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A Multi-Attribute Analysis of Nuclear Waste Disposal Alternatives

by

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Introduction

Energy and the Environment

Today the world faces two major problems related to energy and the environment: Pollution and potential scarcity [Murray, 1989]. The environmental movement of the 1960's brought to people's attention that there was a growing problem of pollution from our industrial civilization. Concerns developed around the world about the release of chemicals to land, air, and water. In the 1970's and 1980's the problem of chemical waste has become prominent. It is clear that large amounts of hazardous chemicals were stored or discarded with inadequate precautions. People have become increasingly aware also of radioactive wastes, those that emit radiation as they break up or "decay."

The Arab oil boycott of 1973 focused attention on the energy problem. Sources of oil are in the hands of unstable or vulnerable countries. Costs of petroleum increased significantly, contributing to economic difficulties in both advanced and emerging countries.

U.S. energy policy is to give each energy type opportunity to compete in the market and to encourage informed choices by Americans, with minimum governmental restraints. Nuclear power is viewed as one choice to meet national needs, along with natural gas, coal, solar and wind energy.

Questions About Nuclear Energy

Although people recognize the need for various energy sources, they often raise the question about nuclear energy, "What is being done with radioactive wastes?" The federal government and the nuclear industry have stated that such wastes were known to be dangerous ever since they first were generated in large quantities in World War II, and that special care has been taken over the years to protect the public. Observers note, however, that decisions about final disposal of wastes have had a lower priority in the overall nuclear development [Murray, 1989].

The search for suitable disposal sites has stimulated public concern. News of disagreements among different branches and levels of government has led many to conclude that we do not know what to do with radioactive wastes.

The question "is nuclear power safe?" is also raised frequently. People are aware of the fearful effects of the atom bomb. They know that a nuclear weapon is not the same as a nuclear reactor, but they tend to associate the two and are uneasy because both involve fission and radioactivity. Many people think of all radiation as mysterious and lethal. When these ideas are combined with Murphy's law. "If anything can go wrong, it will," it is easy to see why many people are uncomfortable, worried about, or frightened by continued or expanded use of nuclear energy. Most people are aware that there are few fatalities due to the use of nuclear energy. The Chernobyl reactor accident of 1986, however, heightened fear of nuclear power throughout the world. People are aware of greater dangers, but feel that in those situations they are in personal control of their safety. The nuclear hazard is less acceptable than other more familiar risks, such as riding in automobiles.

Another question is also heard. "Does nuclear power help solve the problems of atmospheric pollution, acid rain, and the greenhouse effect?" Scientists are expressing alarm about damage to forests and inland waters and a possible global temperature rise due to emissions from burning fossil fuels.

The Need for Information

Approval for new nuclear electric plants and continued use of existing ones may depend on satisfactory demonstration of safe waste disposal. In making decisions about power plants, it is important that citizens and lawmakers alike know the nature of the waste problem and be able to distinguish opinions, feelings, and myth from the facts.

Unfortunately, too little public information on the subject of radioactive wastes is useful. Much of that said or written is rhetoric intended either to frighten or soothe. Debaters exaggerate to try to convince rather than inform. Polarization is such that neither side of the argument is credible to the average person.

The public is often confused by conflicting statements about nuclear energy and the waste problem. Scientists of presumed equal qualifications, for example, Nobel Prize winners are seen taking opposite stands.

There is a wealth of technical literature, but it is written for use by scientists and engineers familiar with the technical terms and background. Reports on plans and progress are in formal governmental language, which is often hard to translate into ordinary English.

Understanding the problem and the decision making process

The most important premise behind this document is that an informed public will make the best decisions. Some of the questions I would like to address in this project are:

1. What are radioactive wastes?
2. Where do most of the radioactive wastes come from? How much do we have on hand and how much is produced each year?
3. What is the difference between high-level and low-level wastes?
4. What are nuclear power plants doing with their used fuel?
5. Why do we not yet have a place to dispose of spent fuel? When will a repository be available?
6. What are the best ways to dispose of wastes?
7. What organizations are responsible for handling wastes?

8. How much does it cost to dispose of wastes? Who pays for it?
9. What is the best disposal alternative for Low Level Waste (LLW) ?
10. What does a systemic analysis of the problem using the Analytic Hierarchy Process (AHP) for the selection of Nuclear waste disposal technology tell us?

Classification of Wastes

Nuclear materials comprise a great variety of isotopes, elements chemical compounds and mixtures. Definitions are important because substances are managed by law and regulation according to classification. Radioactive materials fall into several categories according to their origin [Moghissi 1983], the type of material present, and their level of radioactivity. The first and broadest distinction is:

- Defense Waste
- Commercial Waste

Defense Waste

Defense wastes have been generated over the period during and since World War II, at three main Department of Energy (DOE) Installations [Blasewitz, 1982]:

- Hanford Site near Richland, Washington.
- Idaho National Engineering Laboratory (INEL), near Idaho Falls, Idaho, and
- Savannah River Plant near Aiken, South Carolina.

Plutonium and other isotopes were separated from production reactor spent fuel at Hanford and at Savannah River, while naval propulsion reactor spent fuel was processed at Idaho Falls. In each case the chemical process has left a residue of fission product waste. Other plutonium-contaminated wastes have evolved from weapons fabrication at Rocky Flats, Colorado and several other sites.

Commercial Wastes

Commercial wastes are those produced by reactors used for electrical power, by facilities used to process reactor fuels, and by a variety of institutions and industries. There is only a small volume of commercial wastes from reprocessing because most of the fuel from power reactors has been left in the form of irradiated fuel assemblies. The spent fuel used fuel remains highly radioactive for years after it is removed from the reactor.

The only reprocessing of commercial wastes done was by Nuclear Fuel Services Incorporated, at West Valley, New York, in the period 1966 to 1972

[Blasewitz, 1982]

This plant was shut down because it was uneconomical to operate. Since 1972 spent fuel has been accumulating at nuclear power plants. As more reactors came on line, the rate of growth increased.

Comparisons and contrasts among the principal wastes can be noted. Both defense and commercial reactor wastes stem from the operation of fission reactors, but defense wastes generally are considerably older and less radioactive. Chemical separations used during World War II were designed to extract plutonium well but not to minimize residual wastes. Even though there is a small volume of fission products in defense wastes, the chemicals with which they are mixed add considerable volume. For all practical purposes, there are no separated commercial reactor wastes, but the volume of spent fuel is large because of uranium and metal structures. Institutional and industrial wastes generally have a low radioactivity level since they do not usually contain fission products. The volume is rather large however.

Three Important Types of Wastes

Another distinction among radioactive wastes is:

- High-level.
- Transuranic.
- Low-level.

High Level Wastes (HLW)

High-level wastes (HLW) are those resulting from reprocessing of spent fuel or are the spent fuel itself, either of defense or commercial origin. When spent fuel is chemically processed, the residue consists of fission products and small amounts of plutonium isotopes. Such HLW and spent fuel are the candidates for disposal by burial deep in the ground.

Transuranic Wastes (TRU)

Transuranic wastes (TRU) are those containing isotopes above uranium in the periodic table of chemical elements. They are the by-products of fuel assembly and weapons fabrication and of reprocessing operations. Their radioactivity level is generally low, but since they contain several long-lived isotopes, they must be managed separately. This classification is composed of isotopes with half-lives greater than 20 years and giving a total activity of greater than 100 nanocuries per gram of waste material.

Transuranic wastes give off very little heat, and most of them can be handled by ordinary methods not requiring remote control. For many years they were buried in shallow trenches, but since 1970 they have been placed in retrievable storage.

Table 1.1 Half Lives of Radioactive Isotopes

Radioactive Isotope	Half Life
Plutonium-239	2.411×10^4 yr
Americium-241	432.7 yr
Americium-243	7380 yr
Curium-244	18.11 yr
Curium-245	8500 yr.
Neptunium-237	2.140 million yr.

Low-level wastes (LLW)

Low-level wastes (LLW) are officially defined as all wastes other than those defined above. The bulk of LLW have relatively little radioactivity and contain practically no transuranic elements. Most of them require little or no shielding, may be handled by direct contact, and may be buried in near-surface facilities. Part of the LLW, however, have high enough radioactivity that they must be given special treatment and disposal. Low-level wastes come from certain reactor operations and from many institutions such as hospitals and research organizations and from industry.

There is no standard accepted scheme for listing types of wastes. Other waste classifications are found. For example, in the Department of Energy's Environmental Impact Statement on commercial wastes, one finds these categories, each applied to the word "wastes":

- Primary and Secondary
- Nuclear Power Plant
- Spent fuel basin storage
- Fuel reprocessing plant
- Mixed-oxide fuel fabrication
- Decommissioning.

In an official tabulation of waste inventories prepared by Oak Ridge National Laboratory for DOE, one finds these major classes:

- Spent Fuel,
- Low-level Waste,
- High-level Waste,
- Transuranic Waste,
- Mill Tailings,
- Remedial Action Waste.

The last item refers to material from decontamination and decommissioning activities at several DOE sites.

Amounts of Defense Wastes

A large volume of wastes classified as high-level defense waste is now stored in underground tanks and bins at three main government sites — Hanford, Idaho, and Savannah River. Estimated amounts according to physical form are shown in the next table. In addition there is a large accumulation of transuranic wastes at DOE facilities, also listed in a table here. About an eighth of the TRU could be retrieved, at considerable expense. Not included in the table is a large volume of soil that is slightly contaminated with plutonium.

Table 1.2 Existing High Level Waste

Existing Department of Energy Defense High-Level Wastes.

Location	**Total in 1000 m^3**
Savannah River	127.8
Idaho Falls	9.5
Hanford	232.0

The Hanford plutonium project is seen to have the largest volume of defense wastes. The site was selected immediately after Fermi's successful test of the first nuclear reactor. During World War II and afterward, the federal government constructed a total of nine plutonium production reactors, five chemical processing plants, and 149 underground storage tanks at Hanford.

Leaks of radioactive liquid from the metal tanks at Hanford occurred, apparently because of deterioration of the metal with age plus inadequate attention. Fortunately, the site for the tanks was chosen in part for the impervious nature of the soil, and thus the radioactive material did not migrate very far. Since then, liquid wastes have been put in tanks with double walls to prevent further leaks. In a study published in 1978 by the National Research Council entitled "Radioactive Wastes at the Hanford Reservation," it was noted that there had been no hazard to the public there, but that the wastes stored in underground tanks should be isolated.

We see from the foregoing discussion that there is one radioactive waste problem with three disposal challenges: defense wastes; spent fuel; and low-level wastes.

Other Nuclear Materials

Certain other materials requiring physical security, transportation. or disposal are classified and defined as follows:

1. "Source materials" are uranium or thorium or their ores containing as much as $\frac{1}{20}$ percent of those elements. They serve as the source of fissionable material.
2. "Special nuclear materials" (SNM) are uranium enriched in the isotope Uranium-235 or man-made fissile elements such as Plutonium or Uranium-233. They are special because they can be reactor fuel or weapons.
3. "By-product material" is radioactive material (excluding SNM) produced by irradiation in reactors or is the residue from the extraction of uranium from ore. It is a by-product from another objective, nuclear power.

Spent Fuel from Nuclear Reactors

The main reactor type in use in the US, and throughout the world is the light-water reactor (LWR). It is so named because it uses ordinary water formed from hydrogen (not deuterium, which is used in a heavy-water reactor). The water serves as a "moderator," the substance composed of light elements with which neutrons collide and slow down. The water also serves as a "coolant," the medium that removes the fission heat. Two types of LWR's are in use: the pressurized-water reactor (PWR), in which the water is at high pressure and temperature but does not boil, and the boiling-water reactor (BWR), in which steam is produced directly in the reactor by limited boiling at relatively low pressure.

Reactors in the U.S.

Of the commercial light-water nuclear reactors in the U.S. 75% are PWR's, 25% are BWR's. and there is one high-temperature gas-cooled reactor. As of early 1987, 97 reactors were in operation and 30 were under construction or on order. Some sites have more than one reactor. For example, Duke Power Company operates three reactors —Oconee-1, -2, and -3 near Seneca, South Carolina.

The total power capacity of the 127-U.S. reactors is around 117,000 megawatts. If all were in full operation, they would provide about 20% of the nation's electricity production. The use of nuclear power is growing in countries outside the U.S. The following table shows the status of nuclear power worldwide. A total of 26 countries have operable nuclear power plants, and 7 more have reactors under construction.

Summary

In this project I will concentrate on analyzing disposal alternatives for Low

Table 1.3 World Nuclear Power Plants

World Nuclear Power Plants, Operating and Total, as of January 1, 1988*

	Number of Reactors		Megawatts Electrical	
Country	Operating	Total	Operating	Total
1. Argentina	2	3	935	1,627
2. Belgium	7	7	5,500	5,500
3. Brazil	1	3	626	3,084
4. Bulgaria	5	8	2,713	5,572
5. Canada	18	22	11,804	15,328
6. China PR	0	3	—	2,100
7. Cuba	0	2	—	880
8. Czechoslovakia	8	16	3,160	8,280
9. Finland	4	4	2,350	2,350
10. France	50	63	45,808	62,548
11. Germany DR	5	11	1,702	5,134
12. Germany FR	19	26	18,944	26,770
13. Hungary	4	6	1,640	3,640
14. India	6	14	1,164	2,924
15. Italy	3	8	1,273	5,190
16. Japan	36	51	26,887	40,366
17. Korea	7	11	5,380	9,266
18. Mexico	0	2	—	1,308
19. Netherlands	2	2	507	507
20. Pakistan	1	1	125	125
21. Philippines	0	1	—	620
22. Poland	0	6	—	3,736
23. Rumania	0	6	—	3,540
24. South Africa	2	2	1,840	1,840
25. Spain	8	17	5,668	14,469
26. Sweden	12	12	9,650	9,650
27. Switzerland	5	5	2,930	2,930
28. Taiwan	6	6	4,884	4,884
29. United Kingdom	38	43	11,748	15,643
30. United States	102	126	89,385	116,939
31. USSR	52	76	36,288	59,788
32. Yugoslavia	1	1	632	632
Non-U.S. Total	302	438	204,158	320,231
World Total	404	564	293,543	437,170

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*Adapted from *Nuclear News,* American Nuclear Society, February 1988.

Level Waste (LLW). Most of LLW has very low levels of radioactivity, though about 5% of LLW has radioactive levels high enough to be dangerous and needs to be adequately handled and disposed.

I have focussed on LLW because data for this type of waste is relatively easily available, especially when compared to the data available for defense waste or High level waste, much of which remains classified.

I have used the Analytic Hierarchy Process (AHP) as a tool to aid the decision making process, AHP and it's application to this problem is explained in detail in the Chapter titled "Application of AHP to the Disposal of Nuclear Waste."

Historical Perspective

As with many other technological advances, initial enthusiasm and effort among the scientists, government officials, industrialists, and technicians involved with radioactive materials were narrowly channeled into the primary challenge of separating materials, determining their properties, and developing devices that would allow useful applications of the materials.

Handling and disposal of waste materials were often considered ancillary procedures that could be accomplished using methods in existence of nonradioactive materials. Even in those cases in which special attention was given to the safe containment of highly radioactive materials, plans were made for storage in liquid form in underground steel tanks that provided short-term isolation and radiation shielding. Provision was made for spare tanks into which liquid waste could be pumped when a primary storage tank reached the end of its useful life, more detailed management plans did not evolve until the 1960s.

The timing of changes in the waste management programs was the result of the interaction of several different forces [Berlin, 1989]:

- Continued experience provided the data necessary to characterize waste streams and identify physical, chemical, and radiological factors important to the design, construction, and operation of waste management facilities.

- Waste was accumulating to the point at which initial storage would have to be expanded and therefore it was appropriate to reassess the available treatment and disposal technologies to provide long-term isolation and a need for additional controls in subsequent operations of facilities.

- The transition to a commercial nuclear industry, made possible by the Atomic Energy Act of 1954 (AEA) was beginning to occur. Cooperative government/industry research, development, and demonstration programs were being followed by completely commercial ventures.

- Commercial operations, in turn required the promulgation and enforcement of regulations. Several states negotiated agreements for licensing with the (then) Atomic Energy Commission. Some waste management activities were therefore regulated by state agencies under rules compatible with federal requirements. In other states there was direct regulation by the Atomic Energy Commission.

- Improvements in computing capabilities and continued refinement of health impacts models and environmental transport models made detailed assessment of long-term performance and impact of waste management facilities a more exact science.

Interest in and support for the development of improved waste management technologies increased as the decade progressed. This was consistent with the increasing awareness of general waste management issues and environmental concerns nationwide. Projections indicated a rapid and accelerating growth in the private nuclear industry. Regulators wanted to consolidate the lessons learned from existing governmental and industrial facilities and apply them to new facilities as well as to upgrade existing practice at government and early industrial sites.

One major change was to require solidification of high-level liquid waste for eventual disposal in a federal repository. Without both the schedule and secrecy constraints of wartime operations, the siting and design of new facilities would address waste management as an integral part of the overall process or installation. Passage of the National Environmental Policy Act of 1969 (NEPA) required additional analysis of the planned interaction of the facility and its environment in a major federal action such as issuing a license to construct modify, or operate was involved. These analyses were documented in an Environmental Impact Statements (EIS's) that became a part of the licensing record.

The Atomic Energy Act of 1954 provided a framework for commercial development of radioactive materials applications and regulation of those applications by the AEC or Agreement States. The regulations provided that transfer of licensed material could be made only to a licensed recipient. Other possible methods for disposing of radioactive materials included release to air, water, or the sanitary sewer system in stringently controlled amounts and concentrations. Provision was also made to allow onsite disposal of material if it could be shown to the regulator's satisfaction that limits on exposure of individuals would not be exceeded due to the material so disposed.

In 1966 the Colorado Department of Health determined that uranium mill tailings had been routinely removed from a mill in Grand Junction, Colorado and used as landfill and construction material. The tailings were attractive because they were clean, accessible, relatively homogeneous, and cheap. As a result, several hundred thousand tons of tailings had been removed during the period 1952-1966. The problem posed by such action was twofold [Berlin, 1989]:

- Direct exposure due to γ radiation from the uranium and daughter isotopes present in the tailings; and
- Buildup within enclosed spaces (such as basements and upper levels of homes and schools built on top of, or with, tailings materials) of gaseous Radon-222, a decay product of uranium.

The second factor was the major concern in terms of public health impact. Radon gas is easily respirable and decays to daughter products that emit high energy α particles that can impart a relatively high lung dose. The Surgeon General issued guidelines for taking corrective actions as a function of external γ radiation levels and radon concentration in structures. These guidelines provided that corrective action was indicated when the external γ radiation levels in dwellings exceeded 0.1 $\frac{mR}{hr}$ or the radon daughter concentration exceeded 0.05 Working Level[1] Action may be suggested at externally radiation levels between 0.01 and 0.1 $\frac{mr}{hr}$ or radon daughter concentrations between 0.01 and 0.05 Working Level. It is estimated that over 700 structures qualified for corrective action based on these Guidelines (DOE 1980).

Cleanup began in 1973 as a state-run program with significant financial support from the federal government as authorized by Congress in 1972 . This provision was agreed to since much of the material had been produced incident to the government's uranium procurement program. The Grand Junction experience provided insight into the public health concerns with unregulated use of uranium mill tailings, development of corrective action guides, and cooperative Federal/State remediation on a large scale. It also provided experience with the length of time and amounts of money involved in such programs.

Production and processing of uranium during the 1950s and early 1960s was primarily performed in support of the government's weapons program. Uranium deposits are generally small and dispersed at relatively low

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[1] Working Level is defined as the concentration of radon daughter products per liter of air resulting in the eventual emission of 1.3 x 10S(5)MeV of a energy.

concentrations compared to other minerals such as coal or copper. Such deposits are economically minable because uranium is a concentrated energy source. Mills were developed to support several nearby mines. Because of the small scale of operation, however, many deposits and related milling capacity were opened, mined, and closed at a time when the public health implications of the resulting tailings were not fully understood or appreciated.

Local development subsequent to the closure of some of the facilities resulted in potential exposure to large numbers of people. However, because the facilities were closed and the owners had complied with then-existing rules (when such owners could still be located), it was unclear how corrective action could be accomplished and financed. The benefit to national defense and security of producing the material was further cited in support of assigning responsibility for the sites to the federal government.

The issue was finally addressed by Congress in 1978 with the passage of the Uranium Mill Tailings Radiation Control Act that made the cleanup and recovery of these sites the responsibility of the DOE. The lessons learned with the inactive sites and the stricter standards for stabilization of the tailings were extended to those sites still in operation to prevent the same conditions from being repeated at different locations.

Similar circumstances surrounded sites at which material had been processed to support the operations of the Manhattan Engineering District (MED) and subsequent government procurement and processing programs. Waste was generally disposed onsite. This practice produced several benefits to the individual program including maintaining government control over the material minimizing handling and related occupational exposure, minimizing transportation, and minimizing cost. Many of these facilities were decontaminated to the then applicable limits and released for other use. Other facilities continued to be owned by the government but were no longer used. Studies performed in the mid 1970's by the then AEC identified 31 sites that had once been used by the MED or AEC and required some kind of remedial action. This is being accomplished under the Formerly Utilized Sites Remedial Action Program (FUSRAP). An additional 20 sites were the ongoing responsibility of DOE and decontamination and decommissioning of these facilities are being accomplished under the Surplus Facilities Management Program (SFMP).

Part of the problem with radioactive waste management results from the long lead times needed for evaluation of technologies, site characterization, and development. During that time period, other events may occur that, while peripheral to waste management per se, have a fundamental effect on how the program proceeds. This was the case with high-level waste that was originally stored as a liquid in underground tanks at the site of the reprocessing facilities (both government run and commercial). In 1970 the then AEC promulgated a regulation that required HLW be solidified within 5 years after production and shipped to a federal repository for disposal within 10 years after production. The agency also announced plans to develop the first such repository in a salt deposit in Lyons, Kansas [Berlin, 1989].

The Lyons site had been the location of studies in the mid-1960s of the effects of emplacing spent fuel rods in a geologic setting (Project Salt Vault was conducted from 1965 to 1967). The announcement of the site, however, preceded detailed site investigation. This site was rejected in 1972 because of the presence in the vicinity of wells previously used for solution mining of the salt deposit and uncertainty over the effects of those operations on the long-term integrity of the repository. The Lyons experience has resulted in increased skepticism and resistance on the part of state and local officials and individuals to siting any waste repository.

Subsequent actions to select a repository site and waste form and package have been subject to several revisions reflecting changes in agency responsibility and authorization, independent reviews, and congressional directives. Reorganization of the AEC into the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Administration (ERDA) was a logical point for internal review of the program pace and direction.

Several reviews of available technology, the need for additional data, and institutional requirements for successfully implementing the program were performed in the late 1970s by committees of the National Academy of Sciences (NAS 1979), the American Physical Society (APS 1978), and several federal government agencies (IRG 1979). Together with the Nuclear Waste Policy Act of 1982, these studies have been instrumental in structuring the high-level waste program that exists today. It must be remembered, however, that the program is continually subject to change for technical, social, economic, and political reasons.

The lack of commercial reprocessing capacity, in turn, required extended onsite storage of spent fuel underwater in pools at the power reactor facilities. Such storage capacity was originally planned to accommodate about one full core plus one reload batch of fuel. This would allow for some 6 months of decay between removal from the core and shipment for reprocessing. The plant would also have the flexibility to manage emergency discharge of all the fuel in the core if necessary to protect health and safety. Such spent fuel pool storage volumes were inadequate in light of long-term absence of reprocessing capability.

Many utilities responded by installing new, specially designed spent fuel storage racks incorporating neutron poisons. With the new racks, closer fuel spacing is possible without the potential for unplanned criticality. Onsite storage space was significantly expanded in this way and near term shutdowns of power reactors averted. Storage requirements are now dermed by the schedule for availability of the federal high-level waste repository. Contracts between the utilities and the DOE specify that the government will begin to accept spent fuel—which has become high-level waste by default—in 1998.

Low-level radioactive waste (LLW) produced at federal facilities was initially disposed onsite. This practice provided benefits in terms of continuing government control over the site and material, not distracting from the primary projects of the facilities, and being the most cost-effective means of managing the waste. Shallow land burial was the disposal method of choice because it was an extension of conventional practice with other waste materials it provided shielding for those waste materials with substantive external radiation levels, soil properties would generally retard the migration of contained radionuclides, and the need for transportation of waste was reduced.

There are five primary sites managed by the DOE at which LLW produced in federal government operations is disposed [Majumdar, 1983]:

- Oak Ridge National Laboratory (Tennessee)
- Los Alamos Scientific Laboratory (New Mexico)
- Hanford Reservation (Washington State)
- Idaho National Engineering Laboratory (Idaho)
- Savannah River Plant (South Carolina)

Operations at these facilities began during or immediately following World War 2 and the sense of urgency and security surrounding early operations results in some uncertainty regarding total amounts and characteristics of waste disposed at these sites.

Initially, the small volumes or LLW produced commercially were also disposed at government sites or licensed ocean disposal sites. In the early 1960s several commercial sites were licensed for operation (Beatty Nevada and Maxey Plats, Kentucky in 1962, West Valley, New York in 1966, and Richland, Washington in 1964. The Sheffield, Illinois site began operation in 1967. The Barnwell, South Carolina site opened in 1971. Commercial sites accepted both commercial and government LLW during the 1960's and 1970's. This practice was discontinued in 1979 when commercial disposal capacity was recognized as being in potentially short supply (see subsequent discussion). Since that time, government-produced LLW has primarily been disposed at one of the facilities identified above. It should be noted that some waste produced at "government" facilities continues to be disposed at commercial sites. Waste disposed at the government sites, on the other hand, may differ from the general commercial LLW streams because of the specialized processes producing it and the relatively long time over which the sites have operated. During the approximately 40 years of operation for many of these sites, administrative changes and operating experience have resulted in revisions to waste management practice as discussed in the following paragraphs.

Oak Ridge National Laboratory

LLW management at the Oak Ridge National Laboratory (ORNL) includes storage and disposal of material produced both onsite in government operations (beginning in 1943) and offsite in commercial applications. Six local

Solid Waste Disposal Areas (SWDA) have been identified within the ORNL site. General characteristics of the site that have influenced the performance of the SWDA's include relatively shallow groundwater, high annual precipitation (about 55 in.), and a relatively humid environment. Because there is no significant regional aquifer below the disposal areas and the site soils have relatively high ion-exchange capability, isotope migration rates are low and impact on the biosphere is limited. A variety of conditions experienced at the several SWDA's on the ORNL site have resulted in changes in current and planned practice and, in some cases, entailed remediation of existing disposal units.

Several different disposal technologies have been used and are still in use at the ORNL facility. The largest portion of the waste volume has been disposed in unlined trenches in what is termed "traditional" shallow land burial. Particular wastes, notably α-contaminated materials, have been emplaced in concrete lined trenches and augured holes capped with concrete as well as unlined trenches with a concrete cap. The site changed its α-contaminated waste disposal practices in 1971 in keeping with the AEC directive on disposal of transuranic waste (TRU). Since that time TRU in concentrations greater than $10\frac{nCi}{gm}$ have been stored in structures for subsequent removal and permanent disposal. Liquid wastes have been placed in onsite storage ponds as well as injected as a slurry into shales underlying the site.

Los Alamos Scientific Laboratory

Waste disposal operations at Los Alamos Scientific Laboratory (LASL) benefit from the site's location and characteristics because the combination of low precipitation rates, generally deep groundwater levels, and relatively impermeable soil with good adsorptive properties means there is not a strong transport mechanism for migration via groundwater pathways. With the exception of possible long-term erosion near canyon edges, erosion is not a substantive force that might result in dispersion of the emplaced wastes.

A variety of disposal technologies, including traditional shallow land burial, liquid waste ponds, and deep augured shafts, have been used at the site since disposal started in 1944. Problems encountered at the site included inadequate record keeping and identification of the earliest disposal areas. This inadequacy was common to all sites operating at the time. Changes in site operating procedures have included installation and application or volume reduction programs including sorting and segregating waste and compacting trash.

Overall volume reductions of 20-25 % have been achieved. Liquid waste is no longer disposed into seepage pits. Such waste is now mixed with cement and disposed in deep augured holes. The previous practice of disposing of hazardous chemical waste with radioactive waste has been identified as a probable contributor to fires in disposal trenches, which resulted in temporary airborne contamination. Current practice provides for segregated disposal of hazardous and radioactive waste and covering waste with soil shortly after emplacement. One no longer used disposal area has been surfaced with asphalt and reused as a parking lot by the County of Los Alamos which leases the area from LASL.

Hanford Reservation

The large size (365,000 acres) of the Hanford Reservation (HR) is a major influence on waste disposal operations there. Without the space constraints of later sites in more densely populated areas, it was possible to use disposal methods that might otherwise not be available. For example, two tunnels onsite house railway spurs containing flat cars loaded with large, heavy, or highly contaminated equipment. Over 65 individual disposal sites have been used in several main areas since disposal began in 1944. Wastes disposed include equipment and machinery from the production reactors, construction debris, and liquids as well as waste more typical of industrial operations utilizing radioactive materials.

Like the LASL site, HR has a relatively low annual average precipitation rate (6.3 in.) and is in a dry climate so potential evapo-transpiration exceeds precipitation. Site soils are relatively homogeneous and have high adsorptive capacities. The depth to groundwater varies but is large in the areas currently used for disposal. The unsaturated soils at the site, however, have relatively high permeabilities and are subject to substantial wind erosion that is of concern in ensuring long-term site stability. A major difference between disposal at this site and at other government sites is the continuing disposal of liquid waste in settling ponds and cribs[1].

In addition to the traditional shallow land disposal trenches and the liquid disposal in cribs or ponds, underground caissons of reinforced concrete are used for disposal of higher activity waste. Other variations are utilized as necessary because of the size or activity of the waste or for security reasons. TRU wastes in retrievable storage are stacked in drums and boxes on asphalt pads separated by fire-retardant plywood. The stack is covered with a polymer membrane and over 4 ft of overburden. High-activity waste is stored retrievably in underground caissons.

During the course of waste management at HR over the past 40 plus years problems have arisen from spills and leaks of liquid waste resulting in surface contamination as well as in fires in disposal trenches and a waste storage area. Trench cover designs now incorporate a layer of stone to minimize wind erosion and reduce intrusion by both burrowing animals and plants. These two phenomena had been identified as the transport mechanism of waste from the disposal areas to the local environment. There is an extensive environmental monitoring program onsite and research programs on the behavior of the waste released into the biosphere.

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[1] A crib is a long ditch about 20 ft deep that is backfilled with rock and covered with an impermeable membrane and soil. Liquid waste is uniformly dispersed into the crib through a perforated pipe.

The Idaho National Engineering Laboratory

The Idaho National Engineering Laboratory (INEL) occupies over 500,000 acres of land on the Snake River Plain in Idaho. Most disposal and storage of solid LLW and TRU waste occur within the 143-acre Radioactive Waste Management Complex (RWMC). About 88 acres have been designated as a Subsurface Disposal Area (SDA) for LLW. About 20 acres of this area is still available for use. The Transuranic Storage Area (TSA) occupies about 55 acres of which 44 are still available. The specific portion of the INEL site selected for waste disposal was chosen for a combination of ease of access, substantial thickness (about 20 ft) of unconsolidated sediment with good adsorptive capacity, a single area encompassing tens of acres, and soils that would be easily excavated. Waste disposal at the RWMC began in 1952.

The area has received both waste from operations at INEL which has been primarily mixed fission products and activation from research reactor operations onsite, and waste from other government sites. TRU-containing waste from the Rocky Flats, Colorado site began to be shipped to INEL in 1954. The LLW portion of the site was expanded from an original 12 acres to the present 88 acres in 1957. Another small disposal area was opened and operated from 1961 to 1962 to receive material produced during the recovery and decontamination following the SL-I reactor excursion. The primary purpose of using the additional site was to reduce occupational exposure to the highly radioactive material during handling and transportation.

The Transuranic Storage Area (TSA) provides the ability to store TRU waste as required by the AEC in 1971. Storage is accomplished by stacking waste on aboveground asphalt pads that are placed over a layer of crushed gravel. Some TRU waste is also stored at the Intermediate Level Transuranic Storage Facility (ILTSF) in concrete-filled carbon steel vaults. Some TRU buried prior to the rule change has been exhumed and placed into storage. Exhumation was conducted within double containment. That is, a structure was erected around the area of exhumation and the whole operation took place within an air-supported weather shield.

Experience at the RWMC included several fires in open disposal trenches and surface spills resulting in local contamination. The disposal areas have been flooded several times. During one flood in 1962, uncovered waste at the SL-I disposal area was transported outside the area. The waste was successfully recovered. Changes in waste management practices include increasing the minimum trench depth, increasing the trench cover thickness, more frequent covering of emplaced waste to prevent fires, and employing compaction to improve the waste stability. Changes have also been made in surface drainage systems to enhance flood protection.

The Savannah River Plant

The Savannah River Plant (SRP) in South Carolina, like ORNL, is located in a humid environment. Precipitation is responsible for 20-22 in/yr of recharge to the groundwater. The soil in the area is relatively permeable and consists mostly of clayey sand with good adsorptive capacity. The normal depth to the water table ranges from 20 to 60 ft in the LLW disposal area which occupies about 195 of the 192,000 acres at SRP. Waste disposal and storage began at SRP in 1953. In addition to waste produced by the onsite facilities (production reactors, fuel fabrication, and reprocessing facilities) the site has received Pu^{238}) process waste from Mound Laboratory and LASL and radioactive debris from two United States airplane accidents involving nuclear weapons.

TRU was first disposed at SRP in 1965. At that time waste containing $< 0.1 \frac{Ci}{gm}$ continued to be disposed nonretrievably in designated "α" trenches. Packages containing $> 0.1 \frac{Ci}{gm}$ were placed in concrete containers prior to burial. Subsequent to 1971, TRU waste containing $> 10 \frac{Ci}{gm}$ has been stored in concrete containers, steel boxes, and galvanized steel drums stacked on reinforced concrete pads. Filled pads are covered with a multi-layer barrier that includes sand, soil, plastic sheeting, and 4 ft of overburden. This covering is then topped with a layer of asphalt and additional soil and a vegetative cover is sown. Experience at SRP has been similar to that at other government LLW disposal.

The NRC licensed a portion of the West Valley site for disposal by burial of radioactive waste produced in the reprocessing facility. Monitoring of this area identified migration of radionuclides from the trenches. The major contributor to the movement was the presence of organic liquids from the reprocessing operation Nuclear Fuel Services also operated a commercial LLW disposal facility at another location on the West Valley site. This operation, however, was directly regulated by the State of New York under its licensing agreement with the Nuclear Regulatory Commission. One of the key site characteristics affecting LLW disposal at West Valley was the highly impervious clay till in which the wastes were disposed.

The possibility of repeated unilateral shutdown of the existing LLW disposal sites by the host states raised concern over the impact on health and safety of material stored at the site of generation. Recognizing the benefits of the processes that result in producing the waste (for example, medical and academic research, consumer products such as smoke detectors and luminous safety signs, generation of electric power, and radio-pharmaceuticals), there was a need to develop a system to provide for continued safe disposal of the waste.

With the passage of the Low-Level Radioactive Waste Policy Act of 1980 Congress assigned to the individual states the responsibility for ensuring the availability of adequate disposal capacity for the LLW generated within their borders. This included government waste except for that owned or generated by the Department of Energy or the U.S. Navy (from decommissioning nuclear vessels) or produced from research, development, testing, or production of atomic weapons. States were encouraged to adopt interstate compacts to form multistate regions to manage all of the waste at a single site in the region rather than having a site in each state. There are several advantages to a regional approach:

1. It better matches practical site size to the rate of waste production than having many small sites.
2. It provides cost advantages because much of the disposal costs are essentially unaffected by the amount of waste the site receives.
3. It enhances public protection by limiting the demand for trained operating personnel nationwide.
4. Several regional facilities will result in lower transportation requirements than would fewer facilities nationwide.

This chapter, then lays the foundation for how Nuclear wastes came about, and the political-economic factors that were involved in the decisions involving nuclear waste.

Disposal of Radioactive Material

History of Radioactive Material Disposal

The beginning of the "atomic" age is often linked to the Manhattan Engineering District Project during World War II. The bulk of the work on this project was performed under great secrecy in government-owned facilities in the 1940's. When various waste materials were generated within these laboratories, reactors, and processing plants, it was necessary to employ a disposal practice which was safe, convenient, and secure.

The disposal method of shallow land burial was adopted for several reasons [Blasewitz, 1982]:

1. It could be accomplished quickly with relative ease using conventional construction equipment.
2. The methodology was a modification of an existing waste management practice, sanitary landfill disposal.

3. Even as early as the 1940's, scientists knew that the chemical retention capability of soil minerals could enhance the performance of a disposal site by delaying the movement of radionuclides through the soil.

4. For highly radioactive waste materials, shallow land burial provided some shielding attributes. Shielding was provided to some extent as soon as the waste was lowered into a trench, pit, or hot well shaft. In addition, disposal sites located in close proximity to the waste generator had many security and economic advantages. Sites at or near the point of generation generally eliminated the need for shipping wastes by public transportation systems. Also, the fewer miles required for transportation, the smaller the chance of a transport accident.

Five large government facilities were eventually constructed to support the Manhattan Project. Each facility constructed generated significant waste volumes and each had its own disposal site. These facilities included Oak Ridge National Laboratory (ORNL), Los Alamos Scientific Laboratory (LASL), Hanford Reservation (HR), Savannah River Plant (SRP), and Idaho National Engineering Laboratory (INEL). Activities at ORNL, LASL, and HR (which later contained the first federal low-level waste disposal sites) gained full momentum in 1943. In 1949, the large defense facilities, SRP and INEL, opened. In addition to these five major government disposal sites, some government facilities generated and disposed of small volumes of waste on site. Other government facilities transported their low-level waste (LLW) to existing sites. All of these sites were regulated by the U.S. Atomic Energy Commission.

In the 1950's, the "Atom for Peace" program expanded radioactive materials use to the public sector. Medical, research, and the commercial nuclear power industry started generating significant quantities of waste material. Most of the early generators used commercial ocean disposal contractor services for waste disposal at a few government-approved off-shore sites. As a result of several decisions relating to the economics and potential difficulty in monitoring ocean disposal, disposal of commercially generated waste on land was increasingly encouraged by the government.

The AEC established "interim" usage of government disposal sites for commercial low-level waste. In 1960, two government sites (INEL and ORNL) were designated for interim commercial use. The condition existed until the operation of hydrogeologically suitable commercial sites was established. It was believed then that the existing government sites would fill rapidly if used by both federal and commercial waste generators. Strong emphasis was, therefore, placed on the commercial industry to ease the temporary use of government disposal sites.

The first commercial disposal site was opened in 1962 at Beatty, Nevada by the Nuclear Engineering Company (NECO). Later that same year NECO opened a site in eastern Kentucky on a ridge known as Maxey Flats [Majumdar, 1983]. The INEL and ORNL disposal sites were used until 1963, the first full year of commercial disposal site operation. Thereafter, AEC (and ERDA) waste generators shipped waste frequently to the commercial sites (for economic reasons and to promote their use). In 1979, however, commercial disposal site capacity was limited because of the closure of several commercial sites. For political reasons, therefore, the use of commercial sites for most government-generated waste has been discontinued. Four additional commercial sites were licensed after 1962:

1. In late 1963, Nuclear Fuel Services opened a site near West Valley, New York, near their nuclear fuel reprocessing plant;
2. In 1964, California Nuclear, Inc., opened a site within the Hanford Reservation near Richland, Washington;
3. In 1967, California Nuclear later opened a site near Sheffield, Illinois. (Later NECO, since renamed U.S. Ecology, Inc., acquired and operated the Richland and the Sheffield sites); and
4. In 1971, ChemNuclear Systems, Inc. (CNSI) opened the sixth low-level waste commercial disposal site near Barnwell, South Carolina.

The Table below summarizes the status of the six sites and their low-level waste volume received from 1963 through 1984. The last commercial disposal site was licensed in 1971. Since then, licensing of additional disposal sites have

Table 2.1 **Status Summary of Commercial Disposal Sites**

	Land Area (Acres)	Volume (cubic ft)
Beatty, NV	80	3,400,000
Maxey Flats, KY	252	4,770,000
Richland, WA	22	2,360,000
Sheffield, IL	100	7,788,000
Barnwell, SC	300	17,256,000

been attempted. Due to socio-political problems and anticipation of new burial requirements (10 CFR 61), however, a new operating site has not been opened since 1971.

The lifespan of a disposal site can be separated into 5 main phases [Berlin, 1989];

1. Site selection and characterization;
2. Preoperational licensing;
3. Construction and active disposal operation;
4. Site closure and stabilization; and
5. Institutional control.

Site selection and characterization activities are carried out by the applicant in coordination with NRC, state and local governments. A preferred site is selected and the site characterized in detail. The applicant prepares a license application which includes a preliminary closure plan, environmental report, arrangement for government ownership of the land, lease arrangements for use of the site, and financial arrangements to cover the costs of closure and post-closure activities. The phase usually takes from 1 to 2 years.

Preoperation licensing is the second phase. The application is submitted to the

NRC or to the agreement state with the license fee and docketed. A notice of receipt of the application is published in the Federal or State Register and an opportunity for requesting hearings is provided. Applicable state and local government officials are notified. An analysis of the application is carried out by the licensing staff, including preparation of an environmental impact statement. Public hearings are held, including any commission reviews and appeals. Upon resolution of all hearings and appeals and upon a satisfactory finding, the licensing branch issues the license, notices issuance, and notifies other officials. This phase may take from 1 to 4 years.

The third phase is the construction and active disposal operations. Upon license issuance, the operator begins operations to construct the facility and to receive and dispose of waste. On a periodic basis (about every 5 years, or as stated in the license), the regulatory branch reviews the licensee's program including the preliminary site closure plan, financial arrangements for closure and post-closure activities, and continued assessment of environmental impacts. This phase usually is from 25 to 40 years.

The fourth phase is the site closure and stabilization phase. During active disposal operations, the site is generally stabilized e.g., for shallow-land burial the trench caps are put in place as it is filled). At closure, final site stabilization activities are carried out. Facilities not needed for post-closure activities are decontaminated and dismantled. Costs for closure are provided by financial arrangements of the operator. Upon satisfactory closure, the licensing branch terminates the license and control of the site reverts back to the government landowner. This phase may take from 1 to 2 years. The fifth or final phase consists of institutional control or custodial care of the site. This includes continued government ownership and control of the site and carrying out activities such as maintaining site security, monitoring of the environment, and carrying out any maintenance activities. The institutional control must be maintained at a minimum of 100 years.

At every site, the State or Federal government owns the land. Corporations may have purchased the land and transferred the deed over to the government before receiving their operating license. The corporations which operate these sites, lease the land at a negotiated fee from the State and Federal Government. A regulatory body oversees the operation of each of these sites, helping to maintain the integrity of the environment and the personal health and safety of those employees. If a state chooses to be the regulatory body, the NRC must agree and approve of their program. In an NRC Agreement State, the State Government provides a regulatory branch responsible for regulating the sites. In Nonagreement States, the NRC takes the major role in site regulatory actions.

Many factors are considered in the license; therefore, each disposal site may accept only certain waste types. The site license restricts the waste type and form and provides site operation restrictions. These restrictions reduce site and equipment contamination, occupational exposures, and the potential migration of radionuclide. The site operator also requires the waste users to conform to its operational restriction or site criteria. This is to optimize site operations and reduce occupational exposure and environmental affects.

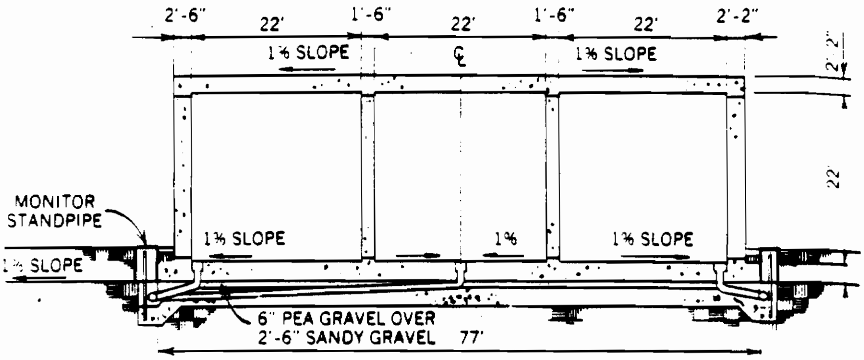
Alternatives to Near-Surface Disposal

Several other options exist to near-surface disposal. Four principal disposal alternatives exist,which are :

1. Vaults,
2. Intermediate depth excavations (greater than 15 m depth),
3. Disposal in deep-mined cavities, and
4. Ocean disposal.

Vaults

"The vault alternative" refers to any enclosed engineered structure constructed below or above the surface of the earth and used for the disposal of low-level radioactive waste materials. Belowground vaults are visually unobtrusive and physically secure to prevent intrusion because of their siting below the ground surface. Access to the foundation elevation may be directly from the earth's surface in the form of a conventional excavation in which the vault is built and then covered over.

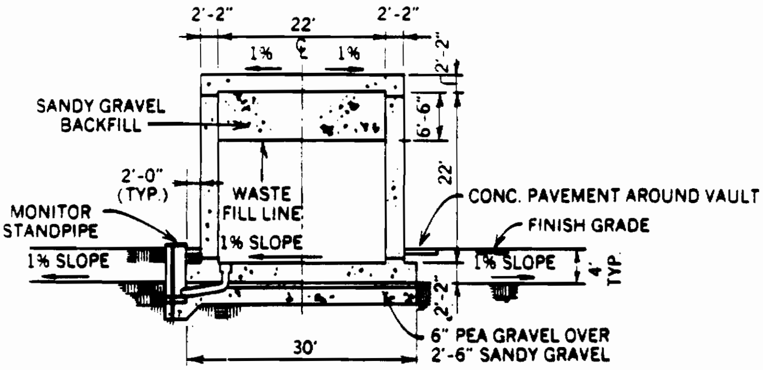


A
8625-04

ABOVE GROUND VAULT SECTION – CLASS A

SCALE: 1" = 10'-0"

0 10 20 30 40 FT.



B.C.
8625-04

ABOVE GROUND VAULT SECTION – CLASS B.C.

SCALE: 1" = 10'-0"

0 10 20 30 40 FT.

Figure 3.1 Vault Disposal

A belowground vault has several performance capabilities that make it attractive as an LLW disposal alternative.

1. The vault is visually unobtrusive. In the event of erosion or mass earth movement, only the vault would be exposed. The waste would still be isolated.
2. Intrusion of groundwater, animals and plants into a belowground vault is unlikely. The belowground vault is itself a barrier to intrusion in addition to the natural barrier of subsurface geologic materials. Inadvertent human intrusion into a vault is highly unlikely both because of its structural competence and its obvious contrast with earth materials.
3. A vault is self-supporting and can support backfilled earth with negligible subsidence. Escape of liquid or gaseous matter from the vault is impeded by the vault structure and the surrounding earth cover. Radiation flux to the surface is limited by the engineered roof and by the earth cover.
4. An appropriately designed vault should remain intact and sealed through all foreseeable or projected seismic, meteorological, and earth movement events. The vault units are easy to locate and could be reentered in the event the waste material is to be retrieved.
5. Design and construction of the vaults can be standardized with potential economic benefits. Standardization of the vaults could lead to standardization of waste handling procedures. Regulatory control of the standardized vaults may be more efficient. Uniformity of facilities and procedures could decrease vulnerability of workers to accidental radiation exposure caused by accidents while performing unfamiliar activities.

There are, however, many serious disadvantages associated with belowground vaults for LLW disposal. The vaults must be protected from flooding during construction and operations. They cannot be visually inspected or monitored. Also, use of remote handling facilities is hampered by the limited access. Consequently, exposure of workers to radiation hazards may be higher than desirable. In addition, the costs are higher than other alternatives.

The aboveground vault alternative disposal unit is different than the belowground vault. It is an engineered structure or building with floor, walls, roof, and limited access openings with its foundation at or very near the ground surface. The engineered structure must also stand alone on its foundation, and through its own design features, satisfy the performance objectives. A wide variety of aboveground vaults have been built and successfully used for warehousing manufactured goods, raw materials, and meat and produce. Their wide acceptance shows that they could be durable and versatile structures. No aboveground vaults are used in the U.S. today, however, to dispose of LLW.

Current geotechnical foundation engineering and structural design methods allow aboveground vaults to be built to withstand a large range of natural hazards including seismic events, erosion, and landslides. Aboveground vaults are less vulnerable to flood damage. These qualities may allow more freedom in siting LLW disposal facilities in regions that demonstrate less than ideal characteristics for other alternative disposal methods.

Some disadvantages may also be expected with aboveground vault disposal

1. There would be no secondary barrier to prevent radionuclide releases to the atmosphere if the vault structure failed after the waste packages deteriorate.
2. Aboveground vaults will be readily visible on the landscape. That characteristic may or may not be a detriment in the sociopolitical acceptance.
3. There would also be less time available to take remedial actions to prevent radioactivity releases to the atmosphere from escaping from the site.
4. In addition, active maintenance requirements could be extensive. The institutional control period required would be much longer than for any subsurface disposal method.
5. As mentioned for belowground vaults, exposure of workers to radiation hazards of high activity wastes could be higher than desired because of the difficulty in adapting remote handling equipment for use in limited access facilities.

Intermediate Depth Disposal

Intermediate depth disposal usually means disposal of waste at depths greater

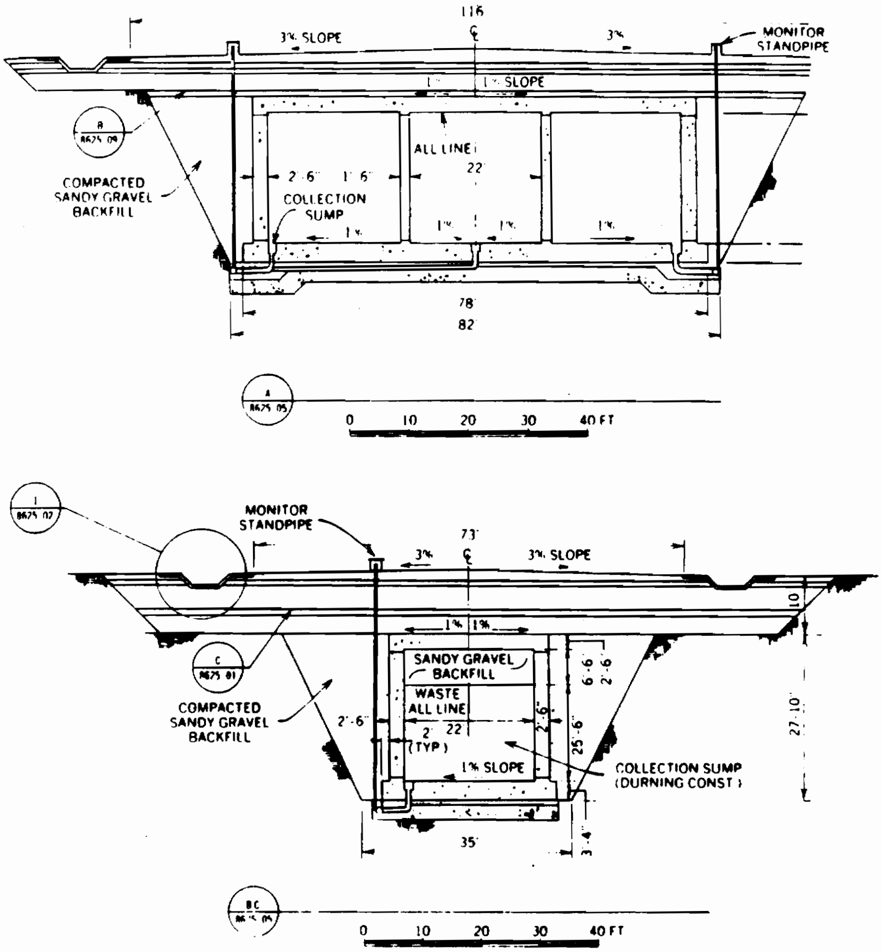


Figure 3.2 Intermediate Depth Disposal

than 50 ft. While 15 ft represents the maximum expected depth for small construction and farming activities (excluding well drilling), the maximum expected depth for heavy construction activities (excluding surface mining) is probably less than 50 ft.

Deep burial at some localities (especially many areas in the humid eastern United States) may be difficult as a result of relatively shallow depth to ground water and heterogenous subsurface media (e.g., fractured rock). However, it is believed that intermediate depth disposal could easily be practiced in a number of areas in the western and southwestern U.S.

In addition, the practicality of construction of a deep trench may be questionable from both a side slope requirement and an operational requirement. The large depth excavation would require (if excavation as a trench were feasible) either substantial shoring to keep the excavation open or would require terracing or gentle slopes. Once the slopes are terraced or gently sloped, the excavation then begins to resemble an Open-pit mine or strip-mine geometry. Another drawback to using very deep trench excavations is the potential difficulty in waste emplacement. Existing conventional lifting equipment would not be adequate. Either modified mine hoists or special unloading would be required. Use of hoists could significantly increase the labor requirements in elevated radiation fields while dropping wastes into deep excavations would probably rupture many waste containers.

Application of strip-mine or open-pit mine technologies appear to be more viable options. Surface mining technologies can be applied to either existing mines that have not been fully reclaimed or to new sites where geologic conditions would permit such large excavations.

Both the design and operation of the intermediate depth disposal facility differ significantly from the shallow-land disposal facility. The excavation is assumed to be a circular open-pit with a spiral access road leading down into the excavation. The excavation is roughly circular, holding many layers of waste. Each layer of waste is emplaced by forklifts and boom cranes within the excavation.

The design and operation unit disposal costs for intermediate depth disposal are higher than for a shallow-land facility. After the final waste layer is emplaced, a final disposal cap of 50 ft of overburden is added, which results in a minimum thickness of 50 ft between the waste and the final grade. The equipment needs for the intermediate depth disposal are similar to a disposal facility, with the addition of more forklifts for waste emplacement activities, pan scrapers to handle the extra overburden volumes, dump trucks to supplement earth moving activities, and extra cranes for waste emplacement. The building and structure requirements are also assumed to be similar to those required for a shallow-land disposal facility. The labor requirements for the intermediate depth disposal facility are also increased as a result of the need for additional heavy equipment operators, dump truck drivers, semiskilled labor, and unskilled labor.

The major benefits of intermediate depth disposal include significant protection for the inadvertent intruder as well as some increased ground after protection. The majority of radioactive waste commercially generated will not require such extensive protection for the inadvertent intruder. The major disadvantage is higher costs.

Mined Cavity Disposal

The two basic options available for mined cavity disposal are:

1. Creation of a new mined cavity; and
2. Rehabilitation of an existing mine.

Construction of a new mined cavity can be accomplished either in salt media or in hard rock media (e.g., granite or basalt). One significant variation from a near-surface disposal facility is the land requirement. To control access to the mine and prevent intrusion (especially in the form of well drilling), between 1000 and 1400 acres of surface property are required for a mined cavity.

Compared to a near-surface disposal facility, a number of additional surface buildings and facilities are required for a mined cavity disposal facility. The additional surface facilities include: a waste receiving building, cap and powder magazines (for hard-rock mining only), a hoist building, and an

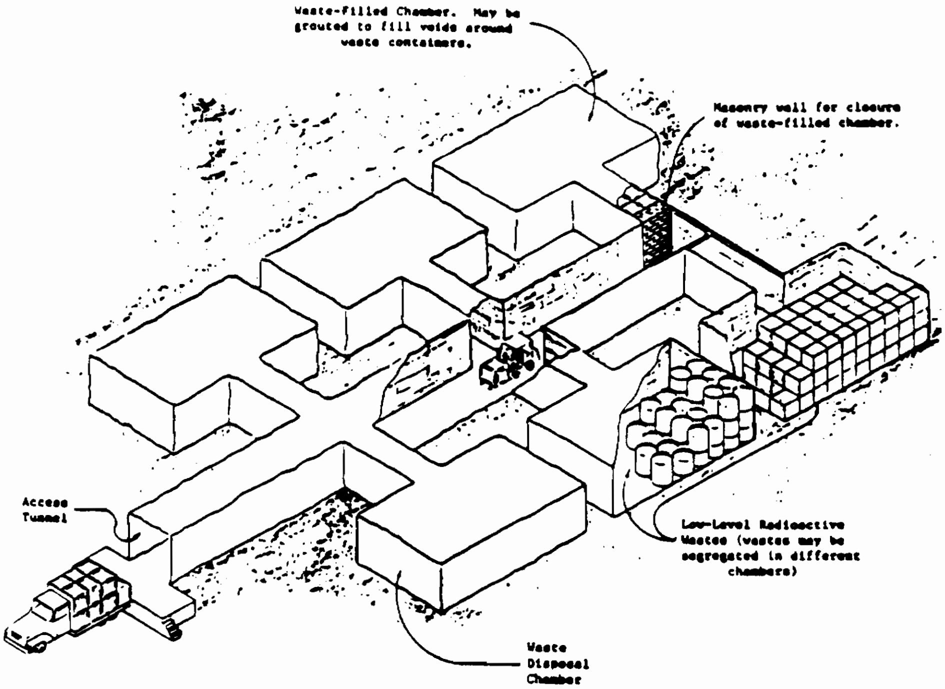


Figure 3.3 Mined Cavity Disposal

electrical substitution for underground power requirements. A significant area (10 ha or 25 acres) would have to be set aside at each mined cavity disposal site for mined material storage from new mines.

Disposal operations require relatively close contact with the waste packages. Waste is handled, in effect, twice: once at the receiving building and once within the mined cavity. As a result of the double handling and the confined working areas, it is estimated that the occupational exposures for mined cavity operation are about four times higher than those experienced at a near-surface disposal facility. A large mined cavity disposal facility will require over twice the personnel requirements for a near-surface disposal facility

Ocean Disposal

The AEC previously licensed disposal of low-level radioactive waste at a number of Atlantic and Pacific Ocean sites. The disposal site locations varied greatly in terms of distance from shore and depth to disposal area. In the early 1960's, the AEC began to phase out ocean disposal of radioactive waste and by the end of 1970 all the U.S. ocean-related disposal activities had ceased. Ocean disposal up to this time had been conducted at five different locations in the Pacific Ocean, one location in the Gulf of Mexico, and eleven locations in the Atlantic Ocean. The waste was not evenly distributed among the seventeen disposal sites, as two Atlantic sites and one Pacific site received about 90% of the low-level radioactive volume disposed at sea.

Although not currently practiced in the U.S., ocean disposal of radioactive waste is practiced by several foreign countries. The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) developed a program which, in 1967, led to the first international disposal operation, involving five countries. Additional international organizations carried out disposal operations from 1969 through 1976, utilizing the International Atomic Energy Agency's (IAEA) guidelines to regulate operations of sea disposal of radioactive waste. The regulations encompassed site selection, packaging and container design, ship design, health physics, recordkeeping, and supervision of dumping operations.

In 1972, the International Ocean Dumping Convention (IODC) made specific recommendations which were adopted in 1974 by the IAEA. Not all radioactive waste producing countries have adopted the IODC recommendations or those standards developed by the IAEA. Thus, international agreement on regulating ocean disposal activities for radioactive waste is presently lacking. In the U.S., the EPA has the responsibility of developing a permit program for ocean dumping of all wastes, including radioactive waste as well as solid and hazardous wastes. EPA was provided with this regulatory responsibility by the Ocean Dumping Act of 1974 (PL 92-532) and since this law was passed, EPA has instituted a domestic criteria and standards development program.

There are two major concepts for sea disposal ocean dumping of packaged wastes and sediment penetration using free-falling projectiles containing several waste packages. However, many technical, legal, and social issues regarding ocean disposal will require resolution in its future use as a disposal technique.

As a result of the controversy surrounding this disposal technology, and the fact that it is not used for currently for waste disposal, it will not be considered in the analysis which follows.

Current Disposal Technology

All new disposal sites will be licensed in conformance with NRC's new regulations, Title 10 of the Code of Federal Regulations, Part 61 (10 CFR 61). These regulations serve to aid in the definition of which wastes are suitable for near surface disposal within the top 15m of the earth's surface. These regulations also cover other alternatives and modifications of near surface disposal concepts such as engineered structures meeting the performance criteria of 10 CFR 61.

10 CFR 61 addresses one general and three specific performance objectives for any disposal method. The general objective ensures that the facility is designed, operated, closed, and maintained so that the calculated radiation

exposure to humans is within acceptable limits. The requirements also place considerable emphasis on the long-term performance of the facility as opposed to the short-term convenience.

The general performance objective includes a site-specific barrier system promoting long term performance by:

1. Appropriate engineering design
2. Proper operational procedures
3. Waste form and packaging criteria
4. Use of the natural characteristics of the sites
5. Proper institutional controls on the land use

The three specific performance objectives include:

1. Protection of the ground water;
2. Protection against any inadvertent intruder; and
3. Safety provisions during operation.

Many factors must be considered in the meeting of the performance criteria, including:

1. Geology
2. Hydrology
3. Natural resources
4. Endangered species
5. Population distribution
6. Existing land use patterns
7. Preliminary waste transportation routes
8. Capital, operational, closure, and long-term costs
9. Impact of waste transport and operations on local resources and economy

The regulations in 10 CFR 61 are results of the events that have transpired from the closing of the first commercial site in 1976 to the new regulations implementation in 1982. Political, industrial, medical, scientific, and public communities lately have focused attention on commercial disposal sites. This attention promoted a national strategy to safely and effectively manage low-level radioactive waste [Majumdar, 1983].

The National Governors Association Task Force on low-level radioactive waste disposal outlined this strategy in a major policy statement in August, 1980. The task force recommended that each state accept primary responsibility for the waste generated within its borders and that a reasonable approach to select and establish a disposal facility should be adopted again. The National Conference of State Legislators, the State Planning Council on Radioactive Waste Management, and the U.S. Department of Energy (DOE) adopted similar positions.

Congress passed PL 96-573, the Low-Level Radioactive Waste Policy Act, in December of 1980 making this strategy a national policy [Majumdar, 1983]. The policy stated that:

1. Each state is responsible for the disposal of low-level radioactive waste generated within its borders, except for waste generated as the result of Federal defense, research or development activities.
2. Management of low-level radioactive waste on a regional basis is the most safe and efficient method.
3. Various states may enter into a regional compact to provide for the establishment and operation of a low-level waste disposal facility; however, a compact shall not take effect until Congress has consented to the compact. Each compact shall also provide that on the 5 year anniversary date of the compact, Congress may withdraw its consent.
4. After January 1, 1986, any compact formed may also restrict the use of the regional disposal facility only for the disposal of low-level radioactive waste generated within the applicable region.

During the period from 1980 to 1986, many states actively sought to develop new disposal sites. As these states began to negotiate and ratify regional compacts, it became evident that the allowed time period was too short to license any new disposal sites by 1986. Many states and generators made requests to Congressional leaders for extension of the 1980 Waste Policy Act deadline of January 1, 1986.

The U.S. Congress responded to the states' request and passed the Low-Level Radioactive Waste Policy Amendment Act of 1985. The Act allowed waste generators in states which had not joined compacts having operating disposal sites continued access to the existing sites until 1993. In return for continued access, the states where these generators are located must meet certain milestones for establishing new sites and their generators must pay additional surcharges ranging from $10 to $120/cu ft.

The Policy stated that the current states with disposal sites (South Carolina, Washington, and Nevada) are required to make disposal capacity available until December 1992, with certain limits and on certain conditions. First, generators in compacts to which the sited states belong are "accorded priority" for their waste. Second, the Act allows each nuclear plant an allocation of the disposal capacity at the three disposal sites. The specific allocation is based on the plant type, location, and length of commercial operation. Finally, the sited states may deny access to generators if the site exceeds the average annual site volume cap (1.2 million cubic feet for

Barnwell, 1.4 million cubic feet for Richland, and 0.2 million cubic feet for Beatty).

The Waste Policy Amendments Act of 1985 amended in its entirety the Low-Level Radioactive Waste Policy Act of 1980. However, the basic provisions of the 1980 Act were preserved. A state is still responsible for providing, either by itself or in cooperation with other states in a compact, for the disposal of low-level radioactive waste. Also, it is still the policy of the federal government that the responsibilities of the states for providing for such disposal can be most safely and effectively managed on a regional basis.

By 1993 the three existing sites in South Carolina, Nevada, and Washington, will no longer be available for commercial waste generators outside their compact regions. All three states with operating disposal sites plan to exercise their exclusionary authority. The regions where disposal sites do not exist are taking action to adopt interstate compacts. The exclusionary authority provision for a regional compact will provide the greatest incentive for establishing new sites by placing tremendous pressure on those states without sites.

These new sites will be the result of many years of experience and the expressed concerns of the public. The experience from the government and the six commercial disposal sites will add to the new and improved disposal methods. These methods or alternatives must all comply with the performance criteria of 10 CFR 61 and the concerns of the public. Many states are determining their disposal methods and how they will be responsible for their low-level waste in the future.

Application of AHP to the Disposal of Nuclear Waste

Introduction to AHP

The Analytic Hierarchy Process (AHP) was developed by Thomas Saaty. The strength of AHP lies in its ability to breakdown complex decision making problems into elementary decision factors, which can then be used to evaluate the alternatives systematically [Canada, 1989].

Decision making and implementation involves the following kinds of concerns:

1. Planning
2. Generating a set of alternatives
3. Setting priorities
4. Choosing a best policy after finding a set of alternatives
5. Allocating resources
6. Determining requirements

7. Predicting Outcomes
8. Designing Systems
9. Measuring performance
10. Insuring the stability of the System
11. Optimizing
12. Resolving conflict

The scope of this project is concentrated on the first four concerns.

The Analytic Hierarchy Process

The steps involved in the AHP can be summarized as follows:

1. State the problem.
2. Analyze the problem and identify the objectives that need to be accomplished.
3. Identify the criteria that influence the behavior of the problem.
4. Structure a hierarchy of the criteria, sub-criteria, properties of alternatives, and the alternatives themselves.
5. To remove ambiguity carefully define every element in the hierarchy.

6. Prioritize the primary criteria with respect to their impact on the overall objective called the focus.

7. Arrange the attributes or alternatives that are to be compared in a matrix form, recognizing that all elements along the diagonal have value equal to one and elements below the diagonal are mirrored with a reciprocal value.

8. State the question for pairwise comparisons clearly above each matrix, while paying close attention to the orientation of the problem, e.g., costs go down, benefits go up etc.

9. Prioritize the subcriteria with respect to their criteria.

10. Calculate the priorities by adding the elements of each column and dividing each entry by the total of the column. Average over the rows of the resulting matrix, which will give us the priority vector.

11. Compose the weights in the hierarchy to obtain composite priorities and also the composite values of the state variables which collectively define the composite outcome.

12. In the case of choosing among alternatives, select the highest priority alternative.

Ranking of Attributes

The general approach is to do a pairwise comparison according to the hierarchy. Saaty suggested the following scale to be used for this purpose.

If Attribute is...	**Then the Preference number is**
Equally important	1
Weakly more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9

Even numbers are used to represent values in between. An important point to remember is that if attribute y is preferable to x then the inverse of the preference number is to be used.

Matrix Operations

After all the numbers have been entered, the matrix is normalized with respect to each column and row averages are computed, the row average represent the priority weight of that attribute.

Pairwise comparisons are then made one level higher. That is, we make pairwise comparisons of each alternative with respect to each attribute after which the same matrix operations as described above are carried out.

The weighted evaluation for each alternative can then be computed by multiplying the matrix of evaluation ratings by the vector of attribute weights

Consistency Ratio Determination

The consistency ratio (C.R.) is an approximate mathematical indicator of the consistency of the pairwise comparisons. According to Saaty, if the ratio of the Consistency index to the Random index is not greater than 0.1 then the comparisons are said to be consistent.

An Example using AHP

We can better understand the AHP technique by illustrating it with an example.

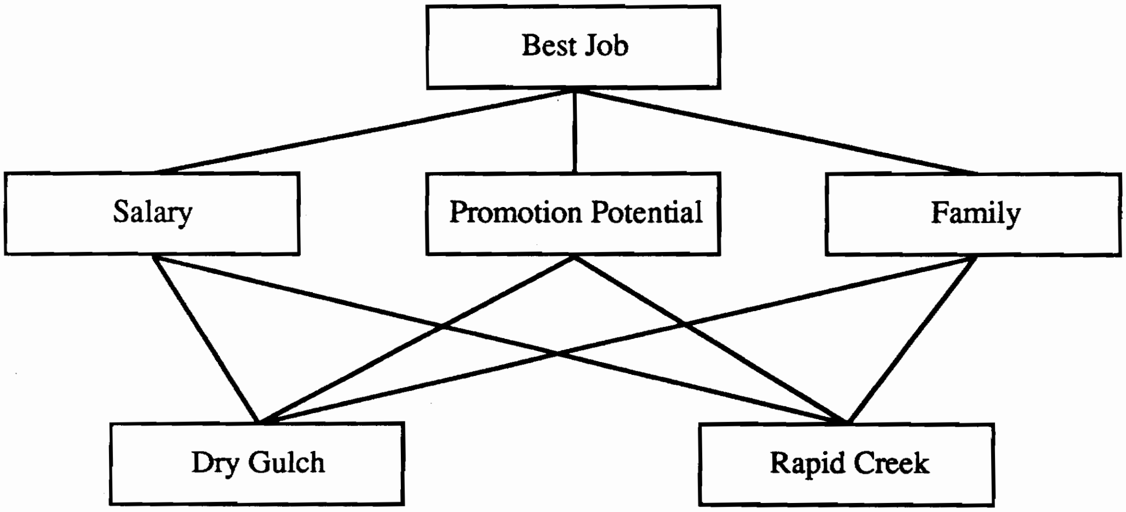
Consider an engineer who has just been transferred from the company's headquarters to it's manufacturing division. He has two choices that he can exercise: either go to Dry Gulch, Nevada or Rapid Creek, Utah. Each of these locations has it's pros and cons and the engineer decides to use AHP to aid his decision making process. The hierarchy is as shown in figure 4.1.

The attributes identified by the engineer are Salary, Promotion potential and Family life.

To determine their relative priorities we do a pairwise comparison of these attributes. This is best performed by ordering them into a matrix as shown below

	Salary	**Promotion**	**Family**
Salary	1.000	$\frac{1}{5}$	$\frac{1}{3}$
Promotion	5	1.000	3.000
Family	3	$\frac{1}{3}$	1.000

Note that the elements in the diagonal all have a value of 1.000, and the elements below the diagonal are reciprocals of the elements above the diagonal.



	Dry Gulch	Rapid Creek
Salary	$40,000	$37,000
Promotion Potential	Fair	Good
Family Life	Good	Fair

Figure 4.1 Hierarchy of Attributes and Alternatives for example problem

The next step is to normalize each column, the normalized column is shown below, the row average is the priority vector.

	Salary	Promotion	Family	Row Average
Salary	0.111	0.131	0.077	0.106
Promotion	0.556	0.652	0.692	0.633
Family	0.333	0.217	0.231	0.260

Normalized Matrix

Priority Vector

Saaty also developed a procedure which can be used to check the consistency of the pairwise comparisons. This gets to be a problem when the matrix of pairwise comparisons is large. He computes a factor called the Consistency Ratio (C.R.). If the C.R. is greater than 0.10 then the comparisons are not valid and need to be revised [Saaty, 1980].

The first step of the procedure consists of multiplying the matrix of pairwise comparisons (Matrix A) by the vector of priority weights (Matrix B) to obtain vector [C]. Next divide each element in vector [C] by it's corresponding element in vector [B] to obtain a new vector [D]. Denote the average value in vector [D] by λ_{max}

$$\underset{[A]}{\begin{bmatrix} 1.000 & 0.200 & 0.333 \\ 5.000 & 1.000 & 3.000 \\ 3.000 & 0.333 & 1.000 \end{bmatrix}} \quad X \quad \underset{[B]}{\begin{bmatrix} 0.106 \\ 0.623 \\ 0.260 \end{bmatrix}} \quad = \quad \underset{[C]}{\begin{bmatrix} 0.319 \\ 1.943 \\ 0.789 \end{bmatrix}}$$

$$\begin{bmatrix} \frac{0.319}{0.106} & \frac{1.943}{0.633} & \frac{0.789}{0.260} \end{bmatrix} = [D]$$

$$\begin{bmatrix} 3.009 & 3.070 & 3.035 \end{bmatrix} = [D]$$

$$\lambda\text{max} = \frac{(3.009 + 3.070 + 3.035)}{3} = 3.038$$

The consistency index (C.I.) for a matrix of size N is given by the formula

$$CI = \frac{\lambda\text{max} - N}{N - 1} = \frac{3.038 - 3}{3 - 1} = 0.019$$

Saaty generated a set of numbers he called Random Indexes (R.I.) based on a large number of simulation runs, for N=3 R.I. = 0.58

$$CR = \frac{CI}{RI} = \frac{0.019}{0.580} = 0.033 < 0.10$$

Therefore the comparisons are consistent.

Next we have to make pairwise comparisons between the alternatives with respect to the attributes, i.e. we have to compare the jobs at Dry Gulch and Rapid Creek with respect to (w.r.t) salary, promotion potential and family life.

The Matrix of paired comparisons along with the resulting priority vector is shown in Figure 4.2 As the matrix is of order 2 (N=2) it is not necessary to check for consistency, as any consistency check will yield a C.R. = 0.0 i.e., matrix is perfectly consistent. At this stage all pairwise comparisons have been made.

Finally we obtain the best alternative by multiplying the priority weights for each alternative by the priority weight for each attribute summing across attributes. In the above analysis Rapid Creek, Utah is found to be the best alternative.

Paired comparison of the jobs w.r.t Salary

	Dry Gulch	Rapid Creek	Priority Vector
Dry Gulch	1.000	3.000	0.750
Rapid Creek	0.333	1.000	0.250

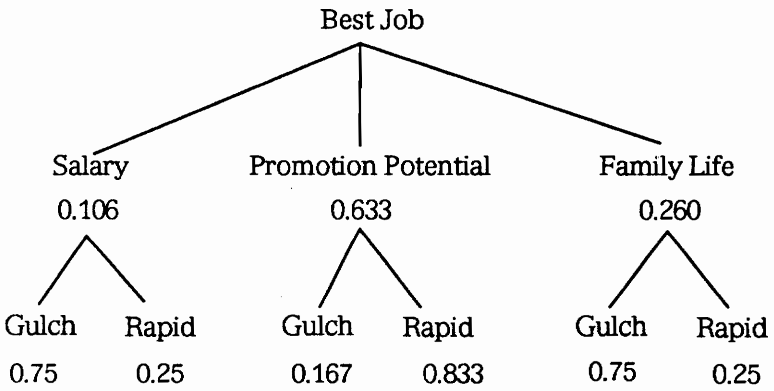
Paired comparison of the jobs w.r.t Promotion Potential

	Dry Gulch	Rapid Creek	Priority Vector
Dry Gulch	1.000	0.200	0.167
Rapid Creek	5.000	1.000	0.833

Paired comparison of the jobs w.r.t Family Life

	Dry Gulch	Rapid Creek	Priority Vector
Dry Gulch	1.000	3.000	0.750
Rapid Creek	0.333	1.000	0.250

Figure 4.2 Paired comparisons of alternatives w.r.t. attributes for the example problem



Dry Gulch = 0.75(0.106) + 0.167(0.633) + 0.75(0.260) = 0.380

Rapid Creek = 0.25(0.106) + 0.833(0.633) + 0.25(0.260) = 0.620

Figure 4.3 Final weights for example problem

Construction of the Hierarchy

The problem of selecting the most suitable alternative for disposal of low level waste is analyzed by the breaking down the problem into a hierarchy of the decision factors. The top level of hierarchy is called the focus and represents the goal, or the broad overall objective. In our case the focus is the optimal disposal alternative for low level nuclear waste.

The focus is then divided into two attributes, namely safety considerations and economic considerations, these have been further divided into sub-attributes. It must be noted that one of the sub attributes falls under both safety and economic considerations, this is taken into account when computing the priority weights.

The complete hierarchy can be seen in Figure 4.4 The hierarchy consists of 4 levels, the top level or the goal is our case is the Optimal disposal alternative for LLW. There are two levels of attributes in the model. The first level consists of Safety considerations and Economic considerations, as safety is a prime concern while disposing LLW, it is assigned a priority of 0.75, while cost is given an priority of 0.25.

The second level of attributes consists of Licensability, Occupational dose, Resistance to natural disruptions, Anticipated degree of protection, Protection of inadvertent intruders, Attractiveness to intruders, Ease of remedial action, Initial cost and Operational and maintenance cost. All these sub-attributes are explained in detail. All of the above attributes with the exception of Cost and Operational and maintenance costs come under the Safety criteria, Ease of remedial actions falls under both.

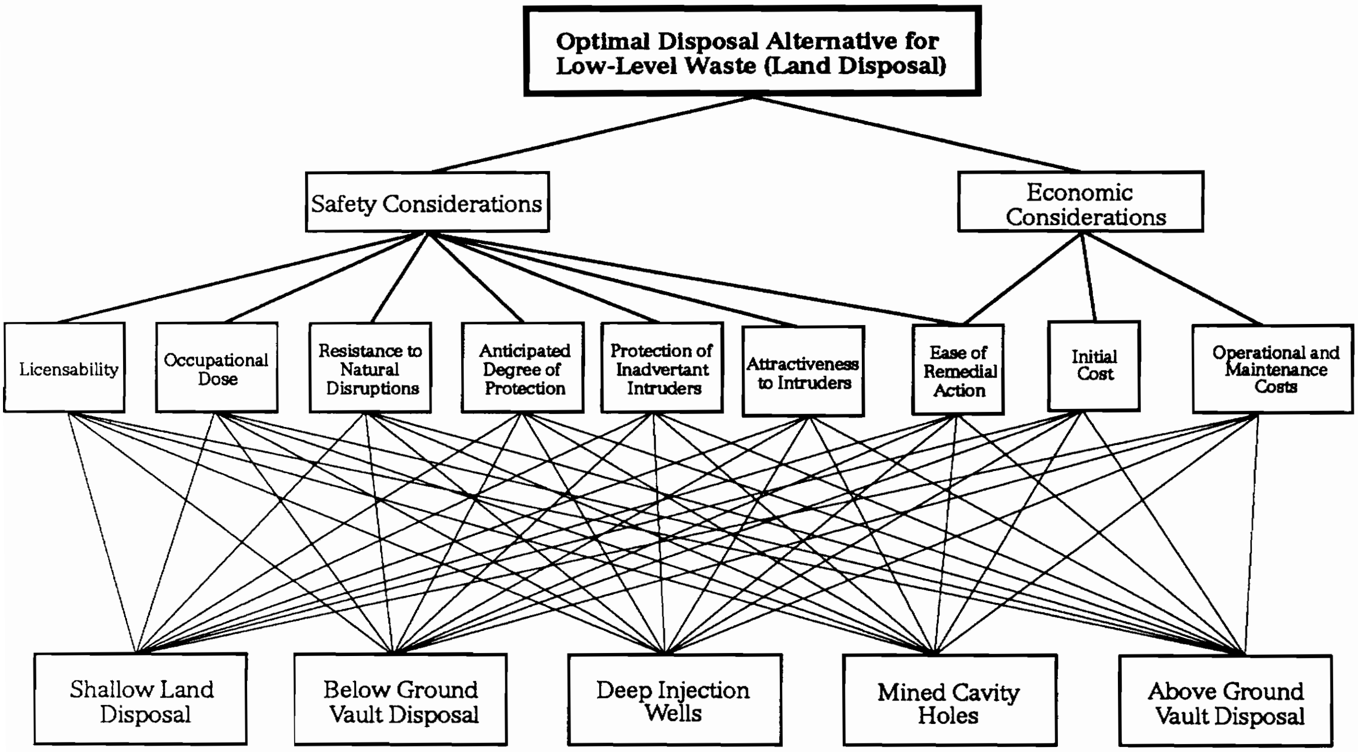


Figure 4.4 Hierarchy of Attributes and Alternatives for LLW disposal

The lowest level consists of alternatives for LLW, these are:

Shallow land disposal, Below ground vault disposal, Deep injection wells, Mined cavity holes, and Above ground vault disposal

Description of the Attributes and Alternatives used in the AHP for Nuclear Waste Disposal.

The attributes used to evaluate the various alternatives available for disposal of low level waste are briefly described in the following sections.

Anticipated Degree of Protection of Public Health and Safety

This attribute represents the ability of the system to contain radionuclides in the waste and keep them from reaching the biosphere. It is a measure of the potential radiation doses to individuals and populations that can occur after the disposal facility is filled with waste and closed. This factor is intended to reflect the best estimate of postclosure performance. Measured as total accumulated radiation exposure in rem.[1]

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[1] 1 rem = 0.01 watt-second energy absorbed per kilogram of tissue weight
Generally the dosage is expressed in mrem, 1 rem = 1000 mrem

Occupational Dose

Exposure of LLW disposal facility workers to radiation is required by regulation 10 CFR 61[1] to be as low as reasonably achievable (ALARA). This attribute represents the potential of radiation dose to workers at the disposal facility and, if waste treatment is required as a consequence of the disposal method, at a treatment facility. Some disposal technologies may be able to achieve low levels of worker exposure with relative ease while others may require elaborate equipment or procedures. In any case "as low as reasonably achievable (ALARA)" may give different exposures depending on the disposal technology chosen. Radiation exposure measured in mrem/hr

Protection of Inadvertent Intruders

Protection of inadvertent intruders is one of the performance objectives of low-level waste disposal given in 10 CFR 61. While it could be considered part of the first attribute, it will be considered separately since the methods for providing this protection are not always the same as for protecting the public

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[1] A Low level waste Management Regulation, 10 CFR 61, provides requirements for waste forms based on a waste classification system. The waste classification system enables waste generators to determine the waste form requirements for disposal dependent on the isotopic concentration of waste.

from releases. Inadvertent intruders are persons who occupy the disposal site and unknowingly disturb the waste or sink wells into an aquifer immediately below or adjacent to the waste disposal area. Radiation exposure measured in mrem/hr

Attractiveness to Intruders

This attribute is a measure of the tendency of a disposal technology to attract intentional or unintentional intrusion either before or after administrative controls are removed. While administrative control must be maintained until the waste no longer represents a risk to the general public, the risk to intruders can continue long after that point. By making the disposal facility less visible or attractive to intruders it may be possible to end administrative control much sooner.

This factor is more difficult to quantify absolutely, but can be ranked on a relative scale quite easily.

Licensability

This attribute represents the ease with which a particular waste management system can be licensed. This is important, since difficulty in licensing inevitably translates into delay and key milestones under the Low-Level Waste Policy Amendments Act may be missed. Ease of licensing in the context used here refers not only to the readiness of regulatory agencies to act on license applications but to the datagathering and analysis activities that support a license application. Some technologies may increase or reduce the importance and duration of collecting certain kinds of data, some may require more difficult performance assessment (analysis), etc.

Time is measured in months that the new technology needs to be reviewed by the Nuclear Council Scientific Board before it is granted approval.

Initial Cost

This attribute represents initial capital cost required to construct the disposal facility. It reflects the total cost incurred by the waste provider to set up the facility, including closure costs.

This attribute is measured in millions of dollars per unit volume of waste.

Ease of Remedial Action

Remedial action at a disposal facility is not a major design consideration. However, the ability to remove the waste from the disposal facility in the face of an unacceptable situation, such as measured high rates of nuclide release, is a concern. This attribute represents the cost of correcting unforeseen problems and can be defined as the unpredictable corrective maintenance costs over the lifetime of the facility. This attribute is related primarily to the depth of cover and the structural stability provided by the facility. As the waste is disposed of at greater depths below the surface, remedial action will be more costly and difficult. If the waste is surrounded by thick layers of steel-reinforced concrete, removing the waste will require breaking of the concrete—also a costly effort.

This attribute also contains a safety dimension. Some disposal alternatives are more likely to produce concentrated accumulation of radioactivity creating increased exposure hazards to facility operators during remedial action

This attribute cannot measured quantitatively but the relative cost and operator exposure hazards can be subjectively evaluated. The costs would be reflected in relative million dollars per unit volume of waste. The safety concerns can be measured on a relative level of operator hazard.

Resistance to Natural Disruptions

This attribute is a measure of the ability of the disposal technology to either avoid potential natural disruptions or to resist them should they occur. In this context, natural disruptions are those caused by the forces of nature that can cause massive failure of the disposal system's ability to protect the public health and safety. These include earthquakes, tornadoes, etc.

Operational and Maintenance Costs

In 10 CFR 61 a period of 100 years after operation is specified for institutional control. This period is provided for inspection of the facility to assure its continued integrity and to monitor for releases. Additionally, institutional control enhances intrusion protection during the period it is in effect.

Disposal technologies that involve man-made materials whose competence is under continual attack by the environment and that must be maintained to meet their projected performance may require an additional period of institutional care and control. Additional control may also be needed for technologies that can attract intruders.

This attribute addresses the burdens on institutions that must provide maintenance of the disposal facility and its intrusion-gaging features. It can be thought of as the predictable corrective maintenance cost and the regular preventative maintenance cost, and the operating costs associated with the given facility design. It can be measured in millions of dollars over the lifetime of the facility.

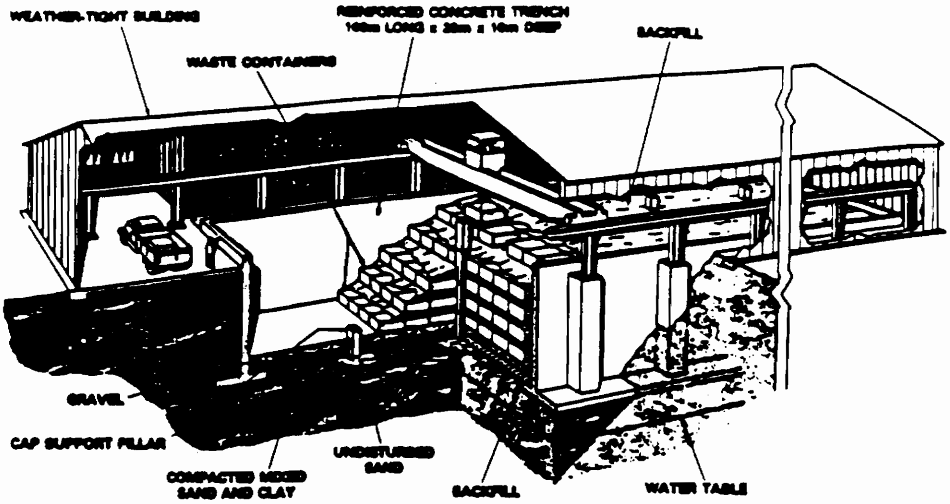
Waste Disposal Alternatives

Shallow-Land Disposal (SLD)

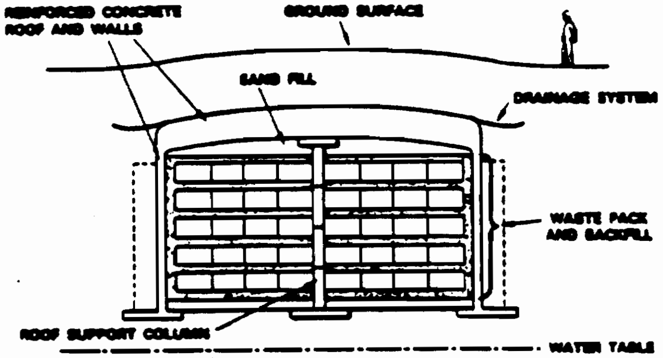
SLD is accomplished by constructing trenches that are approximately 30 ft. deep. Figure 4.5. is a schematic diagram of a SLD disposal facility. It illustrates the ordered stacking of waste packages to minimize voids within the trench that may lead to postclosure trench cover failure. Also illustrated in this figure is the multilayer construction of the trench cover.

The trench cover is the primary barrier preventing (for retarding infiltration of surface water into the disposal unit. It also reduces surface radiation levels to regulatory limits or less and reduces the likelihood of inadvertent intrusion into the waste after the end of the institutional control period.

Class A waste trenches would be larger (270 x 54 ft. at base) than those for Class B-C waste (66 x 22 ft. at base). The smaller B-C waste trenches provide for a thinner layer of waste (12ft) and greater thickness of earthen cover than do the Class A trenches in which waste is stacked to a height or 21 ft. These differences provide additional shielding for the B-C waste and minimize radiation levels at the surface of a closed trench. They also enhance the



INTRUSION-RESISTANT SHALLOW LAND BURIAL FACILITY
DURING THE OPERATIONAL PHASE WITH THE WEATHER-SHIELD
BUILDING IN PLACE



INTRUSION-RESISTANT SHALLOW LAND BURIAL FACILITY
AFTER CLOSURE

Figure 4.5 Shallow Land Disposal

disposal unit's stability and reduce the likelihood of someone's inadvertently coming in contact with the waste because of the increased depth of soil cover. As indicated in this figure, trench floors are constructed to direct any infiltrating water to one side of the trench where a water collection (French drain) system is provided. This design minimizes the length of time water is in contact with the waste and provides a method for measuring the rate of water infiltration and collecting the water for monitoring, treatment if required because of levels of contained radionuclides, and eventual disposal. The measurements or the amount and radionuclide content or the water during operation and after closure are prime inputs into decisions on the need for any remedial action (such as trench cover repair) during the institutional control period.

Waste is placed in the trenches using cranes. The space between the waste packages, and between the stacked waste and the trench walls, is backfilled with sandy soil to improve short-term stability of the disposal unit. Stability requirements for Class B-C waste are met by the waste form and package rather than by the trench. Trench cover design provides for several layers or different materials. These-include sandy materials near the waste to minimize water retention and the possibility of container corrosion and/or radionuclide leaching, clay to minimize water infiltration, larger stones or cobbles to deter intruders and in some cases retard wind erosion, and topsoil to support growth of natural vegetation that also reduces erosion. The specific combination and depth of the individual materials will be based on site conditions and the waste emplaced in a given trench. Class A waste trenches generally have shallower covers with fewer different layers than do Class B-C waste trench covers.

Below-Ground Vaults (BGV).

BGV disposal, as illustrated in Figure 4.6, provides an engineered barrier between the waste packages and the biosphere as well as structural stability by use of an engineered concrete structure below natural grade. The structure consists of reinforced concrete walls and roof. Some designs use a concrete floor whereas others employ a floor using natural materials but with engineered features such as sloping and water collection and monitoring systems. The BGV vault is backfilled with sandy gravel after waste emplacement in much the same way as the SLD trench and MCCD excavation. The current conceptual design provides for emplacement of the concrete vault roof after the disposal unit is full and the backfill layer over the Class B-C waste provides shielding to reduce occupational exposure while the roof is being put in place. There is in addition a 10-ft. earthen cover over the Class B-C vault roof compared to a 6 ft. 5 in. cover over the Class A waste vault roof. The vaults are actually composed of a number of individual cells (36 for Class A waste vaults and 3 for Class B-C waste vaults) that are closed individually as the cell is filled. This reduces the amount of water that may get into the vault from precipitation and provides shielding for workers emplacing subsequent waste packages. As with the other concepts, each cell is discharged to a French drain system that runs the entire length or the vault and from which water may be collected and analyzed.

Analyses performed for the conceptual design study indicate that occupational exposures for a BGV facility will be about 60% greater than those for SLD, primarily due to placing the roof over individual cells. The effect of the structure on delay of the time at which groundwater comes in contact with the waste results in a 45% reduction in the whole body dose to a member of the

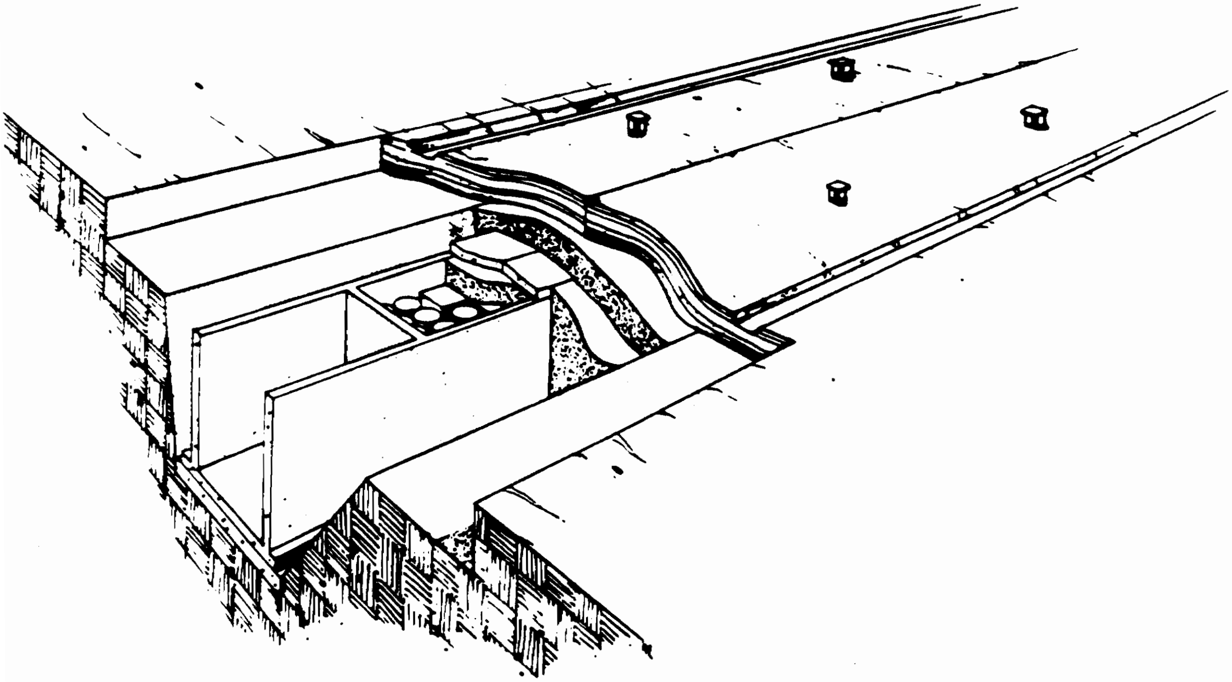


Figure 4.6 Below Ground Vaults

public (15% reduction for thyroid dose), compared to SLD. Doses to an intruder are projected to be 50-90% lower for BGV than SLD for the case in which contact is due to farming and drinking water from a well onsite or construction and direct contact with the waste.

Above-Ground Vaults (AGV).

AGV disposal provides for emplacement of waste in a reinforced concrete structure above the natural grade. Like BGV's, AGV's are composed of multiple individual cells that are filled with waste, backfilled with sandy soil to enhance removal of any water that may enter the vault, and covered with a concrete floor. As illustrated in Figure 4.7, access to individual cells is expected to be via overhead crane. Class B-C waste is covered with a 6 ft. 6 in. backfill layer to provide shielding prior to emplacement of the vault roof.

A major technical uncertainty with AGV technology is the performance of the structural concrete for the hundreds to thousands of years for which the waste is to be isolated. This uncertainty, common to all the alternatives that use structural concrete (that is, except SLD), is crucial for AGV's because there is no earthen cover to provide containment of the waste subsequent to failure of the engineered structure. Location of the AGV at the soil surface results in at least some part of the release resulting in exposure via the surface water pathway rather than only through groundwater as analyzed for below-ground facilities. Analyses for the conceptual design report indicate that whole body

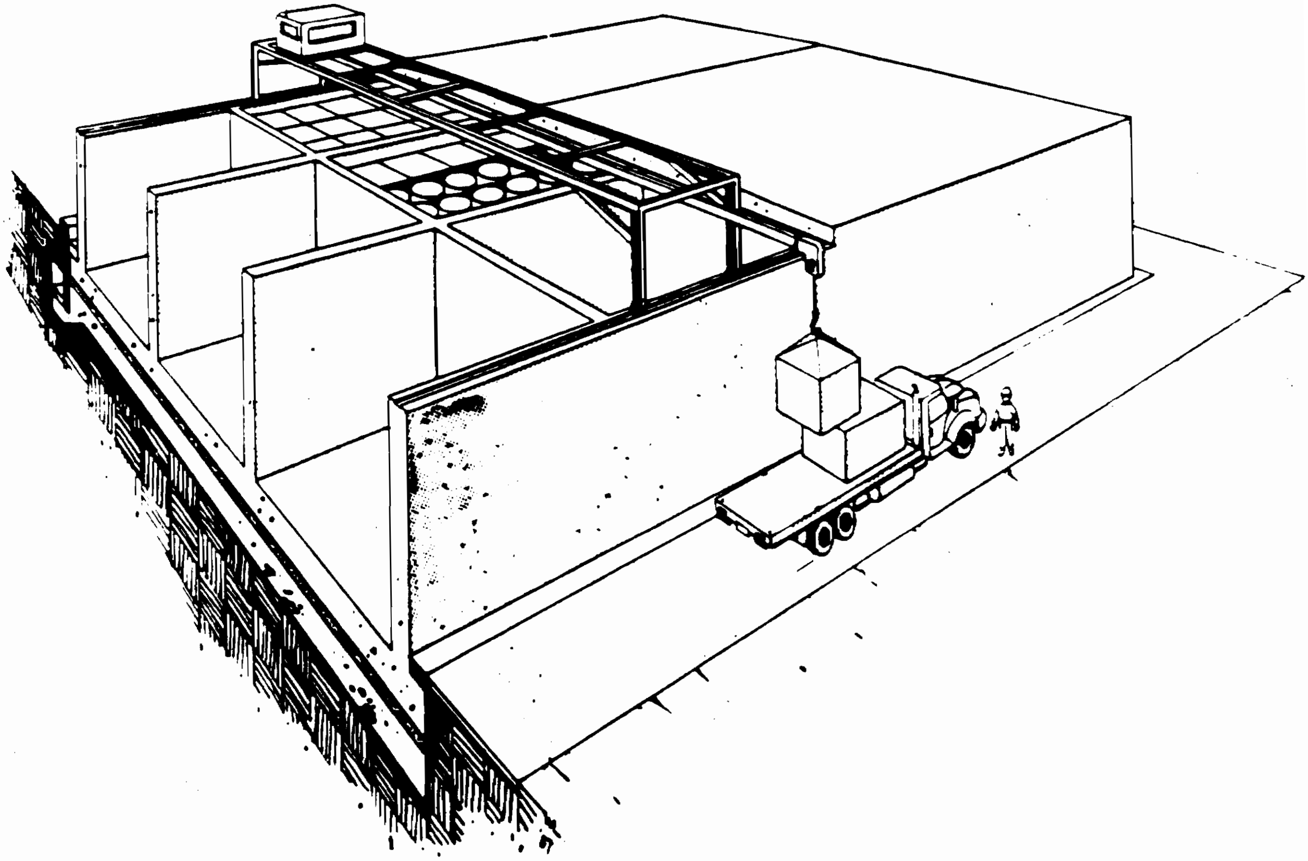


Figure 4.7 Above Ground Vaults

equivalent dose to a member of the general public is four times higher for AGV than for SLD. Thyroid doses exceed those from SLD by a factor of seven. The uncertainty concerning concrete performance also affects the confidence with which doses to inadvertent intruders can be projected. Assuming that the concrete remains intact for 500 years and then fails, the Conceptual Design Report analyses project doses to intruders that exceed those from SLD by a factor of four if someone builds on the waste site. An AGV facility would need extensive monitoring during the institutional control period to verify that the concrete was successfully resisting environmental attack such as acid rain, freeze-thaw cycles, airborne pollutants, and earthquakes. This technology is expected to require the greatest amount of active maintenance during and beyond the institutional control period.

Mined Cavities Disposal

Enclosed cavities developed in the removal of natural resources have also been proposed as useful disposal units for LLW although none has been adopted to date. The major difference between such cavities and the geologic repositories is that for LLW the cavity may be located closer to the ground surface. To minimize interaction between the waste packages and the surrounding soil, geologic formations of limestone or bedded salt are considered to be most attractive. Both previously mined and newly constructed cavities may be used. Preliminary evaluations of mined cavities indicate that an appropriately sited facility, operated and closed in accordance with regulatory requirements would result in minimal public radiation exposure because there is no contact between groundwater and the emplaced waste. However, because of the need to handle the waste both upon receipt at the facility and subsequently at the disposal location below ground it is expected that occupational exposure would be substantially higher for this alternative than for others available for LLW disposal. NRC estimated that the number of people involved in direct handling of the waste would be about a factor or two higher than for SLD. The necessity for close proximity to the waste results in a total occupational exposure or approximately four times that experienced in a near-surface disposal facility.

Deep Well Injection

Deep well injection involves pumping acidic liquid waste to great depths (up to 16,000 ft.). The receiving area is a porous or fractured rock area such as a depleted hydrocarbon reservoir or zone of natural or induced fractures. Isolation of the injection zone below freshwater aquifers might be accomplished by having intervening impermeable formations such as shale or salt. Thermal capacity of the injection zone would be the limiting criterion both for rate of injection and total amount of material so disposed. Waste concentration would be altered to meet the limiting conditions based on the heat generation criterion mentioned above.

In this technology the goal is to maintain the host rock at sufficiently low temperatures (below 100°C) that the waste will not react chemically with the mineral structure of the host rock. Since 60 to 75% of the heat initially generated in LLW is due to the fission products ^{90}Sr and ^{137}Cs, removal of these isotopes can result in an increase in the amount of long-lived radionuclide bearing waste that the formation could accept. Different disposal methods could be used for the relatively short-lived ^{90}Sr and ^{137}Cs. The fact that the waste remains in liquid form provides the possibility of at least partial recoverability by pumping at a later date, if necessary.

Some of the contained waste is expected to adsorb onto the structure of the host rock and would be irrecoverable. Further, depending on local waste chemistry and rock mineral content, there is a possibility of unpredicted reconcentration resulting in thermal "hot spots" or the potential for criticality if plutonium were sufficiently concentrated.

Analysis of Disposal Alternatives

This chapter details the data used in the AHP model. The AHP model and technique is explained in detail in the previous chapter. A spreadsheet program was used to develop the model on a Macintosh IIci. The spreadsheet was used as it provided the flexibility of changing relationships relatively easily, this degree of flexibility and response would not have been possible using conventional programming techniques.

Experts consulted for this project

AHP requires experts who are very familiar with subject to rank the alternatives and attributes. The experts chosen to rank the model have had a great deal of experience in Nuclear waste and laying down policy for Nuclear Waste. A brief vita follows:

Thomas B. Hindman, Jr. is currently a Lab Director at Management Systems

Laboratory and was recently a Director of the Five–Year Plan task force for the DOE, which yielded the first comprehensive plan for radioactive and hazardous waste management. He was the former Director of DOE office of Waste and Transportation Management (DWTM). He is a specialist in management of large programs for treatment, storage, disposal, minimization, and transportation of hazardous and radioactive waste.

Charles D. Simpson was a Senior technical advisor at Management Systems Laboratory, he has extensive knowledge of nuclear reactor engineering and analysis. He also served in a number of senior executive positions including Special Assistant to the Deputy Secretary of Energy, he has also served on the Nuclear Safety Council, Quality Assurance Forum and Coordinator for Unusual Operations Reports.

The pairwise comparisons are Shown in this chapter, first all the alternatives are compared with respect to the attributes, such as licensability, Initial Cost, etc. For each comparison we compute the Consistency Ratio (C.R.), priority weights are also shown. We also compare the attributes among themselves for relative importance, as these attributes are actually sub-attributes (under the cost and safety factors), there are two sets of comparisons.

Shown below is the matrix of paired comparisons of the Alternatives with respect to Operational and maintenace cost:

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		1/7	1	1/5	1/5
Below Ground Vault Disposal			5	1	1
Deep Injection Wells				1/5	1/3
Mined Cavity Holes					1
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.0543
Below ground Vault Disposal	0.3095
Deep Injection Wells	0.0625
Mined Cavity holes	0.3607
Above Ground Vault disposal	0.2130

C.R.= 0.0330 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Alternatives with respect to Initial Cost

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		7	7	7	5
Below Ground Vault Disposal			3	3	3
Deep Injection Wells				1	3
Mined Cavity Holes					1
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.5765
Below ground Vault Disposal	0.1807
Deep Injection Wells	0.1027
Mined Cavity holes	0.0719
Above Ground Vault disposal	0.0681

C.R.= 0.0876 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Alternatives with respect to Degree of Protection

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		5	5	5	7
Below Ground Vault Disposal			3	1	7
Deep Injection Wells				1	3
Mined Cavity Holes					1
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.5320
Below ground Vault Disposal	0.1984
Deep Injection Wells	0.1038
Mined Cavity holes	0.1216
Above Ground Vault disposal	0.0442

C.R.= 0.0654 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Alternatives with respect to Inadvertent Intruders

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		1/9	1	1/9	1/7
Below Ground Vault Disposal			7	1	7
Deep Injection Wells				1/7	1/3
Mined Cavity Holes					5
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.0384
Below ground Vault Disposal	0.4092
Deep Injection Wells	0.0464
Mined Cavity holes	0.3795
Above Ground Vault disposal	0.1265

C.R.= 0.0738 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Alternatives with respect to Attractiveness to Intruders

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		1/9	1/3	1/9	1/5
Below Ground Vault Disposal			7	1	5
Deep Injection Wells				1/5	1/5
Mined Cavity Holes					5
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.0325
Below ground Vault Disposal	0.3919
Deep Injection Wells	0.0642
Mined Cavity holes	0.3701
Above Ground Vault disposal	0.1414

C.R.= 0.0841 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Alternatives with respect to Licensability

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		1	3	1	3
Below Ground Vault Disposal			3	1	3
Deep Injection Wells				1	1
Mined Cavity Holes					1
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.2824
Below ground Vault Disposal	0.2824
Deep Injection Wells	0.1208
Mined Cavity holes	0.1935
Above Ground Vault disposal	0.1208

C.R.= 0.0443 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Alternatives with respect to Natural Disruptions

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		1/3	1/3	1/3	5
Below Ground Vault Disposal			3	1	5
Deep Injection Wells				1	5
Mined Cavity Holes					1
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.1176
Below ground Vault Disposal	0.3380
Deep Injection Wells	0.2192
Mined Cavity holes	0.2831
Above Ground Vault disposal	0.0420

C.R.= 0.0633 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Alternatives with respect to Ease Remedial Action

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		5	7	5	3
Below Ground Vault Disposal			5	1	1
Deep Injection Wells				1/3	1/7
Mined Cavity Holes					1/5
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.4828
Below ground Vault Disposal	0.1428
Deep Injection Wells	0.0396
Mined Cavity holes	0.0955
Above Ground Vault disposal	0.2393

C.R.= 0.0777 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Alternatives with respect to Occupational Dose

	Shallow Land Disposal	Below Ground Vault Disposal	Deep Injection Wells	Mined Cavity Holes	Above Ground Vault DisposalCost
Shallow Land Disposal		7	1	5	5
Below Ground Vault Disposal			1/3	1	1
Deep Injection Wells				5	5
Mined Cavity Holes					3
Above Ground Vault Disposal					

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Shallow Land Disposal	0.4073
Below ground Vault Disposal	0.0806
Deep Injection Wells	0.3475
Mined Cavity holes	0.1020
Above Ground Vault disposal	0.0645

C.R.= 0.0472 < 0.10 therefore ok

Shown below is the matrix of paired comparisons of the Attributes with respect to the Safety considerations

	Licensability	Occupational Dose	Resistance to Natural Disruptions	Anticipated Degree of Protection	Protection of Inadvertant Intruders	Attractiveness to Intruders	Ease of Remedial Action
Licensability		1/9	1/9	1/9	1/5	1/5	1/5
Occupational Dose			3	3	7	7	7
Resistance to Natural Disruptions				1	7	7	5
Anticipated Degree of Protection					5	5	5
Protection of Inadvertant Intruders						1	3
Attractiveness to Intruders							3
Ease of Remedial Action							

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Licensability	0.0200
Occupational dose	0.3805
Resistance to natural disruptions	0.2244
Anticipated degree of protection	0.1979
Protection of inadvertent intruders	0.0655
Attractiveness to Intruders	0.0655
Ease of Remedial action	0.0463

C.R.= 0.0914 < 0.10, therefore ok.

Shown below is the matrix of paired comparisons of the Attributes with respect to the Economic considerations

	Ease of Remedial Action	Cost	Duration of Active Maintenance
Ease of Remedial Action		5	1
Cost			1/3
Duration of Active Maintenance			

For this comparison the priority weights and the consistency ratio (C.R) are shown below:

Ease of Remedial action	0.4796
Initial Cost	0.1150
Operational and maintenance cost	0.4055

C.R.= 0.0251 < 0.10, therefore ok.

The top level of the attribute hierarchy consists of Safety considerations and Economic considerations, Safety is considered more important and is given a weight of 0.75 and Economic considerations is weighed in at 0.25, as this is matrix of order 2, it is perfectly consistent and C.R. is not computed.

Results of the AHP.

The results are aggregated and presented below, as can be seen the Shallow Land Burial is the preferred alternative.

Shallow Land Disposal	**0.3193**
Below Ground Vault Disposal	**0.2112**
Deep Injection Wells	**0.1867**
Mined Cavity Holes	**0.1865**
Above Ground Vault disposal	**0.0963**

Although disposal alternatives that dispose the waste beneath the surface seem intuitively better alternatives, this study concludes that SLD is safer for the following reasons:

1. Workers who are exposed to radiation are at the greatest risk, the general public will in all likelihood (barring natural disasters) never be exposed to radiation levels that high.

2. A large percentage of the total exposure comes from close proximity, with the case of underground vaults and other vaults alternatives, this is unavoidable as the physical movement of the material causes the person handling it to be exposed.

3. SLD also came out ahead as the priority weights for security were not high, since LLW does not contain significant amounts of fissionable material, security is not critical, though this will not be true for Defense or N-waste from power plants.

In summary, SLD is the preferred alternative for LLW, Below ground vault disposal comes in second, Deep injection wells and Mined cavity holes have priority weights that are almost equal and is the third choice, Above ground vault disposal, with a priority weight of 0.0963 is the least preferred alternative.

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Summary

To briefly recap the discussion in the previous chapters, radioactive waste is generated from various sources like Nuclear power plants, by-products from fission enrichment programs for defense purposes, material that has come in contact with Radioactive material and is now contaminated, etc. For the purposes of this project, we can classify the waste by three types, High-level, Transuranic, and Low-level. Disposal of LLW is analyzed in this project.

High-level waste (HLW) is the most lethal, and is the most voluminous of all the types of N-waste, and is mainly generated by Nuclear power plants. Transuranic (TRU) wastes are those containing isotopes above uranium in the periodic table and are the by-products of fuel assembly and weapons fabrication program and reprocessing operations, their radioactivity level is generally low, but as they have very long half lives, they have to be disposed in a different manner. LLW are traditionally defined as those wastes that do not fit in the above two categories.

Nuclear power plants have to dispose of the spent fuel pellets in the assembly rods. By one estimate each assembly weighs around 1200 lbs, and has a volume of 6.7 cubic feet. Sixty assemblies are removed from one reactor every year giving a volume of approximately 400 ft^3 per reactor or 40,000 ft^3 for the U.S. About 3.5% of this spent fuel can be reprocessed, but the rest still has to be disposed.

Radioactive waste, like any other waste has to be disposed. Each different kind of waste has its own disposal technique. High-level waste and TRU waste is best disposed of in underground repositories. LLW is best disposed in Shallow land burial sites. The state of Nevada is scheduled to host the first high-level waste repository in the Yucca mountains.

A number of organizations besides governmental agencies contribute information on waste disposal. These include public interest groups like the Sierra Club, Radioactive waste campaign, Union of concerned scientists, National resources defense council and Friends of the earth. The nuclear industry is represented by the Electric Power Research Institute and the U.S. council for energy awareness. Professional societies that publish papers and sponsor conferences on waste include the: American Nuclear Society, American Society of Mechanical Engineers, American Physical Society.

This project focuses on the disposal of LLW. As with any complex issue there are decisions that have to be made. The greater the complexity the less obvious the correct choice. Disposal of LLW is one such example. There are numerous disposal alternatives available to us today, ranging from ocean disposal to disposal in outer space, for various reasons some of these alternatives are less suitable than others, the object of this project is to use AHP as a decision making tool to narrow down the choices while fully understanding the reasons behind making those decisions.

Recommendations for Further Study

The analysis for disposal alternatives of LLW was undertaken by consulting two experts. Recognizing the fact that other experts could have different opinions, the following factors arise:

- An alternate panel of experts might give different preference numbers for the paired comparisons, resulting in alternate LLW disposal selection.
- An alternate panel of experts could select a hierarchy which is different, resulting in alternate LLW disposal selection.

Furthermore a sensitivity analysis on the preference numbers would indicate the variation required for a different alternative to be selected.

A life cycle analysis of the alternatives is not performed in this analysis. It is recommended that a life cycle analysis be performed for a detailed economic analysis. Such a study will represent financial costs more accurately. Issues that need to be addressed in this Life Cycle Cost analysis are:

- Determination of the appropriate elements to be included in the Life Cycle cost analysis.
- Estimates and justification for each element included.

In summary, it is recommended that a LCC and sensitivity analysis be performed on the disposal alternatives and preference numbers respectively.

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ABSTRACT

Multi-Attribute Analysis of Nuclear Waste Disposal Alternatives

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The objective of this report is to provide a systematic methodology for the analysis of waste disposal alternatives. The Analytic Hierarchic Process (AHP) is used to analyze various alternatives for the disposal of Low-level waste (LLW). AHP helps in breaking down complex problems into simpler ones which can then be more readily analyzed. A model is developed to aid the computation of the alternative selection process and also to enable "what-if" type of analysis.