where they are removed one at a time by overhead crane and taken to the decontamination cell.

2.4.4.4.4 Peripheral Operations

Canister Transportation

One of the keys to the operation of the canister sealing cell is the rail system which is used to move the canisters about the cell. An overview of the canister sealing cell shown in Figure 2.17. shows the main rail circuit used for canister movement. The rail system was selected for two reasons. First, it minimizes the handling of the canisters: after they are loaded on to the rail car they are not again handled until they are lifted by overhead crane to be taken to the decontamination cell. Second, the use of rail cars as opposed to overhead cranes greatly minimizes the chance of a canister drop accident occuring in the cell. A closeup of the rail car is shown is Figure 2.19, which shows the "birdcage" support structure which holds the canisters firmly in place. There are two such rail cars on the rail circuit. This allows one rail car to be loaded with two empty canisters and filled with spent fuel assemblies while the canisters on the other rail car are being welded, backfilled, and leak tested.

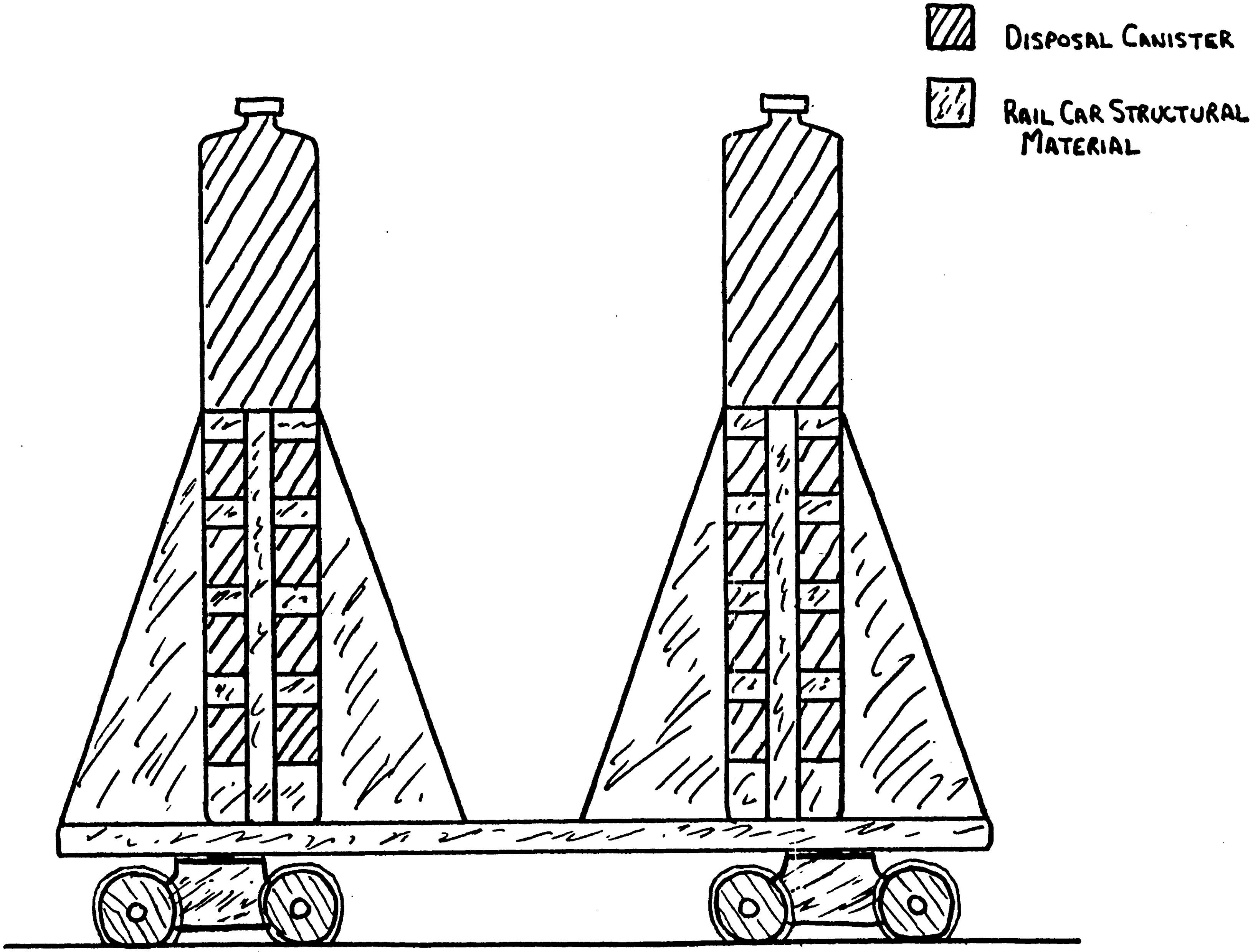


Figure 2.19 - Canister-Carrying Rail Car

Supply Loading

Rail cars are also used to bring fresh supplies of empty canisters and canister lids through air locks into the cell. Empty canisters are loaded into the cell on a rail car which holds eight new canisters. If additional canisters are required during the two operational shifts of the day, the rail car can be moved out through its air lock and reloaded with a fresh supply of canisters. The canister lids are loaded into the cell on the rail–bound lid supply mechanism described in Section 2.4.4.4.2. This mechanism holds a supply of eight lids to match the eight empty canisters. It can also be reloaded during operation.

Overhead Cranes

There are three cranes within the canister sealing cell. The crane which is used to transfer the loaded and sealed canisters to the decontamination cell is an overhead crane equipped with the proper grapple to lift the canister and is conservatively rated at ten metric tons capacity, over three times the weight of a loaded canister. A second crane, rated at twenty metric tons, is capable of removing any item in the cell for repair or replacement through the cell equipment hatch. This second crane is a general purpose service crane which can be equipped with any of several grapples or attachments by a pair of robotic arms which are located at the cell off–normal events station. The third crane is a telescoping boom crane which is used to transfer the empty canisters from the supply car to the rail car used in cell operations. A similar crane is used outside the cell to load the empty canisters onto the supply car.

In–cell Monitoring

Several radiation hardened cameras located in low dose areas of the hot cell are used to visually monitor operations within the cell. Several microphones are also included within the cell to listen for any abnormal sounds or deviations from the normal sound "signature" within the cell. These cameras and microphones are used to augment the information on computer screens and instruments which will be constanly monitored from the operations gallery.

Cell Penetrations

In addition to the supply doors through which empty canisters and lids pass, there are two other vital penetrations into the canister sealing cell. The first is the equipment hatch through which any equipment to be repaired or replaced can be removed from the cell. The second is a personnel hatch which is used for manned entry into the cell when contact maintenance of a piece of equipment is required.

2.4.4.4.5 Off–Normal Events

The most important off–normal event involved in the canister sealing operation is when a canister fails to pass the weld inspection. When this occurs, the faulty canister is not unloaded from the rail car, but is instead moved to the off–normal events station. The station is equipped with a set of manually controlled robotic arms and various manually operated power tools. The station is also equipped with a computer controlled fixed height saw which is used to remove the lid from the canister. After the lid has been removed, the rail car picks up an empty canister on its way to the loading cell where the fuel assemblies are transferred from the faulty canister to the new empty canister. The two canisters are then moved to the welding station where lids are welded on both canisters. Only the filled canister is backfilled and leak tested. From this point on both canisters are treated the same, and the empty faulty canister is put in the underground repository the same as the filled canister. This is done because it is an easy way to dispose of the faulty canister without disrupting the system, and it is assumed to be such an infrequent event that it will have very little effect on the overall estimated costs of the system.

Another possible off–normal event is the canister drop event. Due to the "birdcage" design of the rail cars, the only time this event could occur with a filled canister is when the canister is being moved from the sealing cell to the decontamination cell. This scenario is discussed in some detail in Section 2.4.4.8. Another off–normal event which is not analyzed in detail in this section is the possibility of a criticality excursion within the cell. It is assumed that the possibility of achieving criticality is precluded by the design of the cell which never allows for any planned or unplanned uncontrolled orientations of fuel elements anywhere within the cell.

2.4.4.5 Canister Decontamination

2.4.4.5.1 Design Description

After the sealed canister is unloaded from the rail car in the canister sealing cell, it is then moved by overhead crane through a set of doors into the decontamination cell. While the canister is suspended by the overhead crane, it is washed down with high pressure liquid freon. The canister is then swipe tested in order to ensure that a specified level of surface contamination for the canister has been achieved. Once adequate decontamination has been ascertained, the canister is then moved through a second set of doors and an air lock into the pre–emplacement lag storage cell, which is described in detail in Section 2.4.4.6.

2.4.4.5.2 Decontamination Cell

A close–up of the decontamination cell is shown in Figure 2.20. The decontamination cell has doors on both sides for ingress and egress from the cell. The doors seal tightly upon closing in order to provide contamination control between the canister sealing cell and the pre–emplacement lag storage cell. The doors also contain any possible loss of decontamination fluid from the cell.

Each canister is decontaminated by spraying liquid freon on the canister through several wall mounted high pressure shower heads. The mechanics of the system and the freon reservoir are located through the shield wall to provide for easy maintenance. The liquid freon which accumulates on the decontamination cell floor is collected by two floor mounted drains, and is then cleaned and filtered and recycled for reuse in the

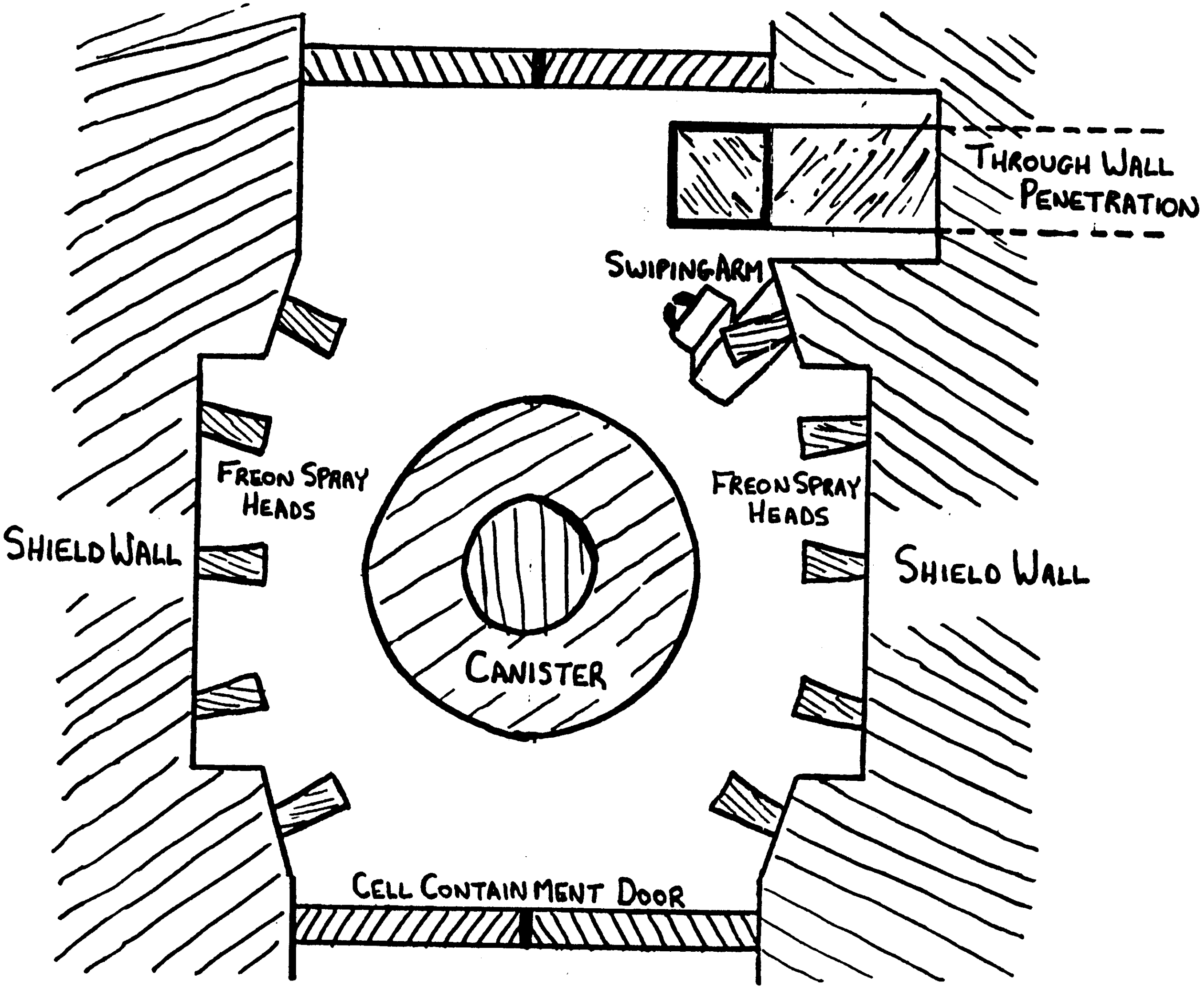


Figure 2.20 - Decontamination Cell

decontamination cell. Over a period of time the freon will build up such a large inventory of non–filterable radionuclides that it will no longer be an effective decontaminating fluid. When this happens, a portion of the freon will be replaced with a fresh supply of freon in order to dilute the radionuclides, and the removed freon will be treated as low level liquid waste.

After the canister has been thoroughly spray decontaminated, it will be swipe tested by a computer controlled robotic arm using a "lollypop" shaped swipe. The swipe is then deposited in a through–wall swipe box which is moved through the shield wall to a place where the swipe can be measured and counted away from the overriding radiation environment in the cell. If the swipe test shows that the canister has been decontaminated below a specific level, the canister is then moved into the pre–emplacement lag storage cell.

All of the operations in the decontamination cell are monitored visually by several cameras in the cell, and by inspection of computer consoles and instruments. These monitoring operations are carried out in the operations gallery.

2.4.4.5.3 Decontamination Cell to Lag Storage Air Lock

To go from the contaminated area of the R&H facility to the clean section, the canister must pass through an air lock. In order to provide contamination control in the facility and the surrounding area, the contaminated areas of the facility: the loading cell, the canister sealing cell, and the decontamination cell; are all maintained at a lower than atmospheric pressure. In this way, any breaches in the facility containment walls will cause clean air to leak into the facility, instead of allowing contaminated air to leak out to the environment.

2.4.4.6 Pre–Emplacement Lag Storage

Once the canister has been sealed and checked for leakage it is sent to a pre–emplacement lag storage (PELS), which is designed for the temporary storage of canistered spent fuel assemblies until they are loaded into the final package. It is assumed that the lag storage capacity will be 50 canisters or one month is worth of disposal canisters.

2.4.4.6.1 Design Description

The design description is based on a closed and sealed cell where canisters are placed in vertical position and attached to a structure as shown in Fig. 2.2.1.

The canister is moved inside the cell through narrow passages to or from the emplacement position. The operations are performed by a remote operated bridge crane. More details of operations will be given in Section 2.4.4.6.4.

The cell is designed to emplace a maximum of 50 canisters in five rows with ten canisters in each row. The distance between the canisters is 1.8 m.

2.4.4.6.2 Shielding and Cooling

Shielding considerations are based on the same criteria applied for the hot cell mentioned in Section 2.4.4.3.2.. The shielding in the lag storage is not exposed to the bare assembly, however, remote systems and cameras are used for additional viewing.

The cooling system is based in air entering the building through openings in the walls, removing the decay heat from the outer canister surface by natural convection and leaving through outlets in the roof as shown in Figure 2.22.

Criticality analysis done for an MRS facility described in the U/L room in Section 2.4.4.3., shown that k (eff) = 0.5 under normal operation. Under two hypothetical off–normal conditions k (eff) = 0.49 and 0.94; that is subcritical under all conditions. One design feature that must be incorporated to prevent criticality is that the canisters must be mantained in a safe geometric configuration.

2.4.4.6.3 Storage Layout

One of the important considerations in the design of the layout of the temporary lag storage room is related to the safety transportation of the canister. Emphasis was given to the emplacement of the canister so that it cannot be dropped like dominoes if they stand free. The other important consideration is the safe transportation of the canister between the corridors even in the case of a failure in the lift of the crane.

A series of beams located at 3 meters over the floor allows the safe movement and emplacement of the canister.

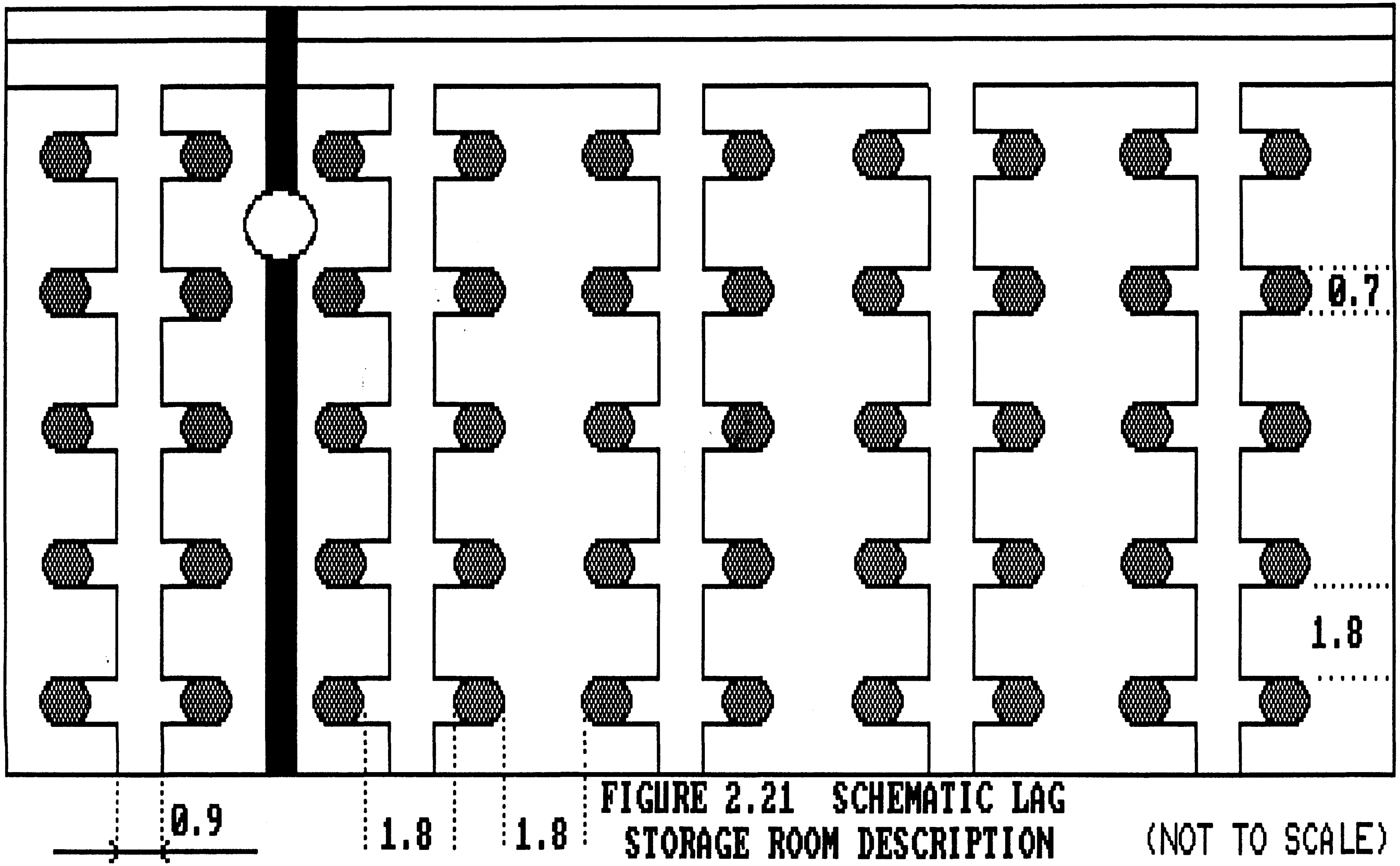


FIGURE 2.21 SCHEMATIC LAG STORAGE ROOM DESCRIPTION

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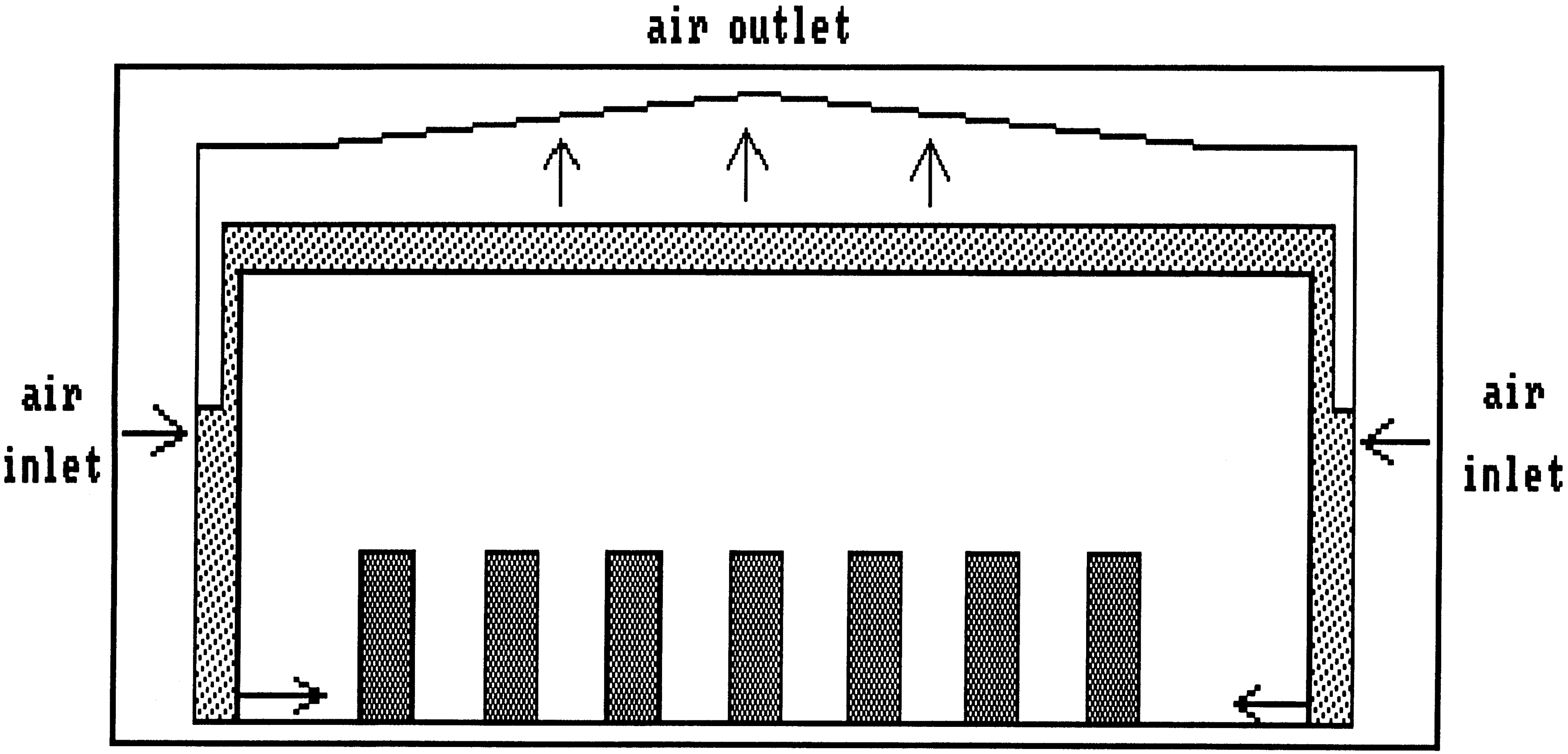

FIGURE 2.22 LAG STORAGE HEAT REMOVAL PRINCIPLE
(NOT TO SCALE)

Once the canister is checked, it is picked up by the crane using a lift with a device like an opening box in the bottom as it is shown in Fig. 2.23. This allows that in case of a rupture of the cable the canister does not fall during the course to its emplacement or from this last point to the emplacement cask loading.

After releasing the canister when it arrives to its emplacement, a remotely operated secure fixes the canister to the structure of beams. Once in this position the canister is completely safe and isolated from the other canisters.

The width of the corridors and the emplacement pitch are 90 cm allowing a margin of 10 cm during the movement of the canister.

2.4.4.6.4 Operations

The operations after the reception in the canister decontamination room and before the emplacement cask loading are described as follows:

a) The canister is picked up with the crane and moved to its emplacement position at no more than 10 cms/s , and at no more than 10 cm from the bottom of the canister to the floor.

b) Automatic controls place secures in the different corridors during the canister motion. The sequence of one of these operations is shown in Fig. 2.24..

c) The same sequence described in b) is done when the canister arrives to its emplacement position as it is shown in Figure 2.25.

d) The canister is lifted down and it is fixed to the structure placing the correspondent secure.

e) For the removal of the canister from the emplacement position, the same sequences described in b), c), and d) must be done until the canister is delivered in the emplacement cask loading room.

f) In the unusual event in which a canister failure occurs due to a drop, it will be picked up and returned to the welding station. If little pieces of the canister or fuel assemblies are dispersed, robots using closed–circuit television and

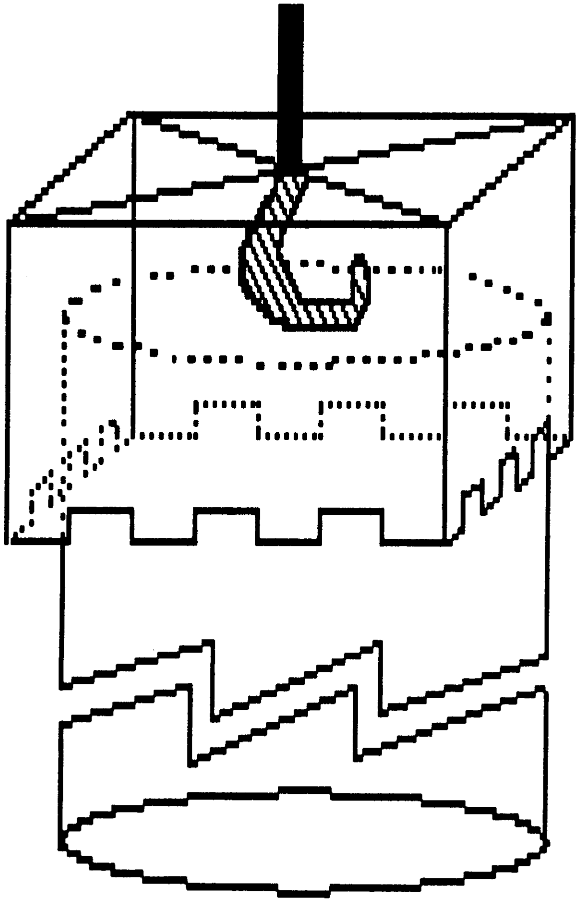

FIGURE 2.23 SAFETY CANISTER HOOK DESIGN

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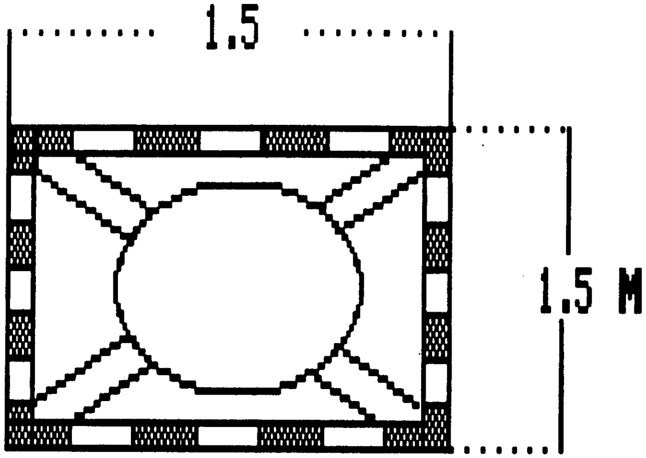
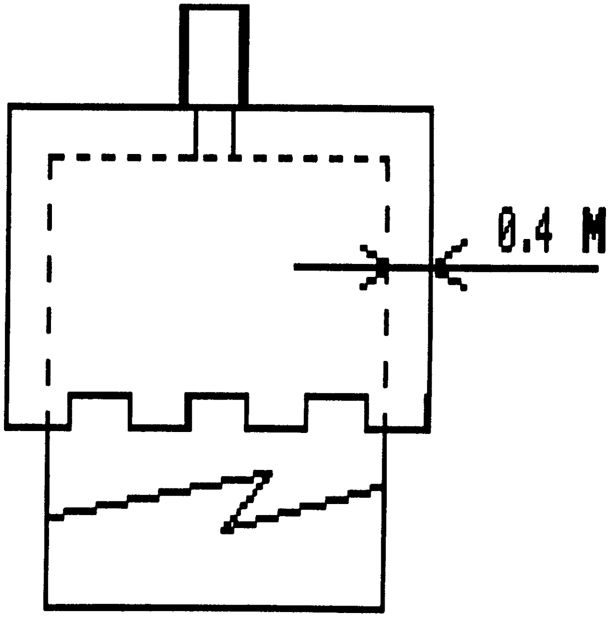
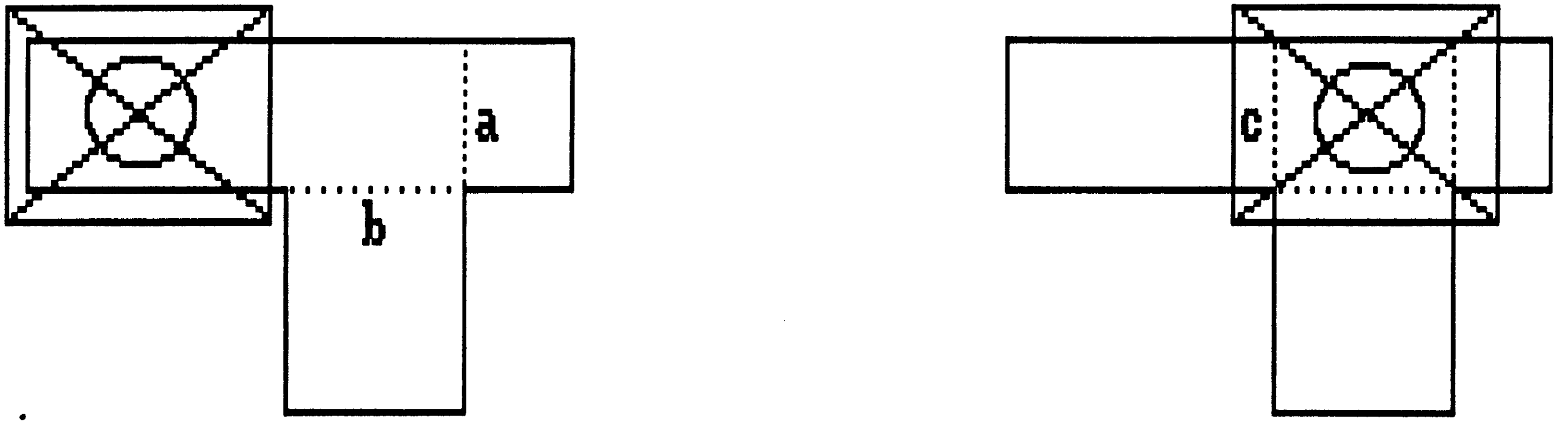


BOTTOM VIEW



FRONT VIEW

FIGURE 2.24 CORRIDOR SEQUENCE OPERATION



1 SECURE A & B LOCKED

2 SECURE C LOCKED

3 SECURE B OPENED

4 TO EMPLACEMENT

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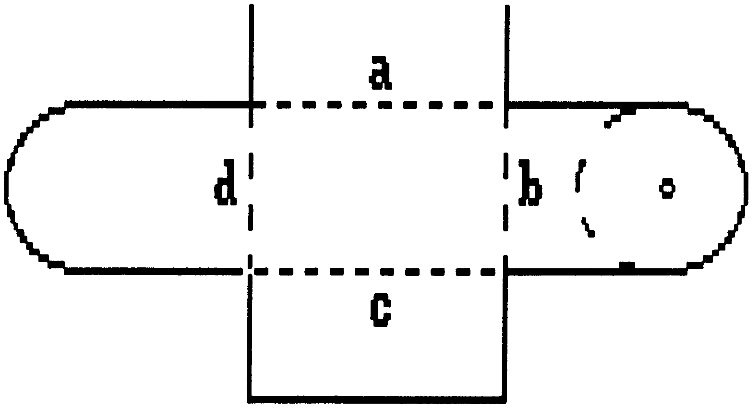
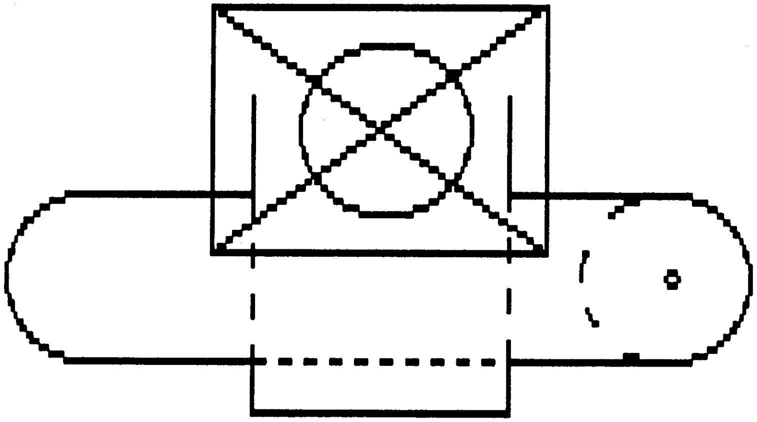
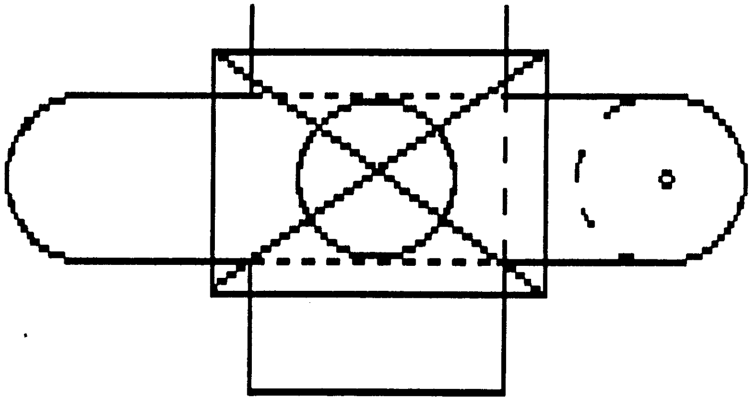
FIGURE 2.25 CANISTER EMPLACEMENT SEQUENCE OPERATION

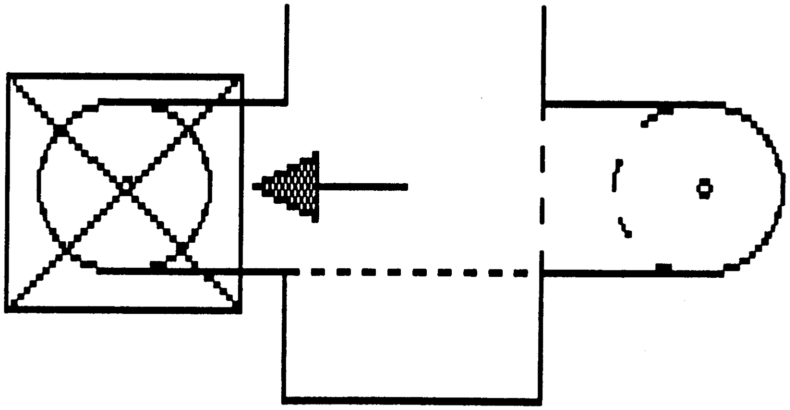




1 SECURES B,C & D LOCKED; A OPENED



2 SECURES A,B & C LOCKED; D OPENED



3 CANISTER EMPLACEMENT

(NOT TO SCALE)

computer control can be used. In any case the operations inside the lag storage room are considered very safe.

2.4.4.7 Emplacement Cask Loading

2.4.4.7.1 Design Description

During each working day, several filled canisters are taken from the pre–emplacement lag storage in the R&H facility down to the underground repository. When a canister is needed underground, it is removed from the pre–emplacement lag storage cell by an overhead crane and brought to the emplacement cask loading cell shown in Figure 2.26. The overhead crane is used to lower the canister into the canister downender in its vertical orientation. The downender is then used to rotate the canister into a horizontal orientation which is required for transfer to the repository transport vehicle discussed in Section 3.2. While these operations are taking place, the repository transport vehicle is being aligned with and then connected with the mating port on the outside of the cell shield wall. Once the coupling between the emplacement cask on the transport vehicle and the mating port is successfully made, two sets of shield doors, one on the emplacement cask and one inside the mating port, are opened to give access to the loading cell. The canister is then transferred to the emplacement cask, after which both sets of shield doors are closed and the transport vehicle is cleared to leave for the underground repository. The entire emplacement cask loading operation is observed from the operations gallery on in–cell radiation hardened cameras, and computer consoles and instruments.

2.4.4.7.2 Canister Downending

The canister is moved from its originally vertical orientation to a horizontal orientation by the canister downender shown in Figure 2.27. The downender moves through a travel arc of ninety degrees, as shown in the previous figure. The downender is motor driven and computer controlled, with final operational approval given from the operations gallery from which the entire loading process is monitored. The long dimension

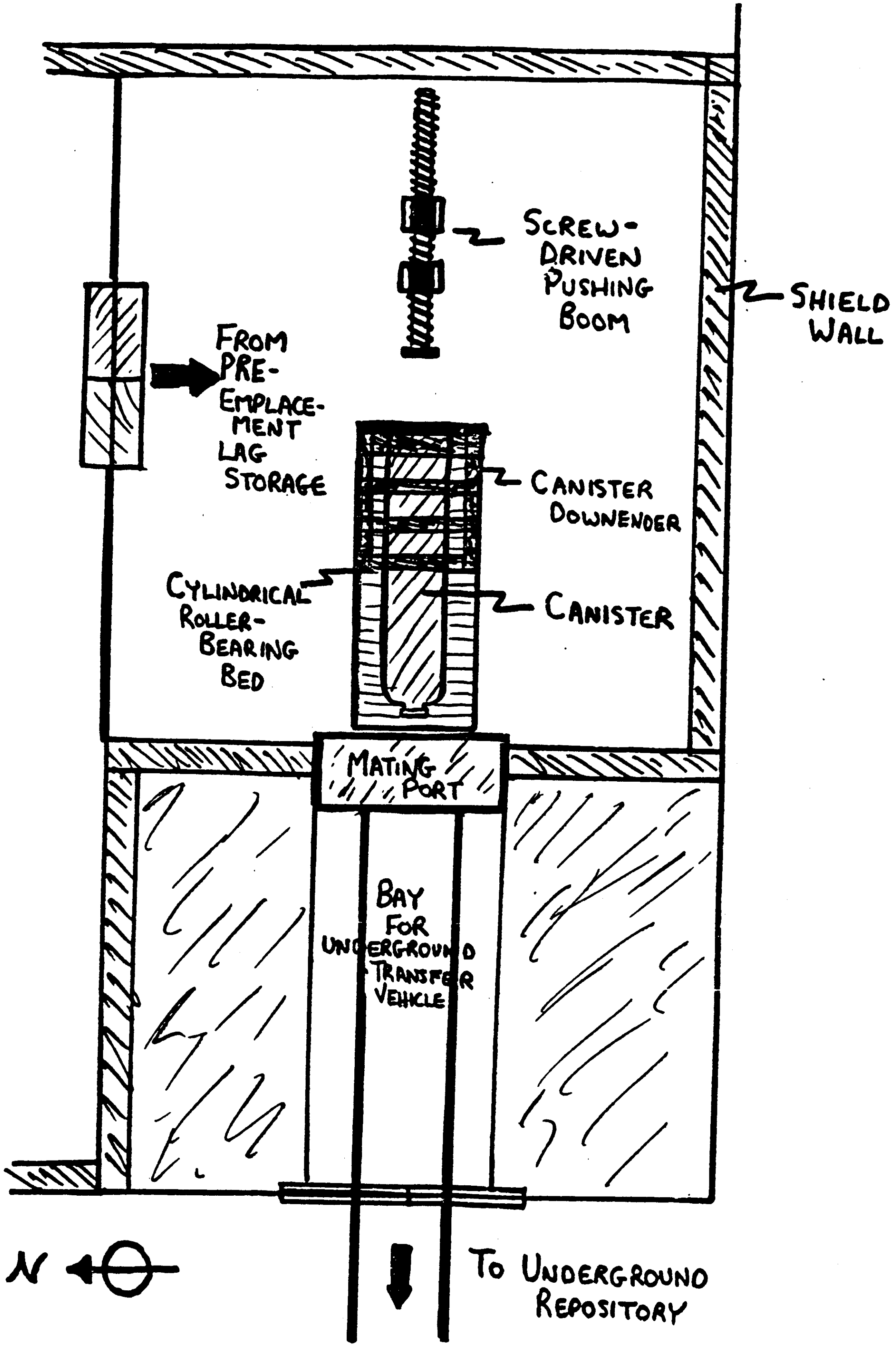


Figure 2.26 - Emplacement Cask Loading Cell

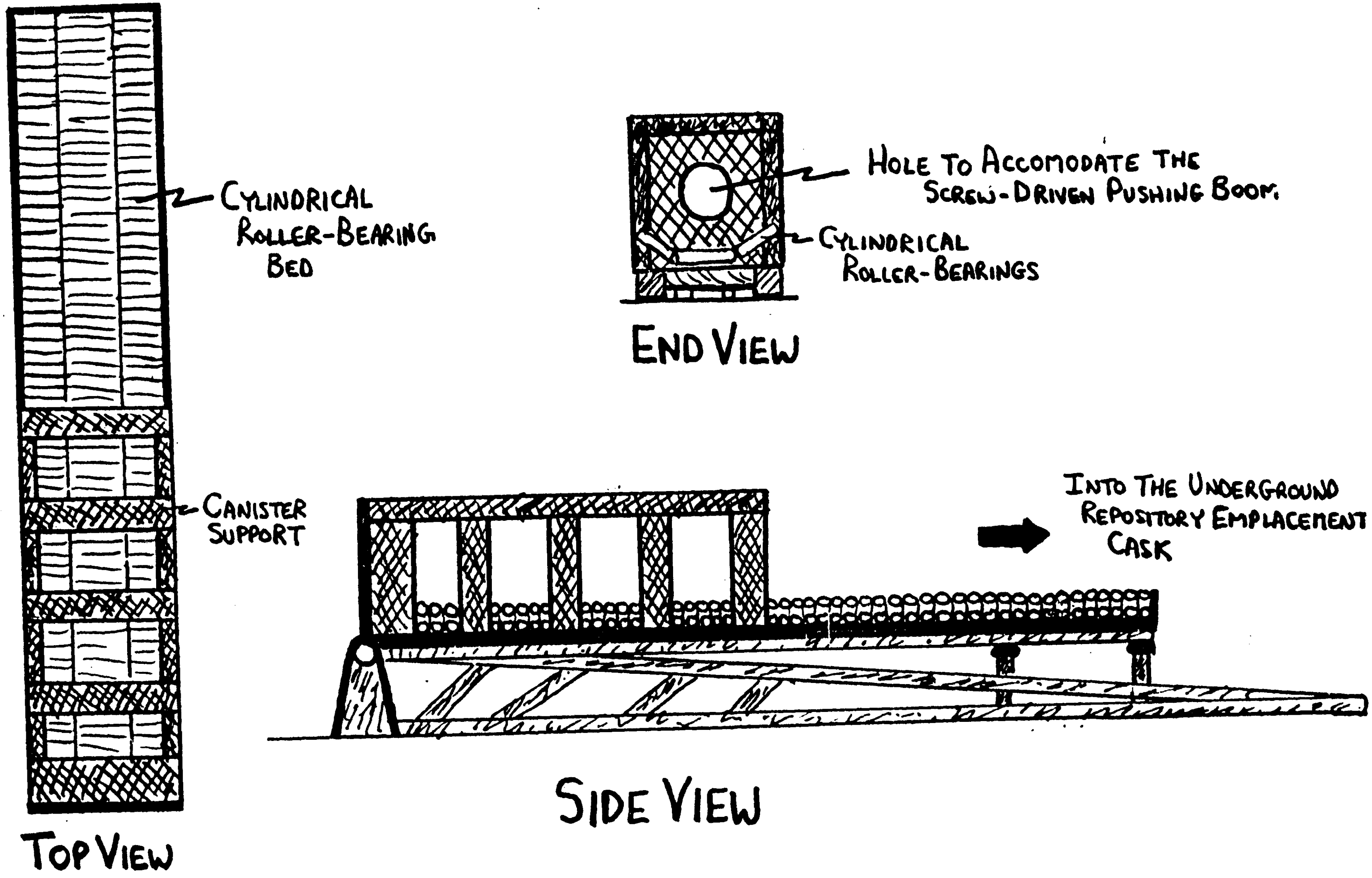


Figure 2.27 - Canister Downender

of the downender is equipped with a bed of cylindrical roller–bearings which reduce drag on the canister during the transfer operation, and a hole in the center of the base plate through which the screw–driven pushing boom is passed when pushing the canister into the emplacement cask.

2.4.4.7.3 Emplacement Cask Loading

After the canister has been downended into a horizontal orientation, it is then transferred to the emplacement cask on the repository transport vehicle. The primary sequence of events in the loading operation are shown in Figure 2.28. The repository transport vehicle first must be aligned and coupled to the mating port which passes through the cell shield wall. Once coupling is successful, the shield doors on the emplacement cask and within the mating port are opened to provide a direct path from the emplacement cask loading cell into the emplacement cask. The emplacement cask is equipped with an interior trolley which is then moved partially out of the emplacement cask until it contacts the end of the downender. At that time the emplacement cask canister grapple is attached to the canister. The canister is then slid onto the trolley by a combination of pushing from the screw–driven pushing boom located within the cell and directly in line with the canister long dimension, and pulling by the winch mechanism within the emplacement cask. Both the downender bed section and the emplacement cask trolley are lined with roller bearings to facilitate this movement. The use of redundant transfer mechanisms greatly reduces the probability of incomplete transfer. Once the transfer has been completed, both sets of shield doors are closed, and the transport vehicle is cleared to move out of the loading bay and down to the underground repository.

2.4.4.7.4 Off–Normal Events

The possiblity of dropping the canister after it has been placed in the downender are minimal. The off–normal events of interest are therefore if the downender fails to operate, or if the transfer operation fails. The possibility of incomplete transfer is greatly reduced

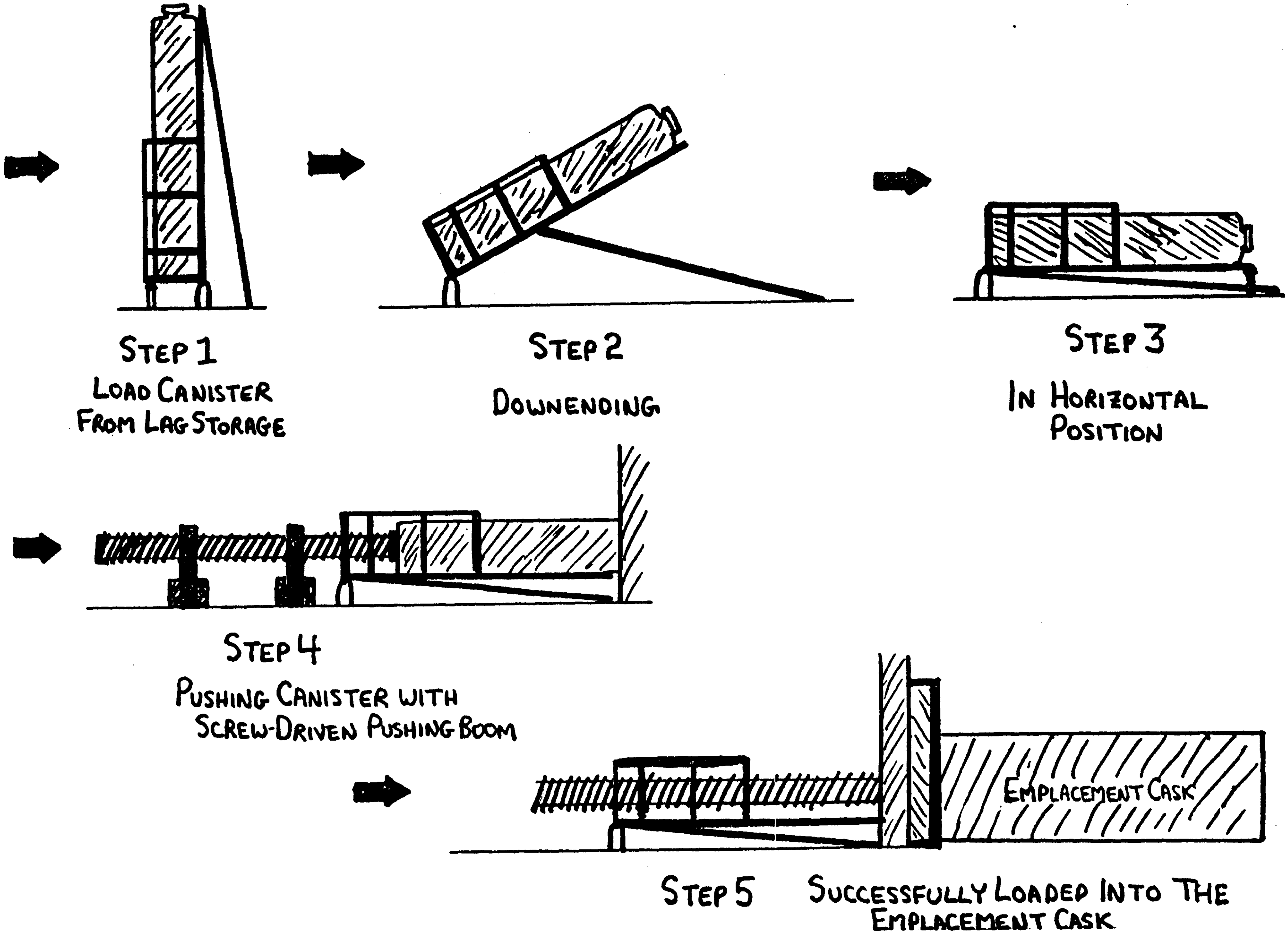


Figure 2.28 - Emplacement Cask Loading Operation Sequence

by the use of two redundant movement mechanisms: the screw–driven boom to push; and the emplacement cask winch to pull. The focus then falls on failure of the downender. The downender is designed so that any failure, such as power loss or motor failure, will cause the downender to fail in a safe manner. All motions of the downender are damped and limited in absolute travel by stop blocks. If the downender does fail partially down, the recovery procedure is to pick the canister up with the overhead crane and move it back to the lag storage cell. The loading cell is equipped with a set of wall–mounted manually operated robotic arms which can assist in fixing the crane grapple to the canister. The robotic arms can also be used to make minor repairs to the equipment and to assist the overhead crane in equipment changeouts. The passage from the lag storage cell to the loading cell is shielded so that if hands on repair and maintenance is required, all radioactive material can be removed from the cell, and manned entry can be safely made.

2.4.4.8 Off–Normal Events for the Surface Facility

2.4.4.8.1 Discussion

Several off–normal events have already been dicussed in the preceding chapters. Each of these events were scenarios specific to that particular section of the R&H facility. There is an overriding accident scenario which applies to the entire facility aft of the initial fuel element loading cell. This is the event in which a filled and sealed canister is somehow dropped to the floor of the facility. The facility design goes to great lengths to preclude this accident scenario whenever possible, but any time the filled canisters are lifted unrestrained by overhead crane, the scenario is a possibility. In order to directly minimize the damage from a canister drop event, the canisters are never lifted more than a few inches off the facility floor. It is assumed that if the canister is dropped, even from this minimal elevation, that it will fall over on its side in order to produce the greatest possible impact to the canister weld, which is assumed to be the weakest point on the canister. In order to minimize the canister drop probability, the overhead cranes are rated at a very conservative capacity many times the weight of a filled canister, and the grapple is designed with redundant gripping mechanisms and is designed to fail closed in the event of a loss of power accident.

If a canister is dropped, it will most likely remain intact. If this is the case, the canister will be again picked up by the overhead crane, after any necessary repairs to the crane and grapple are made, and returned to the canister sealing cell. The canister lid to body weld is then leak tested to assure the integrity of the weld. If the weld is good, and no other visible damage to the canister is seen, the canister is moved through the process like any other canister. If the weld proves faulty, the canister is treated like any other weld failure, unless it is subsequently discovered that the fuel elements inside have been damaged or shattered. In that case a special lid will be manually welded on the canister at the sealing cell off–normal station and the canister will be closely followed through the rest of the process. If the canister breaks open, most likely at the lid to body weld, then special recovery and decontamination procedures are required.

2.4.4.8.2 Remote Recovery and Decontamination Equipment

The combined possibility of canister drop and canister rupture is assumed to be so low that permanently affixed recovery equipment was viewed as unnecessary. Instead, a mobile robotic unit, which can reach anywhere in the facility that the canister could be dropped, is used for remote recovery and decontamination. The unit travels on wheels for maximum mobility, and is controlled remotely from the operations gallery. The unit has an attendent wheeled trailer and cradle unit which is used to transport the open canister. The robotic unit lifts the canister onto the trailer, and then tows it back to the canister sealing cell after it has done cleanup and decontamination using vacuum attachments and wipes in the local area of the canister drop. The open canister is taken to the off–normal events station within the sealing cell. If the fuel assemblies with the canister are found to be undamaged, the canister is moved to the loading cell and the elements are transferred to a new canister. If the fuel elements are found to be damaged, a special lid is welded manually to the canister at the off–normal station, and the canister is closely monitored through the rest of the processes in the R&H facility.

2.4.4.9 Estimated Costs

The evaluation of the costs of the repackaging and handling facility are based in the cost and founding analysis made in DOE/RW–0035/1–Rev 1 Volume 3 of 3 "Monitored Retrievable Storage Submission to Congress", March 1987.

The costs involved in this facility are related with design, construction, training and testing, operation and decommissioning. The costs for complying with regulatory requirements and the program management costs are included in the overall costs of the surface facility in Chapter 2.5, "Surface Facility Overall Costs". The costs associated with the Design element of the Repackaging and Handling Facility include the building itself and the design verification and the design managment and support. The social discount rate is estimated as 10%. A contingency of 20% is also included.

DESIGN COST

(MILLIONS OF CONSTANT 1988 U. S. $)

Building:	58.2
Design Verification:	14.0
Design Management & Support:	7.9
TOTAL DESIGN COSTS:	$ 80.1

The total costs in the construction phase are based in the conceptual design report (Ralph M. Parsons Company 1985). These costs include the cost of the building itself and the construction mangement and support. It is also considered that 2/3 of the building construction costs corresponds to the equipment for the repackaging itself (bridge cranes, robotics, closed circuits, welding machines, etc.). A 25% contingency allowance is considered.

CONSTRUCTION COSTS
(MILLIONS OF CONSTANT 1988 U.S. $)

Building (permanent): 137.8
Equipment: 275.6
Construction Management & Support: 55.3

TOTAL CONSTRUCTION COSTS: $ 468.7

The costs for Training and Testing are considered because of the high technology and complexity of the equipment involved and that the operations must be done with high precision and as safe as possible. Because of the non–consolidation, a reduction of 20% of the costs calculated in the design report is considered. It also includes a 20% contingency allowance.

TRAINING AND TESTING COSTS
(MILLIONS OF CONSTANT 1988 U.S. $)

Operating Procedure & Training: 34.7
Preoperational Testing: 21.6

TOTAL TRAINING AND TESTING COSTS: $ 56.3

The Operation and Maintenance costs include salaries and benefits for the personnel and the costs of major equipment replacement and minor inspections and repairs. A 20% contingency allowance is also included. The following assumptions are made: a) 50 people per shift (2 total shifts); b) $ 60,000 /year/person including direct wages and benefits; c) the maintenance cost is considered as the 5% of the equipment construction cost. The costs of operation and maintenance showed here corresponds to annual costs and the total operation cost will be calculated in Chapter 4 "Systems Economics".

OPERATION AND MAINTENANCE
(MILLIONS OF CONSTANT 1988 U.S. $)

Direct Wages and Benefits: 6.0
Maintenance and Supplies: 13.8

TOTAL OPERATION AND MAINTENANCE COSTS (PER YEAR): 19.8

The decommissioning costs included in this section corresponds only to the Repackaging and Handling building. A 25% of contigency allowance is considered since it is related to the construction costs. The total decommissioning costs are estimated at $ 62.0 millions of constant 1988 dollars, and it is considered at present time.

The total costs of the Repackaging and Handling Facility are shown below:

COST ITEM

(MILLIONS OF CONSTANT 1988 U.S. $)

Design	80.1
Construction	468.7
Training & Testing	56.3
Decommissioning	62.0
TOTAL R & H FACILITY	667.1

Note: The Operation and Maintenance costs are not included in this section because they are annual costs and will be included and calculated for the total operation time in Chapter 4 "System Economics".

2.5 Surface Facility Overall Costs

The surface facility costs are broken down into three groups: transportation, R&H facility, and the remainder of the surface facilities. With the exception of the buffer storage cost calculations, the costs are based on the cost analysis presented in DOE/RW–0035/1–Rev mentioned in section 2.4.4.9.

The costs are further broken down into the categories of design, capital, operation, decommissioning, and program management. A 22% contingency and 10% social discount factor are all incorporated into the following cost estimates.

The design cost includes all activities required to complete the final design documents of the repository surface facilities.

DESIGN COST
(MILLIONS OF CONSTANT 1988 DOLLARS)

R&H Facility	80.1
Support Facilities	13.1
Cask Storage Facilities	2.0
Site Design Data	6.8
Site Improvements	1.8
Utilities	3.1
Design Verification	6.9
Design Management and Support	4.0
TOTAL DESIGN COSTS	117.8

The construction costs cover the expenses incurred to build the facilities based on the drawings and documents prepared by the design element.

CONSTRUCTION
(MILLIONS OF CONSTANT 1988 DOLLARS)

R&H Facility	525.0
Support Facilities	60.5
Storage Facilities	325.0
Site Improvements	71.5
Utilities	6.1
Constr. Management and Support	55.3
TOTAL CONSTRUCTION COSTS	1,043.4

The operations costs include the wages and benefits (at an average cost of $60,000 per person) for all employees of the repository surface facilities as well as funds required for cask purchases, maintenance supplies, and utilities.

OPERATIONS
(MILLIONS OF CONSTANT 1988 DOLLARS/YEAR)

R&H Facility	19.8
Casks Additions	14.6
Personnel	15.2
Maintenance for Facility	18.2
Utilities	24.7
TOTAL OPERATIONS COSTS	92.5

The decommissioning costs cover the clean–up expenses incurred at the end of the repository's life. The major decommissioning costs are associated with the decontamination and disposal of the R&H facility. The following decommissioning costs have been calculated assuming that the casks have no salvage value.

DECOMMISSIONING COSTS
(MILLIONS OF CONSTANT 1988 DOLLARS)

R&H Facility	62.0
Support Facilities	5.7
Storage Facilities	24.7
Site Improvements	7.9
TOTAL DECOMMISIONING COSTS	100.3

The transportation costs are broken down into the initial capital outlay and the annual operating expenses required for maintenance, fuel, and personnel.

TRANSPORTATION COSTS
(MILLIONS OF CONSTANT 1988 DOLLARS)

Initial Capital Outlay	354.2
Annual Operating Expenses	100.0

Program Management costs cover the expenses associated with organization and oversight of the entire repository design, construction, operations and decommisioning.

PROGRAM MANAGEMENT COSTS
(MILLIONS OF CONSTANT 1988 DOLLARS)

System Engineering & Config. Mgt.	20.9
Institutional Relations	4.6
Project Planning and Control	24.2
Subcontract Management	8.0
Management Service	12.5
Quality Assurance	15.6
TOTAL PROGRAM MANAGEMENT COSTS	85.8

The following summary displays the design, construction, operating, and decommissioning costs of the surface facilities and the transportation system.

ITEM	Design	Constr	Operat	Decom
R&H Facility	80.1	525.0	19.8	62.0
Surface Facilities	37.7	518.4	72.7	38.3
Transportation	354.2	100.0	–	–
TOTALS	117.8	1,397.6	192.5	100.3

A life cycle cost estimate for the entire repository is presented in Chapter 4. 2.6

2.6 Chapter Summary

The Surface Facilities and Operations chapter includes all the activities in the high level radioactive waste disposal system between the reactors and the underground repository. The chapter concentrated on four major areas of importance within this scope, including: at–reactor operations; transportation; at–repository surface buffer storage; and spent fuel repackaging. The system design deviates from the U.S. Department of Energy's standard reference system design in several important respects. First, this design uses a dual purpose cask for both transportation from the reactor and storage at the repository surface, while the U.S.DOE design uses a design distinctly different from the storage cask design. Second, this design calls for the use of dedicated unit trains from the reactor sites, while the U.S.DOE has still not settled its design decision. Third, this design does not use a Monitored Retrievable Storage (MRS) facility for storage and repackaging of spent fuel, while the U.S.DOE still hopes to incorporate an MRS into their reference design. Fourth, this system design does not include fuel rod consolidation, while rod consolidation is a central part of the U.S.DOE high level radioactive waste disposal system design. The reasoning behind each of these design decisions was presented at the beginning of the chapter. The implementation of these design decisions resulted in the concrete, simple, and viable reactor–to–repository system design presented in the body of this chapter.

CHAPTER 3

REPOSITORY SYSTEM

3.1 Introduction

This chapter of the document outlines the design of that portion of the high–level waste management system that must interface directly with the geologic environment. That is, all systems located below the surface at the Yucca Mountain site are described: the Engineered Barrier System, the Geologic Repository, and the Repository Operations. In each case, the pertinent criteria and constraints are enumerated.

The Engineered Barrier System section describes all engineered factors in the design that function to enhance containment. Since the scope of the project did not allow for the calculation of performance of several engineered systems and simplicity in the design was encouraged, it was assumed that the waste canister must provide the necessary engineered containment. Considerations and calculations related to the waste canister, such as waste form design, thermal calculations, radiological considerations, and canister mechanical failure are examined in this section.

The Geologic Repository section covers all portions of the design related to the construction of the underground facilities, including the continual construction of emplacement rooms. First, the criteria and constraints to the design are examined, including a brief review of site geology. Second, the design is described in detail. Special attention is given to construction sequence and layout, shafts and ramps, corridors and emplacement rooms, waste emplacement holes, ventilation and ground water control. In short, this design is a horizontal emplacement concept with mechanical excavation throughout. Following the detailed description, repository sealing concepts are discussed, and the geologic repository costs are evaluated.

The Repository Operations section characterizes all operational and maintenance factors in direct relation to the emplacement of the canister into its respective emplacement hole. The canister transportation system from repository to the emplacement hole is outlined along with the emplacement system and procedure. Other operational systems for the underground facilities including radiation protection of workers, environmental control of climate, health and safety of workers, and the backfilling system are described in necessary detail for the scope of this report. In conclusion to this section, an illustration of some off–normal events is given for possible accidents, and an estimated cost evaluation is presented for the repository operations.

3.2 Engineered Barrier System

The engineered barrier system (EBS) refers to the package employed to contain the nuclear waste, along with any other engineered components that would aid in the containment of the waste (e.g., backfills, anodic protection schemes). Beyond the physical engineered systems, the EBS must also provide data that assure that the criteria for containment, cost, and environmental disturbance are met (3.2.1.1). For this report, the scope was not sufficiently broad to allow for addressing all possible criteria. Therefore, a preliminary screening of the applicable criteria narrowed the focus to a manageable number of assessment areas that fed into the design assumptions (3.2.1.2). Data were gathered that describe the constraints imposed upon the design by the physical characteristics of the Yucca Mountain site and by the expected nuclear waste forms (3.2.1.3).

Having imposed certain design assumptions and constraints, a design for the EBS was proposed that attempts to minimize cost while assuring that the applicable criteria are met (3.2.2). Every attempt was made to imbue the design with pragmatic engineering considerations and an attention to the perceived realities of the enormous undertaking of nuclear waste storage. The final portion of this section details cost information related to the EBS (3.2.3).

3.2.1 Criteria and Constraints

3.2.1.1 Technical Criteria

The Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA), among others, have provided the Department of Energy (DOE) with technical criteria related the EBS. These criteria, 10 CFR 60 [3–1] and 40 CFR 191 [3–2] are outlined in Appendix A. The DOE has interpreted these criteria with its own set of criteria that are intended to address those of the NRC and EPA. Those applicable to the EBS are [3–3]:

Principal Functions

"Provide thermal loading, taking into account performance objectives and thermo-mechanical response of the host rock (10 CFR 60.133(i), 10 CFR 60 133(e)(2), and 10 CFR 60.133(h)).

Design Criteria

"Ensure the usable area for the repository will have greater than 200 m overburden, be within the TSw2 portion of the Topopah Spring Member, be more than 70 m above the water table." (see Section 3.3 for additional details)

"Limit on surface environment by limiting surface temperature rise to less than 6 degrees Celsius . . . "

"Establish borehole spacing to assure that areal power density of 57 kw/acre is not exceeded, borehole wall temperatures remain below 275° C, and rock mass temperature at 1 m into rock is below 200° C."

The NRC has also imposed the requirement that the EBS provide " . . . Substantially complete containment . . . " of the waste for a period of 1,000 years. The DOE has interpreted this to mean [3–3]:

> The Department of Energy understands the requirement for substantially complete containment of high–level waste (HLW) within the set of waste packages to mean

that a very large fraction of the radioactivity that results from the HLW originally emplaced in the underground facility will be contained within the set of waste packages during the containment period. Therefore, the requirement would be met if a significant number of the waste packages were to provide total containment of the radioactivity within those waste packages or if the radioactivity released from the set of waste packages during the containment were sufficiently small. The precise fraction of HLW that should be retained within the set of waste packages, number of waste packages that should provide total containment, or constraints that should be placed on the rate of release from the set of waste packages to meet the requirement for substantially complete containment should not be determined until the site is sufficiently well characterized. Such a precise interpretation depends in large part on the level of waste–package performance needed at the site. Therefore, a specific interpretation of the general requirement cannot be made until additional information regarding site conditions and the characteristics of alternative materials and waste package designs subject to these conditions is available.

One final criteria imposed by the course instructor was that the container that is used to contain waste shall never pose a greater threat to the environment than the waste itself.

3.2.1.2 Design Assumptions

The initial phase of this portion of the design depended upon the amount and age of waste that was expected for the repository. The inventory given in Table 3.2–1 was adopted as the expected distribution of waste, age, and amount that is discharged from reactors in the future.

The containment of the waste was assumed to be performed by a single, well–engineered canister of highly corrosion–resistant material. Although the Zircaloy cladding may provide some degree of containment, the predictability of the failure rates of

Table 3.2-1 Spent Fuel Burnups and Ages at Emplacement Normalized to Energy Information Agency (EIA), 1983 Midplane Projections

Discharge year	Burnup (MWD[b]/MTU) vs. year in MTUs 0-5000 BWR	PWR	5000-10000 BWR	PWR	10000-15000 BWR	PWR	15000-20000 BWR	PWR	20000-25000 BWR	PWR	25000-30000 BWR	PWR	30000-35000 BWR	PWR	35000-40000 BWR	PWR	40000-45000 BWR	PWR	45000-50000 BWR	PWR	50000-55000 BWR	PWR	Age (yr) at emplacement	Receipt yr	Total BWR	MTU PWR	Total MTU	Cumulative MTU
1961																							37	(1998)			4*	4
1962																							36	(1998)			6*	10
1963																							35	(1998)			10*	20
1964																							34	(1998)			11*	31
1965																							33	(1998)			11*	42
1966																							32	(1998)			11*	53
1967																							31	(1998)			11*	64
1968																							30	(1998)			11*	75
1969					1		7					8											29	(1998)	8	8	16	91
1970								41		8													28	(1998)		49	49	140
1971			14		8	5						40											27	(1998)	20	45	65	205
1972	142		12		31	8	4	45				9		22									26	('98-'99)	189	84	273	478
1973	9		16		36		40	24				40											26	(1999)	101	64	165	643
1974	60		6	7	122	77	31	40	4	14		74											25	('99-'00)	223	212	435	1078
1975			1	9	46	186	156	12	22	71		41		30									25	('00-'01)	224	339	563	1641
1976			40		108	17	140	147		84		91		37									25	('01-'02)	306	378	682	2323
1977			53		34		174	132	102	126		134		86		18							25	(2002)	362	496	858	3181
1978				2	36	61	119	78	206	46	28	402		73		62							24	('02 '03)	438	713	1151	4332
1979					30	36	82	134	181	56	178	279		238		32							24	(2003)	451	755	1206	5538
1980	15				3	9	66		362	56	110	304		228		29							23	(2003)	528	823	1149	6687
1981						36	73		256		162	304		428		16							22	('03 '04)	491	774	1265	7952
1982					15		41	80	30	80	300	161		381		13							22	(2004)	386	704	1090	9042
1983							36	40	42	48	282	296	16	220		51							21	('04 '05)	394	684	1058	10100
1984	14		9		13	52	3	41	48	16	282	118	14	412		94		3					21	(2005)	364	736	1100	11200
1985			55		52	21	15	70	25	11	349	206		380		193		24					20	(2006)	396	904	1300	12500
1986	14		62		57	46	60	127	7	52	382	107	38	245		284		28					19	(2006)	629	871	1500	14000
1987	29		23		34	59	102	48	127	27	256	123	13	379		349		32					18	(2006)	583	1017	1600	15600
1988			33		90	2	120	80	94	19	514	165	44	508		417		107					18	(2006)	904	1296	2200	17800
1989			44		24	27	41	27	150	64	309	165	118	501		435		95				1	17	(2006)	785	1316	2100	19900
1990			30		15		66	27	31	18	480	93	219	542		460		119					17	(2007)	841	1259	2100	22000
1991			3				47		29	48	808	104	228	629		618		190					16	(2007)	1113	1587	2700	24700
1992					3		3		152	1	470	100	272	771		588		139		1			16	(2008)	900	1600	2500	27200
1993							44	60	27	7	740	63	230	504		703		122		1			15	(2008)	1050	1550	2600	29800
1994									64	7	640	63	258	860		553		157					15	(2009)	960	1640	2600	32400
1995									60		809	73	225	825		592		135		1			14	(2009)	974	1626	2600	35000
1996									70	8	790	32	393	815		731		160		1			14	(2010)	1253	1747	3000	38000
1997									64	7	572	38	356	871		717		175		1			13	(2010)	991	1809	2800	40000
1998									56		806	71	173	848		586		169		1			13	(2011)	1125	1675	2800	43600
1999				21					68	30	638	31	379	849		728		165		1			13	(2011)	1085	1815	2900	46500
2000	1						6		31		758	41	386	1022		507		158					12	(2012)	1182	1818	3000	49500
2001						11			117	10	743	87	300	882		841		208		1			11	(2012)	1160	2040	3200	52700
2002									71	8	916	33	403	853		746		169		1			11	(2013)	1390	1810	3200	55900
2003									33		857	48	508	1167		867		219		1			10	(2013)	1198	2302	3500	59400
2004			36			27	45		109	37	844	81	281	1029		711		199		1			10	(2014)	1315	2085	3400	62000
2005									38		1120	42	615	1040		966		178		1			9	(2014)	1673	2227	3900	66700
2006		4	32	60		14	48	40	34	69	611	60	529	1127		863		228		1			9	(2015)	1254	2446	3700	70400
2007	14	17	87	58		66	93	91	114	118	1009	121	285	982		752		194		1			9	(2016)	1602	2398	4000	74400
2008	20	6	177	49	49	128	204	28	119	68	715	167	427	820		767		166		1			8	(2016)	1711	2189	3900	78300
2009		12	124	83				132	41	271	788	2	428	1120		773		226					8	(2017)	1381	2619	4000	82300
2010		18		61	37	67	144	73	80	142	910	45	273	1132		575		142		1			8	(2018)	1444	2256	3700	86000
2011				42		61		103	68	106	1236	2	481	1381		887		142		2			7	(2018)	1775	2725	4500	90500
2012		12	34	18	34	48		131	83	79	810	22	690	1216		754		167		2			7	(2019)	1551	2449	4000	94500
2013	42		160			59	160		196	83	1095	2	417	1318		787		179		2			6	(2020)	2070	2430	4500	99000
2014	34	9		43	188	99		1	244	138	1122	31	569	1108		804		110		2			6	(2020)	2157	2343	4500	103500
2015		3		63	272			63	333	186	898	63	632	1606		838		143					6	(2021)	2135	2965	5100	108600
2016			265	122	81	75	321		156	181	1225	75	277	1627		692		203					5	(2021)	2325	2975	5300	113900
2017	26			62	137			98	218		1140		404	1375		958		82					5	(2022)	1925	2575	4500	118400
2018									107		1214		547	2271		847		214					5	(2023)	1868	3332	5200	120600
2019			109		109		111		210		1591		198	1945		838		189					5-6	(24 25)	2328	2972	5300	128900
2020		27	111			129	164		113	129	1204		384	1813		1063		93					6 7	(25 27)	1956	3044	5000	133900

[a] Source is DOE (1984)

[b] MWD = megawatt days, MTU = metric tons of uranium, BWR = boiling water reactor, PWR = pressurized water reactor

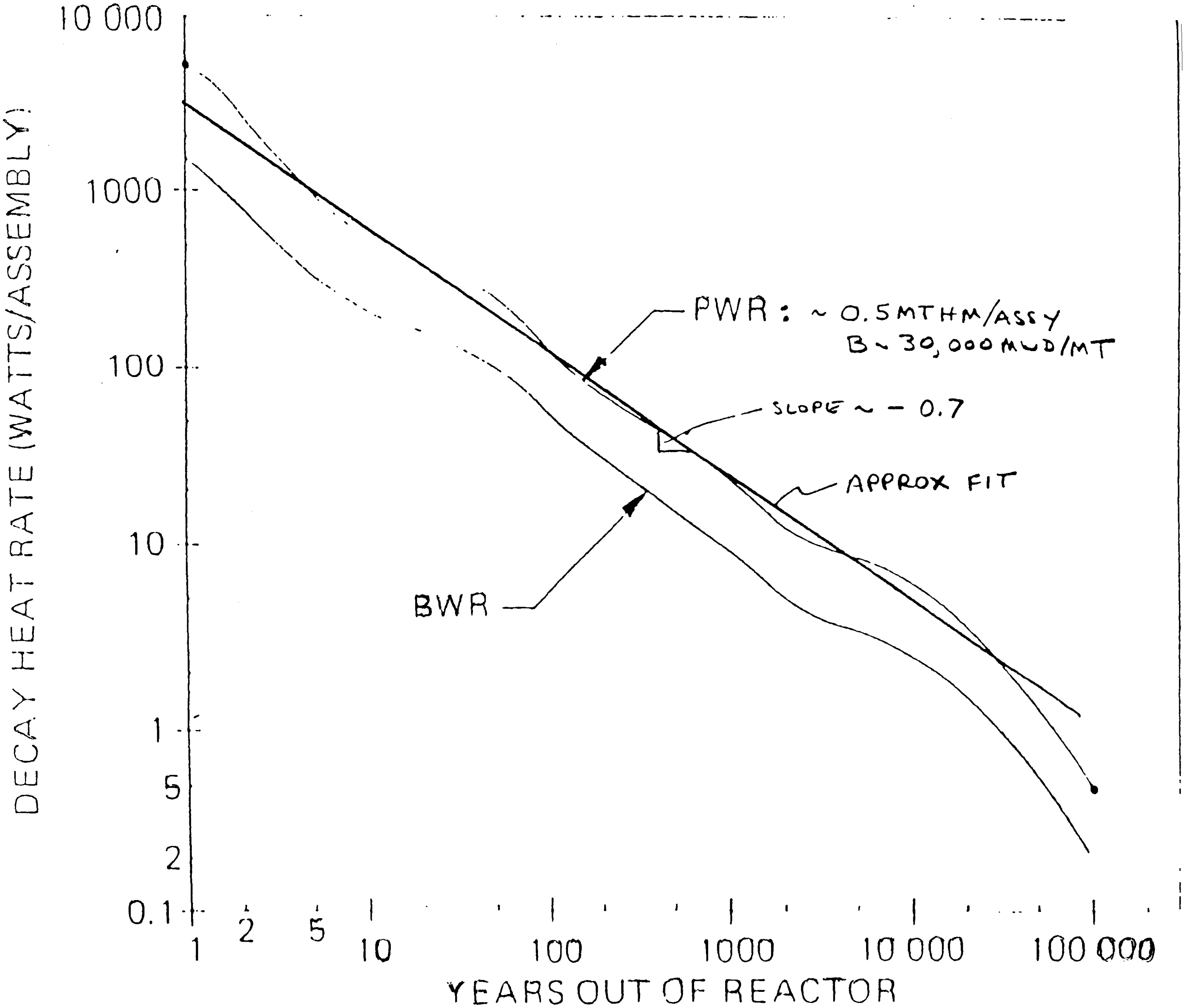


Figure 3.2-1 Spent Fuel Thermal Source Up to 100,000 year Cooling Time

this already highly stressed material is doubtful. For this design, Zircaloy provides a measure of conservatism.

The repository is assumed to remain unsaturated during the containment period. Although portions of the repository may at times become saturated, it has been assumed that saturated flow does not contact a sufficient number of breached canisters to cause significant release. With the uncertainty surrounding the prediction of transport of radionuclides in unsaturated porous media, transport predictions have not been addressed for the design. It has been assumed that the combination of the confinement provided by the canister, retardation of radionuclide movement by the geology in the event of a breach and other conservative assumptions of the design provide the necessary barriers to the release of radionuclides. Implicit within this approach is the assumption that this design meets the criteria of substantially complete containment and hence satisfies all NRC and EPA criteria with regard to the environment. A further underlying assumption considers the relative toxicity of the waste as a function of time; see Fig. 3.2–2. The data in the figure suggest that a high degree of containment during the first 500 years allows the waste to decay to a point where it is less toxic than the ore from which it was originally mined. Rather than providing absolute safety with regard to the isolation, this approach to the toxicity issue provides a more realistic time scale for predictability of containment. This approach also lends itself to the defense that if the waste can be reliably contained for 500 years, it is the same as if the ore were never mined at all.

Pressure loading on the canister is born by the corrosion barrier material. It has been assumed that the canisters are not subjected to stresses above those allowed by the ASME Boiler and Pressure Vessel Code [3–4] for the chosen material and dimensions.

3.2.1.3 Waste form Description and Site Constraints

This design has adopted an unconsolidated spent fuel waste form for the design basis. All waste forms are acceptable, i.e., vitrified high–level and defense waste, fast and gas

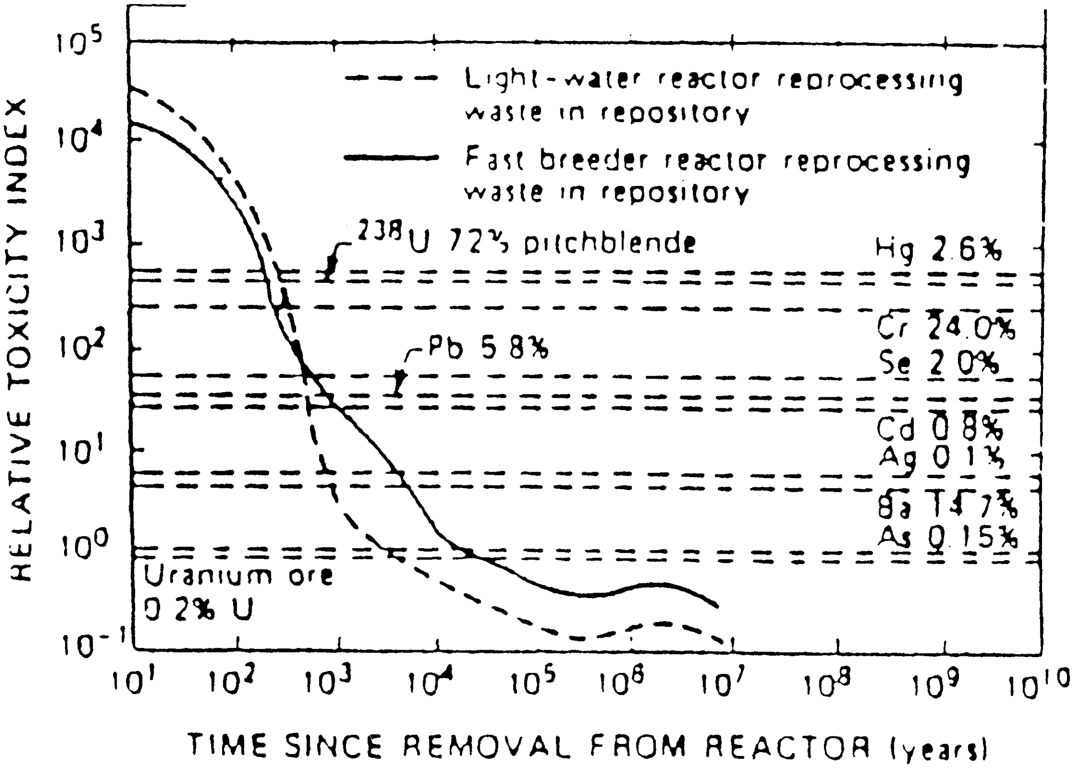


Figure 3.2-2 Toxicity of Nuclear Waste Over Time (relative to that of average mineral ores of toxic elements) Compared to times of Social or Geologic Significance

NUCLEAR SAFETY, Vol. 19, No. 3, May-June 1978 reactor fuels, subject to the thermal loading and geometric limits defined in the next section. The choice of unconsolidated versus consolidated fuel was made for safety, radiologic, handling, and economic reasons with regard to the above–ground operations [2.4.4.1]. The tradeoff is an increase in the number of packages produced; approximately 30 percent more will be needed for unconsolidated versus consolidated fuel.

Given that the receipt (and emplacement) rates of spent fuel are 4,000 Mtu/yr (see Section 2.3.3.4) and the projected year of the start of emplacement is 2005, an analysis of the inventory projects a minimum spent fuel age at emplacement of 16 years (see Table 3.2–2). Unfortunately, the dose rate and heating analyses data are only available for ten–year–old waste. No attempts were made to overcome this deficiency in the data, and therefore, the dose and heating estimates include a conservatism in the form of an additional six–year cooling period that is not accounted for in the calculations.

Table 3.2–2. Year of Emplacement Based on Projected Inventories of Spent Fuel

Material Produced in Years	Will be Emplaced in Year
up to 1978	2005
1982	2006
1988	2008
1990	2009
1991	2010
1993	2011
1994	2012
1996	2013
1997	2014
1999	2015
2000	2016
2001	2017
2003	2018
2004	2019
2005	2020

—no significant change in subsequent years—

The rate of cooling of the spent fuel was calculated from data given in Fig. 3.2–1 [3–5]. This is roughly the same cooling law that was given by Malbrain [3–6] for waste greater than 30 years out of the reactor. Photon release rates and energies are given in Table 3.2–3 for ten–year–old PWR fuel, with 33,000 MWD/MT burnup [3–7]. The details of the above analyses are given in the Design Description Section.

Table 3.2–3. Photon Release Rates and Energies for Reference PWR Fuel

Energy (MeV)	Release Rate (Photons/sec)
0.015	3.1e15
0.025	6e14
0.0375	7.4e14
0.0575	6.5e14
0.085	3.4e14
0.125	2.8e14
0.225	2.9e14
0.375	1.2e14
0.575	5.1e14
0.85	1.8e14
1.25	3e12
1.75	3e12
2.25	6.5e8
2.75	8.3e8
3.5	2.8e7
5.0	1.1e7
7.0	1.3e6
8.5	1.5e5

The site constraints of importance to design beyond the hydrologic ones already mentioned are the thermal characteristics of the rock. Values for the thermal conductivity and heat capacity are given in Table 3.2–4. These values were taken from data given in the SCP [3–3] and averaged between saturated and unsaturated conditions.

Table 3.2–4. Average Thermal Properties of TSw2 Rock

Thermal conductivity (watts/m °K)	1.6
Heat capacity (J/cm^3 °K)	2.1

3.2.2 Design Description

This section describes the geometry, materials selection, and calculations used to arrive at the proposed engineered barrier system. The interdependence of the spacing of the canisters upon the local heating and the overall areal heat loading requires that the pitch of the canisters, number of canisters per hole, and backfilling strategy are determined as a portion of the EBS design.

3.2.2.1 Waste Package Design

The design to accommodate the unconsolidated spent fuel was taken from the reference design proposed by the DOE [3–3]. Figure 3.2–3 depicts the internals of the waste package, Configuration 1. Four BWR fuel elements and three PWR elements are contained within each package. This choice of design almost exactly accommodates the expected inventories of spent fuel. The small excess of BWR fuel will be accommodated in Configuration 2, Fig. 3.2–3. Each package contains 2.13 metric tonnes of spent fuel. The overall length, including the lifting pintel, is 4.76 m. The canisters will be received, loaded with fuel, and welded shut using conventional welding techniques at the surface facility.

It was decided not to try to engineer the environment surrounding the canister with exotic backfills or corrosion protection techniques. The reliability of these measures would be hard to predict over the long isolation period, and therefore the approach taken was to leave the environment as little disturbed as possible. The backfill used in the design is crushed tuff rock that had previously been mined from the repository. The tuff rock will be compacted within the boreholes to a density of ~80 percent of the original rock density. In

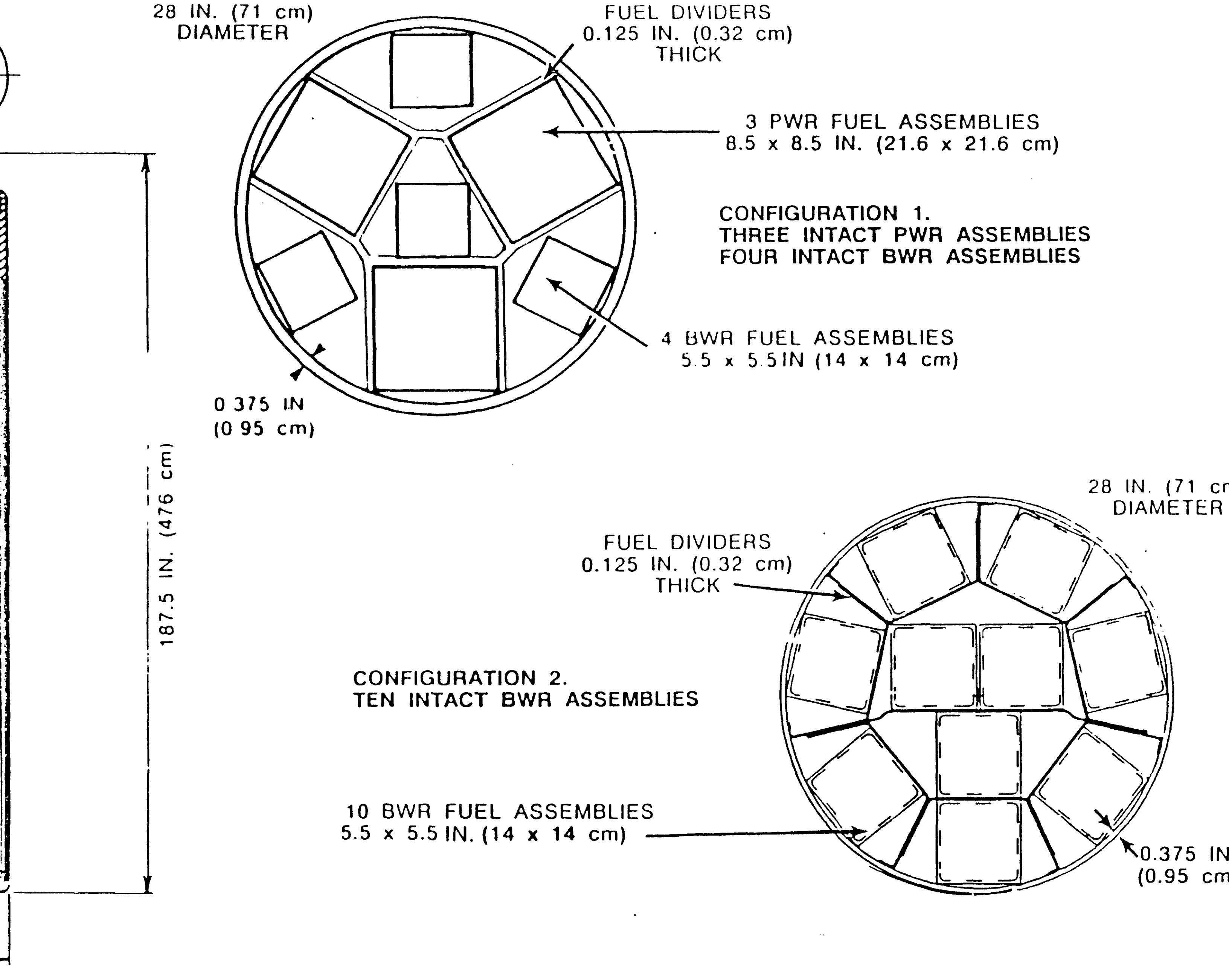


Figure 3.2-3 Spent Fuel Container Configurations

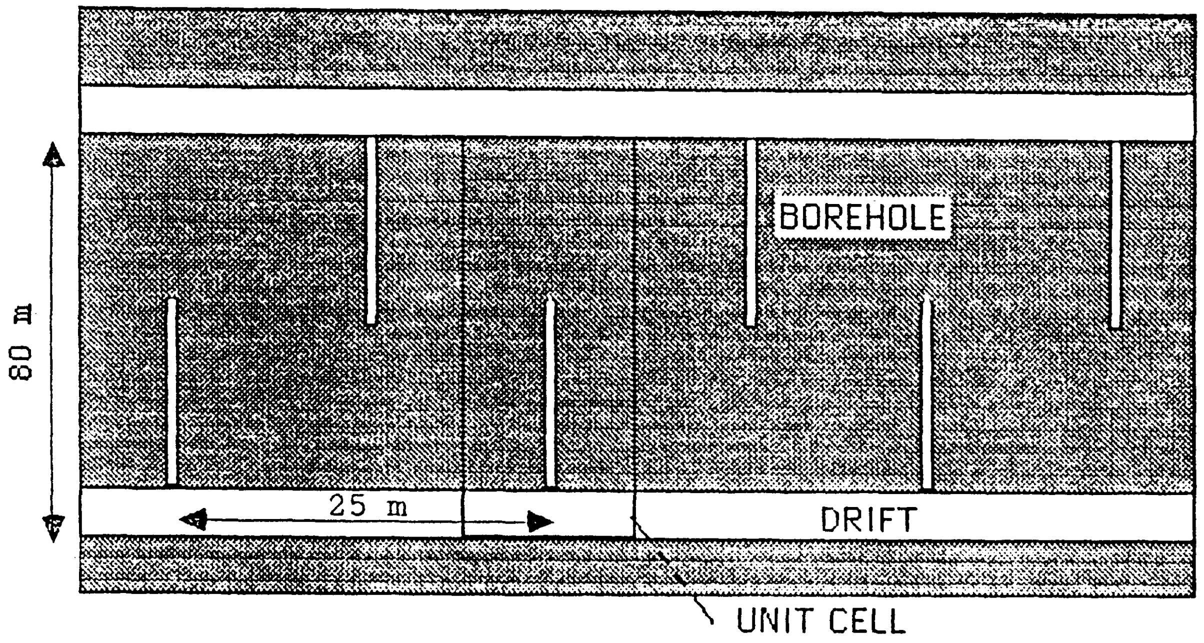


Figure 3.2-4 Unit Cell for Calculation of Repository Pitch for a 57 kw/acre Areal Thermal Loading

this way, no alteration is made to the relatively benign chemical environment expected to already exist in the repository.

3.2.2.2 Waste Package Materials Selection

The main concern with regard to materials to be used in the isolation of nuclear waste are the susceptibilities of the materials to environmental degradation. Also of a more practical concern are the workability, weldability, and cost of the materials to be used. Due to the latter point, the type of materials considered for use was narrowed to metals, and in particular, austenitic iron–nickel–chromium alloys.

The most obvious mode of degradation of metal alloys is the general corrosion of the materials in the hot, moist, oxygenated environment expected for the first 1,000 years of the repository. Preliminary data on the corrosion rates of three alloys are given in Table 3.2–5 [3–3]. As seen from this data, all the materials show excellent corrosion resistance with regard to general attack. If general corrosion is the only mode of degradation, all of the materials would satisfy the requirements for substantially complete containment.

The more insidious side of degradation of metals is the possibility of non–uniform modes of attack by the environment. The one of concern in austenitic alloys is stress corrosion cracking (SCC). The potentially aggressive environment created in the repository due to high temperatures, the presence of oxygen and chlorides, and possibly the radiation field may promote SCC. It was therefore necessary to choose a material that showed good resistance to this type of attack. Since no data were available in the expected repository environment evaluating SCC, proxy data given in Table 3.2–6 [8] were used to choose a material with relatively good resistance to cracking. From this data, along with discussions with Professor R. M. Latanison, it was decided upon to use Incoloy 825. The relative cracking resistance of this alloy as compared to the other alloy being considered, 304SS, is approximately five times better. The Inconel alloy in Table 3.2–6 does show better resistance to cracking than the Incoloy 825, but for almost double the cost, its use

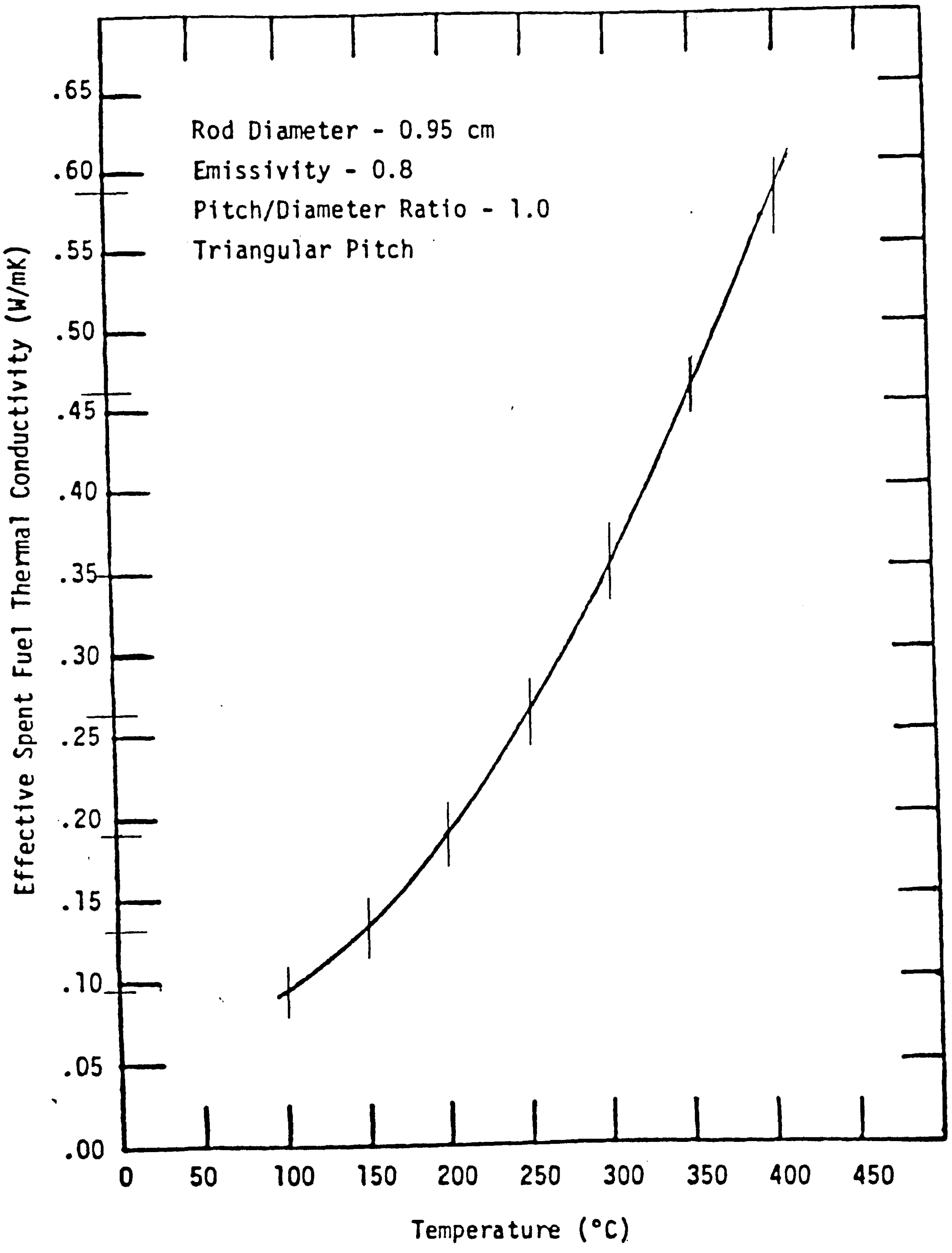


Figure 3.2-5 Effective Spent Fuel Thermal Conductivity

Fig. 3.2-6 Thermal Profiles for Horizontal Emplacement
57 kw/acre, 25 m Pitch, 2200 watts/canister

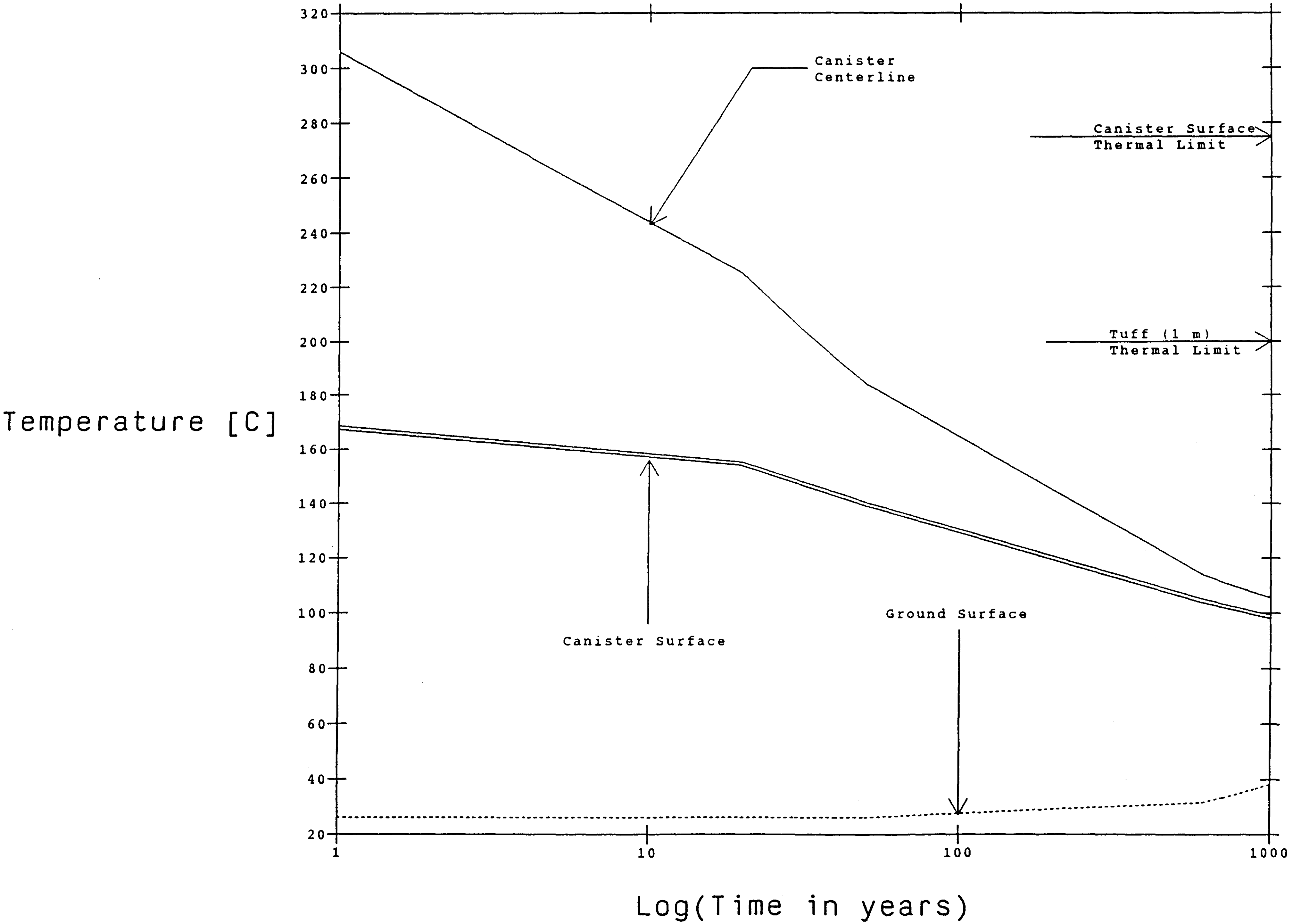


Table 3.2-5 Corrosion Rates of Canidate Waste Container Alloys

				Corrosion rate (μm/yr)[b]	
Alloy	Temp (°C)	Time (h)	Medium	Average	Standard deviation
304L	50	11,512	Water	0.133	0.018
316L	50	11,512	Water	0.154	0.008
825	50	11,512	Water	0.211	0.013
304L	80	11,056	Water	0.085	0.001
316L	80	11,056	Water	0.109	0.005
825	80	11,056	Water	0.109	0.012
304L	100	10,360	Water	0.072	0.023
316L	100	10,360	Water	0.037	0.011
825	100	10,360	Water	0.049	0.019
304L	100	10,456	Saturated steam	0.102	(c)
316L	100	10,456	Saturated steam	0.099	(c)
825	100	10,456	Saturated steam	0.030	(c)
304L	150	3,808	Unsaturated steam	0.071	(c)
316L	150	3,808	Unsaturated steam	0.064	(c)
825	150	3,808	Unsaturated steam	0.030	(c)

[a] Source: McCright et al. (1987).
[b] Average of three replicate specimens of each alloy in each condition.
[c] Not determined.

Table 3.2-6 Average Cracking Time for Commercial Fe-Ni-Cr Alloys Exposed to Boiling MgCl(2) at 154 C

Alloy Designation	Nickel Concentration (wt. %)	Average Time to Cracking (minutes)(2)
Type 304	9	587
Type 310	20	601
Incoloy 800	32	1,795
Incoloy 825	42	6,662
Inconel 718	53	10,153

(1)Specimens 0.38 mm diameter wires, vacuum annealed and rapidly cooled, stressed at 90% of 0.2% offset yield strength.

(2)Each value the average of ten specimens.

Table 3.2-7 Characteristics of Spent Fuel Assemblies

Characteristic	Pressurized water reactor	Boiling water reactor
MECHANICAL CHARACTERISTICS		
Overall length (in.)	149-186	84-179
Width (square assemblies) (in.)	8.1-8.5	4.3-6.5
Fuel rods per assembly	100-264	48-81
Fuel rod diameter (in.)	0.360-0.440	0.483-0.570
Fuel rod length (in.)	91.5-171	80.5-165
Rod pitch (in.)	0.496-0.580	0.640-0.842
MTU[b] per assembly	0.11-0.52	0.19-0.20
Assembly weight (lb)	1280-1450	600
TYPICAL CHARACTERISTICS AS RECEIVED		
FIVE-YEAR FUEL[c]		
Burnup (average conditions) MWd/MTU	33,000	27,500
Actinides and daughters (Ci/MTU)	104,000	93,000
Fission products (Ci/MTU)	453,000	365,000
Decay heat (W/MTU)	1,800	1,400
Photon release (photons/s/MTU)	1.3×10^{16}	1.0×10^{16}
Photon energy release (Mev/s/MTU)	4.8×10^{15}	3.6×10^{15}
Burnup (high condition) MWd/MTU	50,000	
Actinides and daughters	155,000	
Fission products (Ci/MTU)	640,000	
Decay heat (W/MTU)	2,800	
Photon release (photons/s/MTU)	1.9×10^{16}	
Photon energy release (Mev/s/MTU)	7.3×10^{15}	
TEN-YEAR FUEL[d]		
Burnup (average conditions) MWd/MTU	33,000	27,500
Actinides and daughters (Ci/MTU)	83,000	75,000
Fission products (Ci/MTU)	302,000	249,000
Decay heat (W/MTU)	1,100	900

did not seem justified. As this material is a "super" stainless steel, similar to utensil steels, the toxicity of the material with respect to the waste should be minuscule.

Incoloy is composed of ~40 percent Ni, 30 percent Fe, 21 percent Cr [3–8], with the balance being made up of minor constituents. A thickness of 1.5 cm was chosen to provide some measure of structural support for the package without being prohibitively expensive. The canister is cast in two pieces (basically a cylindrical pressure vessel and a cap) that are subsequently machined to the specified geometric tolerances. The surface facility fills the canister with the holding racks and spent fuel, and welds it shut.

3.2.2.3 Waste Package Thermal Environment and Geometric Layout

This section examines what turns out to be the most influential aspect of the repository design. Originally, efforts were made to increase the areal thermal loading and thereby increase the capacity of the repository without increasing the amount of mining that would need to be performed. As is shown below, this approach was stymied by the fact that the criteria with regard to the surface temperature rise could not be met when larger areal loads were evaluated.

It was decided arbitrarily that each borehole would have seven waste packages and a five–meter plug. The boreholes would be staggered to prevent drilling from intersecting of the boreholes from adjacent emplacement drifts. The pitch (distance between holes) was the parameter that was varied to provide an areal loading of 57 kw/acre (the specified maximum in the DOE criteria). The age of the waste was assumed to be ten years, and the wattage limit per canister was placed at 2.2 kw. The 2.2 kw/canister figure was arrived at from data given in Table 3.2–7, assuming 33,000 MWD/MT PWR and 28,000 MWD/MT BWR. Although higher burnup fuel will be a part of the inventory later in the repository life, the age of this fuel is projected to be much older than the ten years allowed for the design basis and therefore should still meet the 2.2 kw/canister limit.

The areal loading was calculated using a unit cell, given in Fig. 3.2–4, and the pitch was varied to obtain the required loading. The equation for the pitch is written as:

$$\text{Pitch [m]} = \frac{(\#\text{cans}) * \left[\frac{\text{kw}}{\text{can}}\right] * \left[\frac{4047\ \text{m}^2}{\text{acre}}\right]}{\left[\frac{\text{kw}}{\text{acre}}\right] * \frac{[2 * [(\#\text{cans}) * (\text{can length}) + (\text{plug length})] + (\text{drift dia.})]}{2}}$$

The number of cans is seven, the length of each in the borehole is 5m, each canister has a heat load of 2.2 kw, the drift diameter is 8 meters, and the thermal loading is 57 kw/acre. Substitution of these values into the equation above gives a pitch of approximately 25 meters.

The thermal design criteria given in Section 3.2.1.1 were evaluated using approximate analytical techniques to show compliance. The repository is to be located 250 to 300 meters below the surface, as specified in Section 3.3. To evaluate the temperature rise at the ground surface, a semi–infinite media approximation was used with a time–dependent heat flux applied at the repository boundary. This approach allows the temperature at the surface to vary, unconstrained by a hard–to–define boundary condition. The following equation is the mathematical representation of this assumption:

$$T_{surf} = T_{amb} + \int_0^t f(t-\tau) * \exp\left[\frac{-x^2}{4\alpha\tau}\right] * \left[\frac{1}{\tau^{1/2}}\right] d\tau$$

Where $f(t-\tau)$ is the heat flux at the top of the repository, assumed to be 5 meters above the horizontal plane of the emplaced canisters. It was assumed that the heat would diffuse both up and down in equal amounts, there $f(t-\tau)$ is half the areal heat loading. The time dependence of the flux is given in Fig. 3.2–1. The spatial parameter, x, is the distance above the repository, taken to be 300 m. The ambient temperature is 26 °C, from Section 3.3. The thermal diffusivity, α, was calculated from the equation:

$$\alpha = \frac{k}{\rho C_p}$$

The numerator and denominator are given in Table 3.2–4.

The above temperature calculation also provided the boundary conditions for determining the local thermal environment as a function of time, i.e., the equation was solved using a small value for x to give a temperature at the top of the repository as a function of time. The local temperature in the tuff rock was determined from the following equation [3–10]:

$$T(r,t) = T(r{=}5m,t) + \frac{Q(t)}{2\pi H e k_{tuff}} * \ln \left[\frac{r}{r_{can}}\right]$$

Where Q(t) is the volumetric heat generation rate, H is the length of the canister, and the radii r, r_{can} represents the selected distance (less than 200 °C at 1m is the criteria evaluated) into the tuff, and the canister outside the radius.

The final criteria is the canister centerline temperature, or the peak fuel temperature. The actual calculation of the heat transfer that occurs with fuel elements in air (or any gas) was assumed to occur only through radiative processes. A correlation developed by Cox [3–11] was interpreted [3–12] in Fig. 3.2.5 and an effective thermal conductivity (k_{fuel}) was selected to be 0.4 w/m/°K. This interpretation allows the following simple expression to be coupled to the above analyses to give a time–dependent centerline temperature:

$$T(\text{℄}, t) = T_{surf}(t) + \frac{Q(t)}{4H\ k_{fuel}}$$

3.2.2.4 Waste Package Radiologic Considerations

As a consideration for the entire repository design, calculations were performed to evaluate dose rates at the exterior of the waste packages and to propose appropriate thicknesses of material to give adequate shielding. The data given in Table 3.2.3 were used with the geometry of the waste package proposed above. These data were input to the computer code ISOSHLD [3–13] that was used to arrive at the canister surface dose rates. ISOSHLD is a point–kernel shielding analysis code that has previously been used for similar applications [3–10].

The technique for approximating the attenuation of radiation in spent fuel region of the waste package is called smearing. This simply involves homogenizing the entire spent fuel region with the appropriate materials. The homogenized densities used in this analysis are given in Table 3.2–8.

Table 3.2–8. Homogenized Materials Densities for Unconsolidated Spent Fuel

Material	Homogenized Density (g/cc)
U	1.65
O (from UO_2)	0.44
Zr	0.36

The dose rate thus calculated was ~ 1 x 10^4 Rad/hour. The neutron component of the dose rate is negligible in terms of the performance of the EBS.

In addition to the surface dose rate, a calculation was made to determine the necessary thickness of the walls of the surface holding facility to reduce the exterior dose rate to less than 5 mRem/hr. The assumptions were made that the canisters would be lined up along a wall of the facility producing a nearly uniform dose rate of 1 x 10^4 Rem/hour on the interior wall surface. To attenuate this through heavy concrete (density 4.0 g/cc [3–14]), the following equation was used:

$$\text{Thickness, } x[\text{cm}] - -\rho \left[\frac{\mu}{\rho}\right]_{\text{concrete}} \ln \left[\frac{4 \times 10^{-3}}{10^{4} \text{ rem/hr} * B(\mu x)}\right]$$

Where $(\mu/\rho)_{\text{concrete}}$ is the mass attenuation coefficient for heavy concrete (= 0.064 cm^2/g for 1 MeV photons), and $B(\mu x)$ is the buildup factor for heavy concrete. The above equation was solved iteratively for x, using appropriate buildup factors from Profio [3–14] to obtain a wall thickness of 73 cm ($B(\mu x) = 45$). Shield provided by the transport cask during transit from the surface facility to the emplacement hole was calculated similarly in Section 3.4.

3.2.2.5 Allowable Pressure Loadings

Given the thickness of Incoloy 825 given in Section 3.2.2.2 of 1.5 cm, it was necessary to determine the allowable loadings that the waste packages may be subjected to in the repository environment. This determination was made using the procedures, tables and equations in Article NB–3000 of the ASME Boiler and Pressure Vessel Code [3–4]. The two stresses of interest are external pressure loadings and axial compression loadings at the design temperatures. The maximum service pressure loading is 208 psi. The maximum axial loading is 8000 psi. The comparatively low values given here indicate that a more extensive stress analysis that takes credit for stiffening provided by the internal structure may be necessary if the packages are found to have to bear large loadings.

3.2.3 Estimated Costs

The EBS is the one element of the design for which there is no substantial experience with the engineering techniques being employed. Since there have been no instances of nuclear waste being isolated for periods of 1,000 to 10,000 years, all the assurances of containment must come from extensive research and experimentation. The cost and timing of the results of this research are highly speculative, but an initial estimate of approximately $50 million per year starting in 1988 and ending in 2005 seems reasonable.

The only hard cost of the engineered barrier system is the cost of the packages themselves. The choice of Alloy 825 comes at a fairly high price. Nominally priced at $22/kg [3–15], the designed canister requires 1290 kg, making the cost of the individual canister in 1988 dollars ~$28,000. At 1,900 canisters per year, the annual outlay is $54 million.

3.3 Geologic Repository

This section of the document outlines and describes both the criteria governing and the design description of that portion of the underground system that is directly related to the specific geologic environment at the proposed repository. More specifically, all of the underground design not directly related to either the engineering barrier system (here defined as that portion of the design confined to the borehole, e.g. the container and any overpack or liner) or operations is covered by this section. First, the boundary conditions of the design are enumerated; followed by a detailed design description. Finally, the estimated costs for this portion of the repository design are evaluated.

3.3.1 Criteria and Constraints

The boundary conditions (as used in the context of this section) are those conditions of fact existing either by decree, by nature, or assumed, that effect or control the design of the geologic repository. That is, these conditions form the design basis. As with any safety oriented system, regulatory bodies have seen fit to specify many specific (and not so specific) technical criteria. However, few of these criteria need to be addressed due to the required adoption of the site chosen by the DOE: Yucca Mountain, Nevada, Topopah Spring Member (TSw2). This is not to say that these conditions were not evaluated, but that several criteria present themselves in the form of site constraints and are no longer considered boundary conditions by decree. The imposed constraints of the site shall be explained. Finally, in what is certainly the most significant (sensitive) section of boundary conditions, the design assumptions will be addressed. The DOE will undoubtedly spend billions of dollars in an attempt to "prove" that the nation's high level waste repository is safe. Even their design will contain countless assumptions (though hopefully less sweeping that those taken here). This is not meant as an excuse, but rather a statement of fact. Several broad design assumptions were used as guides and are supported only by simple arguments.

3.3.1.1 Technical Criteria

When the scope of this project was defined, the conclusion was reached that the existing technical criteria should be viewed from the perspective of a third party government interest who desired to develop the Yucca Mountain site into a radioactive waste repository. Therefore, the specific technical criteria that must be addressed by law are only those promulgated by a regulatory body such as the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Environmental Protection Agency (EPA), or by Congress. Quite often, however, these technical criteria are vague and generally ill–defined. To alleviate this problem, the Department of Energy (DOE) has issued design guidelines that take into account the affected technical criteria and can be used by a repository designer.

Before the specific guidelines effecting this design are enumerated, the project assumptions concerning site geology must be addressed. The NRC has promulgated two sets of technical criteria that affect the geologic repository: 10 CFR 960, General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories; and 10 CFR 60, Disposal of High–Level Radioactive Wastes in Geologic Repositories. The vast majority of geologic criteria are contained in the first document (10 CFR 960). However, as mentioned above, since the Yucca Mountain site was chosen for this design and due to the fact that knowledge from a site characterization phase is not available, it was assumed that the site will be recommended and surpass all the criteria established in 10 CFR 960.

The other, more significant, NRC document, 10 CFR 60, states several criteria that are used in the licensing process. These design criteria have been summarized into three functions that the geologic system must perform [3–3]:

1) "Provide orientation, geometry, layout, and depth of the underground facility such that the facility contributes to containment and isolation taking into

account flexibility to accommodate site–specific conditions (10 CFR 60.133(a)(1) and 10 CFR 60.133(b)).

2) Limit water usage and potential chemical effects, thereby contribution to containment and isolation of radionuclides and assisting engineered barriers in meeting performance objectives (10 CFR 60.133(a)(1) and 10 CFR 60.133(h)).

3) Limit potential for excavation–induced changes in rock mass permeability (10 CFR 60.133(f))."

The specific design guidelines are:

1) "Ensure the usable area for the repository will have greater than 200 meter overburden, be within the TSw2 portion of the Topopah Spring Member, be more than 70 meters above the water table, and be in the primary area.

2) Design accesses, drifts, and boreholes so that drainage is away from containers.

3) Limit quantity of cement, shotcrete, and grout used in borehole and drift construction.

4) Limit quantity of organics introduced during underground construction.

5) Limit underground water usage during underground development to that required for dust control and proper equipment function; remove all excess water.

6) Limit repository extraction ratio to less than 10 percent and limit drift spans to less than 10 meters.

7) Limit potential for subsidence by backfilling underground openings during decommisioning."[3–3]

Since the pitch can be easily altered thereby altering the thermal loading, the geologic system design does not take into account thermal consideration. The thermal criteria were studied and evaluated as part of the Engineered Barrier System design, (3.2.2.3), which in turn defines the pitch in the repository.

Guideline number 7 suggests that backfilling occur during decommissioning to limit the potential for subsidence. No need exists to keep emplacement room open until decommissioning. [For further discussion see Section 3.3.1.3.] Backfilling of emplacement rooms will occur shortly after the rooms are filled, thereby limiting the potential for subsidence.

3.3.1.2 Site Constraints

Unlike other portions of the system design, the geologic repository design is driven primarily by the conditions of the site. The layout and construction sequence as well as all construction methods are all driven by the geology. Furthermore, geologic factors control maximum areal extent, areal heat loading, and ultimate repository size. Based upon experience at G–Tunnel, a repository in the Topopah Springs Member will require only routine mining procedures. Though no excavations have been undertaken at Yucca Mountain, much experience has been gained at the G–tunnel on the Nevada Test Site at Rainier Mesa (~40 kilometers to the northeast). The G–tunnel has been excavated in the welded Grouse Canyon Member (similar characteristics to Topopah Springs Member) and has similar overburden loading, opening dimensions and excavation methods.[3–16] No additional support has been required above the predicted rock bolting and thin shotcrete at G–Tunnel. Thus, experience suggests that Yucca Mountain may be a good location for the construction of a geologic repository, but to better understand the design a brief review of the site geology is required.

3.3.1.2.1 Site Geology

Yucca Mountain is within the Basin and Range physiographic province: a broad region covering much of the desert southwest and characterized by regional high angle normal block faulting. The Yucca Mountain site is a group of north–trending, fault–block ridges that extend southward from Beatty Wash on the northwest to U.S. 95 in the Amargosa Desert (Figure 3.3–1, 3.3–2). Stratigraphically, four major rock groups exists at

Figure 3.3-1 Location of Yucca Mountain Site in Southern Nevada.

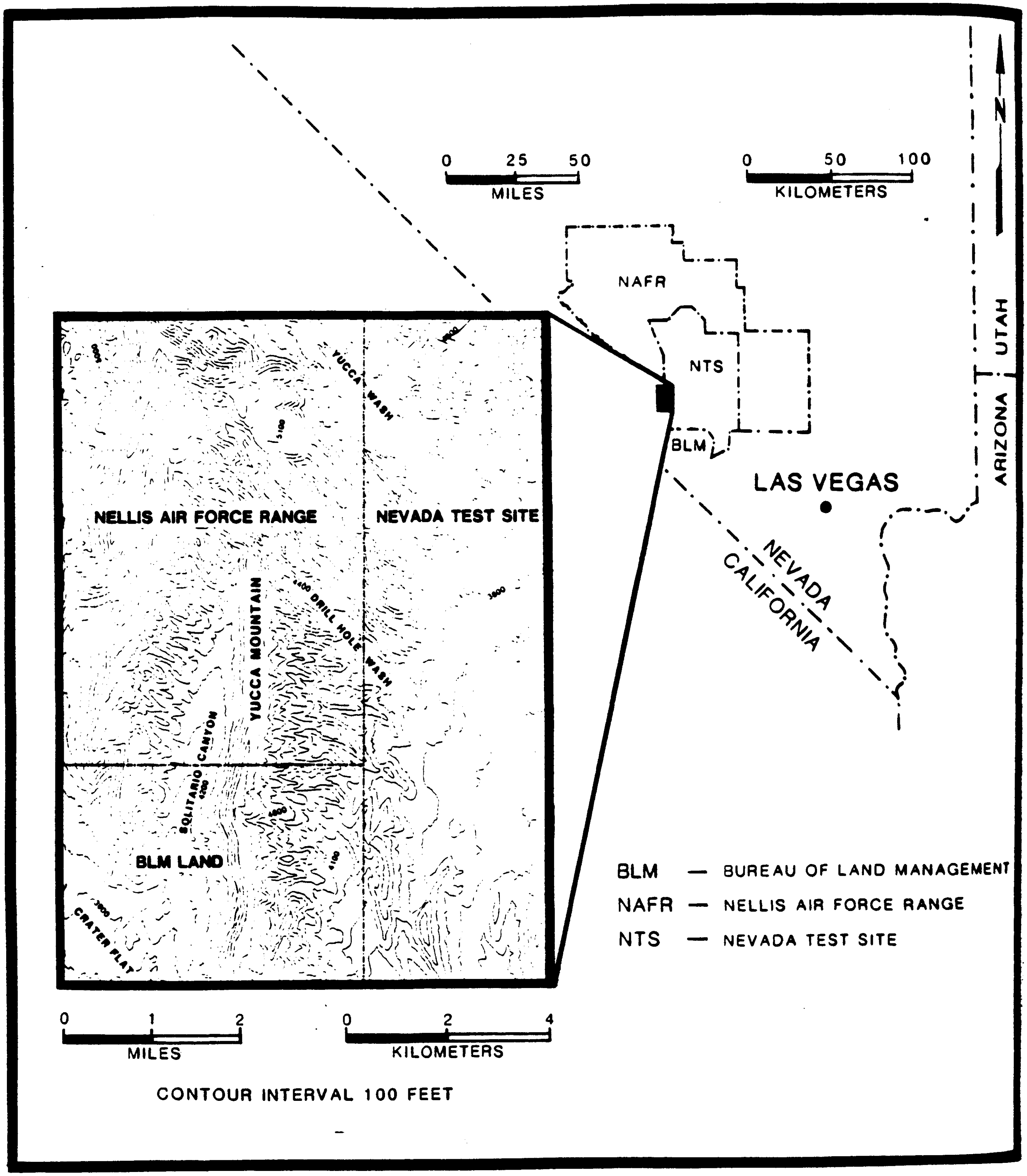
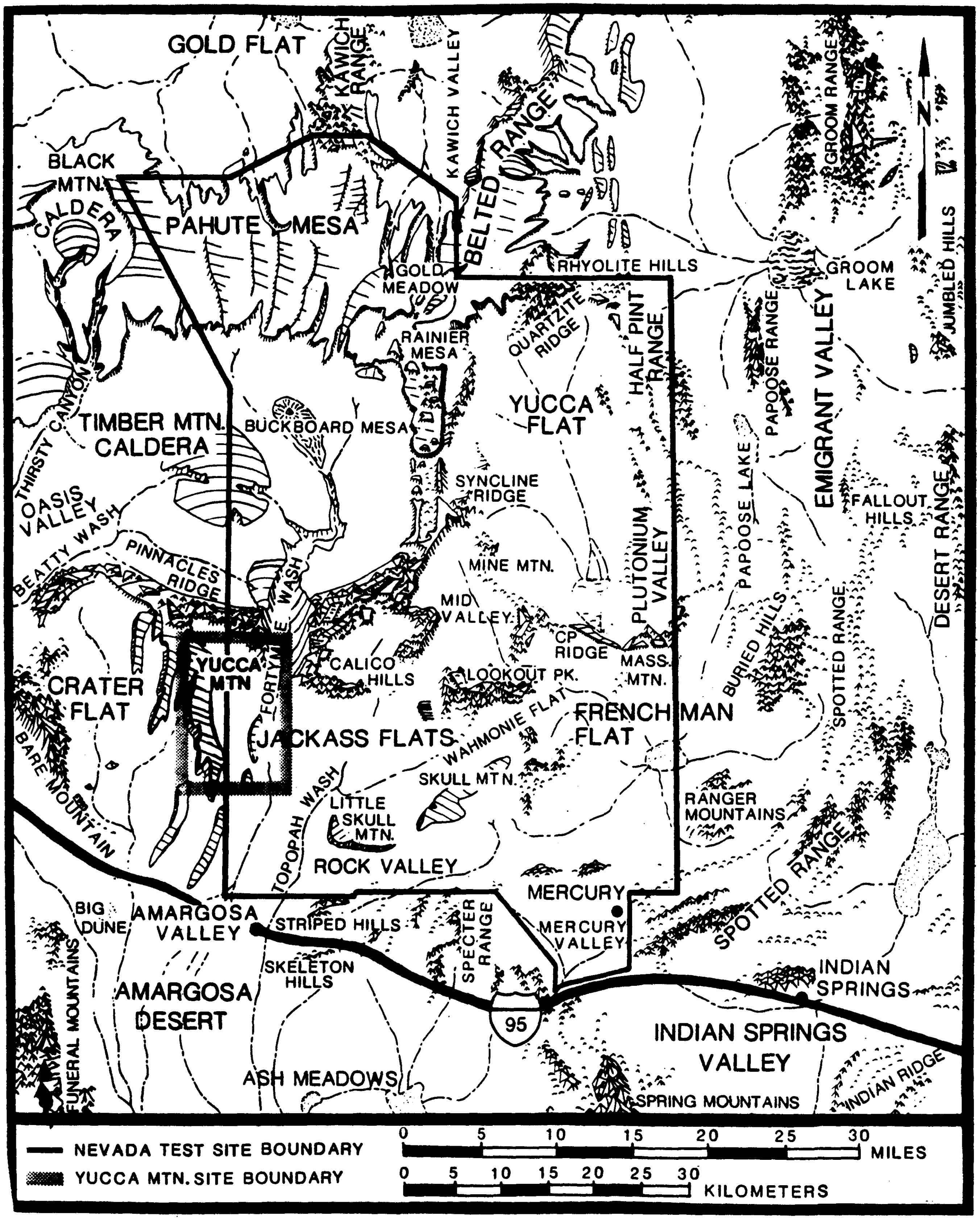


Figure 3.3-2 Physiographic Features of Yucca Mountain.



the site. Precambrian crystalline rocks form the basement but are unexposed in the vicinity. Upper Precambrian and Paleozoic sedimentary rocks (primarily carbonates) are observed 15 kilometers to the east at Calico Hills. The Tertiary volcanics, generated by the mid–Tertiary Ignimbrite Flare–Up, compose at least the upper 2,000 meters and are the group being investigated. They are chiefly rhyolitic ash–flow tuffs, with smaller amounts of dacitic lava flows and flow breccias and minor amounts of tuffaceous sedimentary rocks and air–fall tuffs. Quaternary and upper Tertiary alluvium and unsorted debris flows form the top layer which is up to 200 meters thick in places. Figure 3.3–3 shows the volcanic stratigraphy at Yucca Mountain.[3–3]

The Topopah Spring Member of the Paintbrush Tuff is the horizon for the repository. It is composed of four separate ash–flow sheets and varies in composition from low–silica rhyolite near the top to high–silica rhyolite near the base. Though 350 meters thick at Yucca Mountain, it thins considerably to the south and is altogether absent at the southwestern border of the Nevada Test Site. The ash–flow sheets form four separate zones, see Figure 3.3–4. The second from the top zone, a densely welded devitrified tuff, is considered as the host rock. In particular, the lower portion of the second zone, that has less abundant lithophysae (a hollow, globular mass of crystals having a radial arrangement) and is less densely welded, is the most promising section. The densely welded portions of the tuff are more intensely fractured than the other portions of the Paintbrush Tuff. Fractures in the unit, however, appear to be well healed. Very little fracture surface alteration is present due to the lack of fluid flow. Experience at G–Tunnel shows no problems with fractures or shear zones. Throughout the lateral extent of the proposed repository area geophysical methods have shown no data to suggest that a major shear zone exists.[3–16]

Juxtaposed beneath the Topopah Spring Member is the Rhyolite of Calico Hills. The significance of this unit is its position and composition. Commonly referred to as the

Figure 3.3-3 North-South Stratigraphic Correlation Between Selected Drillholes at Yucca Mountain.

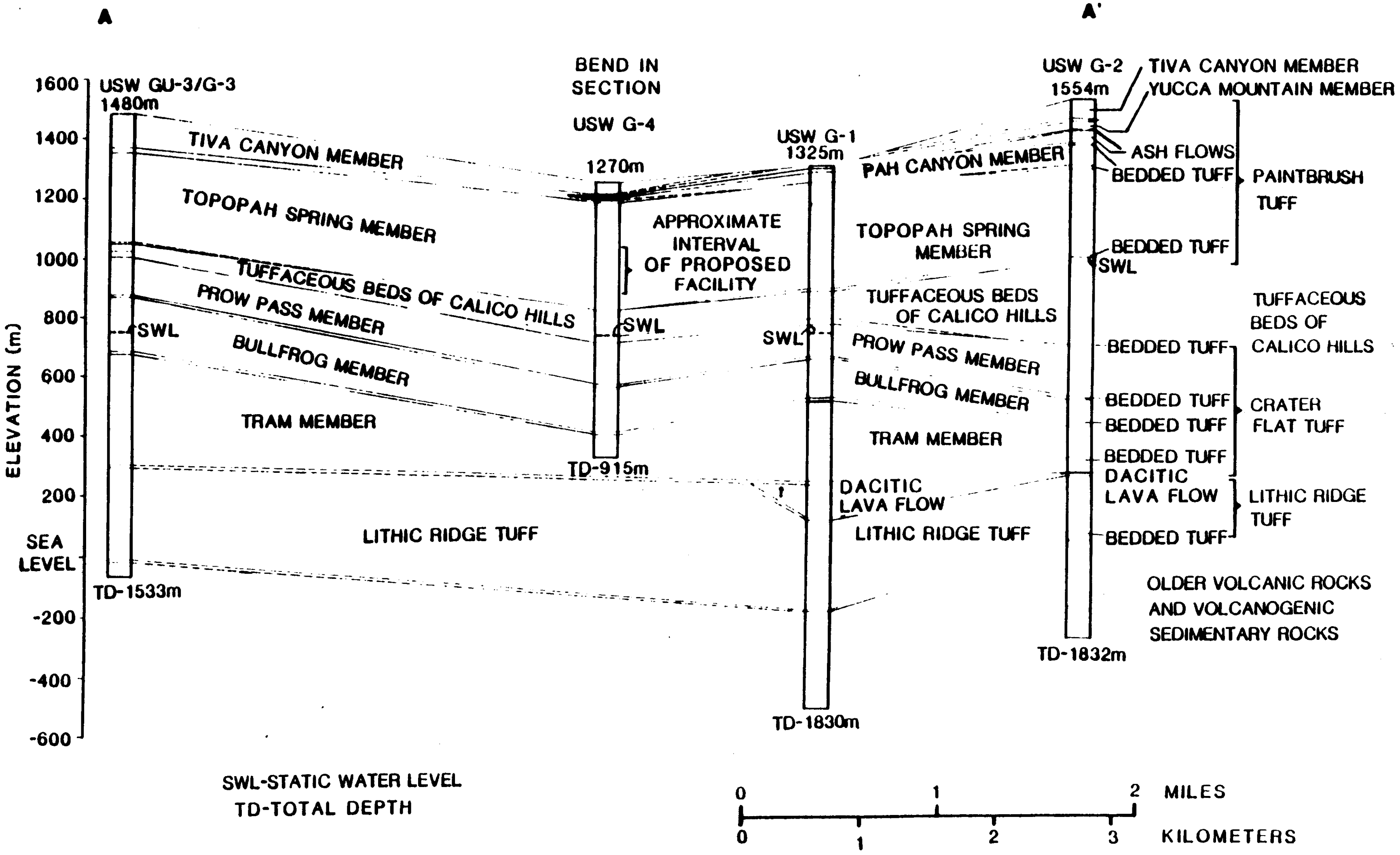


Figure 3.3-3 b Index Map for Selected Drillholes

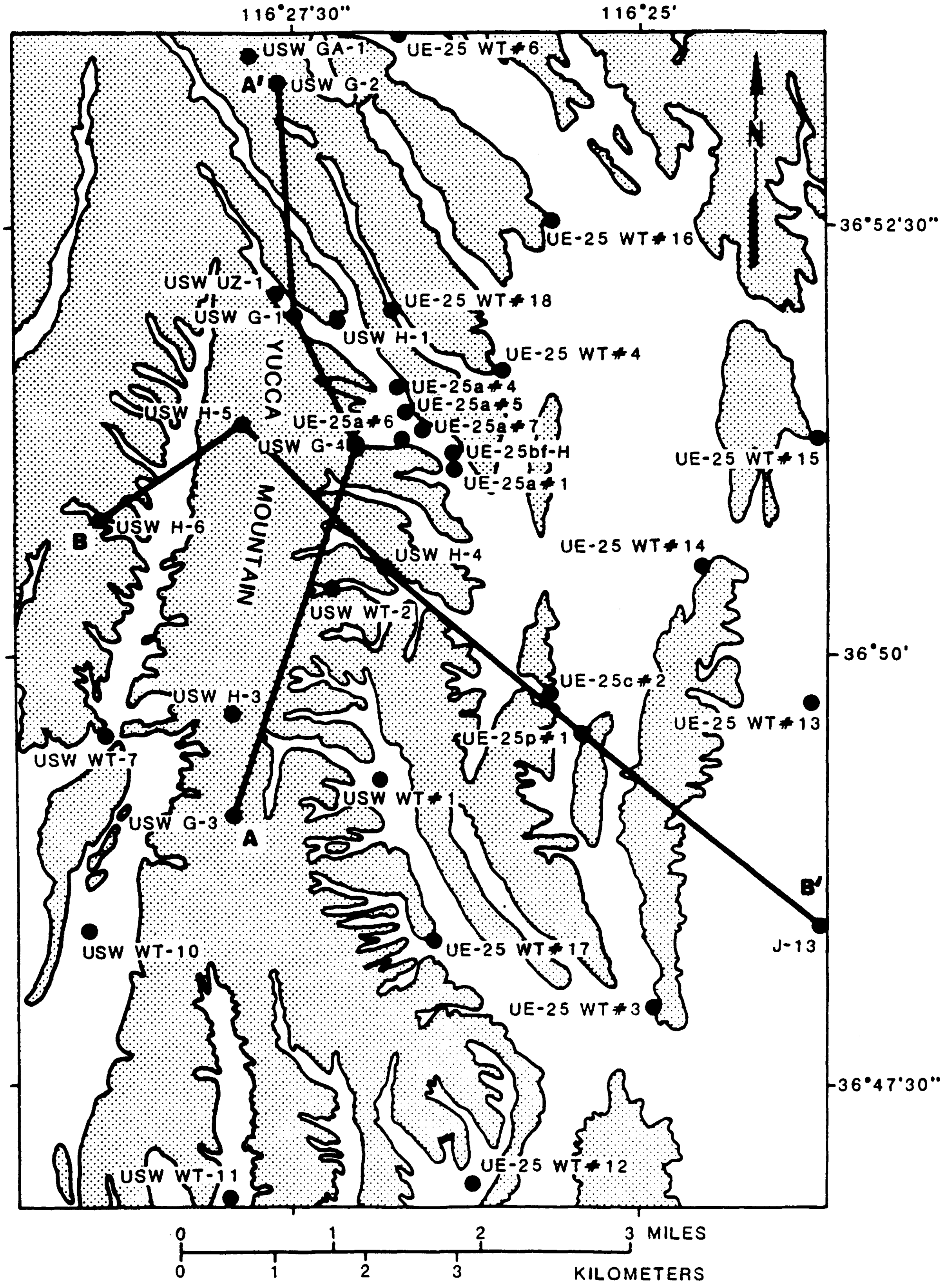
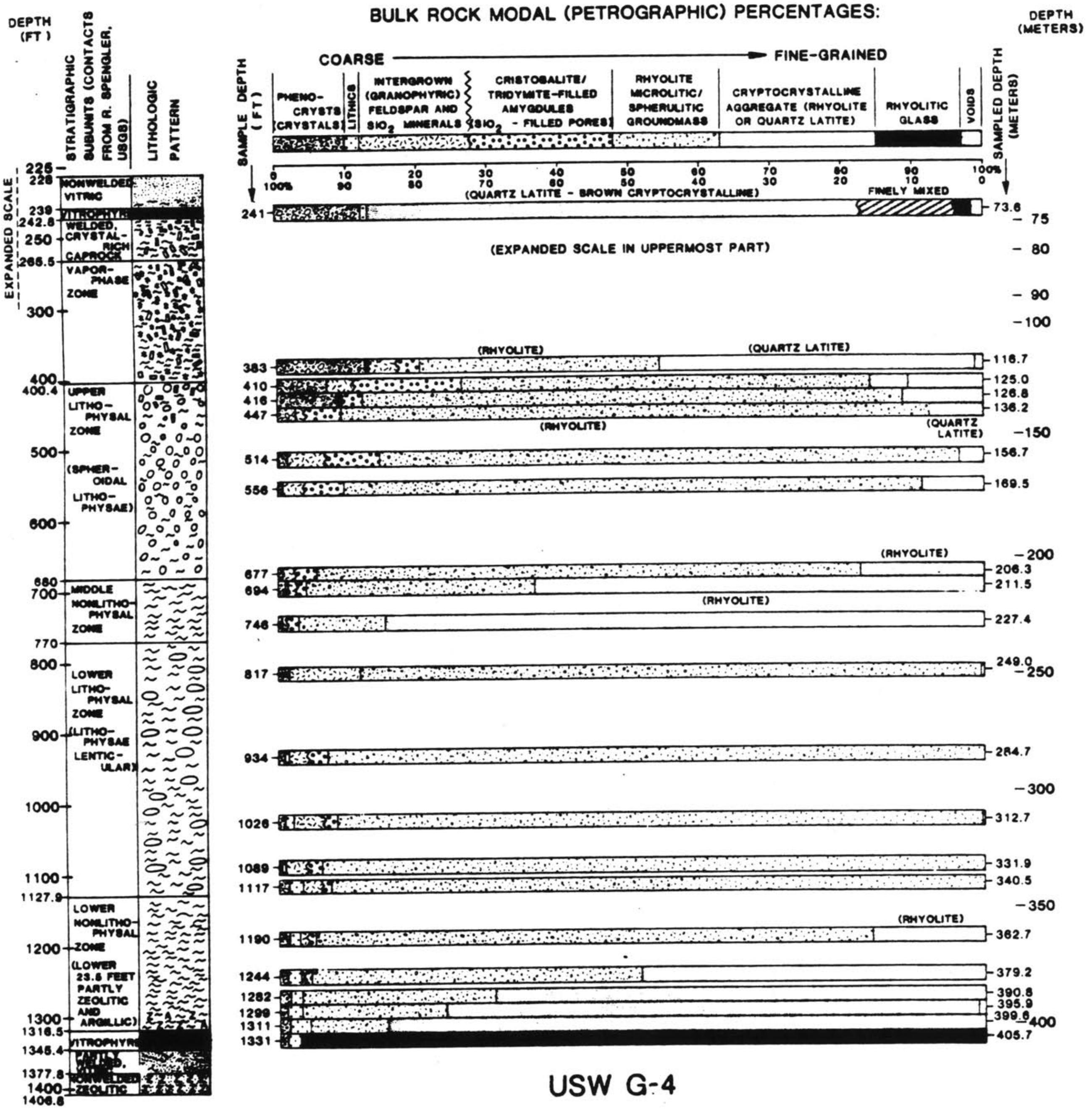


Figure 3.3-4 Petrographic Textural Percentages: Topopah Springs Member.



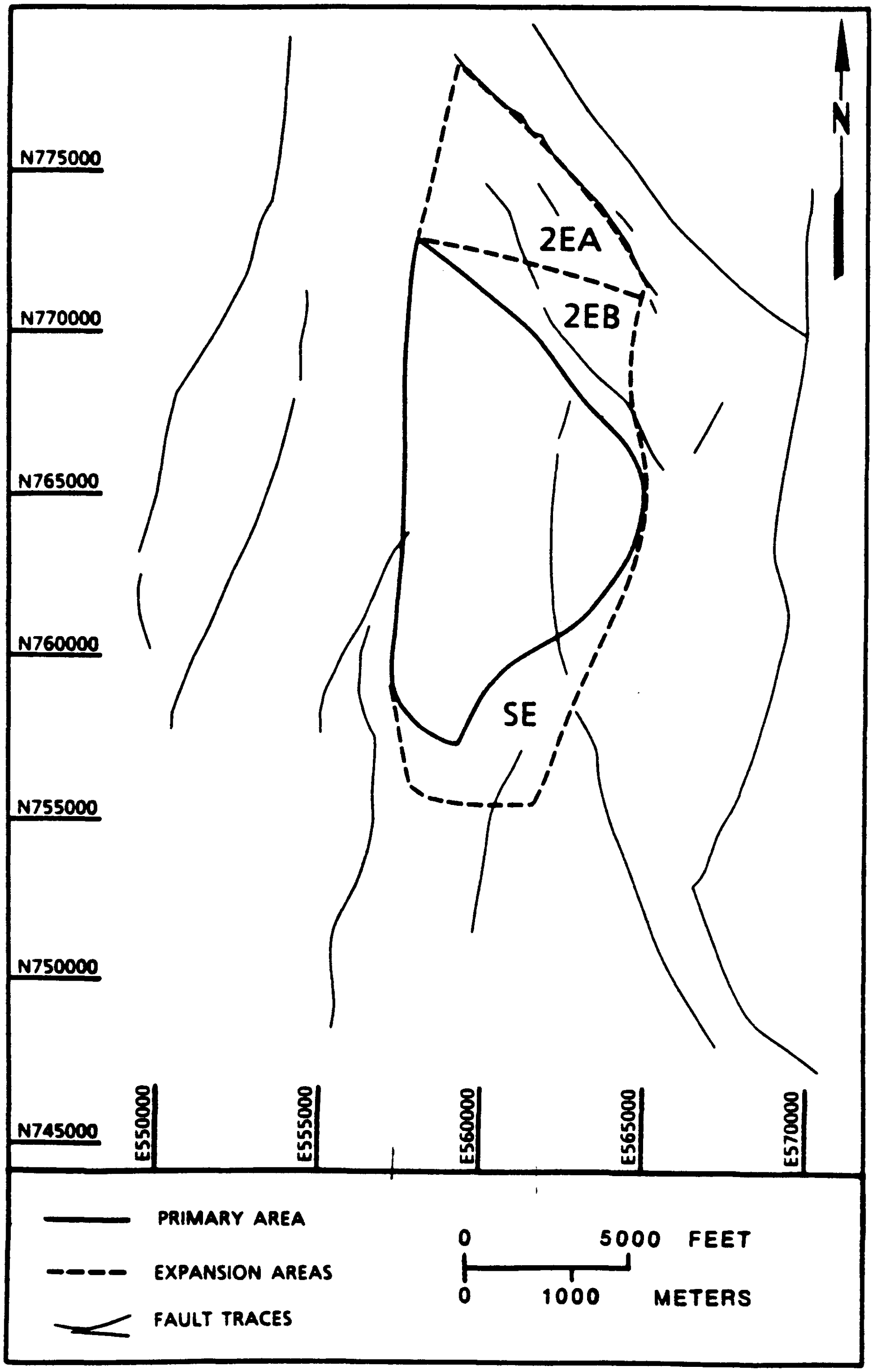
tuffaceous beds of Calico Hills, this rock unit is composed of up to 80 percent volume of zeolites.[3–3] This family of minerals has good ion exchange characteristics and has a very low permeability. The Calico Hills unit forms a natural lower boundary seal between the repository horizon and the carbonate conate aquifers below. These carbonate aquifers are not well understood. Though, borehole piezometric data suggests that they have higher heads than the Paintbrush Tuff, water ingress is not probable. These units lie greater then 2000 meters below the repository.[3–3]

3.3.1.2.2 Site Specific Geologic Imposed Constraints

The site at Yucca Mountain and the thermal/mechanical unit in which the repository is to be located were chosen by the DOE after an extensive siting process. Though the site may be the best available in the U.S., it still presents several constraints on the design. As mentioned above, the repository is to be located in the non–lithophysal, welded portion of the Topopah Springs Member of the Paintbrush Tuff (designated TSw2). At Yucca Mountain, this unit varies in thickness from approximately 40 to 70 m, and slopes to the northeast 1–3 degrees.[3–3] The prospective repository envelope is bounded at depth on the west and north by major faults and on the south and east by increasing non–uniformity and more extensive fracture characteristics. The assumed repository area was derived from the "revised usable portion of the primary area and expansion areas" as developed by DOE.[3–3] This region, depicted in Figure 3.3–5, is approximately 1200 hectares (3000 acres).

The TSw2 unit poses few limitations on the design. The unit is highly fractured but moderately uniform with considerable fracture healing. Little fracture alteration has occured due to lack of water inflow. The unconfined compressive strength varies from 100 to 220 MPa with 166 MPa the average value. These characteristics allow for mechanized excavation.[3–16]

Figure 3.3-5 Usable Portion of the Primary area and Expansion areas.



The *in situ* stress regime poses no significant hazard. At the rather moderate depth of 200–300 meters, the projected vertical stress is not greater than 10 MPa. The ratio of minimum horizontal stress to vertical stress is estimated to be 0.55; the bearing to minimum horizontal stress is approximately N 60 W. For directions nearly perpendicular, the stress field is estimated to be approximately isotropic.[3–3]

Certainly, the most unique feature of TSw2 and the Yucca mountain site itself is the position of the water table and the hydrologic characteristics of the site. The water table lies between the Prow Pass and the Bullfrog Members of the Crater Flat Tuff at a depth of 700–800 meters. At no point will the repository be less than 200 meters above the water table. Within the repository, the unit is estimated to be 65% saturated. The mean in situ temperature is 26 C.[3–3]

3.3.1.3 Design Assumptions

Several design assumptions were required to bring the scope of this project into line with the resources available. Assumptions were made such that the more complex criteria are replacable with easily quantified criteria. The following design assumptions were used for the geologic repository design:

1) The required minimum groundwater travel times will be met.
2) The regional meteorology will not substantially change.
3) The repository is not disturbed by man.
4) No major tectonic event will substantially alter the relationship between the water table and the repository.
5) No specific measures need be taken to ensure that the option of retrieval is preserved.
6) In general, the optimal long–time performance is achieved through "passive" safety; i.e. given assumption number 1, the disturbance to the geologic media must be kept to a minimum.

These assumptions arise primarily for two reasons. First, certain events or scenarios with very low probabilities of occurrence are capable of disrupting any conceivable barrier provided by the geologic environment system. It must be assumed that these events will not occur. Second, several factors affecting repository performance are beyond the scope of this study.

As stated in the technical criteria section, the primary objective criteria for determining suitability of this site for the underground disposal of nuclear wastes is groundwater travel times. This is due to the assumption that the primary form of long–term hazard is through ingestion of contaminated ground water. Since evaluation of ground water travel times is beyond the scope of this study, assumption 1 must exist. Assumption 2 is implicit in assumption 1. Though the regional meteorology will undoubtedly change during the next 10,000 years, the exact nature of those changes is not predictable. But, with no method to predict long–term alterations in climatic patterns, the past is the best guide to the future.

As with possible unpredictable variations in the hydrologic regime, assumptions 3 and 4 are help for the mechanical regime. It is clearly impossible to design a facility that could withstand conceivable damage that future man or major tectonic activity could impart. Though neither disruption by man nor major tectonic activity can be dismissed as impossible, no evidence exists that would suggest tectonic activity, on the scale necessary to disrupt waste isolation, in the next 10,000 years, and it is assumed that a man (future mankind) that is capable of disrupting the waste is also knowledgeable about its dangers.

The NRC, through 10 CFR 60, is quite clear on the matter of waste retrieval: the repository "...shall be designed to preserve the option of waste retrieval...".[3–1] So long as the option of waste retrieval is preserved, any emplacement design is satisfied with respect to this section. The NRC acknowledges that the preservation of the option need not drive design. In 10 CFR 60.111 (b) 2: "This requirement shall not preclude decisions by the Commission to allow backfilling part or all of [the repository]". The TSw2 unit is not expected to undergo creep and will not substantially change form during the retrieval period. Consequently, it was assumed that the option to retrieve the wastes is preserved regardless of the underground operations and design.

Assumption 6 is the most sweeping underground design assumption. Due to the long–time requirement of materials for waste isolation, most modern materials cannot be shown to provide adequate assurance of integrity. Furthermore, for nearly every proposed isolation enhancement feature a scenario in which the feature assisted failure could be postulated. As the design proceeded, it became clear that the maximum assurance of waste isolation was founded on proved stability: the geologic environment at Yucca Mountain. Thus, throughout the design every measure was taken to ensure that the natural environment is altered as little as possible with respect to mechanical, hydrological, and geochemical criteria.

3.3.2 Design Description

The underground repository system is ostensibly a complex mining project, albeit with much larger safety margins. The goal of a nuclear waste repository is, however, much different. This project requires that the waste is placed in a secure environment with the highest degree of safety possible. Not only must the waste be secure, but the repository operations must be very secure. Unlike the typical hard–rock or coal mine, the NRC and the public will be extraordinarily concerned about any events. In this sense, the repository is very similar to nuclear power plants. This design uses some of the lessons learned from the nuclear power industry in that it concentrates an the inherent qualities of the site. Experience at G–tunnel on the Nevada Test site shows that the Topopah Spring Member at Yucca Mountain has very good characteristics not only from the standpoint of waste isolation, but also from ease and simplicity of mining. Thus, the design relies on the outstanding properties that exist such that the reliance on man–made structures is kept to a minimum. To the degree possible, the site is not altered. This is what is meant by "passive" safety, and it is emphasized in this design.

3.3.2.1 Design Methodology

Two overall goals were stated for this project: 1) to have appropriate waste isolation and 2) to minimize the cost. It must be noted that the achievement of goal #1 dictates all design before goal #2 can be realized. Since the scope of this project was restricted such that a complex set of cost–benefit studies could not be done with the underground design, it was felt that a different approach to design optimization was necessary. Specifically, under the assumptions stated in the design, the site geology will provide the required isolation. This "amount" of isolation provides the necessary margin of safety. Since disruption to the environment is, in general, detrimental to the environment's isolation capacity and long–term performance of materials can not be guaranteed, engineered additions to the environment will not enhance isolation. Furthermore, any engineered system must increase repository costs. Thus, no engineered barrier systems are employed, except repository seals and waste packages.

3.3.2.2 Detailed Subsurface Design

The underground design makes extensive use of mechanical construction techniques and conveyor operations for tuff removal. This mining technique is favored because fracture extension can be controlled and little blast wave propagation induced block loosing is generated. Furthermore, since most of the repository is 200 meters above the water table, concentration of pore water pressure is not a problem. All ramps, corridors, emplacement drifts, and ventilation drifts are mined by full–face tunnel boring machines (TBM). Based upon advance rates in rock of similar strength, the expected advance rate is 50 m/day. Average machine utilization during advance is 30–40%.[3–17] Since current TBM's have never been designed for disassembly in their own tunnel, no TBM is currently available that best fits the requirements of the repository. Recent work suggests, however, that downhole dismantling and movement is possible even with currently designed machines.[3–18] If downhole disassembly is designed into the TBM's they should require shorter relocation periods.

The *in situ* stresses are favorable to simple tunnel support designs. The maximum depth of the repository is less than 400 meters and the ratio of horizontal to vertical stress varies from 0.55 to 1.0; bearing to minimum horizontal stress is N 32 E. This stress regime dictates that tall elliptical or ovaloidal tunnels are, in general, most stable. [Note that an elliptical or ovaloidal tunnel with vertical axis/horizontal axis length ratio equal to the ratio of vertical to horizontal stresses has minimum boundary stress.][3–19] This tunnel shape is more difficult to mine and does not lend itself to the large (7 meter) horizontal axis required for waste emplacement. The circular cross–section tunnels provided by the TBM's require only minimal support consisting of rock bolts with welded wire mesh. Localized shotcrete and grouted dowels may be necessary, but their use is restricted so as to minimize chemistry differences. The lack of water flow coupled with the low stress conditions provide for low maintenance underground caverns. The rock bolt–wire mesh support system is inherently a low maintenance system. Localized minor spalling may occur near corners and on walls because of stress relief or intersection of joints.

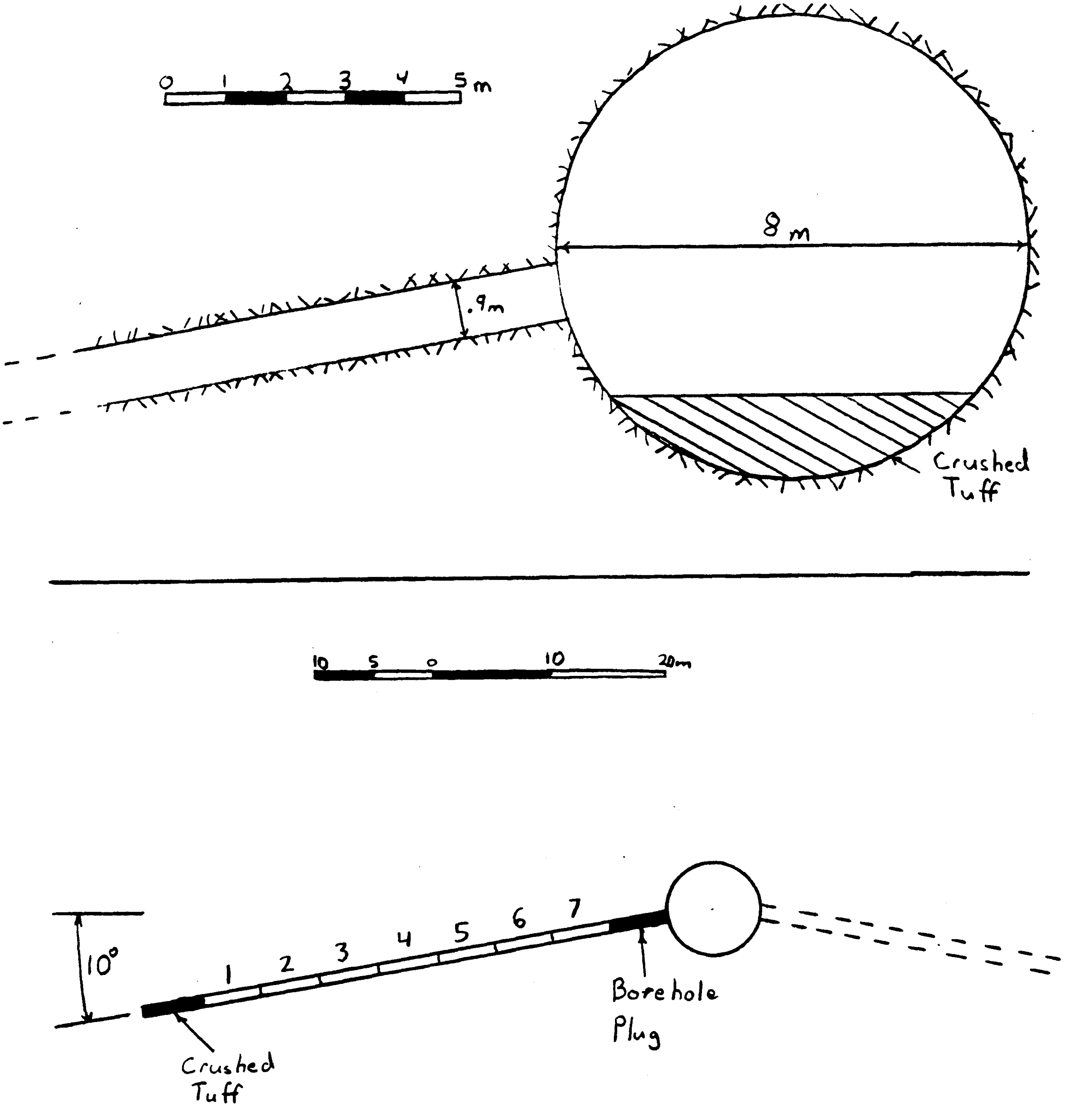
The roads and rail–lines in all ramps, corridors, and drifts are laid down over a bed of crushed tuff. Figure 3.3–6 shows the cross–sections of horizontal excavations. Rail is laid in sections similar to many current mining applications.

Many other facilities underground not mentioned specifically are needed; e.g. tuff crushing plant, vehicle storage and maintenance, radiological office, etc. All of these facilities are constructed in a region to the east and south of the main entrance point. Partial face mechanical excavation, such as the mobile mining machine, is used throughout.[3–20] This excavation commences when the waste ramp TBM reaches the repository entry point.

3.3.2.2.1 Layout and Construction Sequence

The layout was designed to minimize the total distance mined for a given number of canisters per emplacement hole. A plan view of the repository is shown in Figure 3.3–7. This layout has the further advantages of minimizing the number of TBM's, TBM turn–around time, and development time.

Figure 3.3-6 Cross Section of Emplacement Rooms



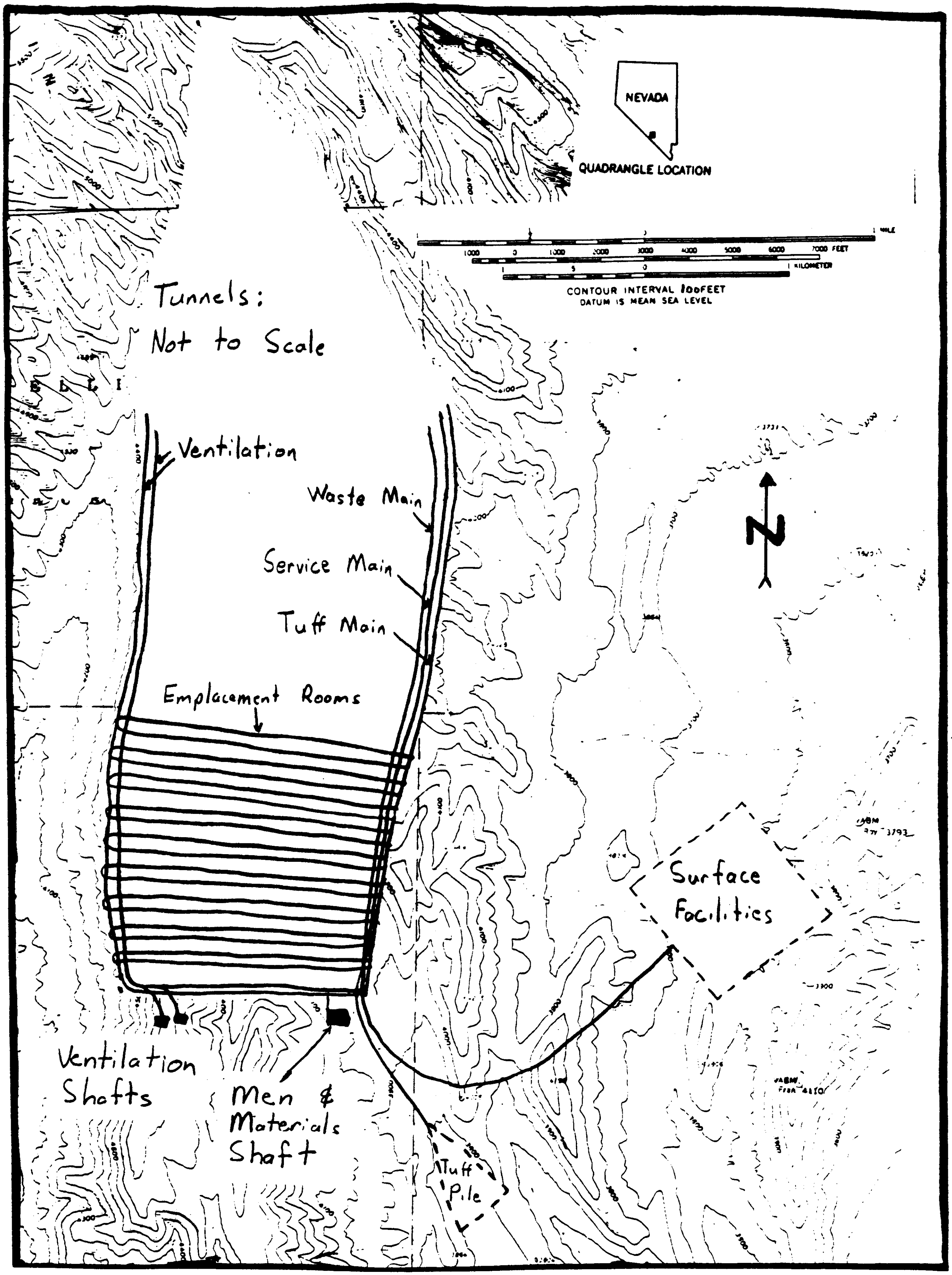
Underground construction begins with the simultaneous advance of the two ramps and the three shafts. The large curves in the ramps facilitate alignment of the respective TBM's with their corridor boring duties once at the repository horizon. The waste ramp TBM bores north and excavate the waste, tuff, and service main haulages. The tuff ramp TBM bores to the west then to the north excavating the ventilation passages. Once these TBM's have proceeded a northern distance of 1000 meters (the distance required for 3 years advance), they are dismantled and relocated to begin excavation of the parallel corridors. This process continues throughout the life of the facility.

Once the waste ramp TBM has reached the southeast corner of the repository, the emplacement room TBM is installed. The emplacement room TBM is a full–face, 8 meter diameter machine with a shortened design to facilitate the 80 meter radius curves. This curve radius is achievable on current machines. The excavation proceeds from the first emplacement room in a westerly direction. When the machine reaches the western boundary (the ventilation drifts) it curves around an 80 meter radius curve and excavates emplacement room 3. Upon completion of this room, the machine is dismantled and relocated at the eastern edge of room 2. In this way, only one relocation cycle is required for each two room excavated. Each two–room sequence is expected to require not more than 150 days. Construction of the boreholes can proceed upon completion of a room.

3.3.2.2.2 Shafts and Ramps.

Since the repository horizon lies underneath Yucca Mountain, the horizon elevation is only 150' below the level of the surface facilities. The surface facilities were placed 2.5 kilometers from the repository boundary. For these reasons, the waste is transported to the repository via an entrance emplacement tunnel. (Figure 3.3–7) The emplacement tunnel is curved such that the design grade is 12% and the outside diameter is 8 meters. At two places along the ramp, a larger chamber is mined so that emplacement vehicles may pass each other. A second tunnel is bored similar to the first for removal of the excavated tuff. The location of the tuff waste pile, also shown on Fig. 3.3–7, was chosen so

Figure 3.3-7 Plan View of the Repository



as to reduce the areal extent. The tuff ramp has a grade of 10% and has a diameter of 5 meters. These tunnel diameters are well within the range of current full–face TBM's.

Three shafts are to be sunk at Yucca Mountain. The men and materials shaft is sunk using standard drill and blast techniques. This is the only method to assure accurate shaft sinking for the 8 meter diameter shaft as required by high speed conveyances. Controlled blasting techniques are to be used throughout the sinking to minimize the tuff overbreak. This shaft houses conveyances for both men and equipment. It is the primary entrance to the underground facilities.

The other two shafts are the emplacement exhaust shaft and the development intake shaft. These shafts are raise bored. In this process, a pilot hole is drilled several centimeters in diameter. When the tuff ramp TBM reaches the underground location of the ventilation shafts, the raise boring machine is placed. A cable attached to a rig at the surface pulls the machine up the hole and it is excavated in a manner similar to a TBM. This not only eliminates overbreak, but provides a relatively smooth surface to enhance airflow without installing a shaft liner.[3–21] A simple air filtering system is installed for the development intake shaft. A double–pass HEPA system is then installed at the emplacement exhaust with radiation monitors.

The access ramps penetrate the upper member of the Paintbrush Tuff Formation. Studies similar to that carried out for the repository proper show only rock bolts–wire mesh and localized shotcrete are needed for stability here as well.

3.3.2.2.3 Corridors and Emplacement Drifts

The three primary corridors and all emplacement drifts are 8 meters in diameter. This diameter is used to provide clearance for the emplacement machines with room to spare for support systems. Crosscuts between the primary corridors are mined by a mechanical excavator (the device used to mine the service facilities) at each emplacement room. These crosscuts are equipped with ventilation boundary doors.

As with the ramps, tunnels have a roadbed of crushed tuff. The highly pulverized tuff is compacted and requires no cementing. (Cementing would also introduce foreign chemistry.) Movable rail sections are then laid on the tuff for the emplacement vehicles. These rail sections double as tuff removal lines. Small ore–cars are used to transport tuff from the advancing emplacement TBM to the tuff main where a conveyor hauls that tuff not used on backfilling process to the surface.

3.3.2.2.4 Waste Emplacement Holes

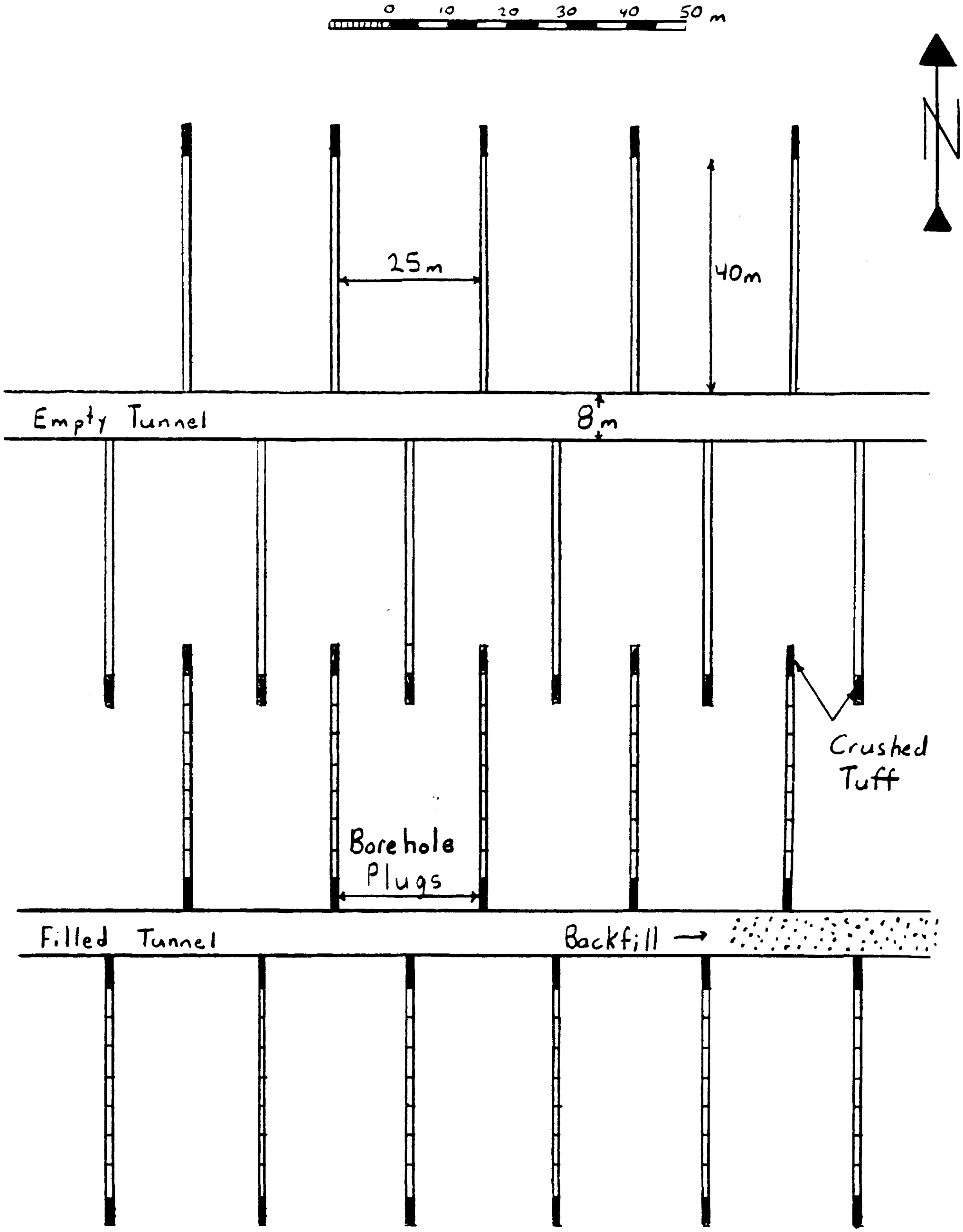
Design boreholes (waste emplacement holes) are 0.90 meters in diameters and are drilled to a length of 45 meters at an angle of 10. The bottom five meters are refilled with crushed tuff. This is done so that if water collects in the borehole, it is less likely to puddle at one end of the canisters. Each borehole contains 7 canisters and has a 5 meter clearance at the emplacement room to reduce dose. The angled hole facilitates canister emplacement. The machinery required to drill this type of borehole is readily available.

The pitch (distance between borehole centerlines on a given wall) varies for differing waste heat loadings. In the reference design, however, the pitch is fixed at 25 meters corresponding to waste of 10 years age and 33,000 Mw–day/MTHM burn–up. To simplify the emplacement process, boreholes are offset wall–to– wall. Figure 3.3–8 depicts the emplacement area. It appears in plan view that the end of boreholes from separate emplacement rooms touch. This does not occur due to the small slope of the repository horizon. That is, these boreholes are offset vertically.

3.3.2.2.5 Ventilation

The underground operations require two separate ventilation systems. The development ventilation system is on an overpressure system. The emplacement system operates with underpressure. In this manner, any air leakage through bulkheads and airlocks must leak from the development to the emplacement. If an accident occurrs where the emplacement side becomes contaminated, the development side is not affected. This also reduces the load on the HEPA filters, since the emplacement side ventilation amounts to about 1/2 of the total ventilation requirements.

Figure 3.3-8 Plan View of Emplacement Rooms



Development intake air is driven by surface fans into the facility. Any air conditioning required can be done at the surface. The air is fed through the development intake corridor, through the most advanced emplacement rooms where no waste has been emplaced, back through the service and tuff mains and up the men–and–materials shaft and tuff ramp. The split–up of flow at the tuff main and tuff ramp reduces air velocities over the tuff conveyor; thus reducing airborne tuff dust. Flow controllers similar to large duct–work are used to direct development air to the emplacement TBM and to the ventilation and main TBM's. Some development air is directed through the service facilities.

At the surface above the emplacement exhaust shaft, large fans pull emplacement air through the emplacement side. Air enters via the waste ramp and is directed into the currently active emplacement rooms. Upon completion of emplacement in a room, airflow to the room is halted and the room backfilled with crushed tuff. In an active room, the air is directed through the room to the emplacement ventilation corridor and up the emplacement exhaust shaft. The surface facilities have extensive radiation monitoring equipment and sufficient HEPA filter capacity. Should radiation alarms go off within the emplacement exhaust shaft, all emplacement air is directed through the HEPA filters.

3.3.2.2.6 Ground Water Control

No liquid water is expected in the repository horizon during operations. At the primary repository area, the water table slopes to the southwest from an elevation of 800 meters to 730 meters above sea level. It is between 200 and 400 meters below the Topopah Springs Member in this region.[3–16] Again to achieve minimum disturbance to the prexisting environment, all measures possible to minimize water use during construction are used. Extensive dust minimization techniques are employed for all tuff extraction, removal, and crushing operations. Should construction operations encounter perched water tables, the region is dewatered and monitored.

To control water inflow in the ramps, periodic diversion channels are placed under the rail/roadway. These diversion channels operate much like a storm sewer collecting runoff water that is pumped back up to the surface. At a points along the ramp, drains are also installed into the wall rock. This intercepts some water drainage that seeps into the ground within the ramp.

Similar measures are used for the shafts. Shaft surface housing controls shaft water inflow and extensive surface drains control water that seeps into ground adjacent to the shafts. The men–and–materials shaft is lined and several sets of drains are installed to mitigate any pore pressures that develop on the surface of the liner.

3.3.2.3 Sealing Design

Among the most important features of the repository is the design of the seals. The purpose of the seals is to return the site to a condition such that the hydrologic and geochemical characteristics of the site post–closure are as close as possible to that of the site pre–excavation. In other words, the seals must compensate for excavations in reducing disruption to the natural state. Obviously, the crushed tuff backfill cannot retain the porosity and permeability of intact tuff. Moreover, the excavation boundaries provide a preferential flow paths that must be tempered. Finally, no penetrations are scheduled for the tuffaceous beds of the Calico Hills. This unit forms a natural barrier between the repository and the water table. If water should penetrate all seals and collect at the repository, the flow path to the environment would still be hindered by the Calico Hills unit.

3.3.2.3.1 Shaft and Ramp Seals

The shaft and ramp design incorporates both water flow mitigating considerations as well as diversionary considerations. The primary sealing component of the shafts and ramps is highly densified crushed tuff. At locations stratigraphically below major moisture conveyances, such as faults or shear zones, cemented tuff plugs are emplaced. These plugs are several meters larger in diameter than the excavations so as to impede boundary flow. As a further measure to keep water ingress to the waste area, all shafts and ramps are extended to several meters below the repository horizon so that water flow down the excavation boundaries meets hard rock at a level below the waste.

3.3.2.3.2 Other Sealing Considerations

Since the repository horizon slopes to the east–northeast, this quadrant of the completed repository has drains installed. Small diameter drillholes, closely spaced, extend several meters into the floor and are filled with densified crushed tuff. This helps alleviate the problem of puddling should any water exist in the repository.

3.3.3 Estimated Costs

In estimating the costs of the geologic repository, great simplifications were necessary. The costs were broken down into capital costs and operating and maintenance costs. These estimates are based upon values for standard civil engineering construction projects coupled with engineering judgement for the application to this site.

The capital costs for repository construction are comprised of machine costs and all mining costs associated with waste emplacement preparation. The mining costs were calculated using figures for the cost per meter mined X the number of meters mined for a given tunnel design or mining method. To facilitate calculation, the capital mining costs were broken down by machine. The 1000 meters of main corridors is 3 years advance. This is the required advance distance for the main corridors. The following is the list of capital costs:

Waste Ramp TBM (8 m diameter):

machine cost = \$10,000,000

mining costs = \$25,000 / m

Ramp @ 4000 m

Service corridor @ 1000 m

Tuff removal corridor @ 1000 m

Primary Waste corridor @ 1000 m

Tuff Ramp TBM (5 m diameter):
machine costs = $8,000,000
mining costs = $20,000 / m
Ramp @ 1000 m
emplacement ventilation @ 1000 m
development ventilation @ 1000 m
other ventilation @ 1000 m
Emplacement TBM (8 m diameter):

machine costs = $15,000,000
mining costs = $10,000 / m
1 year's room @ 3400 m
Tuff crushing and removal = $20,000,000
Men and Materials shaft (8 m diameter)
[no machine]
mining costs = $30,000 /m
shaft depth @ 230 m

- Ventilation shafts (5 m diameter):

machine cost = $5,000,000
mining costs = $20,000 /m
2 shafts @ 300 m

- Costs Associated with All Support Facilities = $50,000,000

Since the entire capital construction operation can be completed in three years, it will be treated conservatively as a point cost in 2002. The total of the above costs is a capital cost in 2002 of $416 million dollars.

The operating costs for this section of the repository are comprised of mining costs associated with continual expansion and costs associated with tunnel support and maintenance. All the following O & M costs are generated each year the repository is open. Only the required meters of mining for a year's expansion is given and note that mining costs are the same for the same machines for this category:

Main corridors: @ 900 m
Ventilation corridors: @ 600 m
Emplacement rooms: @ 3400 m
Emplacement Boreholes: $10,000 per hole @ 275 /yr
Tunnel support: $1000 /m, @ 5000 m
Rail and power installation: $1000 /m, @ 5000 m
Maintenance: $1,000,000 /yr

The operating and maintenance costs are $81 million per year. Once again, these figures are very rough estimates, the mining costs per meter are generally quite conservative given the long time span of this project.

The decommissioning costs of the facility have not been studied. One estimate has been placed at $50 million.

3.4 Repository Operations

This section of the document describes the aspects of the underground repository concerning the operations of equipment and the following systems:

1. Waste canister transportation system.
2. Waste canister emplacement system.
3. Radiation Protection of workers and environment.
4. Environmental Monitoring of working climate.
5. Underground maintenance.

An assessment of the boundary conditions are laid out including the technical criteria, site constraints, and design assumptions of the section. The constraints and other criteria are explained considering only the scope of this section (3.4), followed by the systems descriptions. In conclusion to this section there is an off normal events description and an estimated cost assessment, both operational and capital, for the defined operations in this section of the underground system.

3.4.1 Criteria and Constraints

The boundary conditions for this section are the conditions that exist in the underground repository that govern and affect the scope of this section, underground operations. This section will address the Technical Criteria (3.4.1.1) of the operations, the Site Constraints (3.4.1.2), and Design Assumptions (3.4.1.3).

3.4.1.1 Technical Criteria

The technical criteria addressed in this section are those that pertain to the underground operations and equipment governed by the Nuclear Regulatory Commission (NRC) , the U.S. Environmental Protection Agency (EPA), the International Commission on Radiological Protection (ICRP), and the National Council on Radiation Protection and Measurements (NCRP). The NRC standards for protection are contained in Chap. 1 Title 10 of the Code of Federal Regulations, Part 20 (10 CFR 20)[3–1]. The EPA standards are found in Part VII, Title 40 [3–2].

3.4.1.2 Site Constraints

The site constraints that for the underground repository operations are those that physically control the limits to the operations systems. It is going to be assumed that all equipment used underground does not exceed any physical guidelines presented by the site constraints. It was also assumed that all site constraints described in the 'geologic repository' section of this document do not limit the intended operations underground.

3.4.1.3 Design Assumptions

The design assumptions for this section are the guidelines of the design for the equipment and systems described in the design description. It is assumed that simpler design of equipment in general is better both for utilization and maintenance of the equipment. It is also assumed that worker–waste contact time is minimized. It is a criteria that waste transfer is minimized and therefore one vehicle is used for transport of the canister, from the the surface facilities, and for emplacement of the canister into the emplacement borehole. The disturbance to geologic environment is also minimized.

3.4.1.3.1 Radiological Health And Safety

Radiological health and safety is monitored and controlled. It is a requirement that workers are minimally exposed As Low As Reasonably Achievable (ALARA) to potential radiation sources and that all radiation sources are monitored and properly shielded. All workers exposure time to radiation is minimized through decreasing the amount of time a worker is exposed to radiation.

3.4.1.3.1.1 Worker Exposure

The maximum exposure a worker can receive is 5 rem/year (3.4.1.1). The two largest possible radiation exposure sources are from the canister in transportation and the canisters in the borehole. These dose levels are to be less than 5 millirem per hour. This level is calculated assuming the following parameters:

Hours worked in one week = 40
Working weeks in one year = 50
Maximum dose in one year = 5 rem

Therefore, the lowest reasonable continual dose of a worker is shown by the equation:

$$\frac{(5000\ \text{millirem/year})}{(50\ \text{weeks/year})(40\ \text{hours/week})} = 2.5\ \text{millirem/hour} \qquad (3.1)$$

The maximum dose rate at the outside of the emplacement cask (see Section 3.4.2.4.1) is less than 5 millirem per hour to comply with the above criteria. The maximum dose rate at the outside of the shield door is also less than 5 millirem per hour by the same criteria. The Radiation Protection Office (see Section 3.4.2.6.1) is responsible for the continual monitoring of the underground facilities as well as the continual monitoring of the transportation vehicle and transportation as to verify that the levels of radiation exposure to the workers do not exceed this maximum.

3.4.1.3.1.2 Worker Safety and Monitoring

Worker safety and monitoring consists of personal dosimetry, bioassay, and protective clothing. These measures are taken to protect the worker from potential unnecessary exposures or unnecessary dangerous contaminations.

The personal dosimetry consists of the use, by all workers, of both film badges and pocket ionization chambers. The pocket dosimeters are pencil like self monitoring ionization chambers and require the daily recording of dose received by the worker. The film badge is checked either every 14 or 28 days. Thermoluminescent dosimeters (TLDs) can also be used in place of film badges.

The protective clothing used by the workers depends on the type of job a worker is responsible for. The type of clothing includes 1) washable coveralls, 2) disposable coveralls used over washable coveralls in highly contaminated areas, 3) caps or hoods, both washable and disposable, 4) rubber gloves (usually washable), 5) disposable gloves and tissues, and 6) footwear usually involving ordinary rubbers (washable) worn over disposable plastic foot covering. In–house laundry is done at the repository.

3.4.1.3.1.3 Non–Radiological Health And Safety

It is important to observe in addition to the radiological safety criteria, the non-radiological safety criteria. The following list is a general description of safety considerations for underground repository criteria and worker safety:

1. Ability to identify unacceptable or marginal areas of ground
2. Ability of repository construction to adapt to constraints imposed by rock characteristics
3. Use of reasonably available technology
4. Maintenance of underground openings during repository operation and closure
5. Development of rigorous maintenance procedures and schedules for all repository facilities and operating equipment
6. Air quality (potential for natural gases such as radon or methane, high concentrations of equipment exhaust gases, and harmful dusts)
7. Working temperature
8. Potential for equipment–related accidents (This is not a site–related factor unless site conditions restrict the size of openings or corner radii)

In the above criteria, numbers 1, 2, and 4 are construction criteria. The procedures are well–developed and used in all underground operations. Due to the length of time that this facility is required to remain open and the increased scrutiny of the public, activities required to ensure that these criteria are met assume larger factors of safety than standard civil engineering construction projects. These criteria are, however, monitored by the underground maintenance crew.

Criteria 3 is a criteria to minimize possible accidents. By using existing technology, there is less chance of misuse of equipment and undesirable side effects. Existing documentation for tested available technology makes safety stipulations easier for workers. As much existing technology as available is used.

Items 5, 6 and 7 are also to be covered by the maintenance crew on a daily basis or as necessary. Emplacement cask and transport vehicle are inspected after each emplacement and appropriate maintenance is done. Other maintenance of equipment is done in the most rigorous manner each shift. Constant monitoring of air quality and air temperature are done in the environmental monitoring room by sample reading and meter reading.

By completing the above procedures and stipulations and by following a rigorous safety monitoring schedule and maintenance, consideration 8 is minimized. Note also that the increase in criteria 3 will also decrease criteria 12 as well.

3.4.2 Design Description

This section consists of the design description of all necessary equipment and systems mentioned for the underground operations not mentioned in other sections. It gives the description of the transportation system of the canister, the emplacement system of the canister into the desired borehole, and all other related control systems including radiological and environmental monitoring of the underground facilities, and the construction sequence of the repository after opening.

3.4.2.1 Primary Criteria

It is impossible to make proper cost benefit analysis and still fulfill all constraints and criteria of the repository. It is assumed that first the repository is built considering the design assumptions and technical criteria explained previously and that the repository fulfills the necessary economic criteria. The cost benefit analysis considers that the design criteria and constraints are followed first; then and only then is the most cost effective repository achieved. In other words, the cheapest repository and operations equipment are to be built only after fulfilling the proper criteria and constraints.

3.4.2.2 Construction

The construction (as considered in the context of this section) is the phase of expansion of the repository as the repository. It is necessary to have a detailed plan for expansion of the repository to its final state. This is required if operations are to continue in a safe sequential manner and not interfere with current operations. The continual construction operation is independent from the emplacement operation and is covered in Section 3.3.2.2.1 of this document. The construction of the repository after its operation has begun is a continuous expansion with a one year lead time. This gives sufficient lead time and physical distance of separation between the concurrent operations, emplacement and construction.

3.4.2.3 Canister Transport System

The canister transport system is the system that will receive the canister from the surface facility, transport it down the to the repository via the repository transportation tunnel, and emplace the canister into a borehole. The transportation vehicle is an electric locomotive (see Fig. 3.4.1a – 3.4.1b) for simplicity of use and maintenance and for air quality of workers (i.e. no diesel fumes from diesel–electric vehicles).

There are many design criteria for this vehicle to ensure safe delivery of the canister to its respective borehole. For the scope of this project, the transport vehicle design was not studied in extreme detail. As such, only overall design descriptions and goal are

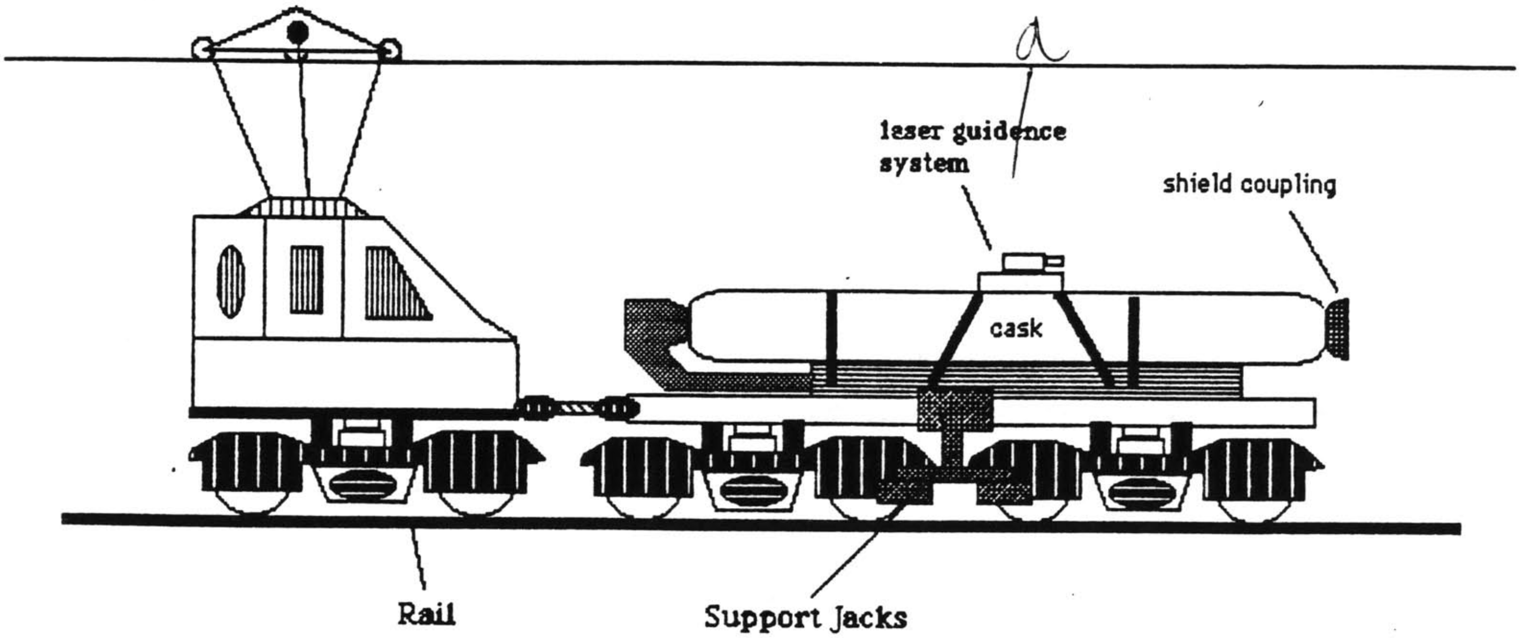


Figure 3.4.1a Transportation/Emplacement Vehicle

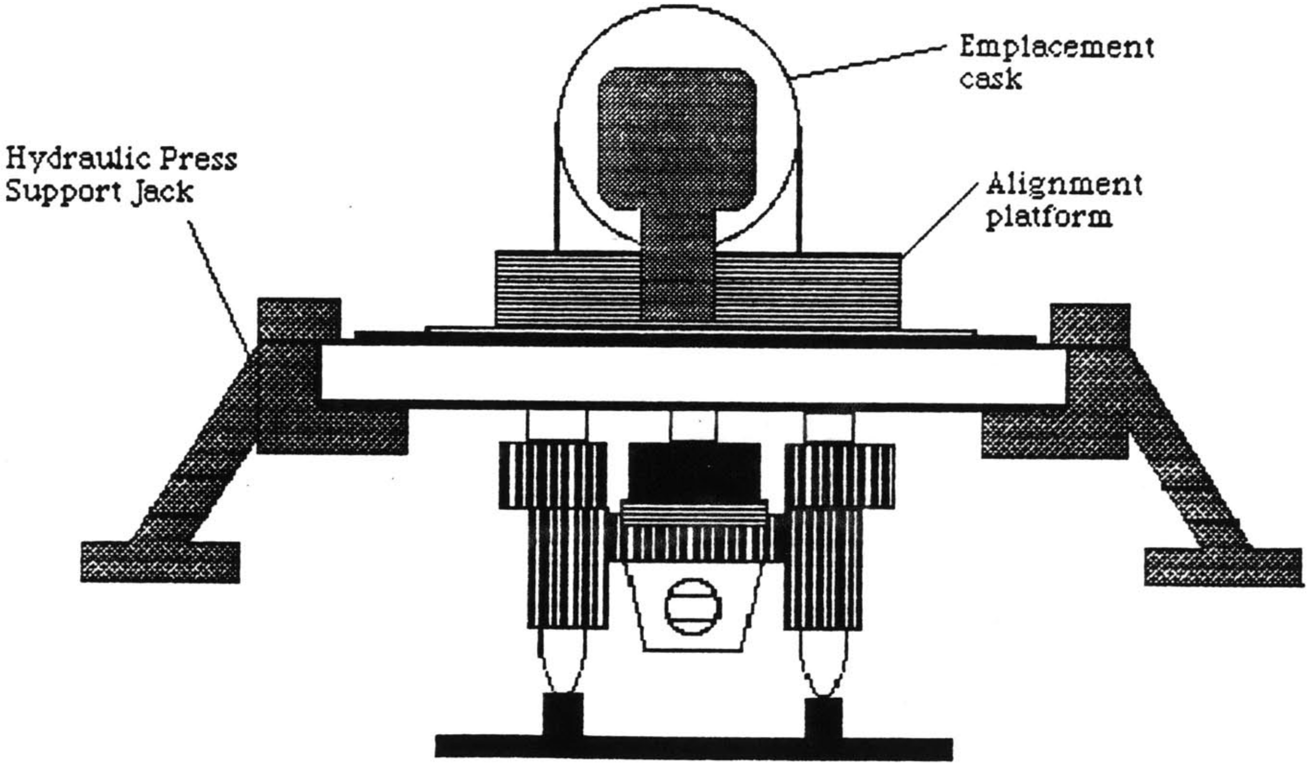


Figure 3.4.1b Rear view of canister transportation/emplacement vehicle

discussed. To the degree possible, currently available technologies are used in the transport rail vehicle design.

The canister transport system is comprised of an electric operated rail vehicle pushing a specially designed rail car. The rail carries the canister and emplacement cask.

Using the transport vehicle, the canister is picked up from the surface facility by coupling the cask with the shield door, and then receiving the canister, and pulling the trolley back into the emplacement cask (see Fig. 3.4–5a).

The transport vehicle transports the loaded cask down the repository entrance ramp to the repository. The repository entrance ramp has a 1.2% design grade and is based on the constant load of the rail car and cask on the locomotive. To transport the required 200 ton payload (the rail car with emplacement cask and canister) a 50 ton electric locomotive is used. The 50 ton locomotive is rated for a haulage capacity of 384 tons at the 2% grade and 1,250 tons on level ground. The following formula [3–25] is used to determine the locomotive haulage capacity:

$$W = L(R+G)/(0.25 \text{ X } 2000 - A) \qquad (3.2)$$

where W is the weight in tons of the locomotive required; R is the frictional resistance of the cars in pounds per ton and is taken at 20 lb; L is the weight of the load in tons; A is the acceleration resistance taken as 20 for less than 10 mi/h; G is grade resistance given in pounds per ton or 20 lb/ton for each percent of grade; 2000 is the factor to give adhesion in lb/ton.

3.4.2.3.1 Vehicle Suspension Design

Primary consideration in the design of the vehicle suspension system is to isolate track input from the vehicle car body. In addition, some specific areas of instability which the suspension system must address are harmonic roll and superelevation.

Harmonic roll is the tendency of a rail vehicle with a high center of gravity to rotate about its longitudinal axis (parallel to the track). This instability is excited by passing over staggered low rail joints at a speed which causes the frequency of the input for each joint to match the natural roll frequency of the vehicle. This speed is typically (for loaded rail cars) from 12 to 18 mi/h [3–25]. This is mitigated or eliminated in the present design by limiting vehicle travel to no more than 10 mi/h and by maintaining improved track surface, and by using damping truck suspension.

Superelevation is the tendency for the rail vehicle to tip toward the outside of a curve as the vehicle passes through a curve. This is due to the centrifugal force acting on the center of gravity of the car body. To compensate for this effect, the outside rail is superelevated, or raised, relative to the inside rail, sharp curves are avoided, and as noted earlier, speed is limited.

3.4.2.3.2 Vehicle Truck System

The wheel set consists of a four–wheel swivel truck with electric motors on the end axles of each truck. Each set of wheels on the truck also has swivel capability. This will maximize the turning capability of the vehicle. The wheels are 40 inches in diameter, as requires to support the required load.

3.4.2.3.3 Vehicle Braking System

The vehicle braking system is one of the most important systems in the vehicle for its' failure can lead to the most dangerous possible accident concerning underground operations: a runaway vehicle.

The first criterion is to design the vehicle to not exceed a maximum velocity of 10 miles per hour. This can be designed electronically and mechanically. The technology for this exists and it was assumed that it is employed to the designed transport vehicle.

The vehicle has a standard locomotive type automatic air brake system as well as an enhanced dynamic braking system that works at the low desired speed. The braking mechanisms are designed with an emergency application to the control valve between the cab of the vehicle and the trailer. This emergency application occurs irrespective of the state of brake application or release; this feature eliminates the possibility of the vehicle being out of control on long grades.

Other emergency features such as emergency hydraulic brakes or exploding axles can be designed and employed if the additional redundancies are required.

3.4.2.4 Emplacement System

The canister emplacement system is the system responsible for emplacing the canister into the designed borehole from the transport vehicle. It is necessary that the canister is properly shielded at all times during the emplacement process as to minimize potential exposure of high radiation levels to underground workers.

The emplacement system consists of the following systems: the Emplacement Cask (3.4.2.4.1), the Temporary Shield Door (3.4.2.4.2), the Cask Alignment System (3.4.2.4.3), and Emplacement Procedure (3.4.2.4.4).

3.4.2.4.1 Emplacement Cask

The emplacement cask is the shielded container housing the waste canister. Lined and covered with a centimeter of stainless steel for material protection the bulk of the cask is constructed of depleted Uranium. This material was chosen to provide the greatest shielding capability with the least thickness, thereby reducing overall cask dimension (see Fig. 3.4–2a).

Inside the cask, at one end, a 20 ton winch is used to release and pull back the trolley. The trolley is a small transport cart with hard rubber wheels on the bottom and a roller bed on top so the canister rolls off easily when released. The trolley has a clasp that holds the canister in place and a door on the opposite end (see Fig. 3.4–2b). Also at this end of the canister is a mechanical arm capable of pushing the cask up to 5 meters.

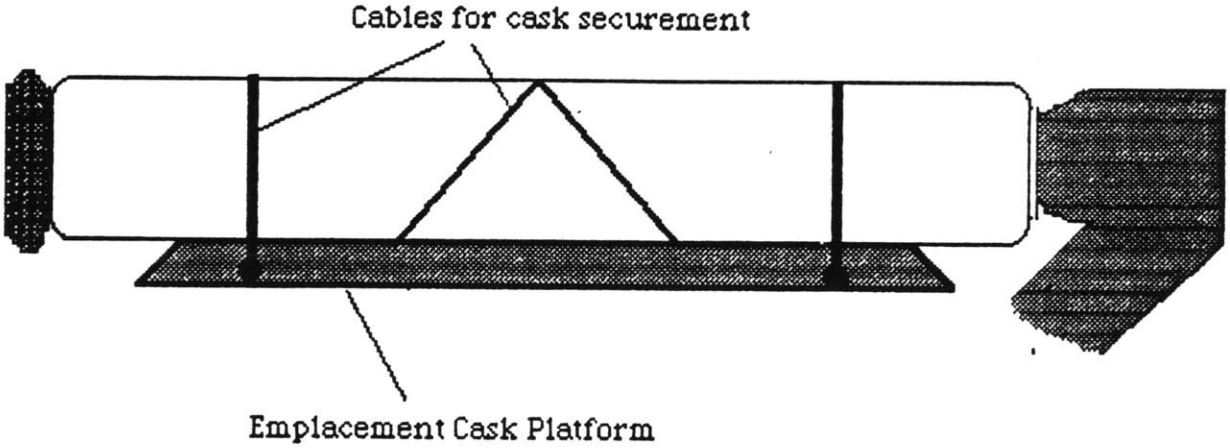


Figure 3.4.2a. Emplacement Cask

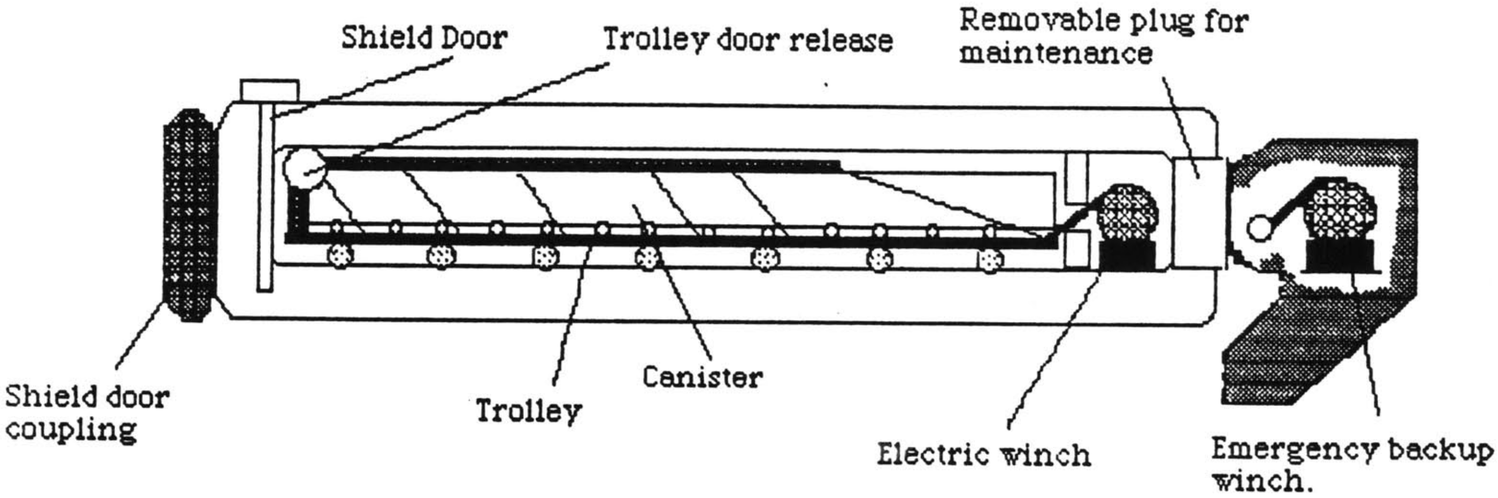


Figure 3.4.2b Emplacement cask crossection

At the front end , the cask has a coupling device that couples with the temporary shield door (3.4.2.4.2). This coupling system also gives power to the temporary shield door. Only when the cask and the shield door are coupled is the shield door of the cask able to open.

3.4.2.4.1.1 Cask Shielding Determination

The dose on the outside of the canister as determined in the 'engineering barrier system' portion of the document is 1.0 x 10^4 rem per hour. The design criteria for the dose on the outside of the emplacement cask is less than 5 millirem per hour as explained in section

3.4.2.1.1.1

The major contributors to the dose are Cs–137 and Co–60, with the majority coming from Cs–137. A 1 MeV beam is assumed for dose calculations. The equation used for dose approximation is:

$$I = I_0 B_m \exp[(-\mu/\rho)\rho x] \qquad (3.3)$$

where I is intensity of dose, B_m is buildup factor for target shielding, μ/ρ is total mass attenuation coefficient of the shielding for the assumed 1 MeV gamma rays, r is the density of the material, and x is thickness of shielding. The values used for this calculation are:

$I_o = 1 \times 10^4$ rem per hour

$I = 5 \times 10^{-3}$ rem per hour

$\mu/\rho = 7.79 \times 10^3\ m^2/kg$

$\rho = 18.9 \times 10^3\ kg/m^3$

The determination of x and B_m is required but buildup factor is a function of x and mean free paths. The mean free path of 1 Mev gammas in uranium is 0.68 cm. An initial estimate ignoring buildup gave a shield thickness (x) of 11 cm. This is 15 mean free paths.

A table from reference [3–26] gives a buildup factor for uranium at 15 mean free paths and 1 MeV gammas of 3.60. Assuming this buildup factor, a thickness of about 12 cm is determined. Thus, a thickness of 15 cm is estimated as a sufficient shield appropriate for the cask. Given the shield thickness of 15 cm uranium and the stainless steel cover and lining, the cask weighs about 50 tons.

3.4.2.4.2 Temporary Shield Door

The temporary shield door is placed onto the emplacement borehole before any canisters are emplaced in the borehole. The door is set at an angle (see Fig. 3.4–3) so as to properly couple with the tilted cask. Only when receiving power from the cask after coupling can the temporary shield door be electronically open. The temporary shield door is removed when the borehole is full and put on the next borehole.

The shield door is constructed similarly to the emplacement cask with an equal thickness of uranium. The rest of the shield door is constructed of high strength steel.

3.4.2.4.3 Cask Alignment System

The cask alignment system (see Fig. 3.4–4) aligns the cask with the temporary shield door. This will be an electronic controlled, laser guided system. The electronic controls control the rotation of the cask on a rotating platform, and the hydraulic press/jack that lifts the platform. The amount of rotation and the amount of tilt for the cask are fixed for every borehole so they are preset parameters. The laser guidance system is a simple laser that is located on the cask. It is used to position the vehicle with respect to the borehole and guides the cask positioning by moving the cask until the laser hits the proper target on the temporary shield door. When the laser, and thus the cask is positioned, a green light indicates to the driver that the coupling procedure may proceed. The cask is shifted towards the temporary shield door until automatic coupling occurs.

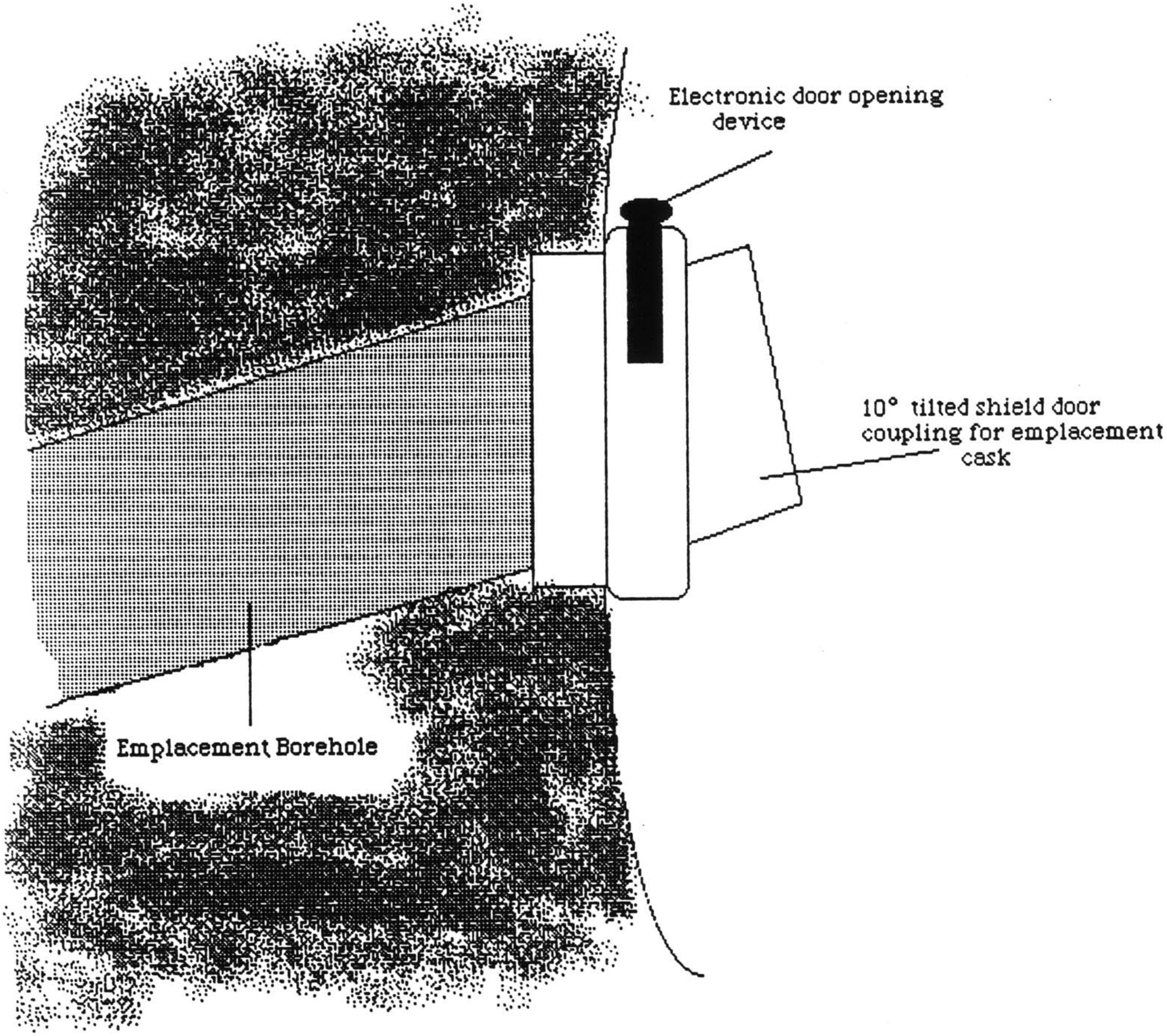


Figure 3.4.3 Temporary Shield Door

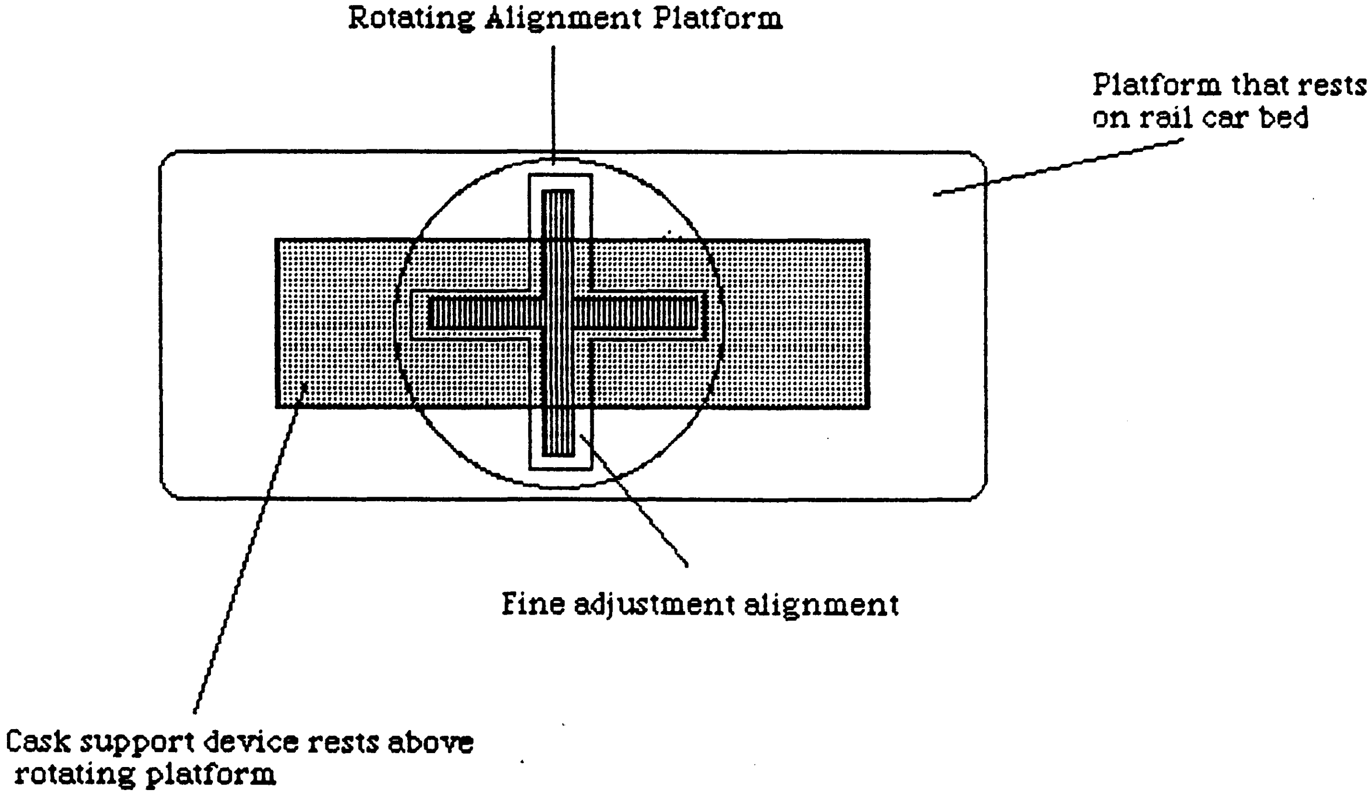


Figure 3.4.4 Cask Alignment System

3.4.2.4.4 Emplacement Procedure

The emplacement procedure (see Figs. 3.4–5a – 3.4–5d) begins with the positioning of the transport vehicle next to the emplacement borehole. Hydraulic press boots are activated to anchor the vehicle trailer. Next, the cask alignment system then rotates the cask 90 degrees so that the front of the cask faces the emplacement hole. The cask is then raised by the hydraulic press/jack and tilted at the angle of the emplacement borehole (10°). The cask is positioned using the laser guidance system and coupled with the temporary shield door. The doors of the cask and temporary shield door are opened and the canister is lowered by the winch via the trolley to its destination in the hole. The trolley door is then opened, allowing the canister to slide off the trolley as the trolley is being pulled back into the emplacement cask. The shield doors are shut, the cask uncoupled, and the cask repositioned on the vehicle.

3.4.2.5 Backfilling System

The underground backfilling system backfills the tunnels and emplacement boreholes with crushed tuff. The backfilling process is a two step process. First, upon complete emplacement of a given borehole, the boreholes are filled with crushed tuff. Second, when an entire emplacement room has been filled, the tunnel itself is filled. Currently available technology achieves greater than 80% maximum theoretical density with blown crushed rock.

The backfilling system for the canister storage borehole has a coupling device to couple onto the temporary shield door (see Section 3.4.2.4.2) before backfilling begins. Only after the coupling is successful can the shield door be opened remotely from the backfilling device. After the shield door is open, the canister borehole is backfilled with crushed tuff to achieve maximum density. The crushed tuff takes up approximately 5 meters distance in the borehole. the temporary shield door is then removed and a solid tuff

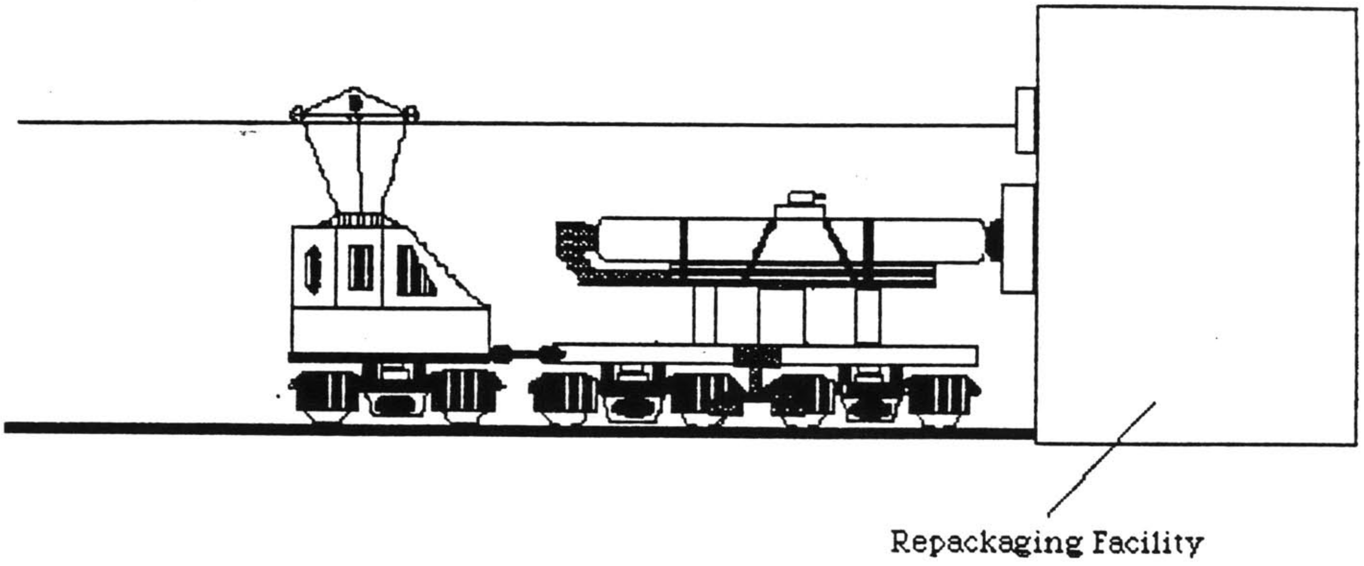


Figure 3.4.5a Canister pickup from repackaging facility

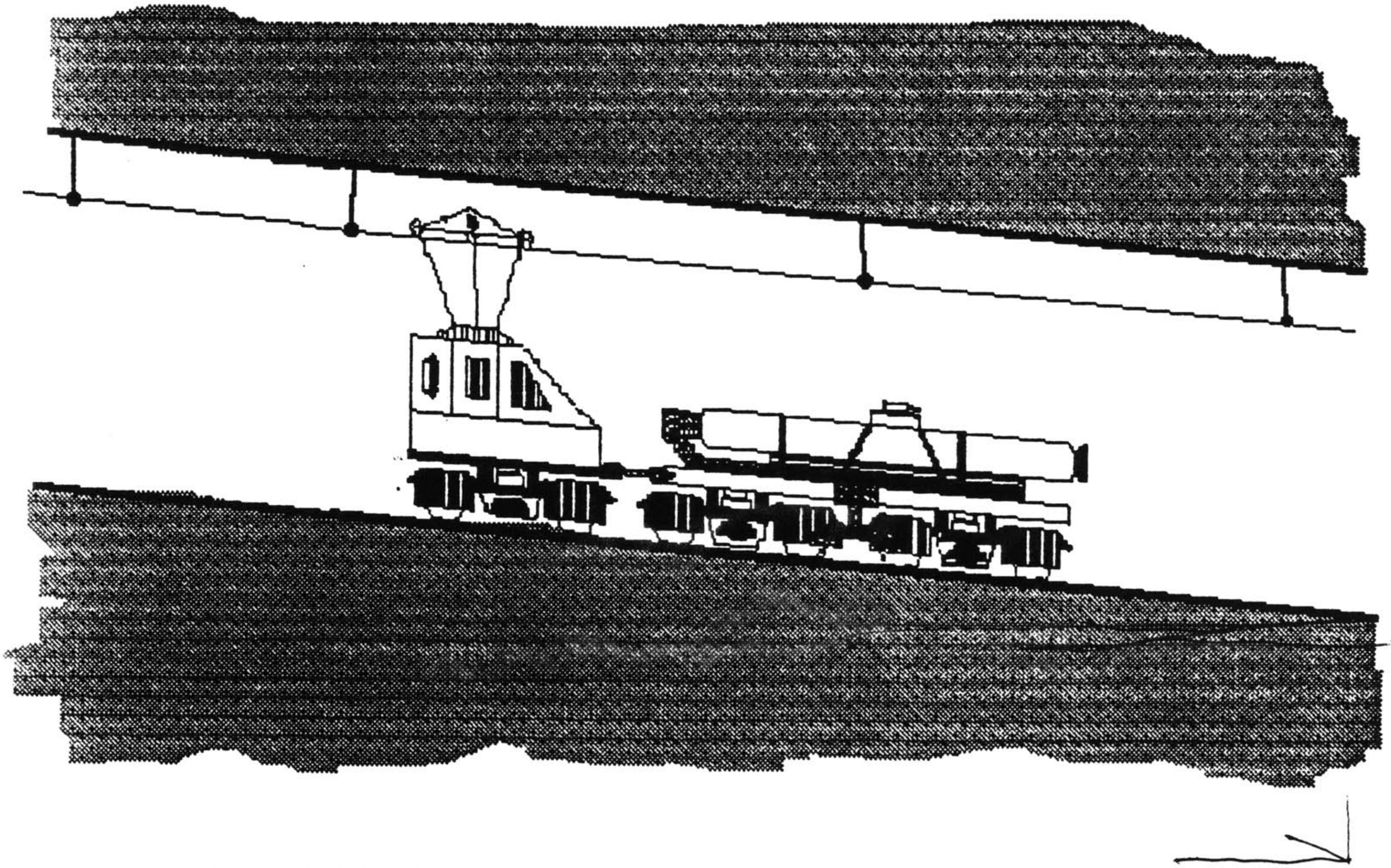


Figure 3.4.5b Transportation/Emplacement vehicle travels down the repository entrance ramp at 1.2% grade.

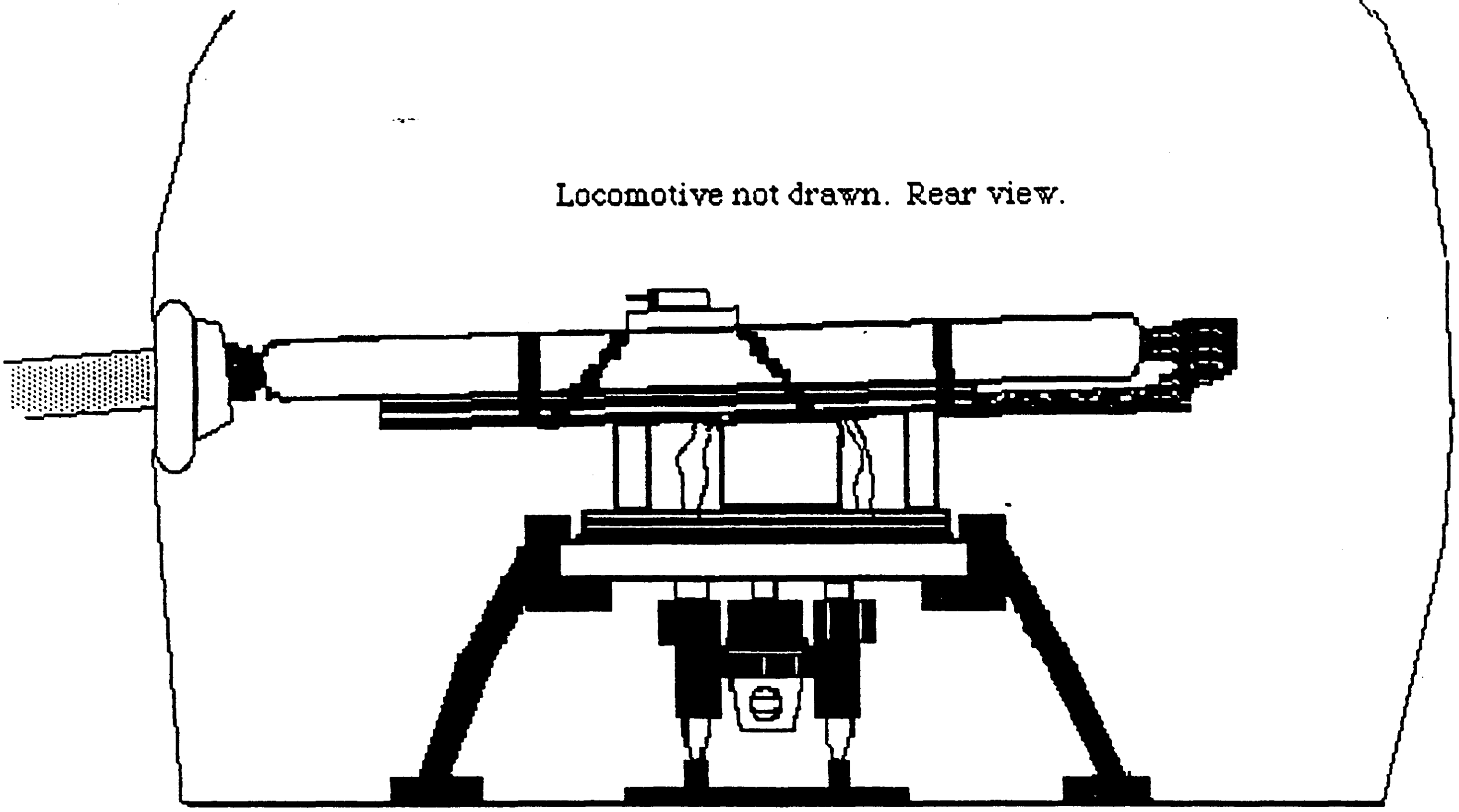


Figure 3.4.5c Emplacement cask coupling with temporary shield door

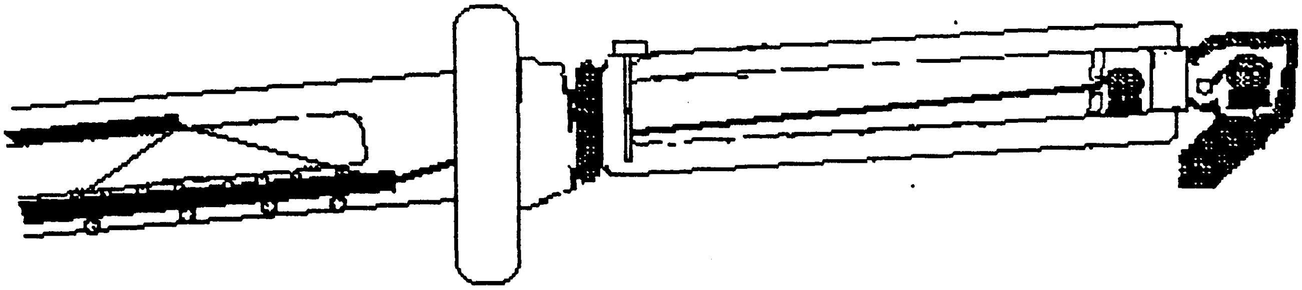


Figure 3.4.5d Canister emplacement into borehole

'plug' is placed at the borehole entrance. The 'plug' is composed of crushed tuff bound together by epoxy and is larger than the diameter of the borehole (see Fig. 3.4–6).

3.4.2.6 Peripheral Operations

The peripheral operations are all operations concerning the underground that are not specifically mentioned in previous sections of this chapter. All operations are listed in this section as referenced to descriptions found later in this document. The underground operations consists of the following:

1. Underground Repository Radiation Protection (3.4.2.6.1)
2. Underground Repository Environmental Monitoring (3.4.2.6.2)
3. Waste Canister Transportation System (3.4.2.3)
4. Waste Canister Emplacement System (3.4.2.4)
5. Tunnel and Emplacement Borehole Backfilling System (3.4.2.5)
6. Underground Construction And Sequencing (3.4.2.2)
7. Underground Maintenance (3.4.2.6.3)
8. Underground Rock Crushing Plant (3.4.2.6.4)

3.4.2.6.1 Underground Repository Radiation Protection

The underground repository radiation protection office is responsible for the radiological monitoring of the workers through dosimeters and film badges. They are also responsible for the radiological environmental monitoring of the underground facilities. Periodic wipe testing is to be regularly performed. It was assumed that a schedule and procedure for radiation protection similar to that of a nuclear power plant but adapted to the underground repository facilities can be determined without great difficulty. Therefore, details of such procedures are neglected for the scope of this project.

3.4.2.6.2 Underground Repository Environmental Monitoring

The underground repository environmental monitoring crew is the crew responsible for the monitoring of the workers physical conditions. The air quality and ventilation of

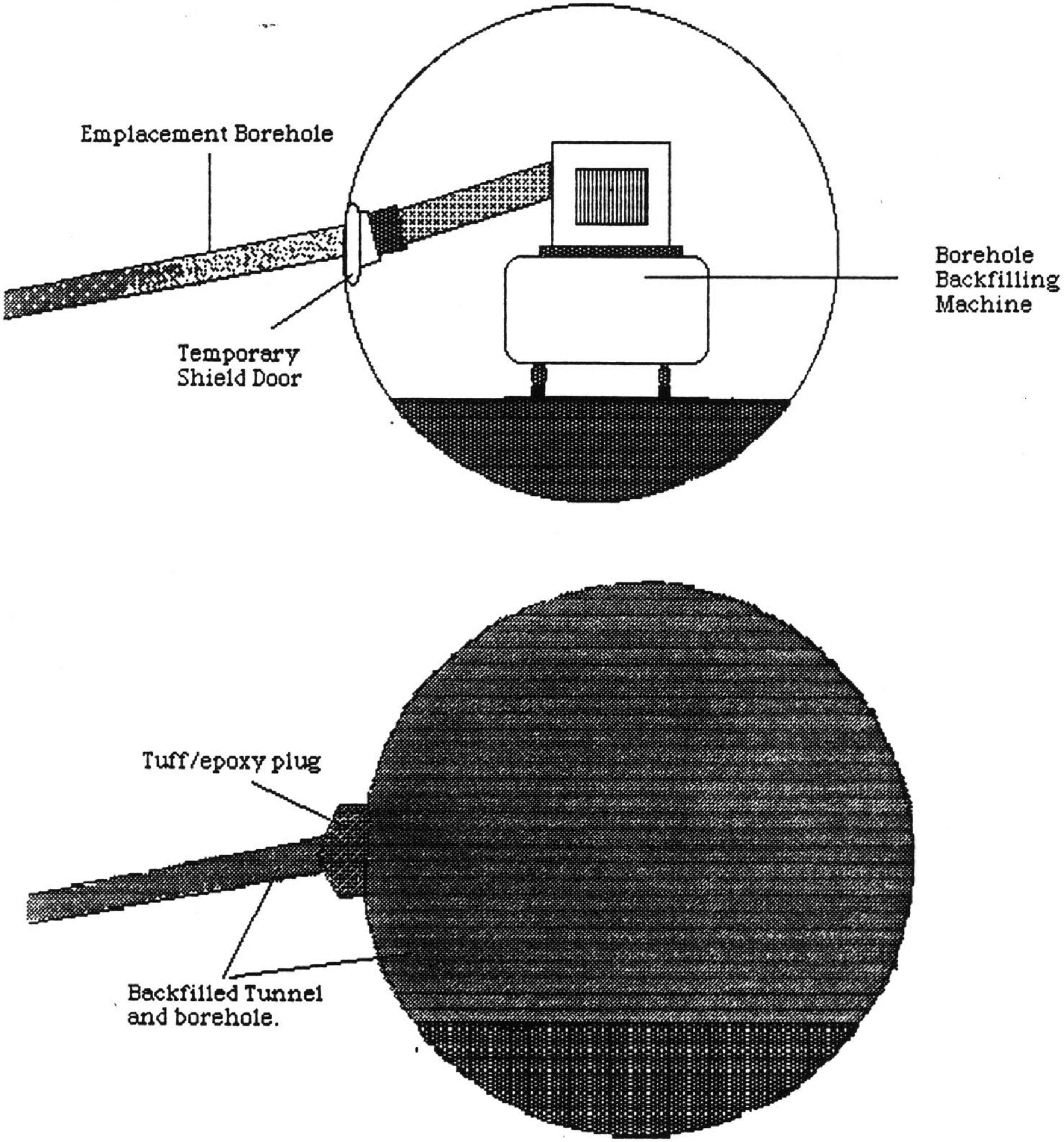


Figure 3.4.6. Tunnel and Borehole Backfilling Procedure.

the underground repository is monitored by this crew as well as the working temperature. The air quality includes the determination of any toxic gas levels in the air as well as other potential hazard levels in the environment.

3.4.2.6.3 Underground Maintenance

The underground maintenance crew is responsible for the upkeep of all underground equipment and the maintenance as required of the corresponding equipment. This duty includes the upkeep of both the transport vehicle and the canister emplacement system. The rail system is also under the maintenance crew's jurisdiction as well as any odd electronic equipment or mechanical equipment required by underground operations.

3.4.2.6.4 Underground Rock Crushing Plant

The underground crushing plant is the source of crushed tuff for the backfilling procedures. This plant is not specially designed. This type of operation is very common in underground mining; it is assumed a standard underground rock crushing plant is constructed.

3.4.3 Off–Normal Events

This section describes any potential extraneous events that affect the design of the underground operations. The exact measures or preventions are not determined in this section, only considerations and suggestions.

In the event of a runaway train, i.e. the transportation rail vehicles' brake systems all fail, the potential exists for the vehicle crash either in the tunnel or in the repository at the bottom. In the event such an accident is to occur there is designed in the entrance ramp two truck ramp turn–offs that are automatic unless the driver comes to a complete stop before hand to switch towards the repository, this turnoff resets after the transportation rail vehicle passes the turn–off. The location of the two turn–offs are half way down, and at the bottom. At the end of the turn–offs is a steep upward incline with a cave at the end, and an aluminum stacked crash barrier.

There are two possible scenarios in the event of a winch failure. One is with the canister still on the trolley, and the other is with the canister already off the trolley. All related failures in the cask emplacement system are grouped into these two categories. If the winch cannot pull back the trolley after releasing the canister or if the winch gets stuck on the way down, the truck has in the cask attachment arm, another winch that is attached to the cable from the broken winch and the trolley is pulled back. If the winch breaks and the trolley slides down the hole uninhibited, the winch cable is cut and the hole may be sealed off if there is leakage from the potentially ruptured canister.

These are the main off–normal events and any others are assumed to be easier to deal with and therefor are not mentioned.

3.4.4 Estimated Costs

The estimated costs of the equipment and operations are described in this section, 3.4 excluding the cost estimations from this section that appear in other sections where their full descriptions are located.

3.4.4.1 Capital Costs

The capital costs of the equipment and facilities for the underground operations are conservative estimates based on existing technologies. The capital equipment and facilities costs are estimated at:

(10) Transportation rail vehicle — 3 million dollars each
(10) Emplacement cask rail vehicle — 2 million dollars each
(10) Emplacement cask — 5 million dollars each
(5) Temporary shield doors — 2 million dollars each
Underground machine shop — 2 million dollars
RPO, Environmental monitoring facilities — 2 million dollars
All other miscilaneous systems and equipment — 2 million dollars

The total underground capital cost estmate used is 120 million dollars. This conservative estimate also assumes that all equipment and systems are purchased with 1988 dollars and all are purchased before repository opens and emplacement begins.

3.4.4.2 Operational Costs

The operational costs consist of equipment maintenance costs and personnel costs. The maintenance costs are estimated with no special stipulations in comparison to maintenance costs of current compatible equipment. The personnel costs are estimated assuming nuclear reactor personnel.

3.4.4.2.1 Maintenance Costs

The maintenance costs for the transportation rail vehicle is estimated at $2,00,000 per year. This value is a conservative estimate in comparison to maintenance costs of standard locomotives in commercial use. The maintenance cost of the specially designed rail vehicle that carries the emplacement cask is similarly estimated at $1,000,000 per year. The estimated maintenance costs of the RPO, Environmental monitoring system, the machine shop, the rail system, and backfilling system is estimated to be a total of $3,000,000. a conservative total maintenance cost of $10,000,000 per year is assumed for the underground operations.

3.4.4.2.2 Personnel Costs

The personnel costs are the cost factors involving the personnel alone. The wages paid to workers (3.4.4.2.2.1), cost of dosimetry (3.4.4.2.2.2), bioassay costs (3.4.4.2.2.3), and cost of protective clothing (3.4.4.2.2.4) are the costs explained in this section. The total estimate of personnel costs is presented in the overall personnel cost estimate section (3.4.4.2.2.5).

3.4.4.2.2.1 Workers Wages

Workers wages include costs of fringe benefits. Supervisory positions at nuclear power plants average about $12 per hour and fringe benefits increase the wage by 0.3 to 0.5 on the average. A conservative estimate, based on these assumptions, of an overall plus benefits wage is made at $20 per worker per hour. This gives a salary, including fringe benefits, of $40,000 per worker per year.[3–27]

3.4.4.2.2.2 Dosimetry Costs

The cost of the two types of dosimetry can be summed up into two values making certain assumptions. Assuming the same average badging period as those in current nuclear power reactors, dosimeter replacement costs the same as for reactors, labor for reading and maintaining the dosimetry similar to that of a reactor, the average film badge cost is $1.50 per badge per person, and pocket dosimeter costs are $0.50 per worker per day.[3–27]

3.4.4.2.2.3 Bioassay Costs

Bio–assay costs are those costs concerning the routine whole body counting. In nuclear power plants, plant workers are counted 1–4 times per year, depending on their jobs. The underground operations crew is counted 4 times a year, once at the end of each quarter. The estimated costs of whole body counting range from $10 to $31 with the average being $20. The individual receiving the whole body counting will average 23 minutes away from the job, but the process need not be one that disrupts a major work period.[3–27]

3.4.4.2.2.4 Costs of Protective Clothing

The cost of protective clothing includes all 6 items listed in section 3.4.2.1.1.2 and assumes an average of 2 complete changes of protective clothing per person per day. This cost is about $2.80 on average per worker per day and includes the replacement cost of worn or severely contaminated clothing.[3–27]

3.4.4.2.2.5 Overall Personnel Cost Estimate

This section will give an overall personnel cost estimation given the assumptions of a given number of workers, and a given number of shifts per day. This cost estimation only considers the number of employees required for operations as specifically defined in this portion (Repository Operations, Section 3.4) of the document.

Two eight hour shifts per day are assumed. This is derived assuming 35 canisters per week are emplaced and a five day week is planned. Seven canisters per day are emplaced and therefore a shift consists of the emplacement of four casks, the environmental monitoring that accompanies it, and the radiation protection procedures.

A crew of ten responsible is emplacement operations; two drivers, one driver supervisor, one emplacement tunnel supervisor, and one emplacement supervisor. The other five are responsible for the rail emplacement, temporary shield door emplacement and removal, and backfilling procedures. Each of the supervisors are also qualified emplacement vehicle drivers. Eight are responsible for the radiation protection procedures, and a twelve–man maintenance crew. The environmental monitoring group consists of five.

A total of 35 people per shift is required the defined underground operations. For cost estimation an underground crew of 40 is used. This determines the salary and fringe benefit cost for the workers at $1,600,000 per year. Requiring that all workers use a film badge and pocket dosimeter, this dosimetry cost is $5,060 per year. Assuming each worker receives four bioassay counts a year at $20 per whole body count, the total yearly cost bioassay is $3,200 per year. The protective clothing costs is $28,000 per year. Therefore the total personnel costs defined in this section is $1,636,260. A conservative estimate of $3 million is given to account for possible errors and discrepancies in the data given, also, the data is referenced in 1979.

3.4.4.2.3 Operational Cost Summary

The total operational cost esimate includes the maintenance of all equipment and systems specifically mentioned in this portion and the personnel costs of all underground operations. The total of both components is 13 million dollars. A total conservative estimate of $15 million.

3.5 Summary

The approach to designing this repository was to build the best repository that met the necessary criteria using the most simple, yet adequate methods available. The result was that this repository design is simpler to construct and also more economical than the designs proposed by the DOE [3–1]. The technical highlights of this portion of the design include:

- Highly reliable corrosion barrier material to contain the waste
- Thermal loading of the design limited to DOE guidelines due to excessive surface temperature rise
- Acceptable radiation levels during all phases of waste emplacement
- Layout that minimizes excavation lead time and total amount mined
- Mechanical excavation used throughout to minimize disturbance to the geologic environment
- Waste delivered to the repository horizon using a gently sloping ramp
- Movement of canisters from the surface facility to the emplacement hole without the need for underground transfer using a rail–mounted vehicle
- Horizontal emplacement in downward sloping waste emplacement holes

In many cases, the technical criteria were not addressed and the performance of the system involved was assumed. The key assumptions were outlined, and justifications were given for their use. Preference was given to "off–the–shelf" technology to provide known reliability and lower cost.

The overall costs of the repository are summarized from Sections 3.2.3, 3.3.3, and 3.4.4. The operating expense from 1988 to 2004 is $50 million per year for research and development activities. The operating expense in 2005 is $200 million for repository mining, operations, research, and waste package materials. The years subsequent to 2005 until the repository is closed have operatin expenses of $150 million. The capital expenditures are assumed to be incurred all in 2005. The capital expenditure in 1988 dollars is $566 million. The final decommissioning cost was assumed to be $50 million. Many assumptions were made as to the costs estimates, and every effort was made to make conservative estimates when limited data was available.

3.6 References

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CHAPTER 4

WASTE DISPOSAL COSTS

4.1 Introduction

4.1.1 Motivation and Overview

Choosing a nuclear waste isolation system involves evaluation of many engineering options. As in any large scale engineering project, cost is a useful if not essential, criterion and motivation for making design tradeoff decisions.

This chapter addresses how a computer model, "WADCOM II — Waste Disposal Cost Model II: An Extension of WADCOM", was employed in exploring the cost–effectiveness of various nuclear waste isolation disposal issues (References D–1, D–2). The model was applied to the Yucca Mountain site, using the design criteria developed in chapters 2 and 3. WADCOM II was obtained courtesy of Spyridon Tzemos, of Battelle Columbus Laboratories and modified by the author of this chapter (M. Siegel) to run on an IBM–PC. Special thanks are extended to Rachel Morton, an MIT computer consultant for the Nuclear Engineering Department, who assisted in getting WADCOM II running. An independent cost evaluation was compiled for comparison with the WADCOM II results.

4.1.2 Research Goals

The main objective of this chapter was to estimate the total waste management system cost using the WADCOM II code and an independent cost evaluation. This objective was divided into:

i) finding the major contributions to the total system cost

ii) compiling an independent evaluation of the total system cost.

4.1.3 Outline of the Present Work

In Section 4.2, the WADCOM II code is introduced. A discussion of the WADCOM II features is immediately followed by a summary of how this code was applied to fit the needs of this project. In Section 4.3, an independent cost evaluation is compiled for comparison with the WADCOM II results presented in Section 4.2.7. In Section 4.4, summaries of the present work are given, and the problems and limitations of the present work and suggestions for future research are discussed.

4.2 WADCOM II (Waste Disposal Cost Model II)

The WADCOM II code described here was used as a quick and flexible way of exploring issues and their implicit economic tradeoffs. By using this model, insight from this preliminary analysis can motivate a more detailed subsequent analysis into the economics of hypothetical waste disposal scenarios.

In choosing an appropriate cost model, the emphasis was placed on successfully finding the major contributors to the total system cost. Due to the innovative design chosen here, accurate data was not readily available.

4.2.1 Background

WADCOM II (D–1) is an extension of the original WADCOM code (D–2). WADCOM II has all the basic capabilities of WADCOM, but also contains additional features that allow simulation of a greater variety of paths by which waste can move from reactor discharge to permanent disposal. This greater variety is attributed to spent fuel (SF) consolidation and possible overpacking in universally usable waste packages. Note, either of these two activities—consolidation and overpacking in universally usable waste packages – may take place at any of various locations.

4.2.2 Outline

The remainder of Section 4.2 is devoted to explaining WADCOM II in greater detail. Whenever possible, a discussion of the WADCOM II features is immediately followed by a summary of how this code was applied to fit the needs of this project. Specifically, a further discussion of the disposal scenarios and model's logic; its data requirements; and its generated waste disposal cost components regarding the Yucca Mountain High Level Waste Repository follows.

4.2.3 Disposal Scenarios and Model Logic

WADCOM II (D–1) is a relatively simple, aggregated representation of various nuclear waste management systems. Its logic is based on a number of factors. The factors discussed in this section are: first, the various disposal scenarios; and second, the model's logic.

WADCOM II is written to allow for a wide array of various hypothetical waste disposal options. It can simulate 10 nuclear waste disposal paths which cover the discharge of spent fuel at reactors, through shipping, storage, reprocessing activities, to ultimate disposal in a mined geologic repository. These paths consist of different sequences of activities such as SF consolidation and overpacking in a universally usable waste package. These activities can take place at either the reactor, monitored retrievable storage (MRS) facilities, or the repository.

The ten paths that can be simulated by WADCOM II are described in Table 4.1. Since this project did not consider reprocessing, paths 3 and 4 were avoided. Also, this project chose no generic packaging, hence paths 5b, 6b, and 9b were ignored. The paths of interest to this project are illustrated in Figure 4.1.

Table 4.1 Definitions of the WADCOM II Nuclear Waste Disposal Paths

Group A: Consolidation and Packaging at Repository

1 Unconsolidated SF transported from reactor to repository where consolidation and overpacking in borehole packages takes place.

2 Unconsolidated SF transported from reactor to MRS; unconsolidated SF transported from MRS to repository where consolidation and overpacking in borehole packages takes place.

3 Unconsolidated SF transported from reactor to reprocessing; CHLW and TRU transported from reprocessing to repository where overpacking in borehole packages takes place.

4 Unconsolidated SF transported to MRS; unconsolidated SF transported from MRS to reprocessing; CHLW and TRU transported from reprocessing to repository where overpacking in borehole packages takes place.

Group B: Consolidation at Reactor; Packaging either at Reactor or Repository

5a Consolidation of SF at reactor; consolidated SF and RHTRU transported to repository where overpacking in borehole packages takes place.

5b Consolidation of SF and overpacking in universally usable packages at reactor; packaged SF and RHTRU transported to repository.

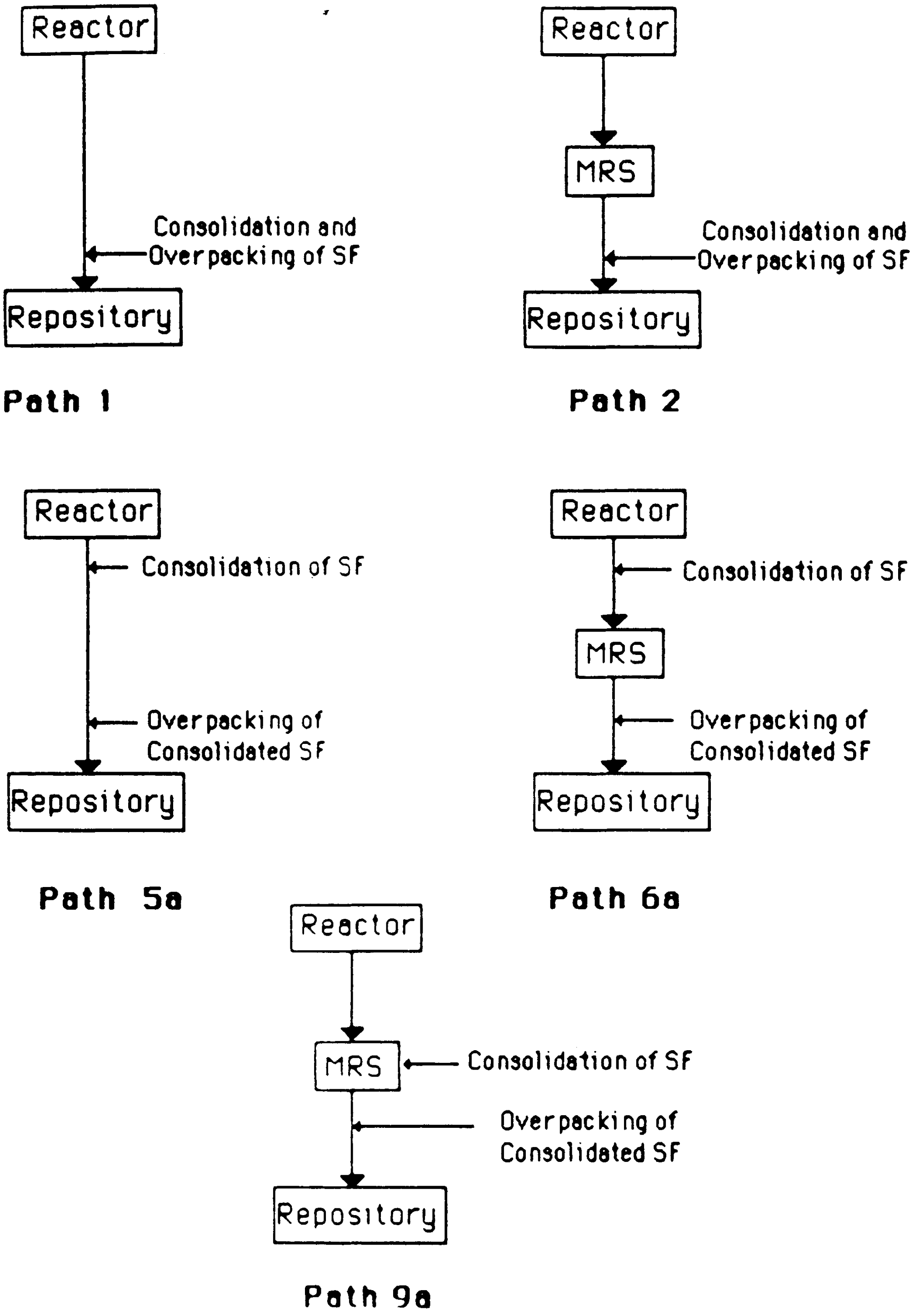
6a Consolidation of SF at reactor; consolidated SF and RHTRU transported to MRS; consolidated SF and RHTRU transported from MRS to repository where overpacking in borehole packages takes place.

6b Consolidation of SF and overpacking in universally usable packages at reactor; packaged SF and RHTRU transported to MRS; packaged SF and RHTRU transported from MRS to repository.

Group C: Consolidation of SF at MRS; Packaging either at MRS or Repository

9a Unconsolidated SF transported from reactor to MRS; SF consolidated at MRS and transported, along with RHTRU to repository.

9b Unconsolidated SF transported from reactor to MRS; SF consolidated and overpacked in universally usable packages at MRS and transported, along with RHTRU, to repository.



Path 1

Path 2

Path 5a

Path 6a

Path 9a

Figure 4.1 Paths of Interest to the Yucca Mountain Project (Paths 1, 2, 5a, 6a, 9a)

Note, this project chose not to consider Spent Fuel Consolidation and thus WADCOM II's DATABASE (section 4.2.6 and Appendix A) was modified to account for this design feature. Figure 4.1 is essentially 2 scenarios when SF consolidation does not occur during the waste disposal flow path: first, reactor to repository – which implies that path 1 should yield the same total system costs as path 5a; and second, reactor to MRS to repository – which implies that path 2 should yield the same total system costs as path 6a or path 9a. Appendix D shows a slight descrepancy in total system costs for these different paths. After defining a scenario, the model 's logic is established.

Depending upon the path being simulated, the main program in WADCOM II calls various material flow and cost subroutines, see Figure 4.2. Note, no optimization with repect to waste package size and spacing in the repository was studied in this project. Specifically, the model begins by calculating SF discharges from reactors. The model then calculates, in various sequences, SF consolidation costs, SF overpacking costs, waste transportation costs, waste storage costs for MRS facilities, and disposal costs for mined geologic repositories.

The particular path chosen, specified by the user in the USERFILE, defines the actual order in which these costs are calculated. The necessary data requirements, which includes a USERFILE and DATABASE, for the WADCOM II code are discussed next.

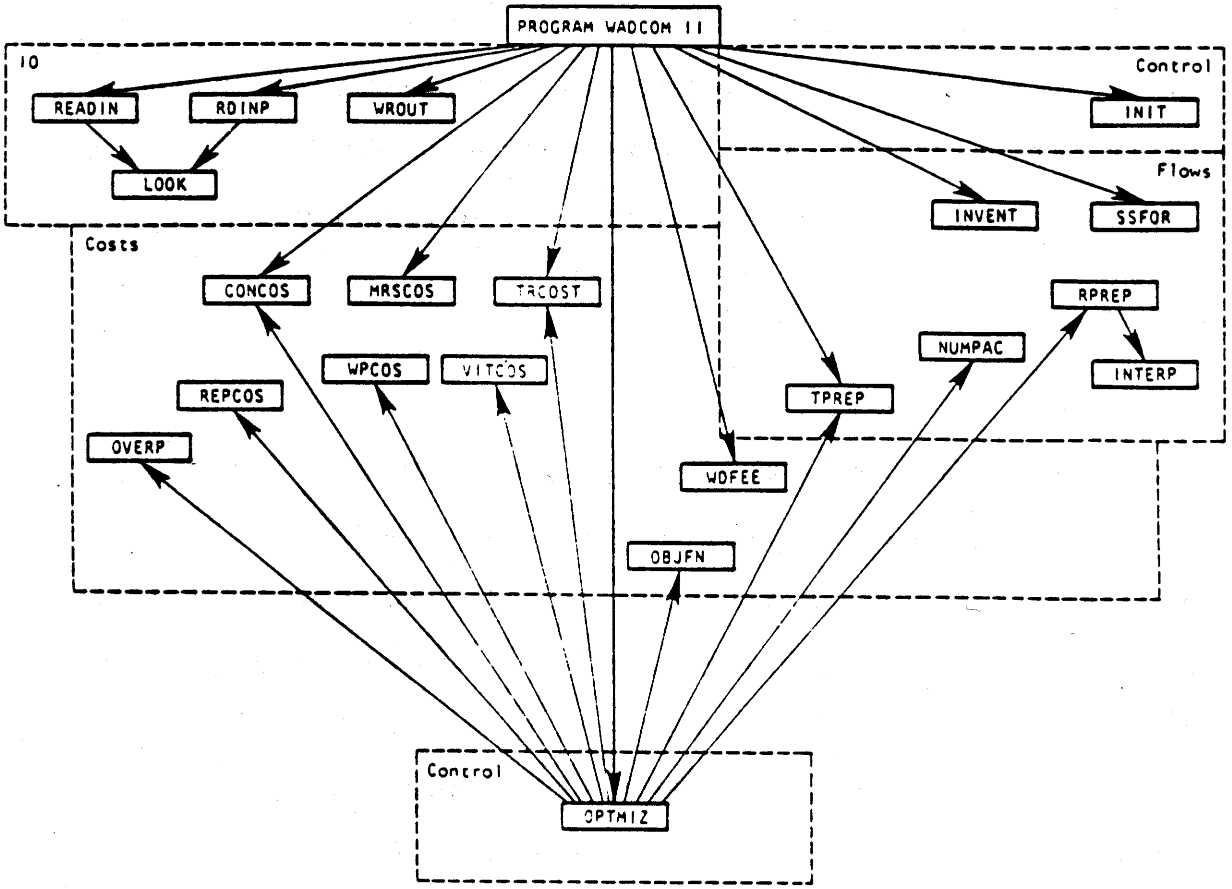


Figure 4.2 Calling Hierarchy of Subroutines in the WADCOM II Model

4.2.4 Data Requirements

WADCOM II requires two sets of data: first, a USERFILE and second, a DATABASE. The USERFILE consists of data inputs that define the particular path one wishes to simulate and initializes other model variables. The DATABASE consists of data inputs that one needs to change less frequently in order to simulate any of the given paths. Data inputs in the DATABASE primarily represents reference design and cost data that are scaled by the code. The DATABASE is where spent fuel consolidation was removed from being a factor in the total system cost for the Yucca Mountain Project (T–1).

4.2.5 USERFILE

The USERFILE is changed frequently so this section addresses how the USERFILE data inputs were tailored to fit the needs of this project. An actual USERFILE is shown in Table 4.2. The major variables that comprise the USERFILE and were of importance to the Yucca Mountain repository are highlighted in Table 4.3. Each of the data inputs is discussed in turn.

Input Echo Flag determines whether the data inputs, from both the USERFILE and DATABASE, are to be printed along with the output of the model simulation.

Spent Fuel Generation Logic Flag identifies whether the forecast of SF used in all the subsequent waste disposal calculations is to be calculated within WADCOM II, by the SFOR subroutine, or to be read from either the high, medium, or low forecasts included within the DATABASE.

Table 4.2 WADCOM II USERFILE

```
                USERFILE FOR WADCOM
                -----------------------

INPUT ECHO FLAG
---------------
1       YES
0       NO
*
0

SPENT FUEL GENERATION LOGIC FLAG
--------------------------------
0       COMPUTE FROM GROWTH RATES (BASE YEAR 1982)
1       HIGH DEFAULT EXOGENOUS
2       MEDIUM DEFAULT EXOGENOUS (1960-2000)
3       LOW DEFAULT EXOGENOUS
*
1

REPOSITORY GEOLOGY SPECIFICATION
--------------------------------
1       SALT
2       TUFF
3       GRANITE
4       BASALT
*
2

RADIOACTIVE WASTE FLOW PATH LOGIC FLAG
--------------------------------------
1       REACTOR TO REPOSITORY WITHOUT CONSOLIDATION
2       REACTOR TO MRS FACILITY
                TO REPOSITORY WITHOUT CONSOLIDATION
3       REACTOR TO VITRIFICATION
                TO REPOSITORY
4       REACTOR TO MRS FACILITY
                TO VITRIFICATION
                TO REPOSITORY
5       REACTOR WITH CONSOLIDATION TO REPOSITORY
6       REACTOR WITH CONSOLIDATION TO MRS TO REPOSITORY
9       REACTOR TO MRS WITH CONSOLIDATION TO REPOSITORY
*
1

GENERIC PACKAGING OPTION
------------------------
0       NO GENERIC PACKAGING
1       GENERIC PACKAGING AT REACTOR
2       GENERIC PACKAGING AT MRS
*
0
```

Table 4.2 (Continued)

```
START OF FACILITY OPERATIONS AND BASE YEAR
------------------------------------------
                                     COST
                MRS        MRS       BASE
REPOSITORY   STORING RETRIEVAL       YEAR
*
      2005      2003      2003       1988

TOTAL CAPACITY OF FACILITY (MTU)
--------------------------------
                MRS
REPOSITORY  FACILITY
*
    150000    150000

DESIGN RECEIPT RATE OF FACILITY (MTU/YR)
----------------------------------------
                MRS       MRS
            FACILITY  FACILITY
REPOSITORY   STORING RETRIEVAL
*
      4000      4000      4000

DESIGN AGE OF WASTE SPECIFICATION
---------------------------------
1        10  YRS
2        20  YRS
3        30  YRS
4        50  YRS
5        100 YRS
*
1

PRICE TREND COMPUTATIONS  0-NO / 1-YES
--------------------------------------
*
1

DISCOUNT FACTOR
---------------
*
0.100

INITIAL INSIDE PACKAGE DIAMETERS (CM)
-------------------------------------
  BOREHOLE    SIMPLE
*
      75.0     100.0
```

Table 4.2 (Continued)

```
NUMBER OF ITERATIONS FOR COST OPTIMIZATIONS
-------------------------------------------
  BOREHOLE    SIMPLE
*
         1         1


PACKAGE DIAMETER STEP SIZES (CM)
--------------------------------
  BOREHOLE    SIMPLE
*
      2.00      2.00


NUMBER OF HEAT TRANSFER CURVES (MAXIMUM-5)
------------------------------------------
*
1


NUMBER OF POINTS PER LIMIT CURVE (MAXIMUM-5)
--------------------------------------------
CENTERLINE NEAR  250        FAR   THERMAL    THERMAL
   500 DEG FIELD DEG      FIELD   LIMIT 4    LIMIT 5
*
         2         0          0         0          0
```

Table 4.3 WADCOM II USERFILE: Yucca Mountain Repository Project Highlights

Spent Fuel Generation Logic Flag	High Default Exogenous
Repository Geology Specification	Tuff
Radioactive Waste Flow Path Logic Flag	varied (Fig. 4.1)
Generic Packaging Option	No
Start of Facility Operations and Base Year	Storing = 2003 Repository = 2005 Cost Base Year = 1988
Total Capacity of Facility (MTU)	Repository = 150,000 MRS = 150,000
Design Receipt of Facility (MTU/Yr)	4000
Design Age of Waste Specification	10 yrs
Price Trend Computation	Yes
Discount Factor	0.10
Initial Inside Package Diameter	Borehole = 75.00 cm
Number of Iterations for Cost Optimization	not studied
Package Diameter Step Size	not studied
Number of Heat Transfer Curves	1
Number of Points Per Limit Curve	2

Repository Geology Specification indicates the geologic medium assumed for the repository and directs a subroutine to select the values representing the appropriate geology.

Radioactive Waste Flow Path Logic Flag guides the model's logic so that the correct path is simulated. Note, a complete specification of one of the ten paths also requires a value for the next input, the Generic Packaging Option. The waste flow path flag does not indicate whether the path involves the use of universally usable overpack.

The value of the Generic Packaging Option was always chosen to be neglected (zero) for this project.

Also, no vitrification path was ever considered , hence as stated in Fig. 4.1 only paths 1, 2, 5a, 6a, and 9a were considered for the Yucca Mountain Repository.

There are four values one must assign to the Start of Facility Operations and Base Year indicator. The first is the repository's initial year of operations. The second is the initial year of storing operations at the MRS (the value is ignored if paths 2, 4, 6, or 9 are not selected). The third is the initial year of retrieval at the MRS (again, the value is ignored if paths 2, 4, 6, or 9 are not selected). The fourth is the base year for cost indexing. The cost indexing value is the year for which costs are discounted; the value is used in the real price trend calculations and the present value calculation.

The values of the Total Capacity of Facility (MTU) variable indicate the maximum inventories of waste, in MTU, to be accomodated at the repository and MRS respectively. When the respective inventories reach these values, the calculations stop. Note, one should always assign to the MRS capacity a value equal to or greater than the repository capacity value, when paths 2, 4, 6, or 9 are being simulated.

Three values must be assigned to the Design Receipt Rate of Facility (MTU/yr) variable. The values are used, along with the actual receipt rates at the respective facilities, to scale both capital and operating costs for the repository and MRS facilities.

The Design Age of Waste Specification variable indicates the assumed age (at least this age, e.g. ≥ 10 years) of the waste at the time of emplacement. This variable is used to select the proper set of thermal limit data in calculating package size and spacing.

The Price Trend Computation variable is used to indicate whether real prices trends are to be incorporated in the cost calculations. If the value is 0, no real price trend calculations are performed; costs are not adjusted for changes in relative prices over time. If the value is 1, costs are adjusted for changes in relative prices over time and then converted back to the desired constant dollar base.

The value of the Discount Factor indicates the real discount rate (net of the rate of inflation) used in discounting costs to the present value. Since all costs calculated in WADCOM II are constant dollar costs, the discount factor should be the real cost of money and not the nominal cost.

The value of the Initial Inside Package Diameter variable is used to initialize the optimization of waste package size and spacing. Since this project did not attempt optimization of waste package size and spacing, this variable and Number of Iterations for Cost Optimization and Package Diameter Step Sizes variables were ignored.

A maximum of 5 curves may be used to define the Number of Heat Transfer Curves variable used to define the design space from which the waste package size–spacing combination is calculated. This variable is generally the minimum necessary to define the design space. These heat transfer curves are then read as data points from the DATABASE.

A maximum of 5 points may be used to define the Number of Points Per Limit Curve variable. This variable indicates the number of points read from the DATABASE for each heat transfer curve read.

4.2.6 DATABASE

The DATABASE consists of data inputs that are changed less frequently (e.g. No SF consolidation) in order to simulate any of the given paths. DATABASE is a sequential data file containing data inputs that the subroutine RDINP reads into the WADCOM II program. The DATABASE contains 120 variables arranged under functional subheadings in numerical order.

Appendix A, an actual listing of the DATABASE used for this project, shows the input by function, number, and title and includes representative values. Appendix B provides a definition of the variables and the source of their values.

4.2.7 Output and Review of Cost Components

WADCOM II produces both summary and relatively detailed cost tables as output. Table 4.4 is an example of a summary cost matrix generated by WADCOM II using this projects criteria for the Yucca Mountain Repository. The breakdown of the summary cost matrix parameters is given in Table 4.5.

Note, the Repository system total costs is approximately 80% of the overall system costs. The major portion of the repository system costs is due to operations costs (83%). Borehole mining is 77% of the operations costs for the repository system.

Appendix C, an actual listing of the WADCOM II output, shows the representative values. Appendix D provides a collection of various summary matrices obtained by editing the USERFILE.

Table 4.4 <u>Summary Cost Matrix I: Project Criteria for Yucca Mountain</u>

```
TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

     1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
     2) REPOSITORY GEOLOGY: TUFF
     3) WASTE FLOW PATH: REACTOR TO REPOSITORY
     4) START OF REPOSITORY OPERATIONS: 2005
     5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
     6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
     7) DESIGN AGE OF WASTE: 10 YEARS


COST UNITS: 1988 $MILLION GIVEN

     1) DISCOUNT FACTOR: .100
     2) A REAL PRICE TREND COMPUTATION


                           ------------------------------------------------------------
                           -              -              -              -              -
                           -   CAPITAL    -              -    DECOM-    -              -
                           - CONSTRUCTION -  OPERATIONS  -  MISSIONING  -    TOTAL     -
                           -    COSTS     -    COSTS     -    COSTS     -    COSTS     -
                           -              -              -              -              -
-------------------------------------------------------------------------------------------
-                          -              -              -              -              -
- INTERIM STORAGE SYSTEM   -          .00 -          .00 -          .00 -          .00 -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- VITRIFICATION SYSTEM     -          .00 -          .00 -          .00 -          .00 -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- WASTE PREPARATION SYSTEM -       171.19 -       199.41 -         1.08 -       371.68 -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- REPOSITORY SYSTEM        -       250.13 -      1247.89 -         1.75 -      1499.77 -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- CONSOLIDATION SYSTEM     -          .00 -          .00 -          .00 -          .00 -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- TRANSPORTATION SYSTEM    -         7.69 -        16.36 -          .00 -        24.04 -
-                          -              -              -              -              -
-------------------------------------------------------------------------------------------
-                          -              -              -              -              -
- TOTAL COSTS              -       429.00 -      1463.66 -         2.84 -      1895.50 -
-                          -              -              -              -              -
-------------------------------------------------------------------------------------------
```

Table 4.5 Breakdown of the Summary Cost Matrix

I. Breakdown of Interim Storage Costs

A. Capital Construction Costs
    1. Receiving and Packaging
    2. Drywell Storage

B. Operations Costs
    1. Total Storing Operations
        a. Personnel
        b. Utility/Maintenance
        c. Drywells
        d. Canisters
    2. Total Caretaker Operations
        a. Personnel
        b. Utility/Maintenance
    3. Total Retrieval Operations
        a. Personnel
        b. Utility/Maintenance

C. Decommissioning Costs

II. Breakdown of Waste Preparation Costs

A. Capital Construction Costs—Packaging Facility
    1. Overhead
    2. Receiving and Storage
    3. Packaging
    4. Disassembly

B. Operations Costs
    1. Packaging Facility
        a. Labor
        b. Support Personnel
        c. Replacement
    2. Materials Components
        a. Borehole Carbon Steel
        b. Borehole Overpack Material (titanium)
        c. Simple Carbon Steel
        d. Generic Package

C. Decommissioning Costs

Table 4.5 Continued

III. Breakdown of Repository System Costs

- A. Capital Construction Costs
  - 1. Total Structure
    - a. Site
    - b. Receiving Facility
    - c. Transfer Equipment
    - d. Ventilation Structures
    - e. Support and Utilities
  - 2. Total Mining
    - a. Waste Shafts and Hoists
    - b. Rooms
    - c. Men and Materials Shaft
    - d. Shaft Pillar Zone
    - e. Corridors
    - f. Rock Handling and Disposal
    - g. Ventilation Supply Shaft
    - h. Development Exhaust Shaft
    - i. Ventilation Flow Paths
    - j. Repository Exhaust Shafts

- B. Operations Costs
  - 1. Total Structure
    - a. Receiving Facility
    - b. Waste Shafts and Hoists
    - c. Transfer Equipment
    - d. Men and Materials Equipment
    - e. Ventilation Structures
    - f. Ventilation Supply Shaft
    - g. Support and Utilities
  - 2. Total Mining
    - a. Rooms
    - b. Boreholes
    - c. Corridors
    - d. Rock Handling and Disposal
    - e. Ventilation Flow Paths

Table 4.5 Continued

IV. Breakdown of Consolidation Cost Components

- A. Capital Construction Costs
- B. Operations Costs
- C. Decommissioning Costs

V. Breakdown of Transportation Cost Components

- A. Capital Construction Costs
  - 1. To Interim Storage Facility—Spent Fuel Assemblies
  - 2. To Repository—Spent Fuel Assemblies
- B. Operations Costs
  - 1. To Interim Storage Facility
    - a. Cask Handling
    - b. Maintenance
    - c. Traffic Management
  - 2. To Repository
    - a. Cask Handling
    - b. Maintenance
    - c. Traffic Management

4.3 Independent Cost Evaluation

The factors comprising total system cost have been studied in Chapters 2 and 3. The goal of this section was to use the summary values obtained from previous chapters. For a breakdown of the summary values refer back to Sections 2.5 and 3.5.

4.3.1 Compiling the Factors Comprising Total System Cost

Table 4.6 is a summary cost matrix compiled from each section's independent cost evaluations. Since the operating costs for the Waste Preparation System, Repository and Transportation were quoted per year the following calculations were necessary to obtain cumulative amounts in 1988 dollars.

Note: (P/A, i%, n) = The present worth of a uniform annual series given an interest rate (i%) and over n years.

from section 2.5 ==> Waste preparation system
Cumulative Dollars = (125$/yr)(P/A, 10%, 40 yrs) = 1222 $

from section 3.5 ==> Repository
Assumption: The operating costs quoted in this section include cost escalation

Given: i) from 1988 – 2004; there is a 50 $ million/yr operating expense for research and development.

ii) at 2005; there is a 200 $ million/yr operating expense for repository mining, operations, research and waste package materials. This is followed by a 120 $ million/yr operating expense until closing in year 2045.

from (i) implies
Cumulative Dollars (i) = (50 $/yr)(P/A, 10%, 16 yrs) = 391.2 $
Cumulative Dollars (ii) = 200 + 120(P/A, 10%, 39 yrs) = 1370.8 $
Cumulative Dollars = 391.2 + 1370.8 = 1762.0 $

from section 2.5 transportation
Cumulative Dollars = (32.5$/yr)(P/A, 10%, 40 yrs) = 317.8 $

Table 4.6 Summary Cost Matrix: Independent Evaluation

```
SUMMARY COST MATRIX : Project Criteria for Yucca Mountain Project

INDEPENDENT COST EVALUATION

TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

     1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
     2) REPOSITORY GEOLOGY: TUFF
     3) WASTE FLOW PATH: REACTOR TO REPOSITORY
     4) START OF REPOSITORY OPERATIONS: 2005
     5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
     6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
     7) DESIGN AGE OF WASTE: 10 YEARS

COST UNITS: 1988 $MILLION GIVEN

       DISCOUNT FACTOR: .100


                           ------------------------------------------------------------
                           -              -              -              -              -
                           -   CAPITAL    -              -    DECOM-    -              -
                           - CONSTRUCTION -  OPERATIONS  -  MISSIONING  -    TOTAL     -
                           -    COSTS     -    COSTS     -    COSTS     -    COSTS     -
                           -              -              -              -              -
---------------------------------------------------------------------------------------
-                          -              -              -              -              -
- INTERIM STORAGE SYSTEM   -      .00     -      .00     -      .00     -      .00     -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- VITRIFICATION SYSTEM     -      .00     -      .00     -      .00     -      .00     -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- WASTE PREPARATION SYSTEM -    1271.2    -     1222     -     100.3    -    2593.5    -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- REPOSITORY SYSTEM        -      536     -     1762     -      50      -     2348     -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- CONSOLIDATION SYSTEM     -      .00     -      .00     -      .00     -      .00     -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- TRANSPORTATION SYSTEM    -     24.2     -     317.8    -      .00     -     342.0    -
-                          -              -              -              -              -
---------------------------------------------------------------------------------------
-                          -              -              -              -              -
- TOTAL COSTS              -    1831.4    -    3301.8    -     150.3    -    5283.50   -
-                          -              -              -              -              -
---------------------------------------------------------------------------------------
```

4.3.2 Comparison with WADCOM II Results

From Table 4.4, WADCOM II gave a total system cost of approximately \$1.9 billion; whereas, fròm Table 4.6, the independent cost evaluation yielded a total system cost of approximately \$5.3 billion — where all amounts are in 1988 dollars.

The major cost components of the independent cost evaluation are the Waste Preparation System (49 % of total cost) and the Repository System (44 % of total cost).

In order to compare the Levelized Unit Cost of disposal in 1988 dollars, it is found that

$$\text{LUC} = \frac{\overset{\text{(Table 4.4 or 4.6)}}{\text{(Total System Cost in mills)}}\overset{\text{(0.10)}}{\text{(Carrying Charges)}}}{\begin{array}{c}\text{(Receiving Rate = 4000 MT/yr)} \\ \text{(or } 9.6 \times 10^{11} \text{ kwhr(e)/yr)}\end{array}}$$

LUC for WADCOM II = 0.2 mills/kwhr(e)

LUC for Independent Cost Evaluation = 0.55 mills/kwhr(e)

4.4 Chapter Summary

4.4.1 Conclusions

Total system costs in 1988 dollars: WADCOM II gave \$1.9 billion ; whereas, the independent cost evaluation yielded \$5.3 billion. In terms of Levelized Unit Cost of disposal: WADCOM II gave 0.2 mills/kwhr(e); whereas, the independent cost evaluation yielded 0.55 mills/kwhr(e). This is still less than the DOE fee of 1 mill/kwhr(e). The difference in total system cost between WADCOM II and the independent cost evaluation can be attributed to this project's design has a large surface storage capability. This large surface storage capability is due to many casks stored on site and this feature was not accounted for in WADCOM II. The differences in Levelized Unit Cost of Disposal between the system economics methods (WADCOM II and the independent cost evaluation) and DOE's can be somewhat attributed to including site characterization and research and development in the DOE cost assessment of 1 mill/kwhr(e).

4.4.2 Problems and Future Work

To obtain the preceding results, a number of assumptions have been made. Of these, some have significantly affected the final results and motivate future work.

i) The lack of accurate or more detailed data.

ii) The WADCOM II thermal limit standards were not able to meet this project's design criteria.

iii) No attempt was made to optimize the combination of waste package size and pitch (in the repository) which would have led to lower total system cost. As previously stated by Seong (S–1), the basis for the correlation of canister diameter, pitch, and waste age subject to the repository thermal design limits – the most essential part of the WADCOM II model – is not clear.

Based on the preceding discussions, the following additional work is recommended.

i) Examination of waste package design concepts and modifying WADCOM II to establish a correlation for relating pitch, waste age, and canister diameter under various thermal design limits. A possible modification is for WADCOM II to adopt the correlation of waste pitch, diameter, and age derived by using Malbrain and Lester's (M–1) discrete/homogenized Thermomechanical Model. The goal here would be to optimize the waste package size and pitch to get lower total system cost.

ii) Examination of the price trends, discount rates and inflation rates regarding the sensitivity of these parameters over a time horizon.

iii) A more detailed or better cost estimates regarding waste package designs and borehole mining.

The two methods to obtain total system costs, WADCOM II and the independent cost evaluation, have motivated the need for more detailed and better cost estimates.

4.5 Chapter References

D–1 D.G. Dippold, S. Tzemos, and P.S. Tarapore, "WADCOM II – A Waste Disposal Cost Model: An Extension of WADCOM," Battelle Columbus Division, P/TM–3, 1984.

D–2 D.G. Dippold, B.E. Urbschat and S. Tzemos, WADCOM: A Waste Disposal Cost Model", Technical Report, Battelle's Columbus Laboratories, ON1–6, June 1983.

M–1 C.M. Malbrain and R.K. Lester, "Impact of Thermal Constraints on the Optimal Design of High–Level Waste Repositories in Geologic Medium", Topical Report, MIT, 1982.

S–1 P.H. Seong, "Optimization of Waste Age and Canister Diameter for Minimum Waste Management System Cost", M.S. Thesis, Dept. of Nucl. Eng., MIT, 1984.

T–1 S. Tzemos, personal communication, Battelle Columbus Division, Telephone Conversation, April 27, 1988.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

A conceptual design has been presented for a High Level Waste (HLW) disposal system based on an underground repository located at Yucca Mountain, Nevada. The system, which includes transportation from reactor to repository, is capable of disposing of all the spent fuel from currently–commited–to U.S. light water reactors through the middle of the next century. It is designed to satisfy contemporary federal criteria related to public health and safety.

The subject design represents a one–term one–subject–worth effort by the nine students registered in the combined graduate/undergraduate systems design subjects of the Nuclear Engineering Department at M.I.T. during Spring Term 1988.

5.2 Summary and Conclusions

Figure 5.1 is a schematic showing the major features of the proposed High Level Waste disposal system, as highlighted in Table 5.1. A more detailed synopsis follows.

The at–reactor operations start with the delivery of thirty storage/transportation casks to a reactor site. A cask transporter is also dropped off at the reactor site to facilitate cask movement. The casks are then taken to the spent fuel assembly pool and filled with the oldest spent fuel. The casks are sealed, leak tested and taken back to the holding pad to await transportation. Reactors that do not have a rail spur use a smaller cask capable of being transported on a truck; in all other respects, the at–reactor operations remain essentially the same. These operations were determined to be the best compromise between the repository and reactors. Although the reactors are required to upgrade their cranes if deemed necessary to lift the smaller truck casks, everything else will be supplied and/or funded by the repository operators.

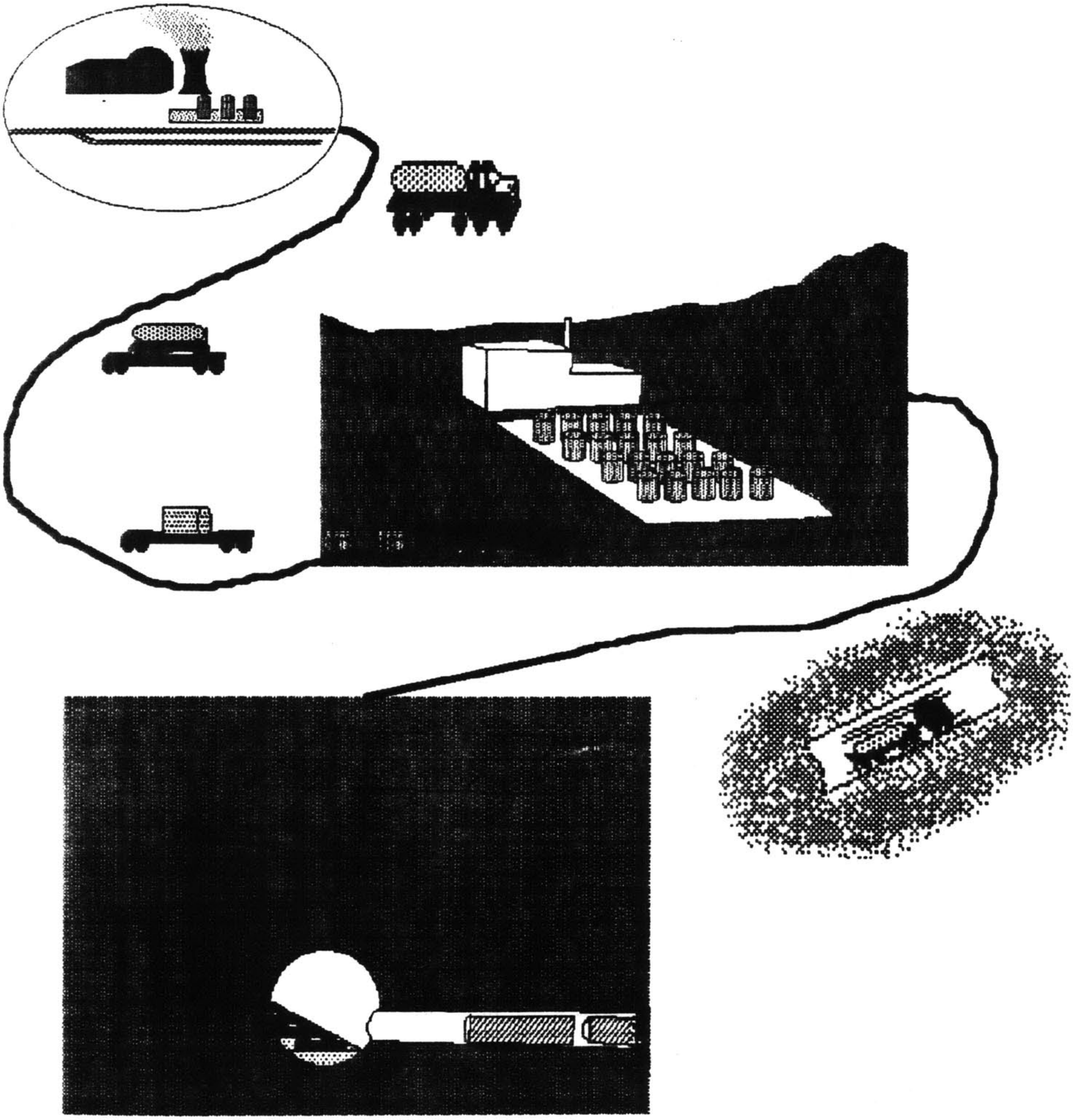


FIGURE 5.1 Schematic of the Repository Design Highlights

Table 5.1 - System Design Highlights

- Use of unit trains (including piggyback cars for truck cask transporters where required) for periodic (once every ten years at each reactor) removal of old (cooled ≥ 10 yrs.) spent fuel from at-reactor storage facilities
- buffer storage at the repository site using dual purpose transportation/storage casks of the CASTOR V/21 type
- repackaging of the spent fuel from the dual purpose transportation/storage casks directly into special-alloy disposal canisters as intact fuel assemblies, without rod consolidation
- emplacement into a repository of modular design having a maximum total capacity of 150,000 MT and an annual handling capability of 4000 MT/yr
- use of excavation techniques that minimize disturbance, both mechanical and chemical, to the geologic environment
- Incoloy 825 waste canisters arrayed to provide 57 kW/acre thermal loading optimized to the projected inventories
- include a unit rail mounted vehicle for both the transportation and emplacement of the canister from the surface facilities to the underground repository
- cost-effectiveness of the Yucca Mountain Site Criteria was studied via: a computer model, "WADCOM-II — Waste Disposal Cost Model II"; and an independent cost evaluation by the members of the design team. The total system cost (in constant 1988 dollars) was 1.9 billion dollars by WADCOM-II, and 5.3 billion dollars from the independent cost evaluation, resulting in a levelized disposal cost of 0.2 mills/kW-hr by WADCOM-II and 0.55 mills/kW-hr by the independent cost evaluation.

Transportation, while not the dominant cost contributor of the waste disposal system, is nevertheless one of the most important issues to address in the early stages of planning and construction. Although most technical issues related to transportation have been resolved, due to the high degree of contact with the general public, there is a greater probability of the transportation phase of operations being delayed or halted by excessive media attention, litigation, and/or political conflicts. Therefore, special care must be taken to insure that critical transportation issues are settled as early in the licensing process as possible.

Use of the CASTOR V/21 type cask greatly simplifies the operations at the repository. The dual transportation and storage licensing of this cask avoids the expense, time, and facilities required to reload the incoming spent fuel from transportation casks into separate storage casks. Since some reactors do not have rail spurs, the repository surface facility cannot rely solely on the large dual purpose casks, and special allowances were made to include truck casks.

The buffer storage facility consists of an initial capacity of 1600 MT of spent fuel, with the ability to increase capacity up to 4000 MT maximum capacity in a modular fashion. This modular design, indicative of dry storage facilities, reduces the initial capital outlay and postpones additional expenditures until they are required.

The Repackaging and Handling (R&H) facility takes the intact spent fuel elements from the dual purpose transportation/storage casks and repackages them into special–alloy disposal canisters. The fuel assemblies are loaded into the canisters intact, and no rod consolidation is done. The filled disposal canisters are welded closed and backfilled with helium. The helium is an excellent gaseous heat conductor, and also provides a simple and effective means for leak testing the sealed canister. The canister is decontaminated by a freon spray wash and moved to a pre–emplacement lag storage cell. Having lag storage available improves system logistical flexibility between the surface facilities and the underground repository. The disposal canisters are removed from lag storage and moved into a horizontal orientation by a downending mechanism. The disposal canister is transferred horizontally into the repository emplacement cask at the surface to underground interface. Aspects related to the design including shielding, criticality, remote equipment, and off–normal events are also discussed. The simple and straightforward approach taken in the design of the R&H facility promotes confidence in the feasibility, constructability, and operability of the facility design.

The most important factor in the design of the geologic repository is the relationship between the needed containment provided by the geologic environment, and the geologic environment. The site at Yucca Mountain appears to provide very favorable hydrologic conditions in its current form. The key to this design, then, is to modify the hydrologic character of the site as little as possible. This implies that disturbance to the rock in all forms, mechanical, chemical, hydrological, must be kept to a minimum. This has been the driving factor in the geologic repository design. The emplacement mode and layout have minimized the amount of mining required, and all full–face mechanical excavation has minimized disturbance to the rock per distance mined. Complimentary with minimizing disturbance to the geology, this design, through distance minimization and the use of full–face tunnel boring machines, also minimizes cost.

An analysis of the projected inventories provided an estimated minimum age of the fuel at emplacement of 16 years. Thermal analysis of a repository with an areal loading of 57 kW/acre indicated that the surface temperature rise may be the thermally limiting criteria. Incoloy 825 was chosen as a highly reliable containment material for the nuclear waste. The waste package design is general enough to allow for any type of waste to be accomodated with reasonable geometric and thermal constraints. The combination of a highly reliable containment material and a benign corrosion environment assure safe isolation of the waste.

Repository operations includes transportation of the waste disposal canister and the canister emplacement systems. The transportation and emplacement systems consist of a single electrically driven unit rail mounted vehicle pushing an emplacement cask loaded rail car from the surface facilities to the underground repository. A description of other underground operations and systems including radiation protection of workers, environmental health monitoring, maintenance, and the tunnel backfilling system is given.

In studying the cost effectiveness of this system, two methods were employed: First, a computer model, WADCOM–II; and second, an independent cost evaluation made by the members of the design team. The total system cost (in constant 1988 dollars) was 1.9 billion dollars by WADCOM–II, and 5.3 billion dollars from the independent cost evaluation. The levelized unit cost of waste disposal was 0.2 mills/kW–hr by WADCOM–II and 0.55 mills/kW–hr from the independent cost evaluation.

5.3 Recommendations for Future Work

If for no other reason than the limited time available for the present study, additional work would be in order. Additional tradeoff evaluations to more closely approach optimization are an obvious general need. In addition, several specific issues have been identified as worthy of further investigation, as follows.

A basic decision was made early on to opt for infrequent large fuel shipments from individual reactor sites to the repository on the basis of presumed better economics and public acceptance. The latter aspect requires verification: is a large shipment every ten years preferable to a steady stream of smaller shipments in the eyes of the general public and state and local officials? The economic issue is also not fully resolved, and it should be noted that the expense of approximately twenty years of at–reactor storage (inevitable for all U.S. reactors because of the late in–service date of a High Level Waste repository) has been treated as a sunk cost, not entering into subsequent analysis.

Compaction of fuel assemblies at the repository surface handling facility was decided against even though a first–cut economic analysis indicated a potentially substantial cost penalty. It is expected, however, that further analysis would reduce the magnitude of this penalty significantly. Indications are that a considerable fraction of the fuel may be consolidated at the reactor site as a storage–expansion option; and optimization of the emplacement canister diameter (to increase the loading) would presumably partially offset the lower density of uncompacted fuel.

Further inquiry into the method of horizontal transfer used in loading the sealed disposal canister into the emplacement cask at the surface facility to underground repository is recommended. The process of sliding the canister along a bed of elongated cylindrical roller–bearings should be examined more closely as to feasibility and potential deleterious effects to the canister and the equipment. Other transfer mechanisms should be investigated for comparison to the system design and for further development.

The future work to be conducted for the engineered barrier system should first verify the suitability of Incoloy 825 as a waste package material through extensive experimentation in site specific conditions. Efforts should also be made to access possible borehole backfill strategies to minimize temperatures and maximize the effective containment period of the package.

Another area worth investigation is the use of in internal filler within the disposal canister used to fill the voids if intact spent fuel is disposed of. The internal filler may assist outward heat transfer, and may provide a greater degree of protection against canister crushing by lithostatic loading or rockfalls of limited extent.

For repository operations it is suggested that the use of a totally remote transportation and emplacement system should be investigated, if the economics and technology permit.

Regarding cost–effectiveness, the following additional work is recommended:

i) Examination of waste package design concepts and modifying WADCOM–II to establish a correlation for relating pitch, waste age, and canister diameter under various thermal design limits.

ii) Examination of the price trends, discount rates and inflation rates regarding the sensitivity of these parameters over a time horizon.

iii) Examination of less expensive borehole mining methods.

Addendum

Critique by Instructor

The following comments are based upon a review of the final report, as written. Some of the points raised here *were* discussed in class; these omissions or shortcomings are thus one of documentation, not lack of consideration.

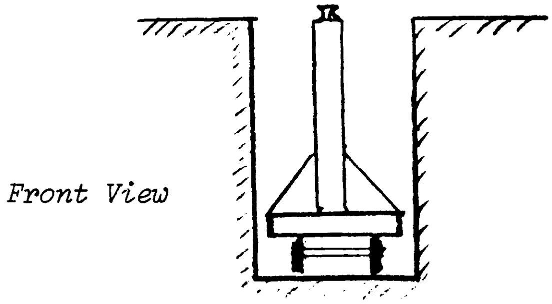
As noted, fuel assembly consolidation at the repository site was not adopted. It should have been made clearer, however, that many utilities are considering consolidation at the reactor, to increase local storage capability. Since the real limits on transportation through emplacement operations are based upon total thermal output, acceptance of this pre–consolidated fuel is not precluded. It would in all likelihood reduce the cost of disposal.

In several instances, readily available quantitative data was not cited in support of project decisions, for example, the relative accident risk of truck vs. rail shipment.

The transportation cost estimates in Section 2.3.6 deserve more discussion. Data should be available on coal unit train costs for comparison and use as a minimum price floor.

The feasibility of construction of a dual purpose (transportation and storage) truck cask should have been addressed.

In Section 2.4.4.2 and Fig. 2.19, the susceptibility of rail car tipover should have been addressed. It might be desirable to confine the cars to a valley—which would also aid in shielding.



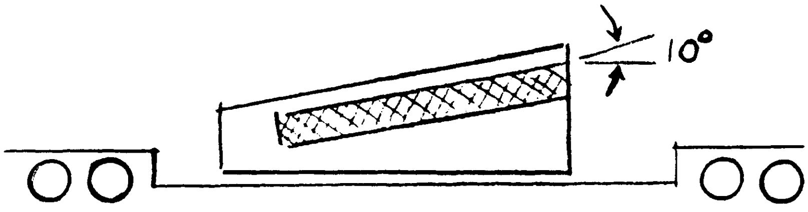
Are the cars self (electric) powered? This was not made clear.

In Fig. 2.20 (and Section 2.4.4.5.1), the extensive use of freon should have been justified against alternatives, since over the long term, its use may be curtailed or proscribed for environmental reasons.

Better coordination between the authors of 2.4.4.2.3 (Fig. 2.28) and 3.4.3.2 might have simplified the overall design in two respects. If the canister were tilted 10° and carried by the emplacement vehicle at that angle, then:

(a) the need for a screw-driven ram to push it into the vehicle might be avoided, or at the very least, the design/rating simplified.

(b) the emplacement gear would only need to provide a simple rotation (no elevation/tilting) at the borehole face



The concept of varying emplacement borehole pitch to accommodate as-measured canister thermal loadings is central to the concept, but is only hinted at in Sections 3.2.2.3 and 3.3.1.1: only later in 3.3.2.2.4 is this feature confirmed. It should have been highlighted and its advantages discussed in more detail—for example, to what extent can this compensate for eschewing consolidation (perhaps significantly if mining costs dominate?).

The emplacement rail vehicle described in 3.4.2.3.2 and Fig. 3.4.1 appears susceptible to tipover sidewise: why wasn't a stepped floor used as for the reactor-to-repository rail car (Fig. 2.6)? It would also appear preferable to rotate the cask and load it from the side (analogous to its unloading maneuver at the emplacement borehole).

Reliable operation of the trolley on which the emplacement cask rides is essential; hence, its design deserves more attention: e.g., why are "rubber wheels" specified in 3.4.2.4.1?

Perhaps the most significant missing piece of documentation is that concerned with the estimation of the canister thermal performance, as displayed in Figs. 3.25 and 3.26. Surface and internal (fuel) temperatures are key attributes related to long–term integrity, and the basis for greater assurance as to the accuracy of these estimates should have been presented. It is not clear, for example, that calculations are conservatively based on an air–filled canister, whereas helium is used as the actual fill–gas.

The cost estimate chapter could have used an additional paragraph or two on the large difference between WADCOM and independent cost estimates. The latter are ~ 2.5 x higher—a large discrepancy even for first iterate comparisons. The one difference cited—the large storage capability in the MIT design—is not quantified. One can infer from other data given in this chapter that this item represents a 2 billion dollar increment. If so, the discrepancy is reduced to 1.5 x, which is more plausible. Also WADCOM *can* provide MRS costs, which could have been used as (an upper limit on?) the cost of providing an equivalent expanded storage at the repository. As it is, the reader is left with an unwarranted feeling that the estimates are more uncertain than they really are.

Finally, in Chapter 5, the recommendations for future work lack specificity. Measures which might enhance canister integrity, such as cathodic protection with magnesium (as used in pipeline service), and specific media for filling up the interior, could have been suggested.

Appendix A

Sample DATABASE File

This section lists an actual DATABASE and shows the inputs by function, number, and title. The values are those pertaining to the Yucca Mountain Repository Project.

```
                                --------------------------------
                                    INPUT DATAFILE FOR WADCOM
                                --------------------------------

                                    -------------------------
                                    1.0 SPENT FUEL GENERATION
                                    -------------------------

------------------------------------------
1.1 HISTORICAL YEARS AND EXOGENOUS FORECAST
------------------------------------------

1. SPTFL                SPENT FUEL SCENARIOS (MTU)

                                  LOW      BASE       MID
*
                1960               4.        4.        0.
                1961               7.        7.        4.
                1962               8.        8.        6.
                1963               9.        9.       10.
                1964              10.       10.       11.
                1965              11.       11.       11.
                1966              11.       11.       11.
                1967              11.       11.       11.
                1968              19.       19.       11.
                1969              58.       58.       16.
                1970              75.       75.       49.
                1971             148.      148.       65.
                1972             244.      244.      273.
                1973             376.      376.      165.
                1974             568.      568.      435.
                1975             725.      725.      563.
                1976             794.      794.      682.
                1977             919.      919.      858.
                1978             956.      956.     1151.
                1979             978.      978.     1206.
                1980             943.      943.     1149.
                1981            1114.     1114.     1265.
                1982            1007.     1007.     1090.
                1983            1097.     1097.     1058.
                1984            1142.     1142.     1100.
                1985            1289.     1289.     1300.
                1986            1431.     1431.     1500.
                1987            1501.     1501.     1600.
                1988            1839.     1839.     2200.
                1989            2025.     2025.     2100.
                1990            2101.     2101.     2100.
                1991            2261.     2261.     2700.
                1992            2613.     2613.     2500.
                1993            2597.     2597.     2600.
                1994            2317.     2317.     2600.
                1995            2624.     2624.     2600.
                1996            2662.     2662.     3000.
                1997            2396.     2396.     2800.
                1998            2832.     2832.     2800.
                1999            2472.     2472.     2900.
                2000            2670.     2670.     3000.
                2001            2834.     2834.     3200.
                2002            2572.     2521.     3200.
                2003            2922.     2756.     3500.
```

```
                2004          2907.     2665.     3400.
                2005          3193.     2679.     3900.
                2006          2701.     1870.     3700.
                2007          3131.     2145.     4000.
                2008          2936.     1761.     3900.
                2009          2831.     1491.     4000.
                2010          2783.     1441.     3700.
                2011          3232.     1721.     4500.
                2012          2490.     1040.     4000.
                2013          3490.     1834.     4500.
                2014          4113.     1429.     4500.
                2015          3929.     1251.     5100.
                2016          3292.     1548.     5300.
                2017          3252.     1326.     4500.
                2018          3232.      486.     5200.
                2019          2957.      684.     5300.
                2020          2887.      702.     5000.
                2021             0.        0.     5000.
                2022             0.        0.     5000.
                2023             0.        0.     5000.
                2024             0.        0.     5000.
                2025             0.        0.     5000.
                2026             0.        0.        0.
                2027             0.        0.        0.
                2028             0.        0.        0.
                2029             0.        0.        0.
                2030             0.        0.        0.
                2031             0.        0.        0.
                2032             0.        0.        0.
                2033             0.        0.        0.
                2034             0.        0.        0.
                2035             0.        0.        0.
                2036             0.        0.        0.
                2037             0.        0.        0.
                2038             0.        0.        0.
                2039             0.        0.        0.
                2040             0.        0.        0.
                2041             0.        0.        0.
                2042             0.        0.        0.
                2043             0.        0.        0.
                2044             0.        0.        0.
                2045             0.        0.        0.
                2046             0.        0.        0.
                2047             0.        0.        0.
                2048             0.        0.        0.
                2049             0.        0.        0.
                2050             0.        0.        0.
                2051             0.        0.        0.
                2052             0.        0.        0.
                2053             0.        0.        0.
                2054             0.        0.        0.
                2055             0.        0.        0.
                2056             0.        0.        0.
                2057             0.        0.        0.
                2058             0.        0.        0.
                2059             0.        0.        0.

---------------------
1.2 COMPUTED FORECAST
---------------------
```

```
2. DENDB              U.S. DOMESTIC ENERGY DEMAND BASE

                                   (1)
*
                                    0.

3. ENDGR              ANNUAL ENERGY DEMAND GROWTH RATE

                                   (1)
*
                                    0.

4. SHARE             NUCLEAR SHARE OF TOTAL ENERGY BASE

                                   (1)
*
                                    0.

5. NSHGR    ANNUAL NUCLEAR SHARE OF TOTAL ENERGY GROWTH RATE

                                   (1)
*
                                    0.

6. BRNUP     BURNUP -- ENERGY OBTAINED (MEGAWATT DAYS/METRIC TON)

                                   (1)
*
                                 33000.

7. THEFF              THERMAL EFFICIENCY (DECIMAL PERCENT)

                                  (1)
*
                                  0.30

                  ---------------------------------
                  2.0 PRICE TRENDS AND CONTINGENCIES
                  ---------------------------------

8. GNPTR                  GNP PRICE DEFLATOR TREND

                                   (1)
*
                                 0.0570

9. NOMTR                   NOMINAL PRICE TRENDS
*
        CAPITAL CONSTR. WASTE PREP. PACKAGING               0.078
        CAPITAL CONSTR. REPOSITORY STRUCTURES               0.078
        CAPITAL CONSTR. REPOSITORY MINING                   0.068
        OPERATIONS WASTE PREPARATION PACKAGING              0.087
        OPERATIONS WASTE PREPARATION MATERIALS, C. STEEL    0.060
        OPERATIONS WASTE PREPARATION MATERIALS, TITANIUM    0.050
        OPERATIONS REPOSITORY STRUCTURES                    0.087
        OPERATIONS REPOSITORY MINING                        0.068
        DECOMMISSIONING REPOSITORY                          0.078
        CAPITAL TRANSPORTATION                              0.073
        OPERATIONS TRANSPORTATION                           0.015
```

```
         CAPITAL INTERIM STORAGE                             0.078
         OPERATIONS INTERIM STORAGE                          0.087
         CAPITAL VITRIFICATION                               0.078
         OPERATIONS VITRIFICATION                            0.087

10. CNTG                    COST CONTINGENCIES
*
         CAPITAL CONSTR. WASTE PREP. PACKAGING               0.338
         CAPITAL CONSTR. REPOSITORY STRUCTURES               0.495
         CAPITAL CONSTR. REPOSITORY MINING                   0.495
         OPERATIONS WASTE PREPARATION PACKAGING              0.300
         OPERATIONS WASTE PREPARATION MATERIALS, C. STEEL    0.000
         OPERATIONS WASTE PREPARATION MATERIALS, TITANIUM    0.000
         OPERATIONS REPOSITORY STRUCTURES                    0.300
         OPERATIONS REPOSITORY MINING                        0.300
         DECOMMISSIONING REPOSITORY                          0.000
         CAPITAL TRANSPORTATION                              0.000
         OPERATIONS TRANSPORTATION                           0.000
         CAPITAL INTERIM STORAGE                             0.500
         OPERATIONS INTERIM STORAGE                          0.000
         CAPITAL VITRIFICATION                               0.000
         OPERATIONS VITRIFICATION                            0.000

                                 ---------
                                 3.0 RATES
                                 ---------

--------------
3.1 REPOSITORY
--------------

11. BSDRR            BASE DESIGN RECEIPT RATE (MTU/YR)

                                    (1)
*
                                  4000.

12. BSDPR            BASE DESIGN PACKAGING RATE (PKG/YR)

                                    (1)
*
                                  1800.

13. WTFAC  WEIGHT FACTORS FOR DESIGN RECEIPT AND PACKAGING RATES
*
                 RECEIPT RATE                        0.50
                 PACKAGING RATE                      0.50

-------------------
3.2 INTERIM STORAGE
-------------------

14. BSSTR   BASE DESIGN INTERIM STORAGE STORING RATE (MTU/YR)

                                    (1)
*
                                  4000.

15. BSRTR  BASE DESIGN INTERIM STORAGE RETRIEVAL RATE (MTU/YR)
```

```
                                        (1)
       *
                                      4000.

       16. BSINV     BASE DESIGN INTERIM STORAGE INVENTORY (MTU/YR)

                                        (1)
       *
                                      1500.

                             -----------------------------
                             4.0 TRANSPORTATION CASK FLEET
                             -----------------------------

       17. CAPAC       HIGH LEVEL WASTE TRANSPORT CASK CAPACITY

                      CONSOLIDATED SPENT FUEL WITH GENERIC PACKAGING

                          10  YEARS 20  YEARS 30  YEARS 50  YEARS 100 YEARS
       *
              .10 M           0.         0.         0.         0.         0.
              .15 M           0.         0.         0.         0.         0.
              .20 M           1.         1.         1.         1.         1.
              .25 M           2.         2.         2.         2.         2.
              .30 M           3.         3.         3.         3.         3.
              .35 M           4.         4.         4.         4.         4.
              .40 M           5.         5.         5.         5.         5.
              .45 M           7.         7.         7.         7.         7.
              .50 M           8.         8.         8.         8.         8.
              .55 M          10.        10.        10.        10.        10.
              .60 M          12.        12.        12.        12.        12.
              .65 M          12.        12.        12.        12.        12.
              .70 M          12.        12.        12.        12.        12.
              .75 M          12.        12.        12.        12.        12.
              .80 M          12.        12.        12.        12.        12.
              .85 M          12.        12.        12.        12.        12.
              .90 M          12.        12.        12.        12.        12.
              .95 M          12.        12.        12.        12.        12.
              1.0 M          12.        12.        12.        12.        12.

                                       CHLW

                          10  YEARS 20  YEARS 30  YEARS 50  YEARS 100 YEARS
       *
              .10 M          44.        44.        44.        44.        44.
              .15 M          44.        44.        44.        44.        44.
              .20 M          21.        21.        21.        21.        21.
              .25 M          19.        19.        19.        21.        21.
              .30 M          14.        16.        16.        20.        20.
              .35 M          10.        10.        10.        10.        10.
              .40 M           8.         8.         8.        10.        10.
              .45 M           5.         8.         8.         8.        10.
              .50 M           4.         5.         5.         5.         5.
              .55 M           3.         4.         4.         4.         4.
              .60 M           1.         3.         3.         3.         3.
              .65 M           1.         1.         1.         1.         1.
              .70 M           1.         1.         1.         1.         1.
              .75 M           1.         1.         1.         1.         1.
              .80 M           1.         1.         1.         1.         1.
              .85 M           1.         1.         1.         1.         1.
```

```
      .90 M              1.         1.         1.         1.         1.
      .95 M              1.         1.         1.         1.         1.
      1.0 M              1.         1.         1.         1.         1.

18. INDSF  INSIDE DIAMETER OF TRANSPORT CASK SPENT FUEL PACKAGE (CM)

                                        (1)      .
*
                                     125.00

19. CAPRHT            REMOTE-HANDLED TRU TRANSPORT CAPACITY

*
                CONSOLIDATED & UNCONSOLIDATED       4.00

20. CAPSCF            SF TRANSPORT CASK CAPACITY (ASSEMBLIES)

*
                UNCONSOLIDATED                     21.00
                CONSOLIDATED                       30.00

21. CAPCHT            CONTACT-HANDLED TRU TRANSPORT CAPACITY

                                        (1)
*
                                        52.

22. CASKW                 TRANSPORT CASK WEIGHT (MT)

                                      SPENT FUEL          CHLW
*
              HLW                           100.          100.
              RHTRU                          73.           73.
              CHTRU                           0.           36.

23. CASKL             TRANSPORT CASK LOAD WEIGHT (MT)

                                      SPENT FUEL          CHLW
*
              HLW                           110.          115.
              RHTRU                          91.           91.
              CHTRU                           0.           64.

24. MTUAS         METRIC TONS OF URANIUM PER PWR ASSEMBLY

                                        (1)
*
                                      0.4620

25. LINKD    TRANSPORTATION LINK DISTANCE (MILES) ONE WAY

                                         SALT    TUFF GRANITE  BASALT
*
      REACTOR TO REPOSITORY           1398.00 1398.00    0.00    0.00
      REACTOR TO MRS                   907.00  907.00    0.00    0.00
      REACTOR TO REPROCESSING          907.00  907.00    0.00    0.00
      MRS TO REPOSITORY               1513.00 1513.00    0.00    0.00
      MRS TO REPROCESSING                1.00    1.00    0.00    0.00
      REPROCESSING TO REPOSITORY      1513.00 1513.00    0.00    0.00
```

```
26. SPEED               SPEED OF TRANSPORTER (MPH)

                               PARAMETERS
*
                 SLOPE                               0.1659
                 INTERCEPT                           0.2027

27. HTIME         HANDLING TIME OF TRANSPORT CASK (DAYS)

                              HLW   RHTRU   CHTRU
*
                               2.       4.       4.

28. UTIL               CASK PERCENTAGE UTILIZATION

                                     (1)
*
                                   0.780

                        ------------------------
                        5.0 TRANSPORTATION COSTS
                        ------------------------

29. TRUCC    TRANSPORT CASK UNIT CAPITAL COST (BASE YEAR $MILLION)

                              HLW   RHTRU   CHTRU
*
                              .80    1.80    1.30

30. TUOPC          TRANSPORT CASK UNIT OPERATING COSTS (DECIMAL PERCENT)
*
                   UNIT MAINTENANCE COST           0.05

31. CPTP      COST PER TON OF UNIT TRANSPORTATION PARAMETERS
*
               LOADED COST COEFFICIENT (LOG)        11.500
               LOADED COST COEFFICIENT (LINEAR)      0.091
               EMPTY COST COEFFICIENT (LOG)         10.800
               EMPTY COST COEFFICIENT (LINEAR)       0.084

32. UL                      USEFUL LIFE OF CASKS

                                     (1)
*
                                      40.

                    --------------------------------------
                    6.0 WASTE PREPARATION/REPOSITORY UNITS
                    --------------------------------------

------------
6.1 PACKAGES
------------

33. UVCHT  UNIT VOLUME OF ROCK MINED TO STORE A CONTACT-HANDLED TRU DRUM (M**3)

                      SALT      TUFF   GRANITE    BASALT
*
                     0.340     0.340     0.340     0.340
```

```
34. HEIGT                        PACKAGE HEIGHT (M)
*
                    HLW                              5.000
                    RHTRU                            5.000

35. WLOAD   WASTE LOADING FACTOR FOR COMMERCIAL HIGH LEVEL WASTE

                                   (1)
*
                                  0.30

36. FILL      PERCENTAGE OF PACKAGE VOLUME FILLED WITH GLASS

                                   (1)
*
                                 0.880

37. ODENS               PACKAGE OXIDE DENSITY (KG/M**3)

                                    (1)
*
                                6700.00

38. GDENS               PACKAGE GLASS DENSITY (KG/M**3)

                                    (1)
*
                                2500.00

39. KGMTU                KILOGRAMS OF WASTE OXIDE PER MTU

                                   (1)
*
                                 86.90

40. NCMTU       NUMBER OF CONTACT-HANDLED TRU DRUMS PER MTU

                            SPENT FUEL      CHLW
*
                               0.00      5.20

41. VRMTU      VOLUME OF REMOTE-HANDLED TRU PER MTU (M**3/MTU)

                            SPENT FUEL      CHLW
*
                              0.048     1.200

42. RDIN                      FUEL RODS PER PACKAGE INTERCEPT

                                   (1)
*
                                - 894.

43. RDSL                        FUEL RODS PER PACKAGE SLOPE

                                   (1)
*
                                  42.7

44. MTURD                            MTU PER FUEL ROD
```

```
                                      (1)
*
                                    0.0018


-------------------
6.2 PACKAGE SPACING
-------------------


45. WTMTU                        WATTS PER MTU

             10 YEARS  20 YEARS  30 YEARS  50 YEARS 100 YEARS
*
               1000.0     893.5     744.6     543.8     285.9

46. PLOAD                    PACKAGE LOADING (WATTS PER PACKAGE)
47. AREAL                 AREAL THERMAL DENSITY (WATTS/METER/METER)

                               10 YEARS, SPENT FUEL, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE  3380.  12.35  3420.  12.35
NEAR FIELD
FAR FIELD   2200.  13.34
TH LIMIT 4
TH LIMIT 5

                               20 YEARS, SPENT FUEL, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE
NEAR FIELD
FAR FIELD
TH LIMIT 4
TH LIMIT 5

                               30 YEARS, SPENT FUEL, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE
NEAR FIELD
FAR FIELD
TH LIMIT 4
TH LIMIT 5

                               50 YEARS, SPENT FUEL, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE
NEAR FIELD
FAR FIELD
TH LIMIT 4
```

```
TH LIMIT 5

                               100 YEARS, SPENT FUEL, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE
NEAR FIELD
FAR FIELD
TH LIMIT 4
TH LIMIT 5

                               10 YEARS, CHLW, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTER 500  5220.  77.76 6264.  64.77 7308.  35.44 7621.   2.05 7947.    .12
NEAR F 250  5220.  43.25 6264.  39.39 7308.  34.77 7830.  32.02 8874.  24.09
FAR FIELD      0.  37.50 6264.  37.50 7308.  37.50 7830.  37.50 8874.  37.50
TH LIMIT 4
TH LIMIT 5

                               20 YEARS, CHLW, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE
NEAR FIELD
FAR FIELD
TH LIMIT 4
TH LIMIT 5

                               30 YEARS, CHLW, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE
NEAR FIELD
FAR FIELD
TH LIMIT 4
TH LIMIT 5

                               50 YEARS, CHLW, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE
NEAR FIELD
FAR FIELD
TH LIMIT 4
TH LIMIT 5

                               100 YEARS, CHLW, TUFF

             POINT A       POINT B       POINT C       POINT D       POINT E
```

```
          WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M WT/PKG WT/M/M
*
CENTERLINE
NEAR FIELD
FAR FIELD
TH LIMIT 4
TH LIMIT 5

48. RTRSP               ROOM TO ROOM SPACING (M)

                          SPENT FUEL     CHLW
*
              HLW              80.00     23.80
              RHTRU            27.50     23.80

49. SPRHT        PACKAGE SPACING FOR REMOTE-HANDLED TRU (M)

                               SPENT FUEL     CHLW
*
                    SALT            2.500     2.500
                    TUFF            2.500     2.500
                    GRANITE         0.000     0.000
                    BASALT          0.000     0.000

-------------------
6.3 ROCK MASS MINED
-------------------

50. DENSI               GEOLOGIC MEDIUM DENSITY (MT/M**3)

                     SALT      TUFF   GRANITE    BASALT
*
                    2.170     2.400     0.000     0.000

51. ROOMH                     ROOM HEIGHT (M)

                          SALT      TUFF   GRANITE    BASALT
*
              HLW         7.20      7.20      0.00      0.00
              RHTRU       7.20      7.20      0.00      0.00

52. ROOMW                      ROOM WIDTH (M)

                          SALT      TUFF   GRANITE    BASALT
*
              HLW         4.00      7.20      0.00      0.00
              RHTRU       7.62      7.62      0.00      0.00

53. ADDRM        ADDITIONAL ROOM SPACE (DECIMAL PERCENT)

                                      (1)
*
                                      0.1

54. ROOML                       ROOM LENGTH (M)

                                      (1)
*
                                   1000.0
```

```
55. NROWS        NUMBER OF ROWS OF WASTE PER ROOM

                      HLW           RHTRU
*
                       7               3

56. PANLL              PANEL LENGTH (M)

                             (1)
*
                           1000.0

57. CORRH             CORRIDOR HEIGHT (M)

                             (1)
*
                             7.0

58. CORRW              CORRIDOR WIDTH (M)

                             (1)
*
                             7.0

59. CRPRM             CORRIDORS PER ROOM

                             (1)
*
                              0

60. PTPSP          PANEL TO PANEL SPACING (M)

                             (1)
*
                             0.0

61. NMCOR          NUMBER OF MAIN CORRIDORS

                             (1)
*
                              3

62. NPCOR        NUMBER OF PERIMETER CORRIDORS

                             (1)
*
                              1

63. XCUTL            CROSSCUT LENGTH (M)

                             (1)
*
                            14.0

64. XCUTH            CROSSCUT HEIGHT (M)

                             (1)
*
                             7.0
```

```
65. XCUTW                    CROSSCUT WIDTH (M)

                                   (1)
*
                                   7.0

66. XCUTS                   CROSSCUT SPACING (M)

                                   (1)
*
                                  200.0

67. CXCUT             MAIN CORRIDOR CROSSCUTS PER PANEL (M)

                                   (1)
*
                                   4.0

68. PXCUT            PERIMETER CORRIDOR CROSSCUTS PER PANEL (M)

                                   (1)
*
                                   2.0

69. REXF                    RE-EXCAVATION FACTOR

                                  (1)
*
                                  1.56

----------------------
6.3 TRANSFER EQUIPMENT
----------------------

70. NEMPL         NUMBER OF EMPLACEMENTS PER TRANSPORTER

                                  (1)
*
                                 10000.

                  ---------------------------------------
                  7.0  WASTE PREPARATION/REPOSITORY COSTS
                  ---------------------------------------

---------------------
7.1 WASTE PREPARATION
---------------------

71. CPX    ANNUAL PERCENTAGE CAPITAL CONSTRUCTION EXPENDITURES

                YEAR 1  YEAR 2  YEAR 3  YEAR 4  YEAR 5  YEAR 6
*
                 0.050   0.150   0.200   0.220   0.230   0.150

72. TPCPB  TOTAL PACKAGING FACILITY CAPITAL CONSTRUCTION REFERENCE
                       COSTS BASES (BASE YEAR $MILLION)
*
             PACKAGING FACILITY OVERHEAD                    1.00
             PACKAGING FACILITY RECEIVING AND STORAGE     100.00
             PACKAGING FACILITY PACKAGING                 200.00
```

```
             PACKAGING FACILITY DISASSEMBLY            10.00

73. ECONT               ENGINEERING COST CONTINGENCY
*
              PACKAGING FACILITY OVERHEAD                  .100
              PACKAGING FACILITY RECEIVING AND STORAGE  .500
              PACKAGING FACILITY PACKAGING                 .500
              PACKAGING FACILITY DISASSEMBLY              0.20

74. BSEXP         BASE DESIGN EXPONENT FOR COST FUNCTIONS

                                  (1)
*
                                  0.6

75. APOPB  ANNUAL PACKAGING FACILITY OPERATING REFERENCE COSTS BASES
                             (BASE YEAR $MILLION)
*
        PACKAGING LABOR                                         5.60
        PACKAGING SUPPORT PERSONNEL                             1.40
        PACKAGING MATERIALS AND EQUIPMENT REPLACEMENT          10.00

76. THICK  COMBINED WALL THICKNESS BY WASTE TYPE AND MATERIAL
*
             HLW CARBON STEEL INTERCEPT                0.064
             HLW CARBON STEEL SLOPE                    0.288
             HLW TITANIUM (CM)                         1.500
             RHTRU CARBON STEEL (CM)                   2.000
             GENERIC PKG THICKNESS INTERCEPT          17.500
             GENERIC PKG THICKNESS SLOPE               1.294

77. PAFAC              PACKAGE ADJUSTMENT FACTOR FOR LID
*
                    HLW CARBON STEEL             0.92744
                    HLW TITANIUM                 0.99886
                    RHTRU CARBON STEEL           0.99350

78. VRPKG  SURROGATE FOR UNIT VOLUME OF MATERIAL IN REFERENCE CASE
                           PACKAGE (CM**2)
*
       CARBON STEEL                                        2846.10
       TITANIUM                                              84.29

79. PCOST   REFERENCE CASE COST OF PACKAGE BY MATERIAL (BASE YEAR $1000)
*
                CARBON STEEL                      12.80
                TITANIUM                          12.80

--------------
7.2 REPOSITORY
--------------

80. FROOM  FRACTION OF BOREHOLE ROOMS MINED DURING CONSTRUCTION

                                (1)
*
                               0.200

81. FRCOR    FRACTION OF CORRIDORS MINED DURING CONSTRUCTION
```

```
                                          (1)
*
                                        0.600

82. FTREQ  FRACTION OF TRANSFER EQUIPMENT PURCHASED DURING CONSTRUCTION

                                          (1)
*
                                        0.330

83. UMNGC   UNIT MINING COSTS FOR REPOSITORY ROOMS (BASE YEAR $/MT)

                          SALT      TUFF   GRANITE    BASALT
*
                        13.560    13.560     0.000     0.000

84. UMGCC  UNIT MINING COSTS FOR REPOSITORY CORRIDORS (BASE YEAR $/MT)

                          SALT      TUFF   GRANITE    BASALT
*
                        16.260    16.260      .000      .000

85. UNITC    UNIT COST OF TRANSFER EQUIPMENT (BASE YEAR $MILLION)

                                           (1)
*
                                          2.10

86. TRCPB TOTAL REPOSITORY CAPITAL CONSTRUCTION REFERENCE COSTS BASES
              FOR VARIOUS REPOSITORY COMPONENTS (BASE YEAR $MILLION)

                                          SALT     TUFF GRANITE  BASALT
*
      SITE                               68.80    68.60    0.00    0.00
      RECEIVING FACILITY                 42.00    42.00    0.00    0.00
      WASTE SHAFTS AND HOISTS            50.97    50.97    0.00    0.00
      ROOMS                              00.00     0.00    0.00    0.00
      MEN AND MATERIALS SHAFT            66.13    66.13    0.00    0.00
      SHAFT PILLAR ZONE                  36.60    36.60    0.00    0.00
      CORRIDORS                          00.00     0.00    0.00    0.00
      ROCK HANDLING AND DISPOSAL          0.50     0.50    0.00    0.00
      VENTILATION STRUCTURES             70.65    70.65    0.00    0.00
      VENTILATION SUPPLY SHAFT           23.70    23.70    0.00    0.00
      DEVELOPMENT EXHAUST SHAFT          13.75    13.75    0.00    0.00
      VENTILATION FLOW PATHS              3.99     3.99    0.00    0.00
      REPOSITORY EXHAUST SHAFT           13.10    13.10    0.00    0.00
      SUPPORT AND UTILITIES              93.95    93.95    0.00    0.00

87. AROPB  ANNUAL REPOSITORY OPERATING REFERENCE COSTS BASES FOR VARIOUS
                REPOSITORY COMPONENTS (BASE YEAR $MILLION)

                                          SALT     TUFF GRANITE  BASALT
*
      RECEIVING FACILITY                  3.11     3.11    0.00    0.00
      WASTE SHAFTS AND HOISTS             2.21     2.21    0.00    0.00
      ROOMS                               0.00     0.00    0.00    0.00
      MEN AND MATERIALS SHAFT             3.83     3.83    0.00    0.00
      CORRIDORS                           0.00     0.00    0.00    0.00
      VENTILATION STRUCTURES             12.05    12.05    0.00    0.00
      VENTILATION SUPPLY SHAFT            0.53     0.53    0.00    0.00
```

```
     VENTILATION FLOW PATHS           0.00    0.00    0.00    0.00
     SUPPORT AND UTILITIES           23.71   23.71    0.00    0.00

88. ATRCB  ADJUSTMENT TO REPOSITORY COSTS BASE FOR CHLW (BASE YEAR $MILLION)
*
  RECEIVING FACILITY, CAPITAL CONSTRUCTION          00.00
  WASTE SHAFTS & HOISTS, CAPITAL CONSTRUCTION       00.00
  RECEIVING FACILITY, OPERATIONS                     0.00
  WASTE SHAFTS & HOISTS, OPERATIONS                  0.00

89. DEPTH         DEPTH OF BOREHOLE BY WASTE TYPE (CM)

                           SALT      TUFF   GRANITE    BASALT
*
               HLW       580.00  40000.00    000.00    000.00
               RHTRU     580.00   1700.00    000.00    000.00

90. BHEXP        BOREHOLE BORINGS COST FUNCTION EXPONENT

                      SALT      TUFF   GRANITE    BASALT
*
                     0.883     0.883     0.000     0.000

91. BCPMD   BOREHOLE BORINGS COST PER METER OF DEPTH (BASE YEAR $)

                      SALT      TUFF   GRANITE    BASALT
*
                   802.000   928.000     0.000     0.000

92. EMPLC          PACKAGE EMPLACEMENT COST (BASE YEAR $1000)

                                     (1)
*
                                    1.90

93. ECDCHT   EMPLACEMENT COST OF DRUMS OF CHTRU (BASE YEAR $1000/PALLET)

                                     (1)
*
                                    0.45

94. RHOPC       COMPONENT ROCK HANDLING AND DISPOSAL OPERATIONS
                               COST COEFFICIENTS
*
                FIXED EMPLACEMENT                  0.00
                HANDLING AND HAULING               0.50
                BACKFILLING                        0.25

-------------------------
7.3 DECOMMISSIONING COSTS
-------------------------

95. DCON                 DECOMMISSIONING CONSTANTS
*
                WASTE PREPARATION                  0.15
                REPOSITORY                         0.15
                VITRIFICATION                      0.15
                INTERIM STORAGE                    0.15

96. DECX  ANNUAL PERCENTAGE REPOSITORY DECOMMISSIONING COST EXPENDITURES
```

```
                YEAR 1  YEAR 2  YEAR 3  YEAR 4  YEAR 5
*
                 0.100   0.150   0.250   0.300   0.200

                          -------------------------------
                          8.0 INTERIM STORAGE SYSTEM COSTS
                          -------------------------------

97. CEXP        COST EXPONENTS FOR INTERIM STORAGE CAPITAL
                          AND OPERATING EXPENSES
*
                 RECEIVING AND PACKAGING                    0.600
                 DRY-WELL STORAGE                           1.000
                 PERSONNEL                                  1.000

98. ISCPX  ANNUAL PERCENTAGE INTERIM STORAGE CAPITAL CONSTRUCTION
                              EXPENDITURES
*
                 YEAR 1                                     0.050
                 YEAR 2                                     0.150
                 YEAR 3                                     0.200
                 YEAR 4                                     0.250
                 YEAR 5                                     0.250
                 YEAR 6                                     0.100

99. TICPB   TOTAL INTERIM STORAGE CAPITAL CONSTRUCTION REFERENCE
                     COSTS BASES (BASE YEAR $MILLION)

                                               FIXED  VARIABLE
*
               RECEIVING AND PACKAGING       219.50     10.00
               DRY-WELL STORAGE                0.00      0.00

100. MTUPC              MTU PER INTERIM STORAGE CANNISTER

                                    (1)
*
                                  10.50

101. AIOPB      ANNUAL INTERIM STORAGE OPERATING REFERENCE COSTS BASES
                             (BASE YEAR $MILLION)
*
                  STORING PERSONNEL                         7.770
                  STORING UTILITY/MAINTENANCE               4.270
                  STORING DRY-WELLS                         0.000
                  STORING CANNISTERS                        0.006
                  CARETAKER PERSONNEL                       0.000
                  CARETAKER UTILITY/MAINTENANCE             4.270
                  RETRIEVAL PERSONNEL                       7.770
                  RETRIEVAL UTILITY/MAINTENANCE             4.270


                          -----------------------------
                          9.0 VITRIFICATION SYSTEM COSTS
                          -----------------------------


102. VCPX  ANNUAL PERCENTAGE DISTRIBUTION OF VITRIFICATION CAPITAL
                           CONSTRUCTION EXPENDITURES
```

*

1990	0.000
1991	0.046
1993	0.082
1994	0.127
1995	0.200
1996	0.210
1998	0.201
1999	0.134

103. TVCPB TOTAL VITRIFICATION CAPITAL CONSTRUCTION REFERENCE COSTS BASES (BASE YEAR $MILLION)

(1)

*

599.00

104. CWALL CANNISTER WALL THICKNESS (CM)

(1)

*

1.260

105. BDSCV BASE DESIGN SURROGATE FOR CANNISTER VOLUME

(1)

*

75.700

106. AVOPB ANNUAL VITRIFICATION OPERATING REFERENCE COSTS BASES (BASE YEAR $MILLION)

*

PLANT OPERATIONS	19.87100
PACKAGE COSTS	0.00800
GLASS COSTS	0.00001
HULL COSTS	0.00090
GPT COSTS	0.00073

107. RDPAS TOTAL NO. OF RODS PER ASSEMBLY (RODS/ASS)

(1)

*

264.0

108. WTPVOL WEIGHT PER UNIT VOLUME OF GENERIC PKG (MT/CU.M)

(1)

*

4.42

109. WTPASS WEIGHT PER ASSEMBLY (MT)

(1)

*

0.938

110. PGCOST GENERIC PKG MATERIAL COST PER VOLUME ($83/CU.M)

(1)

*

```
                              13476.00

111. NYCON       NUMBER OF YEARS OF CONSOLIDATION CONSTRUCTION (YRS)

                                    (1)
*
                                     0

112. CDISTR      CONSOLIDATION CONSTRUCTION COST DISTRIBUTION

                                    (6)
*
                 YEAR 1                                  0.000
                 YEAR 2                                  0.000
                 YEAR 3                                  0.000
                 YEAR 4                                  0.000
                 YEAR 5                                  0.000
                 YEAR 6                                  0.000

113. CCKON       CONSOLIDATION CAPITAL COST AT REACTOR ($83MIL/MTU)

                                    (1)
*
                                   0.0000

114. COKON       CONSOLIDATION OPERATION COST AT REACTOR ($83MIL/MTU)

                                    (1)
*
                                   0.0000

115. TRUTMP      CAPITAL COST OF GENERIC PACKAGE TRANSPORT EQUIPMENT

                                    (1)
*
                                   0.0

116. DECON       CONSOLIDATION DECOMMISSIONING CONSTANT(DEC)

                                    (1)
*
                                   0.00

117. OCONF       CONSOLIDATION OPERATING FIXED COST(MILL 83$)

                                    (2)
*
                                   0.0
                                   0.0

118. OCONV       CONSOLIDATION OPERATING VARIABLE COST(MILL 83 $)

                                    (2)
*
                                  00.0
                                  00.0




119. CCONF       CONSOLIDATION CAPITAL FIXED COST(MILL 83 $)

                                    (2)
*
                                   0.0
                                   0.0

120. CCONV       CONSOLIDATION CAPITAL VARIABLE COST(MILL 83 $)

                                    (2)
*
                                  00.0
                                  00.0
```

Appendix B

DATABASE Definitions and Sources--WADCOM II

This section provides a definition of the DATABASE variables and the source of their values.(D-1)

VARIABLE	DEFINITION	SOURCE*
1. SPTFL	SF discharges from commercial reactors by year (Metric tons of uranium).	8
2. DENDB	The domestic U.S. Energy demand in base year.	8
3. ENDGR	The annual compound rate at which total domestic energy demand changes.	8
4. SHARE	The ratio of nuclear energy generation to total energy demand.	8
5. NSHGR	The annual compound rate at which nuclear energy is a fraction of total energy demand changes.	8
6. BURNUP	The energy derived from one metric ton of spent fuel (Megawatt-days/MTU).	8
7. THEFF	The efficiency with which the energy generated in a nuclear plant is converted to electrical energy.	8
8. GNPTR	The annual compound rate at which the Gross National Product (GNP) deflator is forecast to change over the forecast horizon.	1
9. NOMTR	The annual compound rate at which certain surrogates for various categories of waste management system costs are projected to change over the forecast horizon.	1
10. CNTG	The rate at which different waste management system costs are increased in order to make the final costs an expected value, i.e., a value that is as likely to be more than the actual cost as it is less than the actual cost.	6

* Sources are listed at end of table.

VARIABLE	DEFINITION	SOURCE
11. BSDRR	The annual rate (full capacity) at which the hypothetical reference repository processes waste.	6
12. BSDPR	The annual rate (full capacity) at which the hypothetical reference packaging facility processes waste packages.	6
13. WTFAC	Arbitrary weighting parameters used in scaling the costs of the reference packaging facility. The factors correspond to receiving and packaging functions performed by the packaging facility.	8
14. BSSTR	Annual rate at which wastes are stored in the reference interim storage facility.	4
15. BSRTR	Annual rate at which waste is retreived from the reference interim storage facility.	4
16. BSINV	The total waste inventory for which the reference interim storage facility is designed.	4
17. CAPAC	The capacity, in PWR assemblies, of the universally usable overpack; the capacity in HLW glass logs, of the CHLW transportation cask.	9
18. INDSF	N/A	
19. CAPRHT	Capacity, in canisters, of the RHTRU transport cask.	5
20. CAPSCF	Capacity, in PWR assemblies, of the transportation cask, for both consolidated and unconsolidated SF.	5
21. CAPCHT	Capacity in 55 gallon drums, of the CHTRU transportation cask.	5

VARIABLE	DEFINITION	SOURCE
22. CASKW	The unloaded weights of the waste transportation casks (metric tons).	5
23. CASKL	The loaded weights of the waste transportattion casks (metric tons).	5
24. MTVAS	The metric tons of uranium per PWR assembly.	9
25. LINKD	The one way distance between various origins and destinations within the nuclear waste disposal system.	8
26. SPEED	The speed (mph) with which the unloaded and loaded waste transportation casks move between the various origins and destinations within the nuclear waste disposal system.	5
27. HTIME	The time required to load and unload the waste transportation casks per each round trip between origin and destination.	5
28. UTIL	The percentage of a year that the transportation casks are available for transportation (decimal).	5
29. TRUCC	The cost of the waste transportation cask.	5
30. TUOPC	The transportation cask annual maintenance cost as a decimal percent of cask capital cost.	5
31. CPTP	The intercept and slope coefficients of transportation hauling costs equations for unloaded and loaded waste transportation casks.	5
32. UL	The useful life of the transportation cask.	

VARIABLE	DEFINITION	SOURCE
33. UVHT	The volume of rock mined per CHTRU drum for emplacement purposes.	
34. HEIGT	The usable height of the HLW and RHTRU waste package overpacks.	9
35. WLOAD	The ratio by weight of waste oxides to total waste glass (waste oxides plus glass frit).	7
36. FILL	The decimal percent of the CHLW canister volume filled with waste glass.	8
37. ODENS	The density (weight per unit volume) of the waste oxide produced during waste reprocessing.	7
38. GDENS	The density (weight per unit volume) of the glass frit used in the vitrification process.	7
39. KGMTU	The weight of waste oxides produced for each MTU of spent fuel reprocessed.	7
40. NCMTU	The number of CHTRU drums which are produced when on MTU of SF is reprocessed; equals the volume of CHTRU per MTU divided by the volume per CHTRU drum.	8
41. VRMTU	The volume of RHTRU resulting when one MTU of SF is dissassembled and close packed, or, when one MTU of SF is reprocessed.	8
42. RDIN	The intercept of the equation describing the number of consolidated, close-packed PWR rods contained within a waste package with an inside radius of R.	9

VARIABLE	DEFINITION	SOURCE
43. RDSL	The slope of the equation describing the number of consolidated, close-packed PWR rods contained within a waste package with an inside radius of R.	9
44. MTURD	The MTU per PWR fuel rod.	9
45. WTMTU	The watts per MTU for waste of various ages.	9
46. PLOAD	The package loading, in watts per package, corresponding to an areal thermal loading value; each combination of PLOAD and areal thermal loading corresponds to one point on one of the five thermal thermal limit curves.	9
47. AREAL	The areal thermal loading, in watts/m , corresponding to a package loading value; each combination of AREAL and package loading corresponds to one point on one of the five thermal limit curves.	9
48. RTRSP	The room-to-room spacing, in meters, in the repository, by SF, CHLW, and RHTRU.	9
49. SPRHT	The spacing, in meters, between RHTRU waste packages; by type of RHTRU and geology.	9
50. DENSI	The weight of one cubic meter of a given geologic material.	6
51. ROOMH	The height of the waste emplacement rooms in different geologies.	9
52. ROOMW	The width of the waste emplacement rooms in different geologies.	9
53. ADDRM	A multiplier used to adjust emplacement room costs to account for space for room entry.	8

VARIABLE	DEFINITION	SOURCE
54. ROOML	The length of a waste disposal room in the repository, in meters.	6
55. NROWS	The number of rows of waste packages emplaced in a single room.	6
56. PANLL	The average length of a panel of rooms in the repository, in meters.	6
57. CORRH	The height, in meters, of the main, access, and ventilation corridors in the repository.	6
58. CORRW	The width, in meters, of the main, access, and perimeter corridors in the repository.	6
60. PTPSP	The distance, in meters, from the center of one panel to the center of another.	6
61. NMCOR	The number of main corridors serving the repository.	6
62. NPCOR	The number of corridors in the repository which define its perimeter.	6
63. XCUTL	The length, in meters, of the openings (cross-cuts) which, at regular intervals, connect corridors in the repository.	6
64. XCUTH	The height, in meters, of the openings (cross-cuts) which, at regular intervals, connect corridors in the repository.	6
65. XCUTW	The width, in meters of the openings (cross-cuts) which, at regular intervals, connect corridors in the repository.	6
66. XCUTS	The distance from the center of one cross-cut to another, in the access corridors.	6

VARIABLE	DEFINITION	SOURCE
67. CXCUT	The number of main corridor cross-cuts per panel.	6
68. PXCUT	The number of perimeter corridor cross-cuts per panel.	6
69. REXF	The amount of remining, as a percentage of total mining, which must take place to account for salt creep.	6
70. NEMPL	The average lifetime in waste emplacements of the underground waste transporter.	9
71. CPX	The fraction of total waste preparation/repository capital construction costs incurred during each year of construction.	8
72. TPCPB	The capital costs for portions of a reference packaging facility (excluding contingency and engineering costs).	6
73. ECONT	The design and engineering costs, as a fraction of capital construction costs, applicable to the packaging facility.	6
74. BSEXP	The exponent of the waste preparation facility construction cost equation.	8
75. APOPB	The annual cost, excluding contingency, for operating the reference packaging facility.	6
76. THICK	The parameters of an equation describing the waste package wall thickness (carbon steel); the HLW waste package wall thickness (titanium); the wall thickness of the universally usable overpack.	9

VARIABLE	DEFINITIONS	SOURCE
77. PAFAC	A parameter used in the waste package material cost equation which scales costs for the material in the waste packages' top and bottom.	9,8
78. VRPKG	A surrogate for the volume of material in the reference HLW waste package.	9,8
79. PCOST	The cost of the reference HLW waste package overpacks (carbon steel and titanium).	8
80. FROOM	The fraction of total emplacement rooms mined during repository construction.	8
81. FRCOR	The fraction of total corridor mining which accrues to the capital construction account.	8
82. FTREQ	The fraction of underground waste transport equipment purchased during capital construction of the repository.	8
83. UMNGC	The unit costs, for different geologies, of mining rooms ($/Metric ton).	6
84. UMNCC	The unit cost, for different geologies of mining corridors ($/Metric ton).	
85. UNITC	The cost per waste transporter used to emplace waste packages.	9
86. TRCPB	Capital costs (excluding engineering contingency costs) of various reference repository systems.	6
87. AROPB	Annual operating costs (excluding contingency) applicable to certain reference repository systems.	6

VARIABLE	DEFINITION	SOURCE
88. ATRCB	N/A	
89. DEPTH	Depth of the repository borehole in which the waste package is emplaced.	6
90. BHEXP	The exponent parameter of the borehole drilling cost equation.	6,8
91. BCPMD	The intercept parameter of the borehole drilling cost equations.	6,8
92. EMPLC	The cost per waste package of transporting waste from the repository surface and emplacing it in the borehole.	9
93. ECDCHT	The cost per pallet of transporting CHTRU from the repository surface and emplacing it in the repository drift.	8
94. RHOPC	Parameter of the rock handling disposal cost equation.	9,6
95. DCON	The cost of repository decommissioning as a fraction of repository capital construction costs.	8
96. DECX	The fraction of total decommissioning costs incurred during each year of decommissioning.	8
97. CEXP	Parameters of various MRS cost equations.	8
98. ISCPX	The fraction of MRS capital costs incurred during each year of capital construction.	4,8
99. TICPB	The capital costs (excluding contingency and engineering costs) of a reference MRS facility.	4,8
100. MTUPC	The MTU that can be stored in an MRS dry-well storage canister .	4

VARABILE	DEFINITION	SOURCE
101. AIOPB	The annual operating costs (excluding contingency costs) of a reference MRS facility.	4,8
102. VCPX	The fraction of vitrification capital construction costs incurred during each year of capital construction.	2
103. TVCPB	The capital construction cost for a reference 1,500 MTU per year vitrification facility.	2
104. CWALL	The wall thickness of the CHLW waste canister.	2
105. BDSCV	A surrogate for volume of material in the CHLW waste canister.	2,8
106. AVOPB	The annual operating costs of a reference vitrification facility.	2
107. RDPAS	The number of PWR rods per one SF assembly.	9
108. WTPVOL	The weight per unit volume of universally usable overpack (MT/m).	9,8
109. WTPASS	The weight, in MT, of one PWR assembly.	9,8
110. PGCOST	The delivered fabrication cost for the universal overpack, in $ per cubic meter.	9,8
111. NYCON	The number of years required to construct the consolidation facilties.	3,8
112. CDISTR	The distribution of consolidation facility capital costs, in decimal fraction.	3,8

VARIABLE	DEFINITION	SOURCE
113. CCKON	The capital cost of consolidation facilities at the reactor, in millions of dollars per maximum MTU of throughput.	3,8
114. COKON	The annual operations cost of consolidation at the reactor, in millions of dollars per MTU of throughput.	3,8
115. TRUTMP	The capital cost of any special equipment required in shipping the universally usable waste package.	8
116. DECON	The cost of decommissioning consolidation facilities, as a fraction of consolidation capital costs.	8
117. OCONF	The annual fixed cost of operating reference consolidation facilities at either the repository or MRS, in millions of dollars.	3,8
118. OCONV	The annual variable cost of operating reference consolidation facilities at either the repository or MRS, in millions of dollars.	3,8
119. CCONF	The fixed capital cost for constructing reference consolidation facilities, in millions of dollars.	3,8
120. CCONV	The variable capital cost for constructing reference consolidation facilities, in millions of dollars.	3,8

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Appendix C

Sample Output File

This section lists an actual WADCOM II output file with representative values of the Yucca Mountain Repository project (see Table 4.5).

```
1
                    USERFILE FOR W A D C O M
                    ------------------------

 INPUT ECHO FLAG
 ---------------
 1       YES
 0       NO
 *
 0

1
 SUMMARY COST MATRIX


 TITLE: SPENT FUEL CYCLE COSTS GIVEN

      1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
      2) REPOSITORY GEOLOGY: TUFF
      3) WASTE FLOW PATH: REACTOR TO REPOSITORY
      4) START OF REPOSITORY OPERATIONS: 2005
      5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
      6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
      7) DESIGN AGE OF WASTE: 10 YEARS

 OPTIMIZED AT BOREHOLE HLW PACKAGE DIAMETER (CM): 75.0
              AND BOREHOLE RHTRU PACKAGE DIAMETER (CM):100.0


 COST UNITS: 1988 $MILLION GIVEN

      1) DISCOUNT FACTOR: .100
      2) A REAL PRICE TREND COMPUTATION



                             ------------------------------------------------------------
                             -              -              -              -              -
                             -   CAPITAL    -              -    DECOM-    -              -
                             - CONSTRUCTION -  OPERATIONS  -  MISSIONING  -    TOTAL     -
                             -    COSTS     -    COSTS     -    COSTS     -    COSTS     -
                             -              -              -              -              -
 ----------------------------------------------------------------------------------------
 -                           -              -              -              -              -
 - INTERIM STORAGE SYSTEM    -          .00 -          .00 -          .00 -          .00 -
 -                           -              -              -              -              -
 -                           ------------------------------------------------------------
 -                           -              -              -              -              -
 - VITRIFICATION SYSTEM      -          .00 -          .00 -          .00 -          .00 -
 -                           -              -              -              -              -
 -                           ------------------------------------------------------------
 -                           -              -              -              -              -
 - WASTE PREPARATION SYSTEM  -       171.19 -       199.41 -         1.08 -       371.68 -
 -                           -              -              -              -              -
 -                           ------------------------------------------------------------
 -                           -              -              -              -              -
 - REPOSITORY SYSTEM         -       250.13 -      1247.89 -         1.75 -      1499.77 -
 -                           -              -              -              -              -
```

```
-                          -------------------------------------------------------------
-                          -              -              -              -              -
- CONSOLIDATION SYSTEM     -        .00   -        .00   -        .00   -        .00   -
-                          -              -              -              -              -
-                          -------------------------------------------------------------
-                          -              -              -              -              -
- TRANSPORTATION SYSTEM    -       7.69   -      16.36   -        .00   -      24.04   -
-                          -              -              -              -              -
----------------------------------------------------------------------------------------
-                          -              -              -              -              -
- TOTAL COSTS              -     429.00   -    1463.66   -       2.84   -    1895.50   -
-                          -              -              -              -              -
----------------------------------------------------------------------------------------
1
WASTE PREPARATION/REPOSITORY COST MATRIX

                                -------------------------------------------------------------
                                -              -              -              -              -
                                -   CAPITAL    -              -    DECOM-    -              -
                                - CONSTRUCTION -  OPERATIONS  -  MISSIONING  -    TOTAL     -
                                -    COSTS     -    COSTS     -    COSTS     -    COSTS     -
                                -              -              -              -              -
---------------------------------------------------------------------------------------------
-                               -              -              -              -              -
- WASTE PREPARATION SYSTEM      -     171.19   -     199.41   -       1.08   -     371.68   -
-                               -              -              -              -              -
-   PACKAGING FACILITY          -     171.19   -      84.97   -              -     256.16   -
-     OVERHEAD                  -        .52   -              -              -        .52   -
-     RECEIVING AND STORAGE     -      70.66   -              -              -      70.66   -
-     PACKAGING                 -     100.01   -              -              -     100.01   -
-     DISASSEMBLY               -        .00   -              -              -        .00   -
-     LABOR                     -              -      23.33   -              -      23.33   -
-     SUPPORT PERSONNEL         -              -       8.30   -              -       8.30   -
-     REPLACEMENT               -              -      53.34   -              -      53.34   -
-                               -              -              -              -              -
-   MATERIALS COMPONENTS        -              -     114.45   -              -     114.45   -
-     BOREHOLE CARBON STEEL     -              -      38.58   -              -      38.58   -
-     BOREHOLE TITANIUM         -              -      75.64   -              -      75.64   -
-     SIMPLE CARBON STEEL       -              -        .22   -              -        .22   -
-     GENERIC PACKAGE           -              -        .00   -              -        .00   -
-                               -              -              -              -              -
-                               -------------------------------------------------------------
-                               -              -              -              -              -
- REPOSITORY SYSTEM             -     250.13   -    1247.89   -       1.75   -    1499.77   -
-                               -              -              -              -              -
-   TOTAL STRUCTURES            -     145.85   -     278.49   -              -     424.34   -
-     SITE                      -      36.11   -              -              -      36.11   -
-     RECEIVING FACILITY        -      22.11   -      16.59   -              -      38.70   -
-     WASTE SHAFTS AND HOISTS   -              -      13.10   -              -      13.10   -
-     TRANSFER EQUIPMENT        -       1.00   -      11.01   -              -      12.01   -
-     MEN AND MATERIALS SHAFT   -              -      22.70   -              -      22.70   -
-     VENTILATION STRUCTURES    -      37.19   -      71.42   -              -     108.61   -
-     VENTILATION SUPPLY SHAFT  -              -       3.14   -              -       3.14   -
-     SUPPORT AND UTILITIES     -      49.45   -     140.53   -              -     189.98   -
-                               -              -              -              -              -
-   TOTAL MINING                -     104.27   -     969.40   -              -    1073.68   -
-     WASTE SHAFTS AND HOISTS   -      23.61   -              -              -      23.61   -
-     ROOMS                     -       5.09   -       7.05   -              -      12.14   -
-     BOREHOLES                 -              -     958.80   -              -     958.80   -
-     MEN AND MATERIALS SHAFT   -      30.63   -              -              -      30.63   -
```

```
-     SHAFT PILLAR ZONE        -    16.95  -              -              -    16.95  -
-     CORRIDORS                -      .11  -      .02     -              -      .13  -
-     ROCK HANDLING & DISPOSAL -     2.60  -     3.53     -              -     6.14  -
-     VENTILATION SUPPLY SHAFT -    10.98  -              -              -    10.98  -
-     DEVELOPMENT EXHAUST SHAFT -    6.37  -              -              -     6.37  -
-     VENTILATION FLOW PATHS   -     1.85  -      .00     -              -     1.85  -
-     REPOSITORY EXHAUST SHAFT -     6.07  -              -              -     6.07  -
-                              -           -              -              -           -
-------------------------------------------------------------------------------------
-                              -           -              -              -           -
- TOTAL                        -   421.32  -  1447.30     -      2.84    -  1871.45  -
-                              -           -              -              -           -
-------------------------------------------------------------------------------------
1
 TRANSPORTATION COST MATRIX



                               -------------------------------------------------------
                               -           -              -              -           -
                               -  CAPITAL  -              -   DECOM-     -           -
                               - CONSTRUCTION - OPERATIONS - MISSIONING  -   TOTAL   -
                               -   COSTS   -    COSTS     -    COSTS     -   COSTS   -
                               -           -              -              -           -
-------------------------------------------------------------------------------------
-                              -           -              -              -           -
- TO REPOSITORY                -     7.69  -    16.36     -              -    24.04  -
-                              -           -              -              -           -
-   SPENT FUEL ASSEMBLIES      -     7.69  -              -              -     7.69  -
-                              -           -              -              -           -
-   CASK HAULING               -           -    13.85     -              -    13.85  -
-   CASK MAINTENANCE           -           -      .98     -              -      .98  -
-   TRAFFIC MANAGEMENT         -           -     1.53     -              -     1.53  -
-                              -           -              -              -           -
-------------------------------------------------------------------------------------
-                              -           -              -              -           -
- TOTAL                        -     7.69  -    16.36     -       .00    -    24.04  -
-                              -           -              -              -           -
-------------------------------------------------------------------------------------
1
    SPENT FUEL CYCLE COSTS ITERATED OVER HLW BOREHOLE PACKAGE DIAMETER
                         (1988 $MILLION)

          GIVEN BOREHOLE RHTRU PACKAGE DIAMETER (CM):100.0
          FOR RHTRU PACKAGE SPACING (M):               2.5


INSIDE DIAMETER (CM)       75.0

INTERIM STORAGE              .0
VITRIFICATION                .0
CONSOLIDATION                .0
WASTE PREPARATION         371.7
   CAPITAL CONSTRUC.      171.2
   OPERATING              199.4
   DECOMMISSIONING          1.1
REPOSITORY               1499.8
   CAPITAL CONSTRUC.      250.1
   OPERATING             1247.9
   DECOMMISSIONING          1.8
```

```
 TRANSPORTATION            24.0
 TOTAL SYSTEMS           1895.5
1
     SPENT FUEL CYCLE COSTS ITERATED OVER RHTRU BOREHOLE PACKAGE DIAMETER
                              (1988 $MILLION)

       GIVEN OPTIMIZED BOREHOLE HLW PACKAGE DIAMETER (CM): 75.0


 INSIDE DIAMETER (CM)     100.0

 INTERIM STORAGE             .0
 VITRIFICATION               .0
 CONSOLIDATION               .0
 WASTE PREPARATION        371.7
    CAPITAL CONSTRUC.     171.2
    OPERATING             199.4
    DECOMMISSIONING         1.1
 REPOSITORY              1499.8
    CAPITAL CONSTRUC.     250.1
    OPERATING            1247.9
    DECOMMISSIONING         1.8
 TRANSPORTATION            24.0
 TOTAL SYSTEMS           1895.5



          THE COST OPTIMIZATION RESULTED IN

          BOREHOLE HLW PACKAGE DIAMETER (CM): 75.0
          BOREHOLE RHTRU PACKAGE DIAMETER (CM):100.0

1
 PACKAGE SPACING DIMENSION ITERATED OVER HLW BOREHOLE PACKAGE DIAMETER (M)
           GIVEN BOREHOLE RHTRU PACKAGE DIAMETER (CM):100.0
           FOR RHTRU PACKAGE SPACING (M):                2.5


 INSIDE DIAMETER (CM)      75.0

 HLW PACKAGE SPACING       -1.0
1
 TRANSPORTATION CASK FLEET INFORMATION TO REPOSITORY


               CASK FLEET SIZE       TOTAL CASK TRIPS      CHANGE IN FLEET SIZE


    YEARS   SPENT FUEL ASSEMBLIES  SPENT FUEL ASSEMBLIES  SPENT FUEL ASSEMBLIES


     2005        32     0     0    425.     0.      0.          0     0     0
     2006        32     0     0    425.     0.      0.          0     0     0
     2007        32     0     0    425.     0.      0.          0     0     0
     2008        32     0     0    425.     0.      0.          0     0     0
     2009        32     0     0    425.     0.      0.          0     0     0
     2010        32     0     0    425.     0.      0.          0     0     0
     2011        32     0     0    425.     0.      0.          0     0     0
     2012        32     0     0    425.     0.      0.          0     0     0
     2013        32     0     0    425.     0.      0.          0     0     0
```

```
      2014        32     0     0    425.      0.      0.        0     0     0
      2015        32     0     0    425.      0.      0.        0     0     0
      2016        32     0     0    425.      0.      0.        0     0     0
      2017        32     0     0    425.      0.      0.        0     0     0
      2018        32     0     0    425.      0.      0.        0     0     0
      2019        32     0     0    425.      0.      0.        0     0     0
      2020        32     0     0    425.      0.      0.        0     0     0
      2021        32     0     0    425.      0.      0.        0     0     0
      2022        32     0     0    425.      0.      0.        0     0     0
      2023        32     0     0    425.      0.      0.        0     0     0
      2024        32     0     0    425.      0.      0.        0     0     0
      2025        32     0     0    425.      0.      0.        0     0     0
      2026        32     0     0    425.      0.      0.        0     0     0
      2027        32     0     0    425.      0.      0.        0     0     0
      2028        32     0     0    425.      0.      0.        0     0     0
      2029        32     0     0    425.      0.      0.        0     0     0
      2030        32     0     0    425.      0.      0.        0     0     0
      2031        32     0     0    425.      0.      0.        0     0     0
      2032         5     0     0     66.      0.      0.        0     0     0
      2033         0     0     0      0.      0.      0.        0     0     0
      2034         0     0     0      0.      0.      0.        0     0     0
      2035         0     0     0      0.      0.      0.        0     0     0
      2036         0     0     0      0.      0.      0.        0     0     0
      2037         0     0     0      0.      0.      0.        0     0     0
      2038         0     0     0      0.      0.      0.        0     0     0
      2039         0     0     0      0.      0.      0.        0     0     0
      2040         0     0     0      0.      0.      0.        0     0     0
      2041         0     0     0      0.      0.      0.        0     0     0
      2042         0     0     0      0.      0.      0.        0     0     0
      2043         0     0     0      0.      0.      0.        0     0     0
      2044         0     0     0      0.      0.      0.        0     0     0
1
 RECEIPT RATE AT REPOSITORY (MTU/YR) GIVEN


      1) START OF REPOSITORY OPERATIONS: 2005
      2) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
      3) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
      4) DESIGN AGE OF WASTE: 10 YEARS




           RECEIPT RATE          SPENT FUEL
               (MTU/YR)          BIRTH YEAR

      2005        4000.                1978
      2006        4000.                1982
      2007        4000.                1985
      2008        4000.                1988
      2009        4000.                1990
      2010        4000.                1992
      2011        4000.                1993
      2012        4000.                1995
      2013        4000.                1996
      2014        4000.                1998
      2015        4000.                1999
      2016        4000.                2001
      2017        4000.                2002
      2018        4000.                2004
      2019        4000.                2005
```

```
      2020      4000.               2007
      2021      4000.               2008
      2022      4000.               2009
      2023      4000.               2011
      2024      4000.               2012
      2025      4000.               2013
      2026      4000.               2014
      2027      4000.               2015
      2028      4000.               2016
      2029      4000.               2018
      2030      4000.               2019
      2031      4000.               2020
      2032       548.               2022
      2033         0.               2023
      2034         0.               2024
      2035         0.               2025
      2036         0.               2026
      2037         0.               2027
      2038         0.               2028
      2039         0.               2029
      2040         0.               2030
      2041         0.               2031
      2042         0.               2032
      2043         0.               2033
      2044         0.               2034

 ALL YEARS    108548.

1
                                  WASTE DISPOSAL FEES GIVEN

                                  DISCOUNT FACTOR:     .100


                                              LUMPSUM PAYMENT FOR  MILLS PER KWH OF
                  $ PER KG OF MILLS PER KWH OF  HISTORICAL ENERGY    FUTURE ENERGY
                  HEAVY METAL   NUCLEAR ENERGY     ($MILLION)        NO LUMP SUM

 TOTAL SYSTEM          235.48            .16         853.19             .29

 REPOSITORY            232.50            .16         842.36             .28
1
```

Appendix D

Additional Summary Cost Matrices

Table 4.5 of the text provides a summary of the costs for the Yucca Mountain project. This section presents other summary cost matrices when certain USERFILE values were varied as follows:

Summary Cost Matrix Number	Variation Studied
I	Table 4.5 discussed in the text
II	Table 4.5 with path 2 in place of path 1
III	Table 4.5 with path 5a in place of path 1
IV	Table 4.5 with path 6a in place of path 1
V	Table 4.5 with path 9a in place of path 1
VI	Table 4.5 with salt in place of Tuff
VII	Manual Reference Run using path 1
VIII	Manual Reference Run using path 2
IX	Table 4.5 with Discount Factor = 0.0
X	Sum Cost Matrix II: Discount Factor = 0.0

SUMMARY COST MATRIX II: Table 4.5 with path 2 in place of path 1

```
TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

     1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
     2) REPOSITORY GEOLOGY: TUFF
     3) WASTE FLOW PATH: REACTOR TO INTERIM STORAGE TO REPOSITORY
     4) START OF REPOSITORY OPERATIONS: 2005
     5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
     6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
     7) DESIGN AGE OF WASTE: 10 YEARS


COST UNITS: 1988 $MILLION GIVEN

     1) DISCOUNT FACTOR: .100
     2) A REAL PRICE TREND COMPUTATION



                           -------------------------------------------------------------
                           -              -              -              -              -
                           -   CAPITAL    -              -   DECOM-     -              -
                           - CONSTRUCTION -  OPERATIONS  -  MISSIONING  -     TOTAL    -
                           -    COSTS     -    COSTS     -    COSTS     -     COSTS    -
                           -              -              -              -              -
----------------------------------------------------------------------------------------
-                          -              -              -              -              -
- INTERIM STORAGE SYSTEM   -     141.77   -     134.37   -        .87   -     277.01   -
-                          -              -              -              -              -
-                          -------------------------------------------------------------
-                          -              -              -              -              -
- VITRIFICATION SYSTEM     -        .00   -        .00   -        .00   -        .00   -
-                          -              -              -              -              -
-                          -------------------------------------------------------------
-                          -              -              -              -              -
- WASTE PREPARATION SYSTEM -     171.19   -     199.33   -       1.26   -     371.77   -
-                          -              -              -              -              -
-                          -------------------------------------------------------------
-                          -              -              -              -              -
- REPOSITORY SYSTEM        -     250.13   -    1245.26   -       2.04   -    1497.43   -
-                          -              -              -              -              -
-                          -------------------------------------------------------------
-                          -              -              -              -              -
- CONSOLIDATION SYSTEM     -        .00   -        .00   -        .00   -        .00   -
-                          -              -              -              -              -
-                          -------------------------------------------------------------
-                          -              -              -              -              -
- TRANSPORTATION SYSTEM    -      15.26   -      33.43   -        .00   -      48.68   -
-                          -              -              -              -              -
----------------------------------------------------------------------------------------
-                          -              -              -              -              -
- TOTAL COSTS              -     578.34   -    1612.39   -       4.17   -    2194.90   -
-                          -              -              -              -              -
----------------------------------------------------------------------------------------
```

SUMMARY COST MATRIX III: Table 4.5 with path 5a in place of path 1

TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
2) REPOSITORY GEOLOGY: TUFF
3) WASTE FLOW PATH: CONSOLIDATION AT REACTOR TO REPOSITORY
3.5) NO GENERIC PACKAGING
4) START OF REPOSITORY OPERATIONS: 2005
5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
7) DESIGN AGE OF WASTE: 10 YEARS

COST UNITS: 1988 $MILLION GIVEN

1) DISCOUNT FACTOR: .100
2) A REAL PRICE TREND COMPUTATION

	CAPITAL CONSTRUCTION COSTS	OPERATIONS COSTS	DECOM-MISSIONING COSTS	TOTAL COSTS
INTERIM STORAGE SYSTEM	.00	.00	.00	.00
VITRIFICATION SYSTEM	.00	.00	.00	.00
WASTE PREPARATION SYSTEM	171.19	199.41	1.08	371.68
REPOSITORY SYSTEM	250.13	1247.89	1.75	1499.77
CONSOLIDATION SYSTEM	.00	.00	.00	.00
TRANSPORTATION SYSTEM	6.37	12.09	.00	18.46
TOTAL COSTS	427.68	1459.39	2.84	1889.91

SUMMARY COST MATRIX IV: Table 4.5 with path 6a in place of path 1

TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
2) REPOSITORY GEOLOGY: TUFF
3) WASTE FLOW PATH: CONSOLIDATION AT REACTOR TO INTERIM STORAGE TO REPOSITORY
3.5) NO GENERIC PACKAGING
4) START OF REPOSITORY OPERATIONS: 2005
5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
7) DESIGN AGE OF WASTE: 10 YEARS

COST UNITS: 1988 $MILLION GIVEN

1) DISCOUNT FACTOR: .100
2) A REAL PRICE TREND COMPUTATION

	CAPITAL CONSTRUCTION COSTS	OPERATIONS COSTS	DECOM-MISSIONING COSTS	TOTAL COSTS
INTERIM STORAGE SYSTEM	141.77	134.37	.87	277.01
VITRIFICATION SYSTEM	.00	.00	.00	.00
WASTE PREPARATION SYSTEM	171.19	199.33	1.26	371.77
REPOSITORY SYSTEM	250.13	1245.26	2.04	1497.43
CONSOLIDATION SYSTEM	.00	.00	.00	.00
TRANSPORTATION SYSTEM	12.60	25.22	.00	37.82
TOTAL COSTS	575.68	1604.18	4.17	2184.03

SUMMARY COST MATRIX V: Table 4.5 with path 9a in place of path 1

TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
2) REPOSITORY GEOLOGY: TUFF
3) WASTE FLOW PATH: REACTOR TO CONSOLIDATION AT INTERIM STORAGE TO REPOSITORY
3.5) NO GENERIC PACKAGING
4) START OF REPOSITORY OPERATIONS: 2005
5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
7) DESIGN AGE OF WASTE: 10 YEARS

COST UNITS: 1988 $MILLION GIVEN

1) DISCOUNT FACTOR: .100
2) A REAL PRICE TREND COMPUTATION

	CAPITAL CONSTRUCTION COSTS	OPERATIONS COSTS	DECOM-MISSIONING COSTS	TOTAL COSTS
INTERIM STORAGE SYSTEM	121.87	117.44	.78	240.09
VITRIFICATION SYSTEM	.00	.00	.00	.00
WASTE PREPARATION SYSTEM	171.19	199.33	1.26	371.77
REPOSITORY SYSTEM	250.13	1245.26	2.04	1497.43
CONSOLIDATION SYSTEM	.00	.00	.00	.00
TRANSPORTATION SYSTEM	11.96	24.70	.00	36.66
TOTAL COSTS	555.14	1586.73	4.08	2145.96

SUMMARY COST MATRIX VI: Table 4.5 with salt in place of Tuff

TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
2) REPOSITORY GEOLOGY: SALT
3) WASTE FLOW PATH: REACTOR TO REPOSITORY
4) START OF REPOSITORY OPERATIONS: 2005
5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
7) DESIGN AGE OF WASTE: 10 YEARS

COST UNITS: 1988 $MILLION GIVEN

1) DISCOUNT FACTOR: .100
2) A REAL PRICE TREND COMPUTATION

	CAPITAL CONSTRUCTION COSTS	OPERATIONS COSTS	DECOM-MISSIONING COSTS	TOTAL COSTS
INTERIM STORAGE SYSTEM	.00	.00	.00	.00
VITRIFICATION SYSTEM	.00	.00	.00	.00
WASTE PREPARATION SYSTEM	171.19	199.41	1.08	371.68
REPOSITORY SYSTEM	249.48	300.84	1.73	552.05
CONSOLIDATION SYSTEM	.00	.00	.00	.00
TRANSPORTATION SYSTEM	7.69	16.36	.00	24.04
TOTAL COSTS	428.36	516.61	2.81	947.78

SUMMARY COST MATRIX VII: Manual Reference Run Using Path 1

```
TITLE: SPENT FUEL CYCLE COSTS GIVEN

     1) SPENT FUEL GENERATION: MEDIUM EXOGENOUS FORECAST
     2) REPOSITORY GEOLOGY: SALT
     3) WASTE FLOW PATH: REACTOR TO REPOSITORY
     4) START OF REPOSITORY OPERATIONS: 1998
     5) DESIGN CAPACITY OF REPOSITORY (MTU): 70000.
     6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 3000.
     7) DESIGN AGE OF WASTE: 10 YEARS


COST UNITS: 1983 $MILLION GIVEN

     1) DISCOUNT FACTOR: .000
     2) A REAL PRICE TREND COMPUTATION



                           ---------------------------------------------------------------
                           -               -               -               -             -
                           -   CAPITAL     -               -    DECOM-     -             -
                           - CONSTRUCTION  -  OPERATIONS   -  MISSIONING   -    TOTAL    -
                           -    COSTS      -     COSTS     -     COSTS     -    COSTS    -
                           -               -               -               -             -
-----------------------------------------------------------------------------------------
-                          -               -               -               -             -
- INTERIM STORAGE SYSTEM   -          .00  -          .00  -          .00  -        .00  -
-                          -               -               -               -             -
-                          ---------------------------------------------------------------
-                          -               -               -               -             -
- VITRIFICATION SYSTEM     -          .00  -          .00  -          .00  -        .00  -
-                          -               -               -               -             -
-                          ---------------------------------------------------------------
-                          -               -               -               -             -
- WASTE PREPARATION SYSTEM -       351.00  -      2447.52  -       118.80  -    2917.33  -
-                          -               -               -               -             -
-                          ---------------------------------------------------------------
-                          -               -               -               -             -
- REPOSITORY SYSTEM        -      1437.49  -      4254.15  -       697.91  -    6389.55  -
-                          -               -               -               -             -
-                          ---------------------------------------------------------------
-                          -               -               -               -             -
- CONSOLIDATION SYSTEM     -        79.94  -      4470.21  -        17.56  -    4567.71  -
-                          -               -               -               -             -
-                          ---------------------------------------------------------------
-                          -               -               -               -             -
- TRANSPORTATION SYSTEM    -       249.24  -       228.97  -          .00  -     478.22  -
-                          -               -               -               -             -
-----------------------------------------------------------------------------------------
-                          -               -               -               -             -
- TOTAL COSTS              -      2117.68  -     11400.85  -       834.27  -   14352.80  -
-                          -               -               -               -             -
-----------------------------------------------------------------------------------------
```

```
SUMMARY COST MATRIX VIII: Manual Reference Run using path 2


TITLE: SPENT FUEL CYCLE COSTS GIVEN

     1) SPENT FUEL GENERATION: MEDIUM EXOGENOUS FORECAST
     2) REPOSITORY GEOLOGY: SALT
     3) WASTE FLOW PATH: REACTOR TO INTERIM STORAGE TO REPOSITORY
     4) START OF REPOSITORY OPERATIONS: 1998
     5) DESIGN CAPACITY OF REPOSITORY (MTU): 70000.
     6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 3000.
     7) DESIGN AGE OF WASTE: 10 YEARS


COST UNITS: 1983 $MILLION GIVEN

     1) DISCOUNT FACTOR: .000
     2) A REAL PRICE TREND COMPUTATION



                           ------------------------------------------------------------
                           -              -              -              -              -
                           -   CAPITAL    -              -    DECOM-    -              -
                           - CONSTRUCTION -  OPERATIONS  - MISSIONING   -    TOTAL     -
                           -    COSTS     -    COSTS     -    COSTS     -    COSTS     -
                           -              -              -              -              -
-----------------------------------------------------------------------------------------
-                          -              -              -              -              -
- INTERIM STORAGE SYSTEM   -     234.13   -    9533.60   -      80.82   -    9848.55   -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- VITRIFICATION SYSTEM     -        .00   -        .00   -        .00   -        .00   -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- WASTE PREPARATION SYSTEM -     351.00   -    2447.52   -     118.80   -    2917.33   -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- REPOSITORY SYSTEM        -    1437.49   -    4254.15   -     697.91   -    6389.55   -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- CONSOLIDATION SYSTEM     -      79.94   -    4470.21   -      17.56   -    4567.71   -
-                          -              -              -              -              -
-                          ------------------------------------------------------------
-                          -              -              -              -              -
- TRANSPORTATION SYSTEM    -     454.36   -     454.39   -        .00   -     908.75   -
-                          -              -              -              -              -
-----------------------------------------------------------------------------------------
-                          -              -              -              -              -
- TOTAL COSTS              -    2556.92   -   21159.87   -     915.09   -   24631.88   -
-                          -              -              -              -              -
-----------------------------------------------------------------------------------------
```

SUMMARY COST MATRIX IX: Table 4.5 with discount factor = 0.0

```
TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

     1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
     2) REPOSITORY GEOLOGY: TUFF
     3) WASTE FLOW PATH: REACTOR TO REPOSITORY
     4) START OF REPOSITORY OPERATIONS: 2005
     5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
     6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
     7) DESIGN AGE OF WASTE: 10 YEARS


COST UNITS: 1988 $MILLION GIVEN

     1) DISCOUNT FACTOR: .000
     2) A REAL PRICE TREND COMPUTATION



                           -----------------------------------------------------------
                           -              -              -              -              -
                           -   CAPITAL    -              -    DECOM-    -              -
                           - CONSTRUCTION -  OPERATIONS  -  MISSIONING  -    TOTAL     -
                           -    COSTS     -    COSTS     -    COSTS     -    COSTS     -
                           -              -              -              -              -
-------------------------------------------------------------------------------------------
-                          -              -              -              -              -
- INTERIM STORAGE SYSTEM   -          .00 -          .00 -          .00 -          .00 -
-                          -              -              -              -              -
-                          -----------------------------------------------------------
-                          -              -              -              -              -
- VITRIFICATION SYSTEM     -          .00 -          .00 -          .00 -          .00 -
-                          -              -              -              -              -
-                          -----------------------------------------------------------
-                          -              -              -              -              -
- WASTE PREPARATION SYSTEM -       639.14 -      2934.26 -       308.24 -      3881.64 -
-                          -              -              -              -              -
-                          -----------------------------------------------------------
-                          -              -              -              -              -
- REPOSITORY SYSTEM        -       933.14 -     20694.06 -       499.99 -     22127.19 -
-                          -              -              -              -              -
-                          -----------------------------------------------------------
-                          -              -              -              -              -
- CONSOLIDATION SYSTEM     -          .00 -          .00 -          .00 -          .00 -
-                          -              -              -              -              -
-                          -----------------------------------------------------------
-                          -              -              -              -              -
- TRANSPORTATION SYSTEM    -        27.50 -       180.95 -          .00 -       208.45 -
-                          -              -              -              -              -
-------------------------------------------------------------------------------------------
-                          -              -              -              -              -
- TOTAL COSTS              -      1599.78 -     23809.27 -       808.23 -     26217.28 -
-                          -              -              -              -              -
-------------------------------------------------------------------------------------------
```

SUMMARY COST MATRIX X: Summary Cost Matrix II with Discount Factor = 0.0

TITLE: SPENT FUEL CYCLE COSTS GIVEN (No SF consolidation)

1) SPENT FUEL GENERATION: HIGH EXOGENOUS FORECAST
2) REPOSITORY GEOLOGY: TUFF
3) WASTE FLOW PATH: REACTOR TO INTERIM STORAGE TO REPOSITORY
4) START OF REPOSITORY OPERATIONS: 2005
5) DESIGN CAPACITY OF REPOSITORY (MTU):150000.
6) DESIGN RECEIPT RATE OF REPOSITORY (MTU/YR): 4000.
7) DESIGN AGE OF WASTE: 10 YEARS

COST UNITS: 1988 $MILLION GIVEN

1) DISCOUNT FACTOR: .000
2) A REAL PRICE TREND COMPUTATION

	CAPITAL CONSTRUCTION COSTS	OPERATIONS COSTS	DECOM-MISSIONING COSTS	TOTAL COSTS
INTERIM STORAGE SYSTEM	434.36	2608.88	205.40	3248.63
VITRIFICATION SYSTEM	.00	.00	.00	.00
WASTE PREPARATION SYSTEM	639.14	2917.05	296.35	3852.54
REPOSITORY SYSTEM	933.14	20173.78	480.70	21587.62
CONSOLIDATION SYSTEM	.00	.00	.00	.00
TRANSPORTATION SYSTEM	50.08	338.49	.00	388.57
TOTAL COSTS	2056.73	26038.19	982.44	29077.36