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ABSTRACT

Willie J. Lee, Alternatives to Shallow Land Burial for the Management of Low-Level Radioactive Waste (Under the direction of James E. Watson, Jr., Ph.D. and Linda W. Little, Ph.D.)

The management of low-level radioactive waste involves 1) determining volume and radioactivity content of waste generated, 2) reviewing methods of minimizing waste generation, 3) assessing current disposal practices, which happen to be shallow land burial at this time, and 4) proposing new and better methods of waste disposal. Problems have been identified regarding the use of shallow land burial in the disposal of low-level radioactive waste. Thus, it is prudent to study alternative methods of waste disposal. Five alternatives to shallow land burial have been identified and are analyzed in detail in this report.

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1.0 INTRODUCTION

The use of radioactive material in industry, research institutions, and academic institutions, and the generation of electric power by nuclear reactors unfortunately produces waste requiring special handling and disposal. Since the 1940's it has been evident that the peaceful use of radioactive material combined with its use for defense would necessitate the implementation of some means of radioactive waste disposal.

The first method of low-level radioactive waste disposal was ocean dumping. Wastes were packaged in steel drums, weighted with concrete, and dumped in deep water (usually at depths of at least 1,000 fathoms). At that time the alternative to ocean dumping was considered to be shallow land burial. It consisted of burying packaged waste in shallow trenches. Trenches of preference were those located in soils with low permeability and high absorption properties.

Ocean dumping was expensive in comparison to shallow land burial. In 1960 the former Atomic Energy Commission, since divided into the Nuclear Regulatory Commission and Department of Energy, opened government-owned land disposal sites to all generators of low-level radioactive waste. That, combined with the Atomic Energy Commission's decision not to issue any new licenses for ocean disposal, repositioned shallow land burial into the forefront. Existing licenses issued for ocean dumping were not cancelled at that time; therefore, ocean dumping continued until 1970.

When federally owned land disposal sites were opened for use in Tennessee and Idaho, they were to be made available until commercial, regional disposal sites could be established. These regional sites were to be operated on either federal or state-owned land and could be operated by licensed contractors.

In 1962 the first commercial low-level radioactive waste disposal site, using shallow land burial techniques, was established at Beatty, Nevada. A second site was opened at Maxey Flats, Kentucky in 1963. With the establishment of the first two commercial sites, the Atomic Energy Commission stopped accepting low-level radioactive waste at government-owned sites. Those government-owned sites are now operated by the U.S. Department of Energy. From 1963 to 1971, four more commercial sites were opened, those being West Valley, New York in 1963; Richland, Washington in 1965; Sheffield, Illinois in 1967; and Barnwell, South Carolina in 1971.

Shallow land burial of low-level radioactive waste was performed in a manner similar to the disposal of municipal waste in a sanitary landfill. Criteria for siting and packaging did not exist in the early days. As a result, those early practices, combined with uncertainties in soil geology and hydrology, produced problems for shallow land burial which exist today. Problems encountered will be discussed in more detail in Section 4.

Efforts are now underway to develop and implement alternatives to shallow land burial of low-level radioactive waste, even though regulations have been established to set criteria for land disposal to protect the general population from releases of radioactivity. The feasibility of alternatives emphasizing greater confinement of low-level radioactive wastes is being assessed.

1.1 Purpose of Report

The purpose of this report is to review the current status of shallow land burial of low-level radioactive waste with an emphasis placed on restrictions for future use. Means of waste generation, prevention and volume reduction are outlined and specific alternatives to shallow land burial are discussed and compared to shallow land burial.

The ultimate goal of the report is to outline the present system for the management of low-level radioactive waste and to discuss future trends.

1.2 Definition of Low-Level Radioactive Waste

Radioactive waste is material contaminated with small, but potentially hazardous, amounts of radioactivity. Such wastes range from dry trash, paper, plastic, glass, clothing and discarded equipment to wet sludges and aqueous and organic liquids.

The term "low-level radioactive waste" has been defined as radioactive waste not classified as high level radioactive waste, transuranic waste, spent nuclear fuel, or by product material as defined in Section 11e.(2) of the Atomic Energy Act of 1954. The definition has been interpreted by the U.S. Nuclear Regulatory Commission to mean those low-level radioactive wastes containing source, special nuclear or by-product material acceptable for disposal in a land disposal facility. With this concept in mind, low-level waste can be categorized in two ways: (1) short-lived and (2) long-lived. The generality of the present definition does not indicate that there are indeed concentration limits placed on low-level radioactive waste. Concentration limits for short-lived low-level radioactive waste are presented in Table 1.1 (Ref.1).

TABLE 1.1

SHORT-LIVED LOW-LEVEL RADIOACTIVE WASTE
(BY RADIONUCLIDE AND CONCENTRATION)

Radionuclide	Concentration (Curies/m^3)
Total of all radionuclides with less than 5-years half-life	* No stated limit
Hydrogen 3	* No stated limit
Cobalt 60	* No stated limit
Nickel 63	700
Nickel 63 in activated metal	7000
Strontium 90	7000
Cesium 137	4600

* No limits have been established for these radionuclides.

Practical considerations such as the effect of external radiation and internal heat generation or regulatory limits governing transportation will limit the concentration of these wastes (Ref. 1).

The following is a table of long-lived radionuclides and concentration limits of low-level radioactive waste (Ref. 1):

TABLE 1.2

LONG-LIVED LOW-LEVEL RADIOACTIVE WASTE (BY RADIONUCLIDE AND CONCENTRATION)

Radionuclides	Concentration (Ci/m^3)
Carbon - 14	8
Carbon - 14 in activated metal	80
Nickel 59 in activated metal	220
Niobium 94 in activated metal	0.2
Technitium 99	3
Iodine 129	0.08
Radium and alpha emitting Transuranic radionuclides with half-lives greater than five years	100 Nanocuries/gm
Plutonium 241	3,500 Nanocuries/gm
Curium 242	20,000 Nanocuries/gm

Wastes containing radionuclides in concentrations exceeding those listed in Table 1.1 and 1.2 may not be disposed of in a manner similar to other low-level radioactive wastes. This creates an intermediate category of waste which is neither high-level or low-level, by definition. This was once an official category of radioactive waste in the United States, but this category has been abandoned in recent years, leaving a component of low-level radioactive waste unclassified.

Since some low-level waste presents both a chemical and radiological hazard, work has been undertaken to classify waste by total hazard (Ref. 9). The ultimate disposal of low-level radioactive waste depends upon how waste is defined and classified.

REFERENCES AND GENERAL BIBLIOGRAPHY

1) Code of Federal Regulations, 10 CFR Part 61, Licensing Requirements for Land Disposal of Radioactive Waste.

2) Low-Level Radioactive Waste Policy Act of 1980.

3) North Carolina General Statutes, Chapter 104E, North Carolina Radiation Protection Act.

4) North Carolina General Assembly, Chapter 704, Senate Bill 443, Waste Management Act of 1981.

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6) Understanding Low-Level Radioactive Waste, prepared by E.G.&G. Idaho for the U.S. Department of Energy.

7) Spent Fuel and Radioactive Waste Inventories, Projections and Characteristics, Department of Energy Document NE-006, September 1984.

8) Final Waste Classification and Waste Form Position Papers, U.S. Nuclear Regulatory Commission, May 11, 1983.

9) Waste Classification, A Proposed Methodology for Classifying Low-Level Radioactive Waste, U.S. Department of Energy Report LLW-14T, December 1982.

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2.0 LOW-LEVEL RADIOACTIVE WASTE GENERATION

A determination of the amount of low-level radioactive waste generated in North Carolina and the Nation has been desired for several years. Not until 1982 was this undertaken. The Conference of Radiation Control Program Directors, an arm of the Agreement States Program, initiated a survey designed to document the generation of low-level radioactive waste. Forty-one states were persuaded to participate in the distribution of questionnaires to waste generators in their states. North Carolina was included in that survey.

Questionnaires were sent to facilities thought to be generators of low-level radioactive waste, such as those holding radioactive material licenses. The survey requested information such as total volume generated, radioactivity content and the physical properties of waste forms. The accuracy of the figures generated greatly depended upon each facility's ability to document the actual volume and radioactivity content generated at their facility.

A second attempt is now underway by the Conference to determine the volume and characteristics of low-level radioactive waste generation. This survey will attempt to determine the impact of treatment technologies on low-level waste generation and disposal. It will also attempt to determine the waste form, total volume and radioactivity content of incinerated waste.

2.1 Volume and Radioactivity Content

Table 2.1 shows the total volume of low-level radioactive waste generated and the associated radioactivity content for North Carolina and the United States (Ref. 1). It should be emphasized that the United States figures are for 41 states only. In addition, approximately 7,000,000 cubic feet (200,000 cubic meters) of uranium mill tailings, containing approximately 1,000 curies of radioactivity, is included in the United States figure. North Carolina's generation constituted approximately 4 percent of the waste generated nationally.

Table 2.2 breaks down the waste generation summary by facility subcategory (Ref. 1). Of the waste volume generated in North Carolina in 1982, 93 percent was a result of the fuel cycle. Of the radioactivity generated, 68 percent was reported to be a result of operations in the medical community. It should be noted that the 68 percent radioactivity content from the medical community appears (from interviews) to be inaccurate and probably resulted from errors made in documenting the actual radioactivity of the waste generated. For example, some hospitals may list their entire inventory as waste while others might list the amount purchased, but not used, for clinical purposes. The latter is a more appropriate form of documentation.

Table 2.3 lists projections of future waste generation in North Carolina, based upon the 1982 Conference survey (Ref. 1). It was reported that the projections made were actually based upon amounts to be shipped to commercial sites rather than amounts generated. Errors were made in interpreting this section of the questionnaire. Figure 2.1 provides a bar graph of projected waste generation.

Table 2.4 and 2.5 give an estimation of past volume and radioactivity content of waste generated in North Carolina and the United States, based upon volume and activity disposed of in 1982 through commercial disposal facilities (Ref.

2,3,4). The figures are based on the report that 41 percent of the waste (by volume) generated in 1982 was disposed of commercially. The percentage by radioactivity was 36 percent. The extrapolation to years prior to 1982 assumed that the percentages disposed of were the same as in 1982.

TABLE 2.1

1982 WASTE GENERATION SUMMARY

	Volume	Radioactivity Content
United States (41 States)	9,608,961.5 ft^3 274,542 m^3	4.499×10^5 Curies
North Carolina	379,420 ft^3 10,840 m^3	1.525×10^4 Curies

TABLE 2.2

1982 WASTE GENERATION SUMMARY (N.C.)
BY FACILITY SUBCATEGORY

	Cubic Feet/Cubic Meters Generated	Curies Generated
Fuel Cycle		
Nuclear Power Plant	160,471/4,585	*4.090E+03
Fuel Fabricator	192,330/5,495	3.153E+01
Nuclear Power Plant Lab	105/3	5.600E-03
Medical		
Hospital/Clinic	11,611/332	1.043E+04
Research	7,697/220	6.335E+01
Private Office	8/0.2	1.000E-10
Laboratory	168/4.8	2.501E-01
Industrial		
Research & Development	4,559/130	1.302E+02
Manufacturer	28/0.8	1.262E+01
Non-Destructive Testing	5/0.14	5.260E+02
Devices and Gauges	0.1/0.003	3.000E-03
Academic		
Research	1,172/34	5.248E-01
Education	19/0.5	1.900E+01
Government		
State	361/10	2.173E-02
Federal	983/28	4.119E+00
City-Municipal	1/0.03	2.000E-09
County	7/0.2	6.000E-07
	379,420/10,840	1.525E+04

* Note: E + 03 is equivalent to 1 x 10^3. This terminology applies to other similar numbers also.

TABLE 2.3

STATE OF NORTH CAROLINA PROJECTED
FUTURE GENERATION IN CUBIC FEET/CUBIC METERS

TYPE OF FACILITY	1983	1984	1985	1986	1987
Fuel Cycle	145,297/4,151	105,150/3,004	110,150/3,147	108,550/3,101	130,200/3,720
Medical	21,589/617	22,915/655	23,924/684	25,060/716	26,335/752
Industrial	4,876/139	5,470/156	5,997/171	6,635/190	7,214/206
Academic	1,145/33	1,295/37	1,450/41	1,611/46	1,767/51
Government	1,135/32	1,235/35	1,335/38	1,335/38	1,335/38
TOTAL	174,042/4,972	136,065/3,887	142,856/4,081	143,191/4,091	166,851/4,767

Figure 2.1: ILLUSTRATION OF PROJECTED FUTURE GENERATION OF LOW-LEVEL RADIOACTIVE WASTE IN NORTH CAROLINA (1983-1987, by Volume)

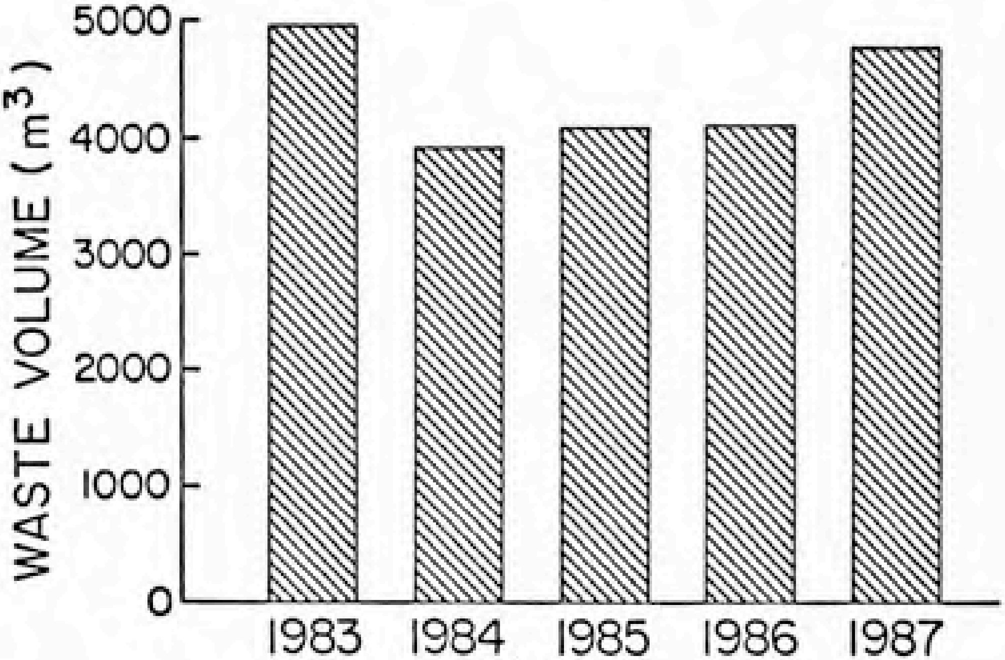

TABLE 2.4

PAST PROJECTION OF THE GENERATION OF LOW-LEVEL WASTE IN NORTH CAROLINA AND THE UNITED STATES, BASED UPON E.G.&G. DATA ON COMMERCIAL DISPOSAL

	1979	1980	1981
North Carolina	452,690 ft^3 12,934 m^3	788,200 ft^3 22,520 m^3	399,700 ft^3 11,420 m^3
United States	6,822,095 ft^3 194,917 m^3	9,114,245 ft^3 260,407 m^3	7,493,500 ft^3 214,100 m^3

TABLE 2.5

PAST PROJECTION OF THE GENERATION OF RADIOACTIVITY BASED UPON E.G.&G. DATA ON COMMERCIAL DISPOSAL

	1979	1980	1981
North Carolina	12,511 Curies	22,356 Curies	21,286 Curies
United States	1.326E+06 Curies	9.246E+05 Curies	7.774E+05 Curies

2.2 Waste Form

Typical radioactive wastes generated can be summarized, by category, in the following manner:

Fuel Cycle

- Compacted trash or solids
- Dry activated waste
- Dewatered ion exchange resins
- Contaminated plant hardware
- Depleted Uranium MgF_2
- Absorbed liquids and slurries

Academic

- Liquid scintillation wastes
- Compacted trash or solids
- Institutional lab or biological waste
- Absorbed liquids
- Animal carcasses

Medical

- Liquid scintillation wastes
- Compacted trash or solids
- Animal carcasses
- Institutional lab or biological waste
- Absorbed liquids

Industrial

- Compacted trash or solids
- Contaminated plant hardware
- Absorbed liquids
- Liquid scintillation wastes

Government

- Compacted trash or solids
- Contaminated hardware
- Liquid scintillation wastes
- Absorbed liquids

The waste forms listed represent a general overview of waste generated in the United States and North Carolina. Table 2-6 lists typical radionuclides contained in low-level radioactive waste.

TABLE 2.6

TYPICAL RADIONUCLIDES CONTAINED IN LOW-LEVEL WASTES, BY SECTOR

Reactors	Academic	Medical	Industrial	Government
^{58}Co	^{51}Cr	^{32}P	^{32}P	^{32}P
^{90}Sr	^{192}Ir	^{57}Co	^{60}Co	^{51}Cr
^{54}Mg	^{35}S	^{35}S	^{14}C	^{58}Co
^{134}Cs	^{125}I	^{51}Cr	^{238}U	^{60}Co
^{65}Zn	^{32}P	^{99m}Tc	^{125}I	^{3}H
^{137}Cs	^{14}C	^{60}Co	^{3}H	^{54}Mg
^{60}Co	^{90}Sr	^{3}H		^{226}Ra
	^{3}H	^{125}I		

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1) 1982 Low-Level Radioactive Waste Generation Summary, Conference of Radiation Control Program Directors, U.S., 1983.

2) The 1979 State-by-State Assessment of Low-Level Radioactive Wastes Shipped to Commercial Burial Grounds, for E.G.&G. Idaho by N.U.S. Corporation, November 1980.

3) The 1980 State-by-State Assessment of Low-Level Radioactive Wastes Shipped to Commercial Disposal Sites, E.G.&G. Idaho, The National Low-Level Waste Management Program, U.S. Department of Energy, June 1982.

4) The 1981 State-by-State Assessment of Low-Level Radioactive Wastes Shipped to Commercial Disposal Sites, E.G.&G. Idaho, National Low-Level Radioactive Waste Management Program, U.S. Department of Energy, December 1982.

3.0 CURRENT COMMERCIAL DISPOSAL PRACTICES

Current disposal of low-level radioactive waste involves the shipment of solidified liquids, slurries and other solid waste to a commercial low-level radioactive waste management site. At this time the site would be a shallow land burial facility.

Commercial disposal involves the transportation of waste to any of the three existing shallow land burial facilities. Those facilities are located near (1) Richland, Washington, (2) Beatty, Nevada, and (3) Barnwell, South Carolina. Shippers of waste are required to classify waste in accordance with the degree of hazard and physical properties. Shippers are also required to prepare a waste manifest form which states (among other things) the waste classification and radioactivity content.

Tables 3.1 (Ref. 1, 2, 3, 4, and 5) and 3.2 (Ref. 1, 2, 3, 4, and 5) and Figure 3.1 present the total volume of waste and radioactivity content received at the three existing shallow land burial facilities. They represent totals for the United States for the period 1979 through 1983. Tables 3.3 and 3.4 provide a listing, by percentage, of the data given in Tables 3.1 and 3.2.

Tables 3.5 (Ref. 1, 2, 3, 4, and 5) and 3.6 and Figure 3.2 give the total volume of low-level radioactive waste and associated radioactivity content received from the state of North Carolina.

TABLE 3.1

LOW-LEVEL RADIOACTIVE WASTE RECEIVED AT OPERATING COMMERCIAL SITES FOR UNITED STATES (1979 - 1983, by Volume)

Disposal Site Location	1979	1980	1981	1982	1983
Barnwell, South Carolina	2,220,505 ft^3 63,443 m^3	2,422,700 69,229	1,529,710 43,706	1,217,265 34,779	1,229,620 35,132
Beatty, Nevada	227,185 ft^3 6,491 m^3	445,095 12,717	117,285 3,351	52,675 1,505	38,885 1,111
Richland, Washington	349,300 ft^3 9,980 m^3	868,665 24,819	1,425,620 40,732	1,386,210 36,606	1,416,030 40,458
TOTALS	2,796,990 ft^3 79,914 m^3	3,736,810 106,766	3,072,615 87,789	2,656,185 75,891	2,684,570 76,702

TABLE 3.2

LOW-LEVEL RADIOACTIVE WASTE RECEIVED AT COMMERCIAL SITES FOR UNITED STATES (1979 - 1983, by Radioactivity)

Disposal Site Location	1979	1980	1981	1982	1983
Barnwell, South Carolina	319,942 Curies	143,502	183,744	273,962	383,450
Beatty, Nevada	8,932 Curies	148,312	52,214	80,929	1,356
Richland, Washington	153,563 Curies	41,031	43,905	59,007	120,534
TOTALS	477,437 Curies	332,845	279,863	413,898	505,340

TABLE 3.3

PERCENTAGE OF LOW-LEVEL RADIOACTIVE WASTE RECEIVED AT OPERATING COMMERCIAL SITES FOR UNITED STATES (1979 - 1983, by Volume)

Disposal Site Location	1979	1980	1981	1982	1983
Barnwell, South Carolina	79	65	50	46	46
Beatty, Nevada	8	12	4	2	1
Richland, Washington	13	23	46	52	53
Total Percentage	100	100	100	100	100

TABLE 3.4

PERCENTAGE OF LOW-LEVEL RADIOACTIVE WASTE RECEIVED
AT OPERATING COMMERCIAL SITES FROM UNITED STATES
(1979 - 1983, by Radioactivity)

Disposal Site Location	1979	1980	1981	1982	1983
Barnwell, South Carolina	66	43	65	66	76
Beatty, Nevada	2	45	19	20	< 1
Richland, Washington	32	12	16	14	24
Total Percentage	100	100	100	100	100

TABLE 3.5

LOW-LEVEL RADIOACTIVE WASTE RECEIVED AT
OPERATING COMMERCIAL SITES FROM NORTH CAROLINA
(by Volume and Radioactivity)

Category	1979	1980	1981	1982	1983
Volume	185,605 ft^3 5,303 m^3	323,155 ft^3 9,233 m^3	163,870 ft^3 4,682 m^3	154,945 ft^3 4,427 m^3	164,430 ft^3 4,698 m^3
Radioactivity	4,504 Curies	8,048 Curies	7,663 Curies	5,450 Curies	6,160 Curies

TABLE 3.6

PERCENTAGE OF LOW-LEVEL RADIOACTIVE WASTE SHIPPED FROM NORTH CAROLINA TO OPERATING COMMERCIAL DISPOSAL SITES (by Volume)

Disposal Site Location	1979	1980	1981	1982	1983
Barnwell, South Carolina	97	88	92	69	79
Beatty, Nevada	0	9	0	0	0
Richland, Washington	3	3	8	31	21
Total Percentage	100	100	100	100	100

Figure 3.1: PERCENTAGE OF LOW-LEVEL RADIOACTIVE WASTE RECEIVED AT OPERATING COMMERCIAL SITES FROM UNITED STATES (1979 - 1983, by Volume)

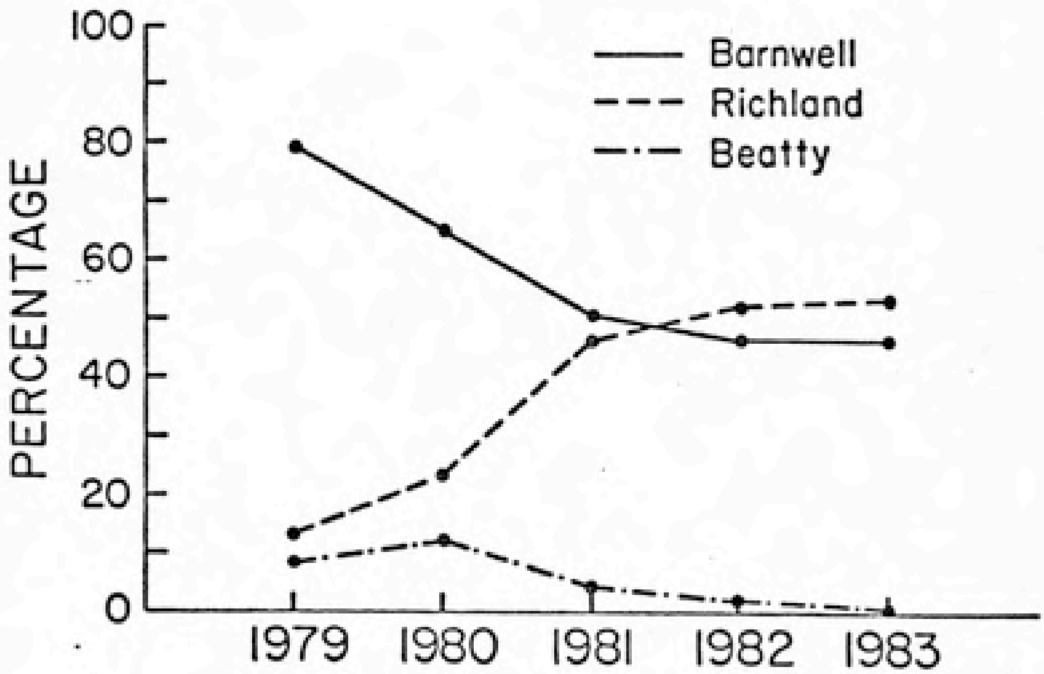
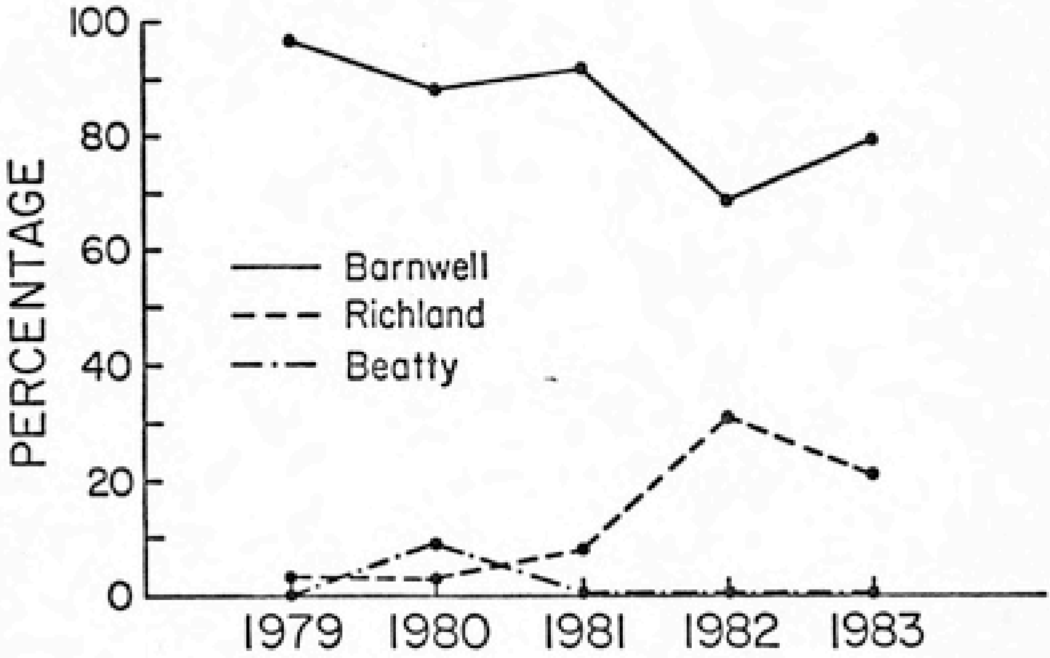


Figure 3.2: PERCENTAGE OF LOW-LEVEL RADIOACTIVE WASTE RECEIVED AT OPERATING COMMERCIAL SITES FROM NORTH CAROLINA (1979 - 1983, by Volume)



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5) The 1983 State-by-State Assessment of Low-Level Radioactive Wastes Shipped to Commercial Disposal Sites, by E.G.&G. Idaho and the Conference of Radiation Control Program Directors for the U.S. Department of Energy, December 1984.

4.0 CURRENT STATUS OF SHALLOW LAND BURIAL OF LOW-LEVEL RADIOACTIVE WASTE

Various forms of shallow land burial are being practiced at the three operating commercial disposal sites. Ideally, sites are selected in areas with substantial layers of loam, dust, clay and conglomerates. Areas containing large amounts of gravel or coarse-grained sand are not suitable. The continuous water table should be at a minimal depth of 5 meters below the surface of the terrain and soil permeability should be within the range of 10^{-8} to 10^{-7} meters per second. Conditions such as these represent a sufficient unsaturated layer where precipitation and groundwater cannot intermingle. Areas receiving limited rainfall are favorable also.

Basic shallow land burial consists of the excavation of a trench into which low-level radioactive waste is placed and covered. Trench dimensions depend on the form and volume of waste disposed. Transport and handling equipment is installed on the periphery of the trench or travels across it. In the former case, the width of the trench should be such as to allow the arm of the filling crane to reach easily beyond the longitudinal axis of the trench. The transverse parameters of the trench depend on the soil load-bearing ability and on the stability of the banks of the trench to secure safe transport, handling and operation.

The dimensions of the trench must be optimized. Relatively narrow trenches have a high proportion of unused space. Broad trenches do not allow adequate control of deposited materials in the middle part of the trench. The depth of the trench is governed by 1) the necessary height of the trench bed above the water table, 2) the possibility of depositing materials in layers, and 3) the economic utilization of filling machinery and handling efficiency. Trench width is governed by 1) the reach of the filling equipment and 2) the efficient use of trench space.

Waste in 55 gallon drums or special containers is placed in the trench. The trench is filled gradually with each layer of deposited waste so as to fill the whole of the storage space. Upon completion, the deposited material is covered with earth and the earthfill is compacted and graded. The earthfill may also be covered with a layer of insulating material, such as clay, and capped with a thin layer of earth and planted with turf. An underdrain or peripheral drainage system may also be used.

4.1 Siting Restrictions

As implied previously in this section, the siting of a shallow land burial facility involves the selection of a location with suitable characteristics for waste disposal. Those characteristics can be summarized in the following categories (Ref. 5):

- Geography
- Meteorology
- Hydrology
- Geology

4.1.1 Geography

Terrains located at altitudes between 200 and 600 meters above sea level are very suitable. Terrains at altitudes of up to 200 meters above sea level will be generally suitable in so far as the locality is not in the proximity of medium-sized or powerful water courses or water reservoir, which usually means that there is a low-land aluvium with a high water table. Terrains with altitudes between 600 and 800 meters are less suitable as they abound in steep slopes along rivulets and streams with extensive groundwater circulation. Altitudes greater than 800 meters combined with areas with a gradient of more than 5 percent are excluded.

4.1.2 Meteorology

Meteorological factors are very important in selecting a suitable site. Suitable climatic conditions and amount of precipitation falling in a prospective area are crucial.

Climatic parameters include the average annual temperature, maximum and minimum temperature deviations, number of days per annum with snow cover, and the number of days per annum when the temperature drops below 0^{o} C. Less suitable areas are those with large temperature fluctuations, large number of days per annum with temperatures below 0^{o} C and large number of days per annum with snow cover.

Concerning precipitation, the lower the level of precipitation in any prospective area, the more suitable it is for waste disposal. Areas with levels less than 0.5 meters of precipitation per year are desired, but higher levels may have to be accepted.

4.1.3 Hydrology

Prospective sites in close proximity to drinking water reservoirs and rivers are unsuitable. The absence of surface water-bearing conditions is desired. Areas with extensive circulation of groundwater and a high permeability of rocks are unsuitable. The velocity of the flow of groundwater is closely linked to the permeability of rocks. A slow flow of groundwater indicates low rock permeability.

4.1.4 Geology

Geological formations of a site impact significantly on the ability to prevent the migration of radioactive material into areas surrounding the site. Suitable materials for that purpose are 1) clays for their sorportion properties, 2) chernozemic soils, 3) some acid brown soils, and 4) weathered rock. Less suitable are pseudogleyic soils, brown soils, podzolic and illimerized soils. Sands, slates, gravel, calcareous soils and almost all igneous rocks are unsuitable.

4.2 Problems Encountered

Of the six established commercial shallow land burial sites in the United States, three have been closed. The site at Sheffield, Illinois was closed when a license amendment request to open new trenches was not granted and the cost of conducting additional hydrogeologic investigations became prohibitive. The sites at Morehead (Maxey Flats), Kentucky and West Valley, New York were both closed when radioactive materials were found on the surface of these sites. This contamination resulted from the following processes:

- the trenches had been constructed over impervious strata;
- the construction of the trenches caused the surface to become permeable;
- storm water infiltrated into the trenches;
- water accumulated in the trenches and became contaminated by the waste;
- vertical migration of the contaminated water carried the contamination to the surface, and
- lateral migration of the contaminated water carried the contamination to areas outside the site.

As a result of these conditions, remedial actions were necessary to reduce the potential for off-site migration of the radioactivity.

These sites now require corrective measures and decommissioning to some extent. The plan for such activities involves the following steps:

- the water is pumped from the trenches to reduce the potential for migration;
- the water is processed with evaporators to reduce the quantities that must be stored;
- the concentrate and sludge are solidified and buried in another location;
- a permanent drainage system with lined channels is being constructed to convey surface water from the site;
- plastic membranes are being used to cover the trenches to reduce infiltration and the quantity of water that must be removed from the trenches;
- after pumping, the trenches will be allowed to stabilize; and
- permanent intrusion barriers will be installed after the trenches stabilize.

It is obvious that if sites cannot continue to meet design objectives, the cost of custodial care, decommissioning and perpetual care will be high. This experience with shallow land burial facilities makes it wise to consider alternative disposal methods. Although the physical state of waste buried has improved with the development and implementation of new federal regulations (e.g., 10 CFR Part 61), it may appear logical to assume that the problems encountered in Kentucky and New York can be repeated at other sites. However, it must be stated that the problems documented were site specific and would not be necessarily applicable to other sites.

Alternatives may be considered to be improved versions of shallow land burial. The concept of "enhanced shallow land burial" has been perpetuated, which includes the insertion of plastic liners in excavated trenches prior to the introduction of waste. This is considered to be a simple form of enhanced shallow land burial and is designed to reduce the infiltration of groundwater into the trench and prevent the subsequent migration of radionuclides from the trench site. More advanced forms of enhanced shallow land burial make use of concrete liners in the place of plastic liners.

4.3. Future Capacity

Prior to outlining the estimated future capacity of the three operating shallow land burial facilities, it is important to review the total volume and radioactivity content buried to-date. Table 4.1 (Ref. 13) provides an accounting of the total volume of waste burial at the three operating shallow land burial facilities through 1984. Table 4.2 (Ref. 13) gives the total radioactivity content burial at the three commercial sites through 1984.

TABLE 4.1

TOTAL VOLUME OF LOW-LEVEL RADIOACTIVE WASTE BURIED AT THE THREE OPERATING COMMERCIAL DISPOSAL SITES CUMULATIVE THROUGH 1984

Site	Total Volume	First Year of Operation
Barnwell, South Carolina	16.436E+06 ft^3 (4.496E+05 m^3	1971
Beatty, Nevada	3.437E+06 ft^3 (9.83E+04 m^3	1962
Richland, Washington	7.78E+06 ft^3 (2.223E+05 m^3	1965

TABLE 4.2

TOTAL RADIOACTIVITY CONTENT OF LOW-LEVEL RADIOACTIVE WASTE BURIED AT THE THREE OPERATING COMMERCIAL DISPOSAL SITES CUMULATIVE THROUGH 1984

Site	Special Nuclear Material	Source Material	Other
Barnwell, South Carolina	4028.74 lbs[A] (2014.37 kg)	12.53E+06 lbs (5.695E+06 kg)	2.91E+06 Curies
Beatty, Nevada	497.596 lbs[B] (226.18 kg)	1.71E+06 lbs (7.77E+05 kg)	0.45E+06 Curies
Richland, Washington	297.33 lbs[B] (135.15 kg)	9.80E+06 lbs (4.455E+06 kg)	1.41E+06 Curies

A) No Plutonium
B) Includes Plutonium

As indicated, Barnwell has received and buried the majority of the waste volume and radioactivity content to-date, despite the fact that it has been operating the shortest period of time.

Table 4.3 (Ref. 13) gives an estimate of future available capacity at two of the three operating shallow-land burial facilities.

TABLE 4.3

PROJECTED FUTURE AVAILABLE CAPACITY OF COMMERCIAL DISPOSAL SITES FROM 1985

Site	Future Available Capacity
Barnwell, South Carolina	18.1E+06 ft^3 (5.17E+05 m^3)
Beatty, Nevada	2.5-3.0E+06 ft^3 (7.14-8.57E+04 m^3)
Richland, Washington	information not available

It is very difficult to estimate the number of years it will take to exhaust the projected capacity at each site. Social and political factors, as well as contamination problems, could force early closing. In addition, site longevity is a function of the rate at which waste is buried. It has been estimated that all existing disposal capacity at the operating commercial sites will be exhausted by the mid-1990's (Ref. 11). This projection is based upon a fairly significant increase in waste generation over the next several years.

4.4 Cost

The cost of constructing and operating a shallow land burial facility in the 1980's and beyond would depend on a number of factors, such as 1) geographical location of the site, 2) property values, 3) equipment and labor costs, and 4) licensing fees. It is misleading to generate one figure for the total cost of shallow land burial and expect it to be valid in all suitable areas of the country.

Recently the State of Maine conducted a study to determine the cost of a small shallow land burial facility in the New England area, which gives an indication of the amount of dollars needed for a specific need (e.g. 30,000 cubic feet, maximum capacity, annually for a period of 25 years) (Ref. 12).

Costs were divided into four basic categories as follows:

1) pre-construction,
2) construction,
3) operation, and
4) site closure.

Pre-construction cost was estimated to be between 4.0 and 4.9 million dollars. This included such things as the costs of site selection, site characterization, environmental impact statement and licensing.

Construction cost was estimated to be between 724 and 898 thousand dollars. This primarily included facility construction.

Operating cost was estimated to be between a maximum of 1.57 and 2.33 million dollars annually. This includes such things as labor and environmental monitoring. Included in the overall total was an estimate of an additional 4 million dollars for the use of techniques to prevent radionuclide migration. These techniques include grouting and multilayered capping of the trenches.

These costs add up to be a maximum total price of approximately 12 million dollars. The cost of a shallow land burial facility is a function of the site of a facility. The larger the burial capacity, the greater the construction, operation and site closure cost, thus the greater the overall cost to an extent.

Table 4.4 (Ref. 12, 14) gives a comparison of the number of dollars per cubic foot charged to generators from the estimated Maine figures as opposed to current charges of the three operating commercial sites.

TABLE 4.4

COMPARISON OF ACTUAL AND PROJECTED COST TO GENERATORS FOR THE DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE BY SHALLOW LAND BURIAL (by Volume)

Site	Cost
Barnwell, South Carolina	\$24.90 per cubic foot
Beatty, Nevada	\$17.85 per cubic foot
Richland, Washington	\$21.76 per cubic foot
Maine (Ref. 12)	\$44.00 per cubic foot

These figures represent basic charges, which do not include additional taxes and surcharges on weight and radioactivity content. It can be theorized that the difference between the projected figure (Maine) and actual costs occur because of 1) the reduction in overall capacity of the projected site as opposed to operating sites and 2) the length of time the operating sites have been in existence. Lower pre-construction and construction costs were incurred when the three operating sites were placed in service.

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5.0 MINIMIZATION OF LOW-LEVEL RADIOACTIVE WASTE

When considering the overall problems and controversy surrounding the final disposition of low-level radioactive waste, the application of volume reduction techniques prior to disposal becomes more and more important. It is desirable to decrease the volume of low-level waste requiring disposal to a level as low as possible. The information presented in this section describes how that goal might be accomplished.

5.1 Prevention

The volume of low-level radioactive waste requiring disposal can be reduced by (a) decreasing the rate of generation, and (b) reducing the volume of waste after generation. Prevention falls within the confines of the first approach. The four basic concepts of prevention can be summarized in the following manner:

5.1.1 Design and Engineering

The design and engineering features of use areas should be considered early in the conceptualization and planning phases of radioisotope utilization. Significant reduction in waste generation can be realized by designing facilities and purchasing equipment aimed at isolating contaminated, yet reusable, items. Also, the operation of equipment according to specifications and the identification of aging or out-of-date facilities and equipment can lead to waste reduction.

5.1.2 Operation and Maintenance

Day to day operating and maintenance procedures can dictate the generation of low-level radioactive waste in many instances. Adequate training programs and nonradioactive "mockups" help personnel feel more confident when performing tasks, thereby helping to prevent accidents and waste generation. Routine preventive maintenance is a logical method to reduce unexpected equipment failure while working with radioactive material and it helps to extend the life of the equipment.

5.1.3 Decontamination

When required, the proper selection and use of decontamination methods can help reduce the generation of low-level waste by minimizing the production of secondary waste and allowing reuse of contaminated equipment or disposal as nonradioactive waste. Prompt identification, collection and isolation of contaminated materials and equipment can reduce the spread of contamination to other areas. Decontamination agents should be selected on the basis of maximum radioactive material removed per volume of agent used.

5.1.4 Administrative

The documentation of a comprehensive waste prevention plan allows personnel to study the procedures which have been implemented to reduce volume. Strict enforcement of administrative controls is necessary in order to maximize benefits from the volume reduction plan. The correct application of prevention methods requires continuous management overview. In addition, the implementation of sound laboratory safety procedures is another means by which administrative controls can help reduce the volume of low-level radioactive waste generated.

5.2 Volume Reduction

Reducing the volume of low-level radioactive waste after generation can be accomplished by taking advantage of the following methods:

a) Pre-treatment (segregation, sorting, shredding)
b) Treatment (filtration, evaporation, compaction, incineration, size reduction, melting-casting immobilization/solidification)
c) Deregulation or de minimis levels
d) Storage-for-decay

Incineration is discussed in detail in Section 6 of this report.

5.2.1 Pre-Treatment

General low-level radioactive waste consists of many materials, both combustible and noncombustible. Combustible solids consist of a variety of items such as paper, rags, plastic sheeting, protective clothing, gloves, rubber shoes, wood and filter cartridges, as well as some partially combustible items such as HEPA (high-efficiency particulate air) filters encased in wooden frames. The noncombustible portion consists typically of metal, glassware, construction and insulating materials, metal-encased HEPA filters, small discarded equipment, tools, filters and other mechanical devices. Pre-treatment of waste, (i.e., the physical or chemical processes necessary to prepare waste for primary treatment and/or disposal) includes operations such as segregation, sorting, and shredding. These methods are outlined as follows:

5.2.1.1 Segregation

Segregation is accomplished primarily by the designation of specific waste containers for specific categories of waste. This operation is performed at the time of waste generation. Waste containers can be labeled in accordance with radionuclide, short or long-lived radionuclides, combustible or noncombustible, class A, B or C, chemical or physical state, and chemical toxicity. Segregation may encompass any or all of the above.

The segregation of nonradioactive from the radioactive components of waste is a fundamental aspect of volume reduction also. This involves the implementation of some method of screening waste to determine what components are radioactive and which are not. Appropriate radiation detection instrumentation, such as Geiger-Mueller survey instruments, can be used to perform the task. Other more elaborate instrumentation is also available for use. This type of screening is mostly limited to items contaminated with energetic beta and/or gamma emitting radionuclides. Segregation by screening can be done manually, or in the case of large generators, a mechanical device can be put to use to work automatically.

5.2.1.2 Sorting

Sorting is considered to be the application of waste segregation. Hand sorting is the simplest method of segregating mixed waste into components that are amenable to treatment by a particular technology. Hand sorting is used to assure separation of compactible from noncompactible or combustible from noncombustible, as well as material deleterious to the operation of volume reduction equipment. It is also used to identify and remove hazardous materials (e.g., pyrophoric or explosive substances) from the waste stream.

It is generally desirable to segregate and sort solid waste into combustible and noncombustible fractions. Following suitable pretreatment, combustible waste can be combusted, decontaminated, compacted or packaged. Similarly, noncombustible waste may be treated using methods which will be discussed later in this report. The categories into which wastes are sorted will be determined by whatever primary treatment options are available for use.

The separation of solid from wet waste is also an important sorting process. Wet waste consists mainly of aqueous solutions and slurries, evaporator concentrates, spent demineralizer resins, filter sludges and organic chemicals, oils and solvents. Treatment options for wet waste range from simple filtration to high temperature drying techniques.

5.2.1.3 Shredding

Potentially combustible waste materials can be shredded to produce small pieces for subsequent treatment or disposal. The principal types of shredding equipment are knife cutters, hammermills, and variations or combinations thereof. These devices have the capacity of crushing or shredding waste depending on the required objective. Volume reduction factors of 4:1 have been documented (Ref. 3).

5.2.2 Treatment

The treatment of low-level radioactive waste has evolved with the increased utilization of radioactive material in science, medicine and industry. Treatment is designed to volumetrically reduce waste and improve the waste form to restrict mobility during transport to a final disposal site. The most common treatment modes are outlined as follows:

5.2.2.1 Filtration

Filtration is the most commonly used method for the removal of radioactive particulates from liquid waste. In fuel-cycle facilities, filtration techniques are a very important component of overall waste treatment (Ref. 2). High-efficiency particulate filters can be used as a basic means of removing particulates. The filtered particulates are then included with the filter media as solid waste. Ion exchange and reverse osmosis are examples of more advanced forms of filtration. Ion exchange involves the removal of ionic species, principally inorganic, from aqueous waste. The process consists of an exchange of ions between the liquid and a solid matrix component, containing ionizable polar groups. The exchangers can be regenerated or disposed of as solid waste.

Reverse osmosis involve removing a liquid from a solution by passing the solution through a device (membrane or other) which retains the solid components, including dissolved solids. The extremely small pore size used separates this process from basic filtration. Control of pressure, temperature, and pH may be used to enhance separation.

5.2.2.2 Evaporation

Evaporation is considered to be the most widely used technique for reducing the volume of liquid radioactive waste in fuel cycle facilities. Through evaporation, a solution or slurry is concentrated by vaporizing away the solvent, normally water. An evaporator consists basically of a device to transfer heat to the solution and a device to separate the vapor and liquid phase. Vapor-liquid separation is the most important factor in the operation of an evaporator. Evaporators can separate water from solids very effectively and a decontamination factor of 10^4 to 10^5 can be expected from a single phase operation (Ref. 2).

5.2.2.3 Compaction

Compaction consists of compressing suitable dry waste into smaller volumes. A compactor includes a hydraulic or mechanical drive, a platen, a base plate, structural supports, a drum positioning platform and a control panel. Waste is loaded into a drum and the unit is activated by bringing the platen down onto the waste in the drum. The platen is raised, the drum is refilled, and the process is then repeated. Typically compaction pressures range from 30 to 150 Kg/cm^2 depending on reduction factors required (Ref. 2). Very dense items such as metal, pyrophoric or explosive substances, and wastes containing free-standing liquids are not suitable for compaction.

Compaction is an important component of volume reduction in non-fuel cycle facilities. Compaction in 55-gallon drums is the most common application although supercompactors are now being promoted. Supercompactors, commonly called high tonnage compactors, are systems which process waste by high pressure compaction to effect a higher net volume reduction. Compaction forces of several hundreds of tons to thousands of tons may be applied. Supercompactors can reduce the volume of compactible waste by a factor of approximately 7 to 1 (Ref. 8). They have been used in Europe for approximately two and one-half years. There are two well known suppliers of supercompactors used for volume reduction of low-level radioactive waste. These companies are Gesellschaft Fur Nuklear-Service mbH (GNS) of West Germany and Machinefabriek A. Fontijne of Holland. Both companies have in operation machines designed specifically for processing dry active waste generated by nuclear power plants, hospitals, and research facilities.

The 1500-ton rating of both machines was determined as a result of research and development efforts designed to optimize press forces relative to the volume reduction achieved for the type of waste processed. The GNS "FAKIR" supercompactor is being marketed in the United States by representatives based in Atlanta. Stock Equipment Company in Chagrin Falls, Ohio, is licensed to manufacture and market the Fontijne supercompactor in the United States.

The Fontijne supercompactor, showed in Figure 5.1, has been specifically designed to compact 55-gallon D.O.T. 17H drums containing dry active waste. Design and construction of the compaction press allows for it to be operated in an enclosure with remote controls. The principle of design is for a 40 year life with minimum maintenance requirements. The following basic components are required for the operation of the supercompactor:

1) Press - Welded base
   Welded crown with main cylinder
   Welded press mold with guides
   Welded plunger-construction with guides
   Guide columns for the mold and plunger

2) Hydraulic system - Hydralic fluid reservoir
   Pump and motor
   Oil cooler

3) Press loader

4) Drum piercing system

5) Drum unloader

6) Infeed conveyor

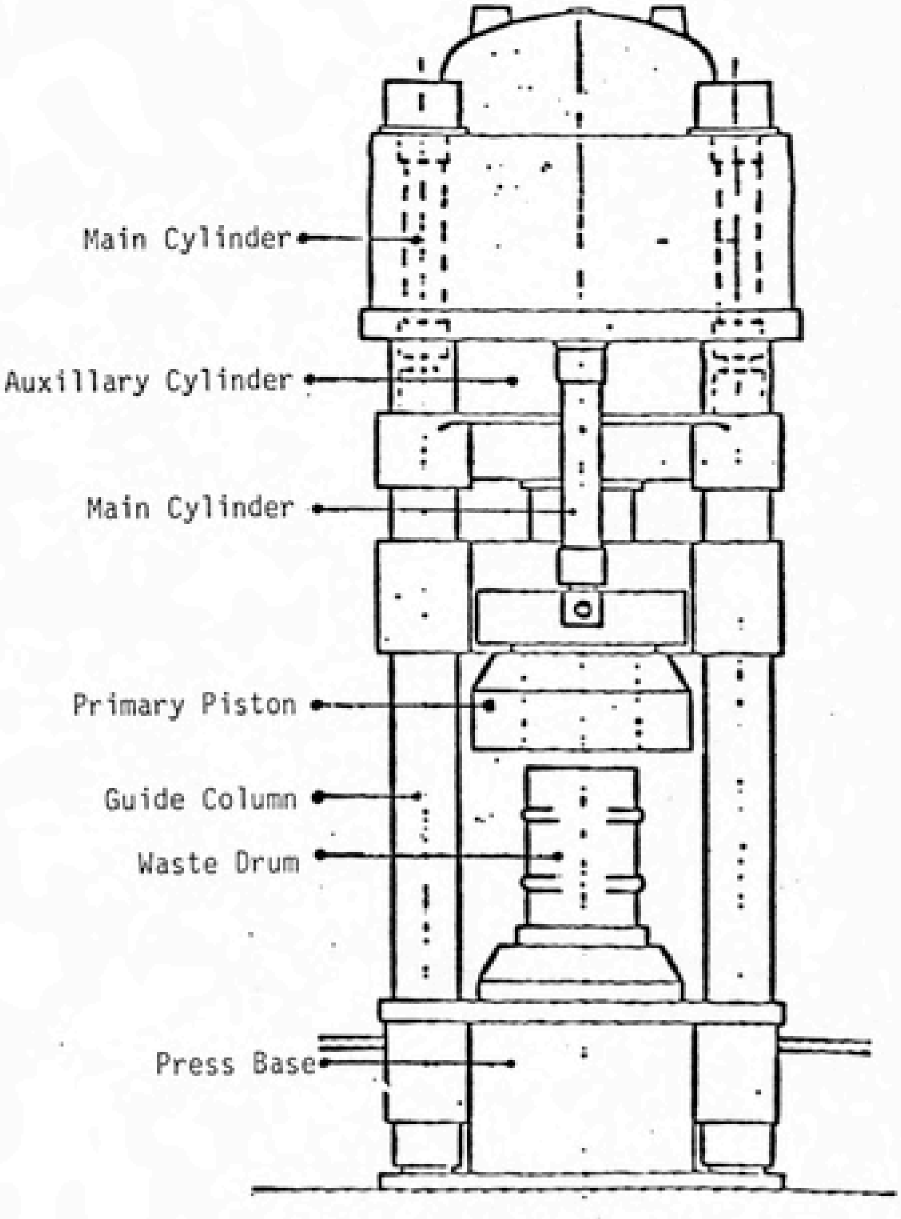
The main cylinder is mounted in the crown of the press. The total cycle for compaction of a drum takes about two minutes. The drum is compacted within a mold, fitted with an interchangeable lining. The press mold is mounted to the crown of the press and actuated by two double-acting cylinders. When the press mold is lowered around the drum, it seats over a round hardened pressplate which is mounted to the base of the press. This forms a closed chamber for compacting the drum. The waste is then pressed into pellets which can be packaged into 83 gallon drums. The dimensions of the press are as follows:

Press capacity	- 1500 tons
Throughput capacity	- 30 drums per hour
Press stroke	- 39 inches
Height	- 236 inches
Base dimensions	- 6 feet by 6 feet
Weight	- 40 tons

During operations, the compacting process can be performed under negative pressure, with the effluent air being vented through high efficiency particulate filters or impregnated charcoal filters. The prevention of the release of radioactive particulates is the major concern. The possibility of releases should be minimal.

Figure 5.1

Mechanical Components of a Fontigne Supercompactor



Source: Proceedings on Incineration of Low-Level Radioactive Waste, Tucson, Arizona, March 1985

5.2.2.4 Size Reduction

Mechanical disassembly of contaminated equipment is the main constituent of size reduction of low-level radioactive waste. Dismantling reduces the volume of waste and simplifies handling. Shearing, cutting, and torching can be viable means of size reduction.

Size reduction operations are applied to equipment too large to transport directly. These operations tend to be time-consuming and costly. Typically, size reduction is used only when required.

5.2.2.5 Melting/Casting

Meltdown and casting of contaminated equipment, after decontamination or size reduction, are treatment options not fully developed. Like size reduction, these operations are costly and are not significant contributors to the overall volume reduction effort in the majority of facilities. The process of melting incorporates the radioactive material into the matrix of the metal where it is immobilized. The process is considered to be an important element in future decommissioning of large fuel-cycle facilities.

5.2.2.6 Immobilization/Solidification

The objective of waste immobilization/solidification is to convert general or pretreated liquid waste or incinerator ash into a stable form to minimize the potential for release of radioactive material to the environment during storage, transport and final disposal. Immobilizing or absorption media, such as vermiculite or diatomaceous earth, have been used to stabilize liquid waste. Solidification agents, such as cement or polymers, have been used to contain other waste in a solid, stable form. The solidification of waste requires a certain amount of time for the solidification agent to harden after the introduction of the liquid waste to the solidification media. Commercial disposal facilities require a certain amount of immobilization or solidification of liquid waste prior to accepting it for final disposal.

5.2.3 Deregulation or de minimis Levels

Various concentrations of waste generated in non-fuel cycle facilities (e.g. institutional) have been deregulated or exempted from disposal requirements. In the medical community, excreta from patients undergoing treatments that require the administration of radioactivity is exempted from disposal regulations. Also, hospital laboratories utilizing certain radioactive materials manufactured and distributed for *in vitro* testing purposes, within a quantity specified by state and federal regulations, are exempted from waste disposal requirements. In institutions involved in medical or bioresearch there is now an exemption for liquid scintillation media and animal carcasses containing 0.05 microcurie or less of C-14, H-3, and I-125 per gram of media. This material can be disposed of without regard to its radioactivity provided the generator is able to measure and document that the waste does not exceed the maximum concentration limits. The U.S. Nuclear Regulatory Commission has amended 10 CFR 20 "Standards for Protection Against Radiation" to allow licensees the ability to apply for, and obtain, NRC approval to dispose of residual thorium or uranium (as natural ores or without daughters present) at specific concentration limits in a manner specified by 10 CFR 20.302. Finally, state and federal regulations allow the release of small quantities of specific radionuclides to the air and sewer.

Deregulation has not been advocated as a principal means of low-level radioactive waste volume reduction. It has been debated whether or not the introduction of the deregulated radionuclides into the environment poses a risk to the general population.

5.2.4 Storage-For-Decay

At institutions, particularly medical, using short-lived radionuclides, the waste can be held at the facility until radiation levels reach background. Short-lived radionuclides are considered to be those which have a half-life of less than 60 days. Once it has been determined that waste has reached background radiation levels, the waste can be disposed of as municipal trash.

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6.0 INCINERATION

Incineration has been developed and used over a number of years as a means of treatment for various types of waste material. Only in recent years has incineration been applied as a process to reduce the volume of radioactive waste. For the purposes of this report, an incinerator is considered to be any engineered device used to thermally decompose low-level radioactive waste material.

Numerous types of furnaces are used for incineration. They range from single-chamber systems to complex multi-chamber units. They are classified according to shape (open pit or multiple chamber), the amount of air used (controlled air or excess air) and to moving parts (rotary or moving grate). The examples given are just an illustration of incinerator classification. They do not represent a complete list of all the incinerator technologies available.

The necessary conditions for achieving complete combustion in any incinerator are 1) adequate residence time; 2) adequate temperature (to promote complete combustion); 3) turbulence (to promote good mixing); and 4) sufficient oxygen. Problem areas have included warping of construction materials, incomplete combustion (leading to excess carbon in the ash which creates problems for the off-gas clean-up system), clogging, fires outside the combustion chamber, inadequate ash handling and corrosion (particularly if sulfur or halogen-containing compounds are part of the waste).

6.1 Application

A description of waste forms suitable for incineration can be summarized as follows:

a) Non-fuel cycle, solid waste

- Biological (animal carcasses, excreta, bedding, tissue, etc.)
- Dry (syringes, tubes, paper, gloves, etc.)

b) Non-fuel cycle, liquid waste

- Liquid scintillation (fluids and vials)
- Organic (alcohols, ketones, acids)

c) Fuel cycle, solid waste

- Dry (cloth, paper, plastic, rubber, wood, filters)

d) Fuel cycle, liquid waste

- Aqueous (solutions, slurries, concentrates, sludges)
- Organic (chemicals, oils, solvents, demineralizer resins).

Selection of a particular incinerator technology depends on the type of waste to be incinerated. Newer technologies tend to include additional special requirements for scintillation and aqueous waste with such modifications as liquid injection and special refractories. Typical fuels are fuel-oil and diesel fuel.

6.2 Technology Development

The primary processes of incineration are (a) waste preparation and feed, (b) combustion, and (c) off-gas treatment and clean-up. Secondary processes are (a) ash generation, (b) secondary waste generation (e.g. scrubber/quenching liquid, filtration devices) and, (c) off-gas effluent generation. Technology development is dependent upon the type of combustion chamber or combustion process used. The following is a brief description of the various technologies considered to be applicable to the incineration of low-level radioactive waste.

6.2.1 Acid-Digestion

Shredded solid wastes (with the exception of teflon and HEPA filters) and liquid waste (except highly volatile liquids) are fed onto a shallow tray where they come in contact with nitric acid and recirculating sulfuric acid which is air-lifted from a heated reservoir. Combustible wastes are converted to gaseous products (CO_2, H_2, HCl and sulfate residues) by digestion in H_2SO_4 at 230 to 250° C in the presence of HNO_3 oxidant. Off-gas treatment is required. Residue is in the form of a dry salt cake, primarily inorganic sulfates and oxides. Gaseous effluents contain NaCl and small amounts of nitrate and sulfate compounds. Operating capacity has been rated at 5 kilograms/hr.

6.2.2 Agitated Hearth

An agitated hearth incinerator developed by Environtech, Inc., San Mateo, California has been tested in a pilot program with non-radioactive waste (Ref. 7). The plant processed approximately 4 kilograms/hr of waste, primarily from the nuclear industry. A larger unit, with a capacity of 70 kg/hr, is planned by Environtech. The unit will be designed to treat mixed radioactive waste. This form of incinerator technology is proposed to be used at Rocky Flats to process low activity waste containing less than 0.02 gram of plutonium per gram of waste material.

The Rocky Flats agitated hearth is a stationary, refractory lined steel circular vessel 2.6 meters in diameter by 4.6 meters high with rotating rabble arms (Ref. 7). The rabble arms tumble the waste through the combustion zone and push the accumulated ash to the output port.

Wastes are processed through the incinerator on a batch basis using a semi-continuous feed. The incinerator is oil-fired and is operated at a temperature of 600 to 800° C. Gases and fly ash are combusted in an after burner operated at 1,000° C. Process effluents are combustion gases and spent alkaline scrub solution.

6.2.3 Controlled-Air

Controlled-air incinerators use the concept of multiple chamber burning to achieve complete combustion of solid waste. Waste is fed into the first chamber where it is burned in the presence of substoichiometric quantities of air. The products of partial oxidation and volatization flow into a secondary combustion chamber where excess air provides complete combustion. This mode of operation produces a nonturbulent combustion environment in the first chamber and minimizes the entrainment of fly ash into the second chamber.

This technology is a popular one because of flexibility in accepting a wide range of waste compositions, ease of combustion rate control, minimum particulate emission due to low turbulence in the primary combustion chamber, ability to tolerate relatively high levels of noncombustibles, and the use of off-the-shelf technology resulting in a relatively low cost system.

The primary chamber is operated at 500 to 800° C. The secondary chamber is normally operated at 1,000 to 1,500° C. The Los Alamos National Laboratory operates one of the first controlled air incinerators. It has a capacity of 45 kg/hr (Ref. 6).

Off-gas treatment may be utilized. Effluents are combustion gases and neutralized off-gas scrubber solution.

6.2.4 Cyclone Drum

The cyclone drum incinerator burns waste in a vertical chamber with air forming a swirling motion in the burning chamber. The swirling air cools the outer walls of the incinerator and provides intimate contact with the waste. The combustible materials may be hand loaded into a stainless steel burning chamber, or alternately, a pre-loaded drum may be used as the burning chamber. This system provides effective combustion, basic design, and low capital cost; however, particulates are normally present in the off-gas and waste is not completely oxidized.

Capacity has been rated at 14 to 19 kg/hr when operating on a batch basis using drums and 31 kg/hr when operating as a continuous process.

Residue is in the form of dry ash and effluents consist of combustion gases. The combuster operates at 1,100° C.

6.2.5 Fluidized-Bed

The fluidized-bed incinerator is a vertical cylinder made of stainless steel plates with a vee bottom. Two air distribution plates form the sides of the vee with a screw discharge conveyer forming the bottom of the vee. Shredded waste is introduced beneath the surface of a fluidized bed of sodium carbonate by a screw compression feeder. The heated combustion air introduced at the bottom of the bed agitates and causes the sodium carbonate to act like a fluid. This action improves mixing and combustion of the feed material. The salt bed material helps stabilize the temperature because of its heat dissipation properties and mass. It also provides in situ neutralization of the acidic components of the effluent. This simplifies the off-gas treatment system, when required.

Design capacity is 80 kg/hr.

Residue consists of inert dry oxide ash with dry salt powder. Effluents consist of acid-free combustion gases. The combustor operates at 525 to 600° C.

6.2.5 Molten-Salt

The combustor is an alumina brick-lined, cylindrical salt incinerator. The molten salt, sodium carbonate, serves as a heat transfer medium and as a neutralizing agent for acidic gases such as HCl and SO_2 formed during combustion. Molten sodium sulfate is also added to the molten bath and is used to catalyze the combustion reactions and to minimize the evolution of carbon monoxide and volatile hydrocarbons. The combustible wastes are burned with air in this molten bath. Inorganic products such as metallic oxides, ash, sodium chloride and radioactive material are retained in the melt.

The off-gas clean up problems in the molten salt process are considerably simplified due to the in-situ neutralization of HCl. A supplemental heat source is required to maintain salt in molten condition during short shutdowns. Sodium chloride solid waste is generated with incinerator ash. Ash is approximately 20 percent of the waste residue. Practically all radioactive materials remain in the salt; however, there is a possibility of some radioactive material migration into the combustor refractory lining.

Combustion has been demonstrated in a pilot plant with a capacity feed of 50 kilograms per hour (Ref. 6).

Process effluents are nonacidic combustion gases. Operating temperature ranges from 800 to 880° C.

6.2.6 Pyrolysis (Controlled-Air)

A pilot model was built at the Savannah River Plant for test incineration of wastes containing high specific activity contamination which poses a serious hazard (Ref. 7). A ceramic primary chamber is heated by electric heaters located in the top of a chamber. The chamber has a "starved air" atmosphere. The off-gases then pass into an oxygen rich secondary chamber for complete combustion.

Primary and secondary combustion chambers operate at 1,000° C.

Input capacity is 0.5 kilograms per hour.

This incinerator is considered to be a combination of the controlled-air and pyrolysis process. Pyrolysis is the thermal decomposition of organic material into solid, liquid and gaseous constituents, the amounts of each depending upon the composition of waste and incinerator operating conditions. Pyrolysis units are similar to controlled-air incinerators, with the exception that in the primary chamber the air supply is 25 to 35 percent of stoichiometric, versus 75-plus percent for controlled air units.

Low amounts of particulates are produced in the off-gas. There is a longer residence time for the burning of the off-gas in the secondary chamber. There is a possibility of radioactivity migration into the combustor refractory lining.

6.2.7 Rotary-Kiln

The rotary-kiln incinerator is an inclined, horizontal cylindrical kiln (1.8 meters in diameter by 4.6 meters in length) rotating on its longitudinal axis about 1 to 2 revolutions per minute. The waste materials are fed by a ram feeder to the upper end of the kiln. The rotary action of the kiln exposes unburned material for combustion and causes the waste to move slowly in a cascading manner through the kiln. The combustion chamber operates on a two chamber process. The primary chamber operates at 600 to 800^{o} C at a residence time of approximately one hour. The secondary chamber operates at 1,000^{o} C with a residence time of 5 seconds.

Capacity has been rated at about 40 kilograms per hour (Ref. 7). Ash is continuously removed from the system, thereby minimizing radioactivity inventory. The rotary kiln results in a shorter refractory life. It is also vulnerable to radioactivity migration and build-up in the refractory linings.

6.2.8 Slagging Pyrolysis

This incinerator is designed with a conical primary chamber. A burner is directed downward from the apex of the cone. Waste material is fed from a ring column confined by an outer shell. Plows attached to the outer shell force the waste toward the center of the furnace floor. A hole in the floor provides an outlet for the off-gases as well as the molten slag. As the waste is burned and melted, a combustion chamber is formed by the waste itself. The slag residue coats the entire combustion chamber and then drips into the quenching pool below the hole in the floor. Added air is fed along the sides through the waste for combustion in the bottom chamber. Between the slagged waste surface and the waste supply are zones of pyrolysis and oxidation.

The primary chamber operates at 1,500 to 1,600^{o} C. The secondary (slag) chamber operates at 1,100 to 1,200^{o} C. Capacity has been rated at 100 kilograms per hour.

This technology was developed primarily for the incineration of waste containing large amounts of glass and metal. Radioactive material is physically or chemically bonded in the glass or metal slag. Some control of the waste mix must be maintained to ensure efficient combustion.

Process effluents include corrosive off-gases.

6.3 Controlled-Air Incineration

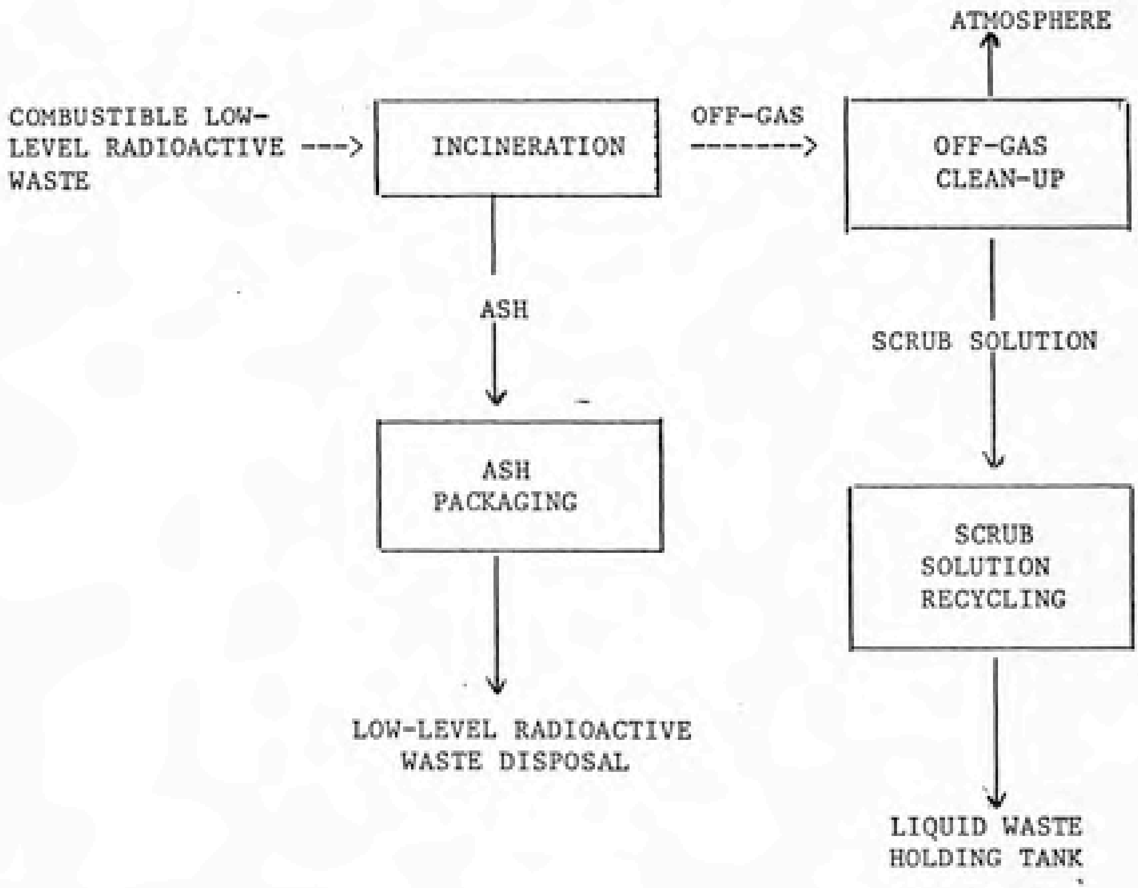
Controlled-air incinerators are of particular interest because of their current popularity and high flexibility of incinerating varying mixes of waste material. Removing noncombustibles (glass and metal) is optional. The ready availability of controlled-air incinerator technology and components make it the most widely used technology, to date, for the incineration of low-level radioactive waste. The existing technology is easily modified for the incineration of liquid waste as well.

This technology is currently used at academic, medical and research institutions.

Figure 6.1 gives a flow-chart representation of the controlled-air incineration process.

Figure 6.1

CONTROLLED - AIR INCINERATION FLOWCHART



6.3.1 Engineering Concepts

The controlled-air incineration process can be divided into five subsystems: 1) waste preparation and introduction, 2) actual incineration, 3) off gas clean up, 4) pneumatic ash transfer and 5) scrub solution recycle. Figure 6.2 provides an engineering schematic of this process. The primary process consists of a two-staged, refractory-lined, natural gas-fired incinerator combined with a high-energy aqueous scrub solution and HEPA filter banks. An induced-draft configuration maintains negative internal pressure to insure radioisotope containment.

Waste is prepared for incineration typically by placement in cardboard boxes. It is introduced into the incinerator by an enclosed ram feeder. The top door of the feeder and the inner door to the incinerator are interlocked to prevent possible flashback if both were opened at the same time.

The incinerator combustion unit design allows for a retention time of approximately three hours in the primary chamber for complete combustion. A large secondary combustion chamber provides extended retention for flue-gases. Additional air mixing nozzles may be added in the secondary chamber to ensure complete combustion of flue-gases.

Exhaust from the incinerator secondary (upper) chamber, containing mineral acids and a small amount of particulates, can be forced to pass through a quench column, venturi scrubber, packed column and HEPA filters before release to the environment, if so desired. In the quench column, exhaust gases are cooled from 2,000 to 200^{o} F by direct spray contact with recycled scrub solution. The cooled gases then pass through a variable-throat venturi, designed to provide high turbulence mixing of the gas stream, and provide liquid droplet control with the scrub solution to remove most remaining particulates. Residual mineral acids are removed from the gases by counter-current contact with recycle scrub solution. A packed column condenser removes the bulk of the water vapor from the scrubbed gas stream. Reheaters raise the gas temperature to avoid condensation and clogging of the filtration system. Finally the gas stream is passed through roughing and HEPA filters for final removal of particulates and through impregnated charcoal filters for removal of radioactive iodine.

In a dry ash handling system, the ash is removed by a pneumatic transfer system which pushes the ash through an outlet directly into a drum or hopper to be prepared for final disposal.

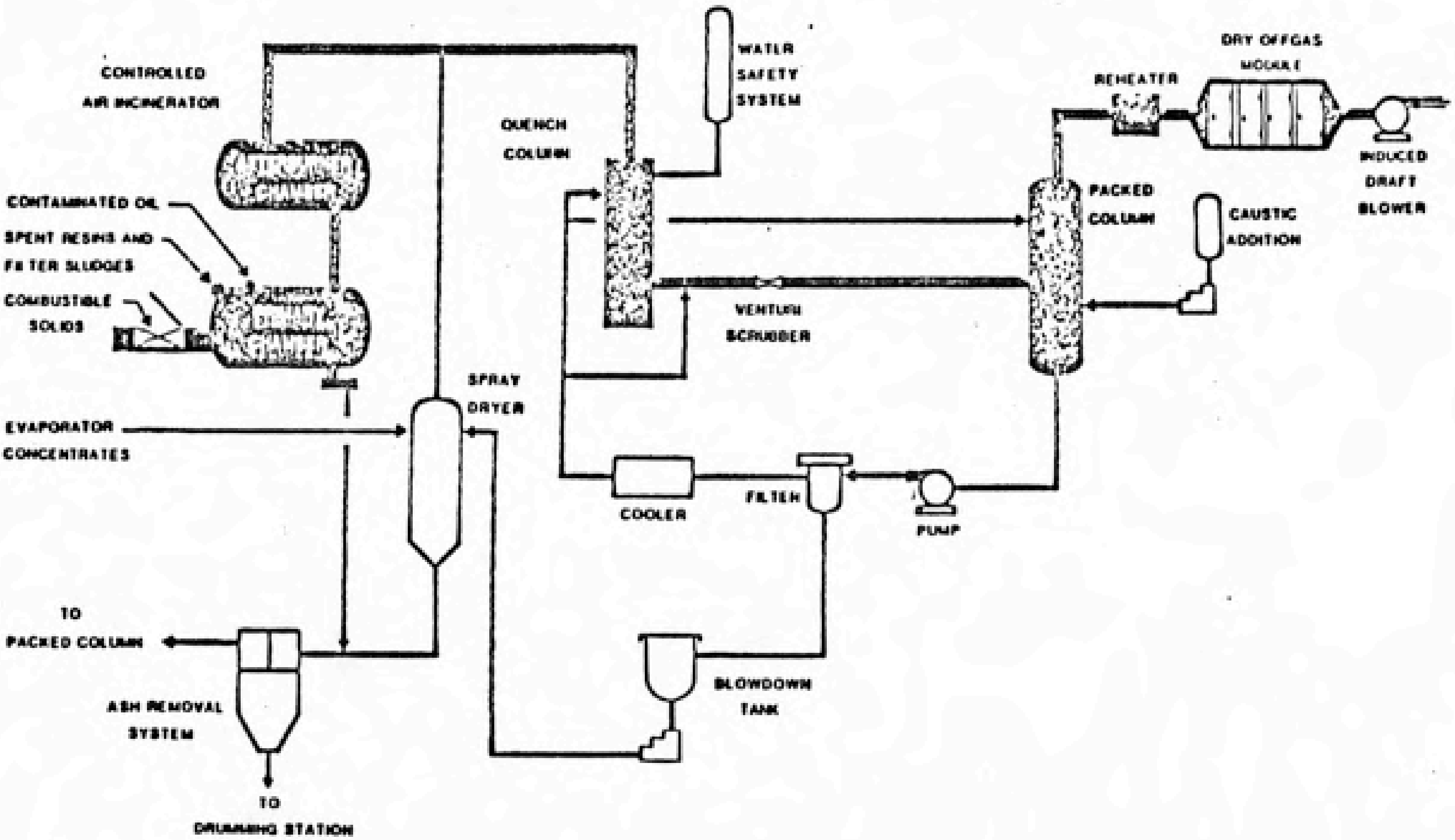
The use of scrub solutions is a wet method of obtaining off gas filtration. Scrub solutions can consist of water or specially prepared chemical solutions. Flue-gases are mixed with atomized water droplets. The water droplets collect particulates and dissolved gases. Caustic addition to scrub solution is an effective method for acid gas neutralization. The scrub solution is recirculated or recycled to minimize the amount of solution needed for wet filtration. This is important because the scrub solution will absorb radioactive contaminants from the gas stream and must be treated as liquid radioactive waste. Scrub solution also cools the off gas effluent.

6.3.2 Effectiveness

Mass reduction and volume reduction ratios of 10:1 and 40:1, respectively were realized for incineration of a simulated design basis feed (35 percent cellulosics, 23 percent polyethylene, 12 percent PVC and 30 percent rubber) (Ref. 5). This nonradioactive test was conducted at the Los Alamos National Laboratory (LANL) in 1979, prior to the incineration of transuranic waste. Consequently, the LANL controlled-air incinerator has operated at a design feed rate of 45 kg/hr with good agreement between the nonradioactive and actual radioactive burns. To date, commercial controlled air incinerators for radioactive waste volume reduction are based on the technology developed at LANL. Thus, it can be assumed that the volume and mass reductions documented at LANL are being realized at other facilities using similar technology, assuming similar waste characteristics.

Figure 6.2

Mechanical Components of a Controlled-Air Incinerator



Source: Proceedings on Incineration of Low-Level Radioactive Waste, Tucson, Arizona, March 1985

6.3.3 Environmental Impact

For the purposes of this report, the term "environmental impact" is confined to the radiological impact to man from the release of radioactive materials through the effluents of controlled-air incinerators.

There is not a significant data base regarding the release of radioactive materials to the environment from controlled air incinerators. There is not a complete list of all incinerators in use in the United States and abroad. Considering the off-the-shelf availability of controlled-air incinerator technology, a strong case can be made for assuming that the majority of the incinerators in use are of the controlled-air variety.

The federal government and medical/academic institutions have been in the forefront in using incineration as a treatment technology for low-level radioactive waste. A study commissioned by the U.S. Department of Energy attempted to determine the types of incinerators in use in the medical/academic community and the amount of radioactivity being released to the environment (Ref. 8). The study was not successful. Incinerator technologies were not identified. In addition, actual releases of radioactive material were not assessed. Most facilities included in the survey did not actually monitor the amount of radioactivity released. Instead they were able to demonstrate compliance with state and federal maximum permissible concentration limits by calculating concentration limits based upon everything incinerated, or a portion thereof, being released through the effluent stack.

Ideally, it is desirable to have operators of all incinerators (including controlled-air) calculate a radiation dose to humans in the nearest unrestricted area and report it to applicable state or federal agencies for analysis. These results could then be collected and used to estimate the radiological impact of the incineration of low-level radioactive waste on humans. Calculations would involve 1) the determination of the activity of each radionuclide released to the environment and 2) the conversion of that activity to a concentration and total dose at a certain distance from the facility. With suitable dose estimates, a calculation of radiological health effects can be made for exposed populations.

When considering doses from routine releases of radioactivity such as those from incinerators, it is assumed that doses are sufficiently low that the only health effects requiring consideration are the stochastic effects (e.g., somatic and hereditary effects). The most important somatic effect is the induction of cancer some time after exposure to radiation. This cancer may or may not have a fatal outcome. A risk estimate of 1.65×10^{-4} cancers (somatic and hereditary) per rem of total body exposure has been proposed based upon current scientific knowledge (Ref. 15).

As an illustration, one facility incinerating low-level radioactive waste in North Carolina calculated a maximum projected dose of 0.050 rem/yr. to unrestricted areas surrounding the facility (Ref. 14). This calculation was based upon a worse case scenario whereby all the radionuclides licensed to be incinerated were combusted and the total radioactivity released through the stack. This is a conservative approach, and information is now available suggesting that varying percentages of radionuclides are retained in the incinerator chamber. Using the conversion factor stated in the previous paragraph, it might be assumed that the stated dose could represent an impact of eight additional cancers per million individuals exposed per year. However, if the maximum dose is 0.050 rem/yr, the average dose to one million exposed would be much less than the maximum dose, resulting in a health effect significantly less than eight cancers per million individuals exposed. More recently, this facility calculated a maximum whole body dose based upon radionuclides actually incinerated for 1984 and 1985. Results indicated totals of 0.033 and 0.074 millirem respectively. These doses were projected to occur within 0.5 kilometer of the incinerator. Obviously these actual figures represent much less of a health effect than the worst case scenario.

6.3.4 Licensing

In general, the licensing of incinerators is governed by 10 CFR Parts 20 and 61, or equivalent state regulations. Part 20.101 establishes radiation dose standards for individuals in restricted areas. Part 20.103 establishes limitations on the concentration of radioactive material that individuals in restricted areas may inhale and/or absorb through the skin. Part 20.105 addresses permissible levels of radiation in unrestricted areas. Part 20.106 establishes limitations on the radioactivity levels in effluents to unrestricted areas. Part 61 establishes criteria for waste form, radioactivity content and waste classification of ash and noncombustibles requiring disposal.

Recently, efforts have been directed towards providing more specific criteria regarding the licensing of incinerators. For instance, North Carolina has adopted regulations regarding the licensing of certain incinerator facilities, specifically those used as part of a radioactive waste processing facility. The main topics required to be addressed are as follows:

- description of the applicant
- description of the site
- incinerator design
- facility design
- management and staffing
- description of waste
- treatment of waste to be shipped off-site
- prelicensing and operational public information program
- method of maintaining doses as low as reasonably achievable
- off-site impact assessment for routine operations
- monitoring programs and systems
- other regulations, standards and permits
- accident analysis
- emergency response plan
- decontamination and decommissioning.

No effort will be made to elaborate on the specific details of the categories mentioned above. Instead, the reader is urged to consult Supplement No. 5 of the North Carolina "Regulations for Protection Against Radiation", issued by the Radiation Protection Section, North Carolina Department of Human Resources.

Incinerators which are not a part of a waste processing facility are not directly subject to all requirements outlined in the North Carolina Regulations, although some requirements may apply. All the requirements outlined in 10 CFR Part 20 and most of Part 61, promulgated by the U.S. Nuclear Regulatory Commission, are embedded in the North Carolina Regulations. These requirements are applicable to all incinerators, including controlled-air incinerators.

6.3.5 Cost

Cost of low-level radioactive waste incineration depends upon 1) the initial cost of the incinerator plus accessories and 2) operating cost after the incinerator has been set up for operation.

The cost of an incinerator, plus accessories, depends upon the intended use (e.g. commercial versus private). Non-commercial incinerators are usually less expensive because they are usually smaller in capacity and do not utilize costly accessories such as sophisticated off-gas treatment and filtration systems. The purchase price of controlled air incinerators can range from approximately 200 thousand dollars for non-commercial units to approximately 1.5 to 2 million dollars for commercial units, depending upon volume capacity.

Operating costs depend upon the number of burns per time interval and the overhead costs thereof. Overhead costs include fuel (oil, natural gas, etc.), waste containers, labor, and ash disposal if applicable.

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7.0 COMPARISON OF SUPERCOMPACTION AND INCINERATION AS A TREATMENT METHOD FOR LOW-LEVEL RADIOACTIVE WASTE

It is currently being debated whether or not supercompaction is a safer and more effective means of treatment of low-level radioactive waste than incineration. There is no clear-cut answer to this question. The answer depends upon what comparative criteria are most important. For the purposes of this report, five categories were identified. They are:

1) Acceptable Waste Form
2) Final Waste Product
3) Volume Reduction
4) Environmental Impact
5) Cost

7.1 Acceptable Waste Form

Waste form can be expanded to detail specific types of waste in the overall waste stream. It is then desirable to determine which types of wastes are amenable to supercompaction and incineration. The following is a presentation of what types of waste are considered:

Waste Type	Supercompaction	Incineration
Absorbed Liquids	Not Probable	Yes
Animal Carcasses	Not Probable	Yes
Aqueous or Organic Liquids	No	Yes
Contaminated Trash or Solids	Yes	Yes
Contaminated Plant Hardware	Probable	No
Demineralizers	Yes	Yes
Depleted Uranium	No	No
Dewatered Filter Media	Yes	Yes
Dewatered Ion Exchange Resins	Yes	Yes
Gaseous Sources	No	No
Spent Medical Generators	Yes	Yes
Liquid Scintillation Waste	No	Yes
Radioactive Devices or Gauges	Not Probable	No
Concrete Solidified Waste	Yes	No
Bitumen or Polymer Solidified Waste	Yes	Yes

The most significant difference may be the inability of supercompactors to handle liquid scintillation waste and animal carcasses, which are a large part of institutional and biomedical waste.

7.2 Final Waste Product

Supercompaction produces a stable waste form, primarily consisting of organic materials. After burial, the possibility of generation of gases such as $^{14}CH_4$, $^{14}CO_2$, and CH_3T (tritiated methane) exist (Ref. 5). These gases could then diffuse from burial trenches, spreading radioactive contamination.

The incineration of low-level radioactive waste will result in an organically inert waste form, thereby eliminating the possibility of organic gas production. However, there must be solidification of the incinerator ash in order to obtain a stable waste form similar to that of supercompaction.

7.3 Volume Reduction

Volume reduction ratios for supercompaction vary from source to source. Volume reduction by supercompaction, with precompaction, was reported to be 14:1 (Ref. 1). With no precompaction, a ratio of 15:1 was reported (Ref. 1). However, precompaction is desirable in order to avoid voids. Other reports indicate volume reduction ratios of 7:1 (Ref. 3), 8:1 (Ref. 2) and 8.3:1 (Ref. 3). Overall volume reduction ratios are dependent upon waste composition and compressive capacity of the supercompactor.

Reported volume reduction ratios for incineration range from 10:1 (Ref. 3), 20:1 (Ref. 1) to 30:1 (Ref. 2). Overall volume reduction of low-level radioactive waste is dependent upon waste composition, combustive capacity of the incinerator and the extent of ash solidification. It is generally accepted that incineration affords better volume reduction than supercompaction.

7.4 Environmental Impact

With supercompaction there is little possibility of effluent releases due to the compaction process. Particulates (radioactive, chemical or otherwise) are the prime concern and can be filtered efficiently under proper operating conditions.

With incineration, particulates can be filtered out but the release of contaminated combustion gases is probable, even with the use of wet and dry filtration systems. Therefore, there is a possibility of the release of certain radionuclides to the environment due to incineration. The magnitude of such releases may be within acceptable limits.

7.5 Cost

Capital costs for supercompaction range from one million dollars (Ref. 4) to 5 million dollars (Ref. 2). Costs for commercial incineration range from 4 million dollars (Ref. 4) to 33 million dollars (Ref. 2). The range of costs reflects the differences in engineering designs and variability in construction, operation and maintenance costs.

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8.0 ALTERNATIVES TO SHALLOW LAND BURIAL

Efforts are now underway to determine the feasibility of designing, building and operating facilities aimed at greater confinement of low-level radioactive waste. Techniques for engineered disposal other than traditional shallow land burial are likely to be introduced to the NRC or Agreement states for licensing consideration in the near future. Many feel that any new permanent disposal facility would be more acceptable to the public if it provided greater confinement capabilities; however, it is also understood that such facilities would carry a higher construction cost than traditional shallow land burial. Bennett, et al. (Ref. 1) have prepared an excellent document on alternative disposal methods, on which the discussion below relies in large part.

Concepts in use, or under consideration at this time, are (1) below-ground engineered vaults, (2) above ground engineered vaults, (3) earth mounded concrete bunkers, (4) mined cavities and (5) augered holes. Each of these disposal techniques has either been proposed as an alternative to shallow land burial or is currently being used or considered for use in other countries.

8.1 General Application

Shallow below-ground vaults are currently being used for storage of low-level radioactive waste in Canada and for storage of transuranic wastes at Oak Ridge National Laboratory in Tennessee (Ref. 1). Deep below ground vaults in hard crystalline rock are being studied in Canada for final disposal of low-level radioactive waste.

Above ground vaults are being used in Canada for storage of low-level radioactive waste and have been promoted by a private firm involved in waste disposal technology for disposal of low-level radioactive waste at the Maxey Flats site in Kentucky (Ref. 1). Above ground vaults are also being promoted by others in the United States.

Earth mounded concrete bunkers are being used in France for disposal of low and intermediate level radioactive waste (Ref. 1). In Canada, rectangular concrete trenches and cylindrical concrete chambers with removable covers are used for low-level radioactive waste storage and these are considered as variations of the bunker concept.

Mined cavities have been used in West Germany for disposal of low and high-level radioactive waste as well as hazardous waste (Ref. 1). In Sweden, a 400,000 m^3 underground repository for low and intermediate level radioactive waste is under construction. The U.S. Department of Energy and the Tennessee Valley Authority have studied the feasibility of mined cavity disposal of both low and high-level radioactive waste.

Augered hole disposal is also being studied by the U.S. Department of Energy (Ref. 1). In Canada, variations of augered holes (called tile holes) are used for storage of ion exchange resins and filter canisters (Ref. 1). Oak Ridge National Laboratory uses augered holes for low-level radioactive waste storage, and in West Germany a disposal concept of bore holes in the floor of a salt mine at Gorelbon is under consideration (Ref. 1).

8.2 Technology Development

Several low-level radioactive waste management technologies which are currently under development are described below.

8.2.1 Below-ground Vaults

Below-ground vaults are any engineered structures constructed below the earth's surface. These vaults are visually unobtrusive and physically secure to purposeful intrusion because of their siting below the ground surface. Access to the foundation elevation may be directly from the earth's surface or from the entrance of an existing cavity. Figure 8.1 shows a conceptual view of a below-ground vault.

The vault structure can be built from masonry blocks, reinforced formed or sprayed concrete, fabricated metal, or plastic or fluid media molded into solid shapes. The configuration of a vault may or may not have a floor constructed of man-made materials but will be laterally bounded by constructed walls and provided with a roof structure. The architectural design may be a function of construction materials used and stability desired. Designs range from rectilinear, to arched enclosures to semi-spherical dome-like structures. As a rule the vault has limited access to its interior space, accomplished by a doorway, portal or hatch opening. Design and construction of the vaults could be standardized. Standardization could lead to better waste handling procedures and less radiation exposure to workers, since this allows sufficient time to desdign safety procedures.

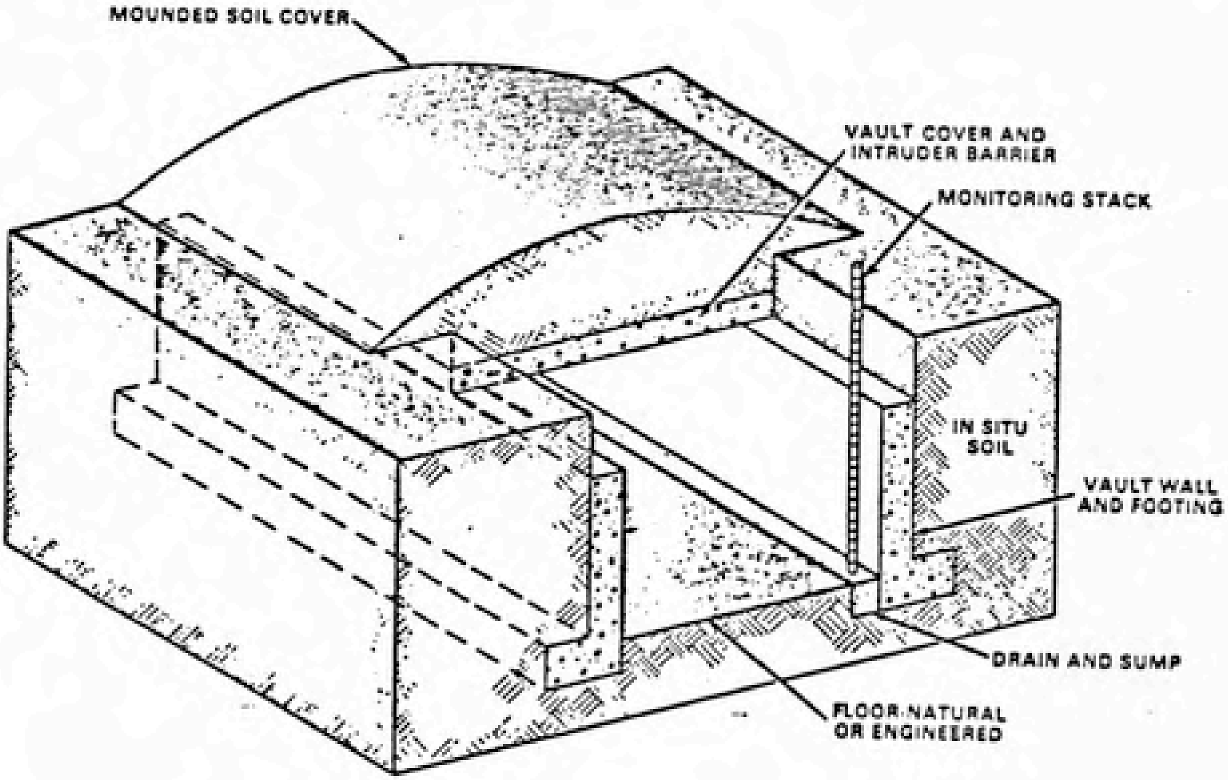
An appropriately designed vault should remain intact and sealed through all reasonably foreseeable or projected meterological and earth movement events. The vault units should be easy to locate and re-enter in case it becomes necessary to retrieve the waste. Design and construction efforts should verify that the foundation and abutment geological structure is competent to support the structure. Soil and ground-water chemistry must be checked to avoid soils that could corrode the structure.

The vault structure should provide lateral confinement and overhead cover, and should not depend on its contents for structural stability. The vault should be designed to safely support all dead loads, including the vault cap, the earth cover and all operating loads necessary for placement of the waste and earth cover.

Design should include provisions for temporary closure during operation and permanent closure afterwards. Features of the vault and surroundings must allow for continuous environmental radiation monitoring during all phases of facility life. The facility must be reasonably self-sustaining after any institutional control period ends.

Interfaces between construction stages must incorporate prevention of radionuclide escape and intrusion by biota and groundwater. The construction of a below-ground vault must be accompanied by a rigorous quality control program to assure that all performance objectives are met.

Figure 8.1: CONCEPTUAL CUTAWAY VIEW BELOW-GROUND VAULT DISPOSAL



Source: U.S. Nuclear Regulatory Commission, NUREG CR-3774, Volume 1, 1984.

8.2.2 Above-ground Vaults

The above-ground vault is an engineered structure or building with floors, walls, roof and limited access openings with its foundation at or very near the ground surface. The vault fabrication could be similar to that of below-ground vaults. Unless design criteria are explicitly established no constraints would be placed on material selection or shape of the vault as long as it can be shown that performance objectives can be met. Figure 8.2 and 8.3 presents possible engineering approaches for above-ground vaults.

Above-ground vaults are readily visible on the landscape. That characteristic may or may not be a detriment regarding the public's acceptance of this technology as a viable disposal alternative.

In the design of above-ground vaults, considerable architectural freedom is available because this technology is totally man-made and does not depend on geological formations for waste isolation. Current engineering and structural designs allow above-ground vaults to be built to withstand a large range of natural hazards, including erosion and land slides. Above-ground vaults are less vulnerable to flooding, which allows more freedom in siting such facilities.

Physical security can be engineered into the design. Appropriate designs should render the entries as secure as the entire structure itself.

The visibility of above-ground vaults is an advantage in preventing inadvertent human intrusion; however, some consider above-ground vaults a means of interim storage, not a mechanism for final disposal of low-level radioactive waste.

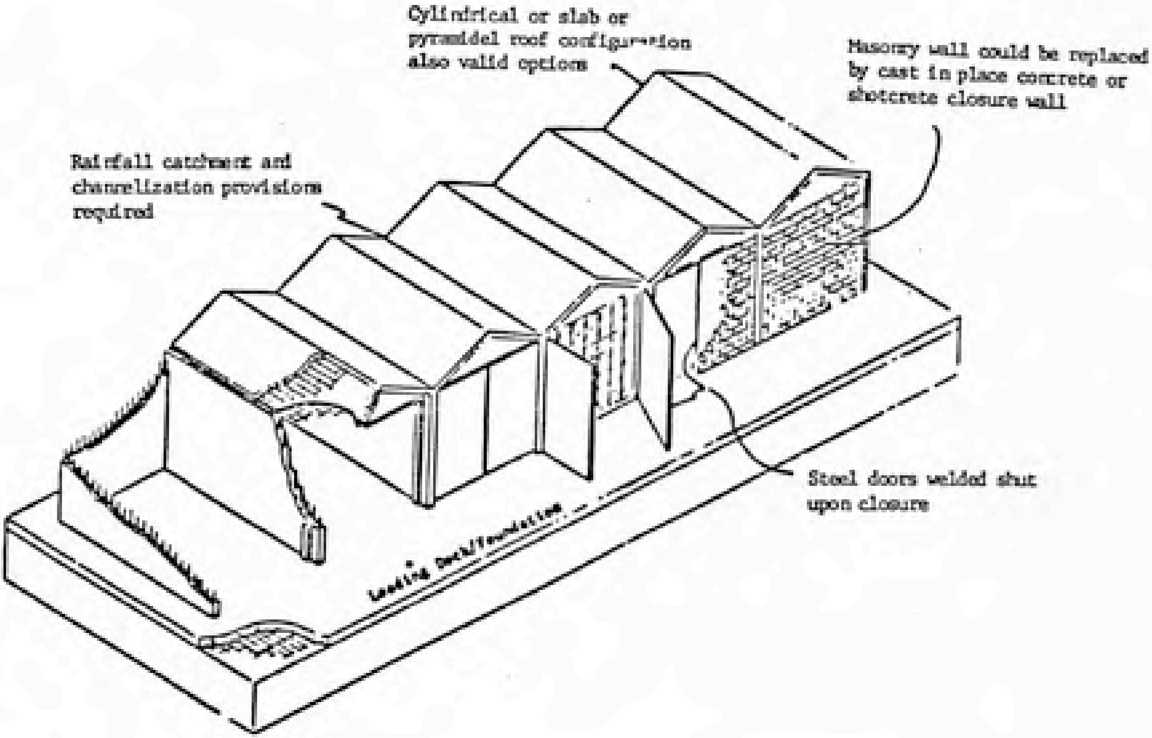
Interfaces between construction materials can be sealed, as well as the structure itself, to impede radionuclide migration. However, there are no secondary barriers to prevent radionuclide releases should the integrity of waste containers and the structure itself fail.

Venting or retrieval of waste material can be designed into the original structure. Monitoring of above-ground vaults is enhanced by their accessibility.

Active maintenance requirements could be more extensive than other alternatives. The institutional control period would be much longer than for any subsurface disposal method. Also, as with below-ground vaults, exposure of workers to radiation hazards from high activity waste could be higher than desired because of the difficulty in adapting remote handling equipment for use in limited access facilities.

A wide variety of above-ground vaults have been built and successfully used for warehousing manufactured goods, raw materials, meat and produce. They have been shown to be economical, durable and versatile. Above-ground vaults are used in Canada for storage of low-level radioactive waste (Ref. 1). The New Brunswick Electric Power Commission has built storage vaults on bedrock at its Pt. Lepreau site completely above-ground (Ref. 1). An above-ground storage facility is also being used at Ontario Hydro's Bruce site (Ref. 1).

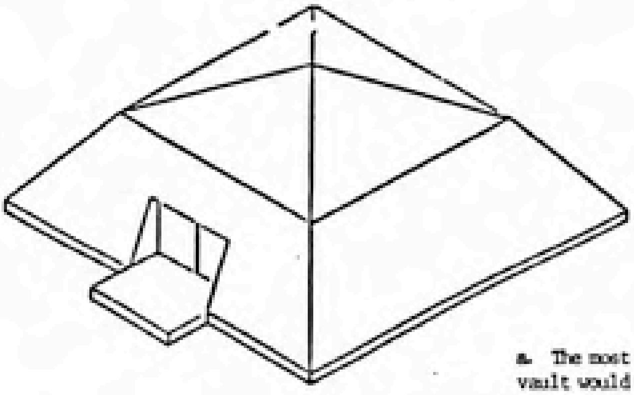
Figure 8.2: CONCEPTUAL SKETCH OF CELLULAR ABOVE-GROUND VAULTS FOR DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE



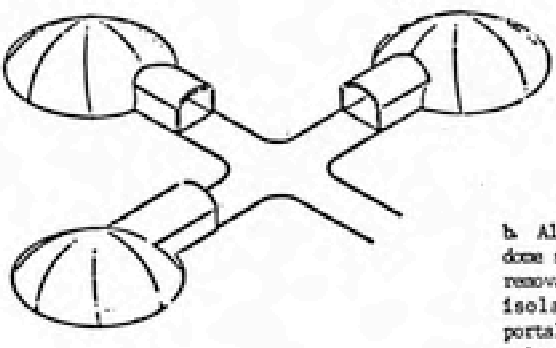
The separate cells of the overall disposal vault structure could be constructed and used progressively as needed. The construction depicted here is primarily of reinforced concrete, cast in-place to minimize leakage-prone joints. As a cell is filled to capacity it is sealed permanently, while neighboring cells are in operation. Cellular disposal reduces quantities of leakage in the case of a single cell failure. Truck unloading docks are included as part of the foundation. Cellular vaults are inherently feasible for waste requiring strict segregation.

Source: U.S. Nuclear Regulatory Commission, NUREG CR-3774, Volume 1, 1984.

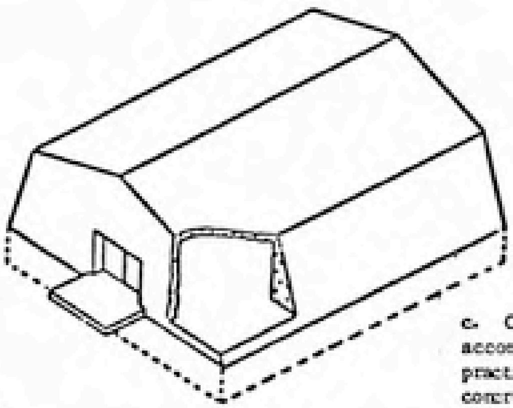
Figure 8.3: CONCEPTUAL SKETCH OF PYRIMIDAL, DOME AND RECTANGULAR ABOVE-GROUND VAULTS FOR DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE



a. The most durable structural alternative of an aboveground vault would be a pyramidal form made of thick monolithically poured reinforced concrete. The expense of such construction would be higher per unit of capacity than other alternatives but it would be most durable in the face of catastrophic hazard.



b. Alternative configurations for aboveground vaults include dome shapes made by shotcrete shells sprayed on inflatable, removable forms. Clustering of units enhances segregation, isolation, and progressive construction sequences. The portal assemblies shown could be moveable and reusable after unit closure.



c. Conventional rectilinear aboveground vaults would accomodate common warehouse operations as presently practiced. The structures could be formed from reinforced concrete incorporating buttressed walls for protection of the disposed waste as well as enhancing structural durability. Metallic or masonry construction would be inherently less stable and offer less leakage prevention than concrete.

Source: U.S. Nuclear Regulatory Commission, NUREG CR-3774, Volume 1, 1984.

8.2.3 Earth Mounded Concrete Bunkers

Earth mounded concrete bunkers were first put into use in France in the 1960's. Their basic design requires segregation of waste according to the level of radioactivity. Intermediate level wastes are embedded in concrete monoliths below-ground; and low-level or intermediate level wastes, with appropriate packaging, are stored above-ground in earthen mounds over the concrete monoliths. Figure 8.4 provides a view of the earth-mounded bunker concept.

A wide trench is first excavated above the water table. The sides of the trench are shaped to form temporarily stable side-slopes and the bottom of the trench is covered with a reinforced concrete pad. A drainage system is provided around the concrete pad to collect any run off or construction debris. The trench is sub-divided into compartments according to level of radioactivity. After each layer within a compartment is completed, it is backfilled with concrete. When the last layer of waste has been placed in a compartment, reinforcing steel is placed on the top of the layer and the compartment is completely back filled with concrete, creating a large concrete monolith.

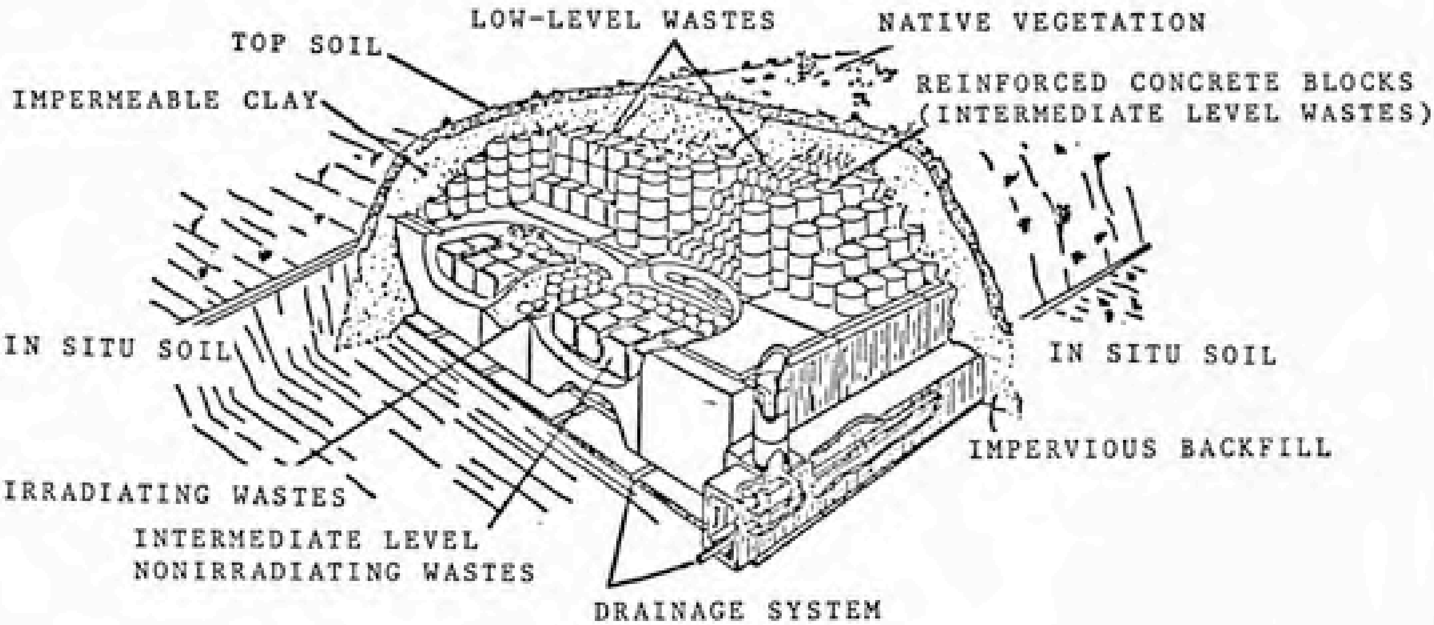
To reduce the external hazard of high activity wastes, the narrow void between monoliths is temporarily covered by a concrete slab in the interim between placement of wastes. Then the void between monoliths is filled with high activity waste and covered with concrete, creating a smaller concrete monolith surrounded by two larger ones.

The construction sequence of creating monoliths side by side is continued until the bunker is filled. Once the last monolith is completed, the bunker is waterproofed with a layer of asphalt. Impervious back-fill material is placed on the trench slopes to the top level of the monoliths, and another drainage system is installed for monitoring and filtration purposes after the site is closed. Drums of low-level and solidified intermediate level wastes are then placed on top of the monolith creating mounds. The concrete blocks containing intermediate level wastes provide a structural framework for the mounds. Metal drums, containing low-level waste, are placed between the rows of concrete blocks. Periodically during the placement of metal drums, cohesionless backfill material (such as sand) is added to the voids between the drums to insure mound stability.

The entire mound is then covered with a thick layer of impermeable clay, which is in turn covered with a layer of topsoil. The structure, which now forms an earthen mound, is surrounded by a final drainage system designed to collect and channel rainwater flowing over the mound area. The bunker is completed by planting the newly formed tumulus with native vegetation to stabilize the surface soil and encourage drying.

The earth mounded concrete bunker technology involves above-ground and below-ground construction, encapsulation and backfilling with earth, concrete or any variation thereof. During cold or rainy weather,it has been proposed that an air supported weather shield be installed over the bunkers during construction and operation. Such a concept has potential application in the construction of above and below-ground vaults as well, but would increase the overall cost.

Figure 8.4: PERSPECTIVE VIEW OF AN EARTH-MOUNDED CONCRETE BUNKER



The perspective view of an Earth Mounded Concrete Bunker depicts the approximate locations of wastes which are separated according to level of activity. Intermediate-level wastes are embedded in concrete monoliths belowground: low-level wastes, or intermediate-level wastes with appropriate packaging, are stored aboveground in earthen mounds over the concrete monoliths. A drainage network is provided within and around the structure to prevent contact of water with the wastes and to provide collection and monitoring capabilities.

Source: U.S. Nuclear Regulatory Commission, NUREG CR-3774, Volume 1, 1984.

This technology has been applied successfully in France as evidenced by the storage of over 170,000 m^3 of waste between 1969 and 1982 at the Centre de la Manche facilities (Ref. 1). This represents about one-half the capacity of the facility. The performance objectives of waste confinement, protection from inadvertent intrusion and protection of individuals during operation appear to have been satisfactorily met. Public acceptance is considered to be satisfactory. The institutional control period has been projected to be 200 to 300 years after site closure.

8.2.4 Mined Cavities

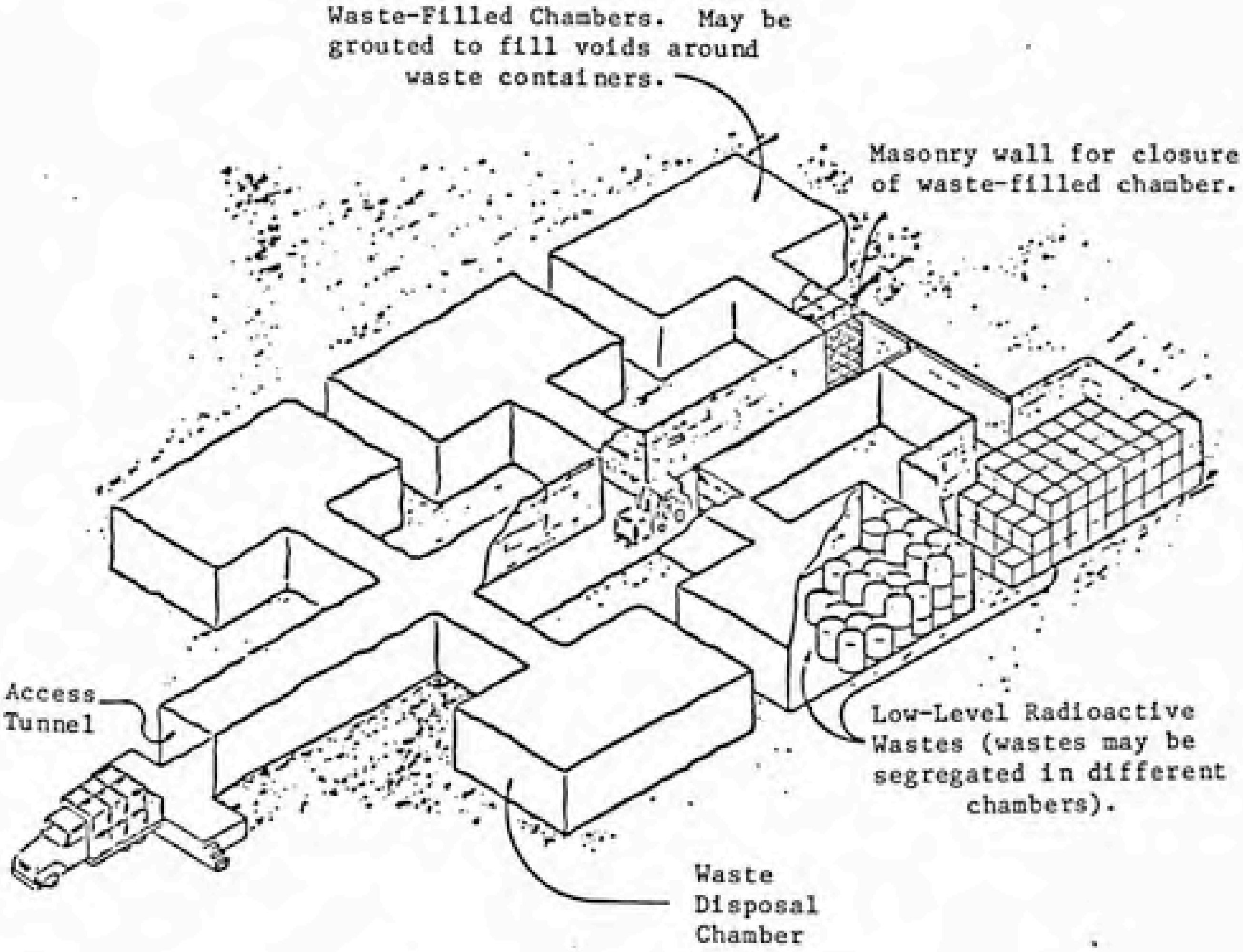
The use of mined cavities for the disposal of low-level radioactive waste include under-ground cavities developed as a result of the removal of natural resources. Most underground cavities or mines were developed in the United States as a consequence of the recovery of coal, limestone, salt (halite or gypsum), copper, iron, lead or zinc. Coal mining produces the largest volume of underground space in the United States. Although space is available in coal mines, they are generally not suitable for disposal of low-level radioactive waste because of poor roof stability, the presence of acidic drainage water, and the problem of explosions and/or fires from methane given off. Figure 8.5 provides a view of the mined cavity concept.

Mines developed from the exploitation of metallic mineral deposits cover extensive areas, but are generally irregular in layout. The direction of mining is changed frequently to follow the areas of richest mineralization. In addition, the major metal mining operations in the United States are performed in areas of sulfide mineralization. Drainage from metal sulfide mines is usually corrosive and would affect steel drums or concrete - based solidified wastes, thus making this type of mine unsuitable for low-level radioactive waste disposal.

Limestone mines are generally very regular in layout with uniformly spaced cavities and pillars since all the material excavated is equally valuable. Drainage from limestone mines is slightly alkaline and does not significantly accelerate corrosion of steel or concrete. Dry, stable limestone mines have been used in the United States for storage of manufactured products. In 1975, the Kansas City area had 13 million square meters of mined space being used at 13 commercial sites in the metropolitan area. No major instability or safety problems have occured. Depleted limestone mines have been proposed but never used for storage or disposal of hazardous or low-level radioactive waste.

Salt deposits occur in the United States as bedded units or diapiric (intruded) units. Diapiric salt deposits are those that have been forced upward into or through overlying geologic formations. Explosive methane production is a problem in diapiric mines. Bedded salt mines are similar in many respects to limestone mines. Since all the material is equally valuable, the cavities are laid out in a uniform manner. Drainage water is corrosive to steel drums but dry salt presents no special problems for storage of steel drums or concrete-encased waste. The Asse Salt Mine in the Federal Republic of Germany has been used for low and high-level radioactive waste disposal and is currently being used as a research facility (Ref. 1). The best disposal sites within the mine are those units that contain high purity halite (over 98%) NaCl. No major operational or corrosion problems have been observed. Salt cavities are limited to specific areas of the country.

Figure 8.5: MINED CAVITY CONCEPT FOR DISPOSAL OF RADIOACTIVE WASTE



Modified Room and Pillar Mine in Bedded Limestone or Salt. Wastes may be segregated by chamber if required. If retreat method of filling chambers is used, the connecting passage ways may be filled with wastes and grouted to fill voids. Individual chambers may be sealed off when full by masonry or cast in place concrete walls.

Source: U.S. Nuclear Regulatory Commission, NUREG CR-3774, Volume 1, 1984.

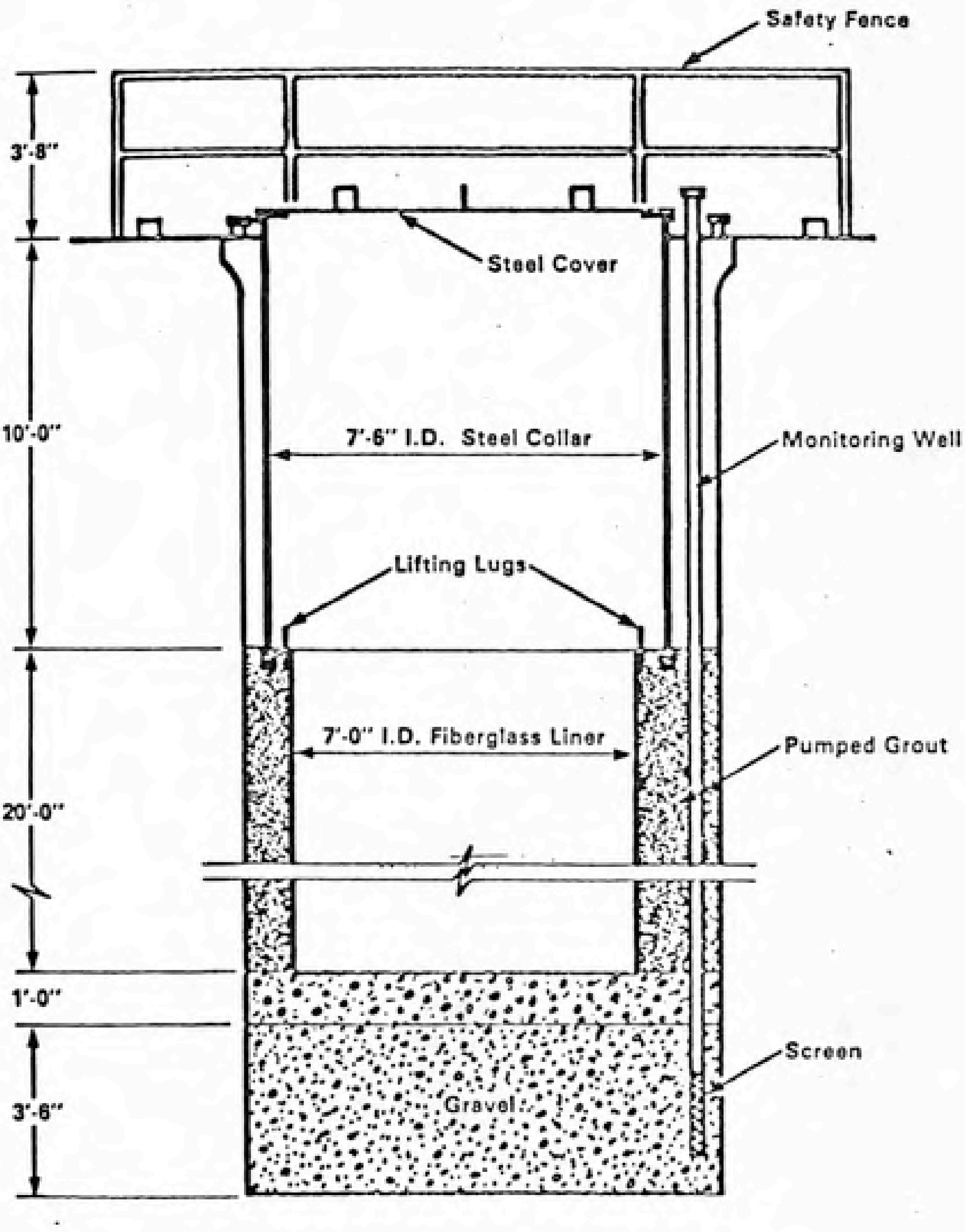
8.2.5 Augered Holes

The production of augered holes basically involves the boring of holes through soil or rock at any depth and diameter achievable. There are practical depth and diameter contraints placed on the development of augered holes. Large diameter augers slow the drilling process. Auger rigs also work best in soft to firm consistency cohesive soils. At the Nevada Test Site, the U.S. Department of Energy is currently evaluating the use of large diameter augered holes for disposal of high specific activity low-level radioactive waste (Ref. 2). The Department of Energy Greater Confinement Disposal Test, which began in 1981, calls for a central waste shaft surrounded by smaller holes for placement of instrumentation. The central waste shaft is 10 feet in diameter and 120 feet deep with a waste layer of 40 feet. Figure 8.6 provides a view of borehole design.

The Canadians have been using a version of augered holes for several years (Ref. 3). "Tileholes" or concrete pipes set vertically on concrete foundations with the entrance port positioned at the ground surface have been used for storage of ion exchange resins and filter canisters at Ontario Hydro's Bruce Station and at Chalk River National Laboratory, Ontario, Canada. The tileholes are a considerable distance above the watertable and an underdrainage system was installed to provide for a controlled and monitorable discharge.

At Oak Ridge National Laboratory in Tennessee, transuranic wastes are being stored in shallow holes at Solid Waste Storage Area No. 6 (Ref. 5). The average hole depth is 21 feet with a minimum of 2 feet of undisturbed shale maintained between the bottom of the hole and the water table. When waste and backfill reach to within 4 feet of the ground surface, the hole is topped off with loosely placed backfill to within 1 - 1/2 feet of the surface. Six inches of concrete is poured into the hole, allowed to set, and the hole is then backfilled to the surface with soil. Upon completion of a grid of these holes, a surface treatment is applied.

Figure 8.6: AUGERED HOLE DESIGN FOR DISPOSAL OF RADIOACTIVE WASTE



Source: U.S. Nuclear Regulatory Commission, NUREG CR-3774, Volume 1, 1984.

8.3 Suitability of Alternative Methods

The suitability of each alternative discussed is based upon its ability to meet basic performance objectives. These objectives include 1) simplicity and feasibility of design and operation, 2) greater confinement capability, 3) ease of site monitoring, 4) period of institutional control after site closure, 5) reduction of radiation hazard, and 6) resource exploitation. Each of the methods exhibit both positive and negative characteristics in meeting the performance objectives. The following is a brief summary of the favorable and unfavorable characteristics of each alternative:

8.3.1 Below-ground Vault

Advantages

a) Below-ground vault design and construction can be standardized for safe, efficient operations. The vaults are visually unobtrusive and structurally stable. They are not susceptible to damage or exposure of the waste packages from erosion, weathering, surface disturbances or soil settlement.

b) They provide an effective barrier to inadvertent human intrusion, groundwater infiltration and radionuclide migration. They also provide an effective extra barrier to plant or animal intrusion.

c) Long-term active maintenance should be minimal.

d) Site selection is less dependent upon meterological conditions.

e) They are amenable to the use of remote handling equipment for high activity waste which would reduce occupational radiation exposure.

Disadvantages

a) Below-ground vaults must be protected against rainwater and groundwater intrusion during construction and operation. They must be protected from structure degradation caused by corrosive soils and are not amenable to visual inspection after site closure.

b) They are not easy to monitor for radionuclide migration within the disposal cell after closure.

8.3.2 Above-ground Vaults

Advantages

a) Above-ground vault design and construction could be standardized for safe, efficient operations. These vaults are structurally stable and do not depend on geological materials for waste isolation. They can be designed and constructed to resist damage or degradation from most foreseeable hazards and can be easily inspected.

b) They provide an effective barrier to inadvertent human and animal intrusion, groundwater infiltration and radionuclide migration.

c) Above-ground vaults may prove to be more easily monitored than below-ground vaults due to increased accessability to the disposal cells.

Disadvantages

a) Active maintenance requirements are likely to be more extensive than for other methods because of their exposure to the elements, thus adding to the overall cost.

b) They are not amenable to the use of remote handling equipment due to the presence of a roof prior to waste emplacement, which could result in high occupational radiation exposure unless temporary shields are used. In addition, they possess no secondary barrier for the prevention of radionuclide release. Insufficient time may be available for remedial actions should radionuclides be inadvertently released.

c) The institutional control period is likely to be substantially longer than for other options.

d) They are considered to be mechanisms of interim storage and not a means of final disposal.

8.3.3 Earth-Mounded Concrete Bunkers

Advantages

a) The feasibility of the earth-mounded concrete bunker concept is proven by several years of successful experience in France. The bunkers are structurally stable and provide effective barriers against intrusion and water infiltration.

b) They are amenable to the use of remote handling equipment for high activity waste which would reduce occupational radiation exposure.

c) Long-term active maintenance should be minimal.

d) Site selection is not dependent upon geological conditions.

Disadvantages

a) Earth-mounded concrete bunkers must be protected against rainwater and groundwater intrusion during construction and operation. Strict packaging requirements and waste disposal sequencing requirements must be followed during operations. They are not amenable to visual inspection after site closure.

b) Monitoring for radionuclide migration within disposal cells is not easily accomplished.

8.3.4 Mined Cavities

Advantages

a) Suitable, dry mined cavities are structurally stable. Use of mined cavities produces no new impact and presents less of an impact on resources than that which has already occurred from mining operations. The cavities provide a protective barrier against intrusion and water infiltration. Surface developments are not likely to adversely impact performance.

b) Mined cavities offer the possibility of suitable long-term waste isolation and limited radionuclide migration.

<u>**Disadvantages**</u>

a) Little can be done to enhance performance capabilities of marginally suitable existing mines. Construction of new mines solely for the purpose of the disposal of low-level radioactive waste would be expensive.

b) Siting would be limited to existing cavities, primarily located in the Williston, Permian and Appalachian basins, along with the Gulf Coast Embayment. They are not suitable for low volumes because of the effort and expense of modifying cavities and placing waste.

c) Mined cavity disposal (as presented in this report) is not amenable to the use of remote handling equipment, thereby increasing occupational radiation exposure.

d) Monitoring is complicated by remote locations and limited access.

8.3.5 <u>Augered Holes</u>

<u>**Advantages**</u>

a) Structurally stabilized augered holes offer good potential for long term isolation of waste. The operating period for individual holes is relatively short, thus minimizing the possibility of rainwater intrusion. Closure of individual holes does not adversely affect the formation of new holes.

b) Human, plant and animal intrusion is unlikely.

c) The use of remote handling equipment is feasible in order to reduce occupational radiation exposure. Augered holes are suitable for low volume operations.

<u>**Disadvantages**</u>

a) The creation of voids and surface slumping may occur if compaction and backfilling of holes are not properly performed.

b) The disposal site cannot be fully utilized because of the low volume capacity of the holes as compared to the higher volume capacity of the unused surrounding property.

c) Monitoring of the holes is complicated because of hole depth.

8.4 Radiological Impact

The release of radioactivity from a compartment at a waste disposal site involves a series of mechanisms, such as leaching, diffusion, dissolution and ion exchange. It is believed that the shift toward alternatives to shallow-land burial developed as a result of leaching and migration problems described in Section 4 of this report. Site selection and design, along with the introduction of migration barriers, is an attempt to slow or stop the movement of radioactive contaminants.

The dose to the general public is a consequence of such releases of radionuclides and generally will be a decreasing function of distance from the site. For distances far removed from the site, the individual doses (in all probability) would be insignificant as compared to natural background radiation. A cut-off distance of 80 kilometers (50 miles) has been established for assessment of radiological impacts from the operation of nuclear power plants (Ref. 4).

The entire process can then be expressed in quantitative terms by the implementation of the following generic formula:

Equation 8.1

$$D(x,y,t) = \sum_{\substack{\text{pathways (i)} \\ \text{radionuclides (j)}}} (D/E)_{ij} \times (E/C)_{ij} \times (C/R)_{ij} \times (R/S)_{ij} \times S_j$$

where the summation is over all pathways (i) and radionuclides (j) and where S_j are the radionuclide concentrations; R is the rate of release of a radionuclide from the waste field (the region defined by the boundaries of the trench, hole or structure in which the waste is placed) or the intensity of the emitted gamma radiation at the waste field boundary; C is the concentration of radionuclides in food, water, air or ground at a point of exposure; E is the exposure rate (picocuries/year of inhaled or ingested radionuclides for internal exposure or mR/year for external exposure; and D(x,y,t) is the dose rate to the whole body or organ of an exposed individual at a location x,y relative to the site at the time t. Acute exposure is based upon the 50 year dose-equivalent commitment (i.e., the dose received during 50 years as a consequence of the exposure received during the first year). Chronic exposure is based on the dose-equivalent for the dose received during the 50th year of an exposure period lasting 50 years. The ratios, D/E, E/C, C/R, and R/S are the transfer factors for different radionuclides and pathways. They are determined by the various mechanisms that control migration and transport of the radionuclides through the different pathways from source to organ, and are functions of the parameters that characterize the facility, environment and biological processes (Ref. 4).

In order to rank the alternatives based upon a generic analysis of public and occupational radiation exposure, it is necessary to carry out a pathway analysis based upon: (1) identifying the source terms; (2) identifying the pathways by which exposure can occur; (3) identifying the scenarios that affect the release rate and likelihood of exposure; (4) estimating the transfer factors; and (5) using Equation 8.1 to calculate and/or estimate occupational and public exposure. The U.S. Nuclear Regulatory Commission has instituted such an analysis (Ref. 4). Much of the following information is taken from Reference 4.

8.4.1 Source Terms

The parameters that characterize the source term include the total inventory of radionuclides in the waste, the dimensions of the waste field, the radionuclides present and their distribution, and the physical and chemical form of the material present in the waste. Radionuclide concentrations in waste streams that have been identified as candidate waste for greater confinement disposal are presented in Table 8.1. The radionuclides listed are those included in the environmental impact statement prepared in support of 10 CFR 61 regulations governing commercial low-level radioactive waste disposal (Ref. 4). They are considered to be representative in the sense that other radionuclides are either unlikely to be present in sufficiently high concentration to merit disposal in a greater confinement facility or unlikely to affect the ranking because the radiological and chemical properties do not differ significantly from the corresponding properties of the listed radionuclides which exist in greater concentrations.

Three representative waste streams are identified for use in the NRC analysis: (1) a high-activity low-level waste stream, (2) an intermediate-activity low-level waste stream for commercial waste, and (3) an intermediate-activity liquid low-level waste stream. The high-activity low-level waste stream is based on data for Department of Energy defense waste. The intermediate-activity low-level waste stream is based on data from commercial waste. Waste was identified by selecting, for each radionuclide in Table 8.2, the waste stream with the highest average concentration of that radionuclide. Maximum radionuclide concentrations, under normal conditions, would not exceed those specified in 10 CFR 61 as Class A, B, or C waste.

8.4.2 Pathway Diagrams

The terrestrial, aquatic and atmospheric pathways from the waste stream to the radiation exposure of the general population are complex. A schematic representation of the various elements that must be taken into account in a pathway analysis is shown in Figure 8.7. Each connecting line in the diagram corresponds to a transfer factor. Each box in the diagram represents a complex system that may be broken down into smaller components. This leads to a replacement of each transfer factor in the pathway analysis (which corresponds to a line connecting two boxes in the diagram) by a sum of products representing the entire source-to-dose analysis. The overall radiological impacts that result from migration of radionuclides through this network are thus given by Equation 8.1. A simplified pathway diagram, on which the NRC dose analysis is based, is shown in Figure 8.8. It is simply a different representation of information outlined in Figure 8.7.

The structure of a specific pathway diagram depends upon the category of the exposed individuals. For example, different pathway structures are needed for an off-site resident, an occupation worker or an on-site intruder.

TABLE 8.1

RADIONUCLIDES INCLUDED IN CANDIDATE GREATER CONFINEMENT DISPOSAL WASTE

Radio-Nuclide	Half-life (years)	Radiation Emitted	Radioactive Decay Products [1]	Principal Means of Production
C-14	5730	β	-	N-14(n, p)
Fe-55	2.60	X-rays	-	Fe-54(n,γ)
Co-60	5.26	β, γ	-	Co-59(n,γ)
Ni-59	80,000	X-rays	-	Ni-58(n,γ)
Ni-63	92	β	-	Ni-62(n,γ)
Sr-90	28.1	β	Y-90	Fission
Nb-94	20,000	β, γ	-	Nb-93(n,γ)
Tc-99	2.12×10^5	β	-	Fission; Mo-98(n,γ) Mo-99 (β-)
I-129	1.17×10^7	β, γ	-	Fission
Cs-135	3.0×10^6	β	-	Fission, daughter Xe-135
Cs-137	30.0	β, γ	Ba-137m	Fission
U-235	7.1×10^8	α, γ	Th-231+	Natural
U-238	4.51×10^9	α, γ	Th-230+	Natural
Np-237	2.14×10^6	α, γ	Pa-233+	U-238(n, 2n)- U-237(β-)
Pu-238	86.4	α, γ	Th-234+	Np-237(n,γ)- NP-238(β-); daughter Cm-242
Pu-239	24,000	α, γ	U-235+	U-238(n,γ)- U-239(β-)- Np-239(β-)
Pu-240	6,580	α, γ	U-236+	Multiple n-capture
Pu-241	13.2	α, β, γ	Am-241+	Multiple n-capture
Pu-242	2.79×10^5	α	U-238+	Multiple n-capture; daughter Am-242
Am-241	458	α, γ	Np-237+	Daughter Pu-241
Am-243	7,950	α, γ	Np-239+	Multiple n-capture
Cm-243	32	α, γ	Pu-239+	Multiple n-capture
Cm-244	17.6	α, γ	Pu-240+	Multiple n-capture

1 A "-" indicates a stable decay product. A "+" following the symbol for the first radioactive decay product indicates that one or more of the subsequent decay products are also radioactive.

2 Pu-239 and Pu-240 are treated as a single radionuclide in the analyses because they generally cannot be radiochemically distinguished. The activity of Pu-240 is added to that of Pu-239.

Source: Wild et al. (1981--Table 8.2), as cited in T. L. Gilbert, C. Luner, Alternatives for Greater Confinement Disposal of Low-Level Radioactive Waste, Final Report, November, 1985)

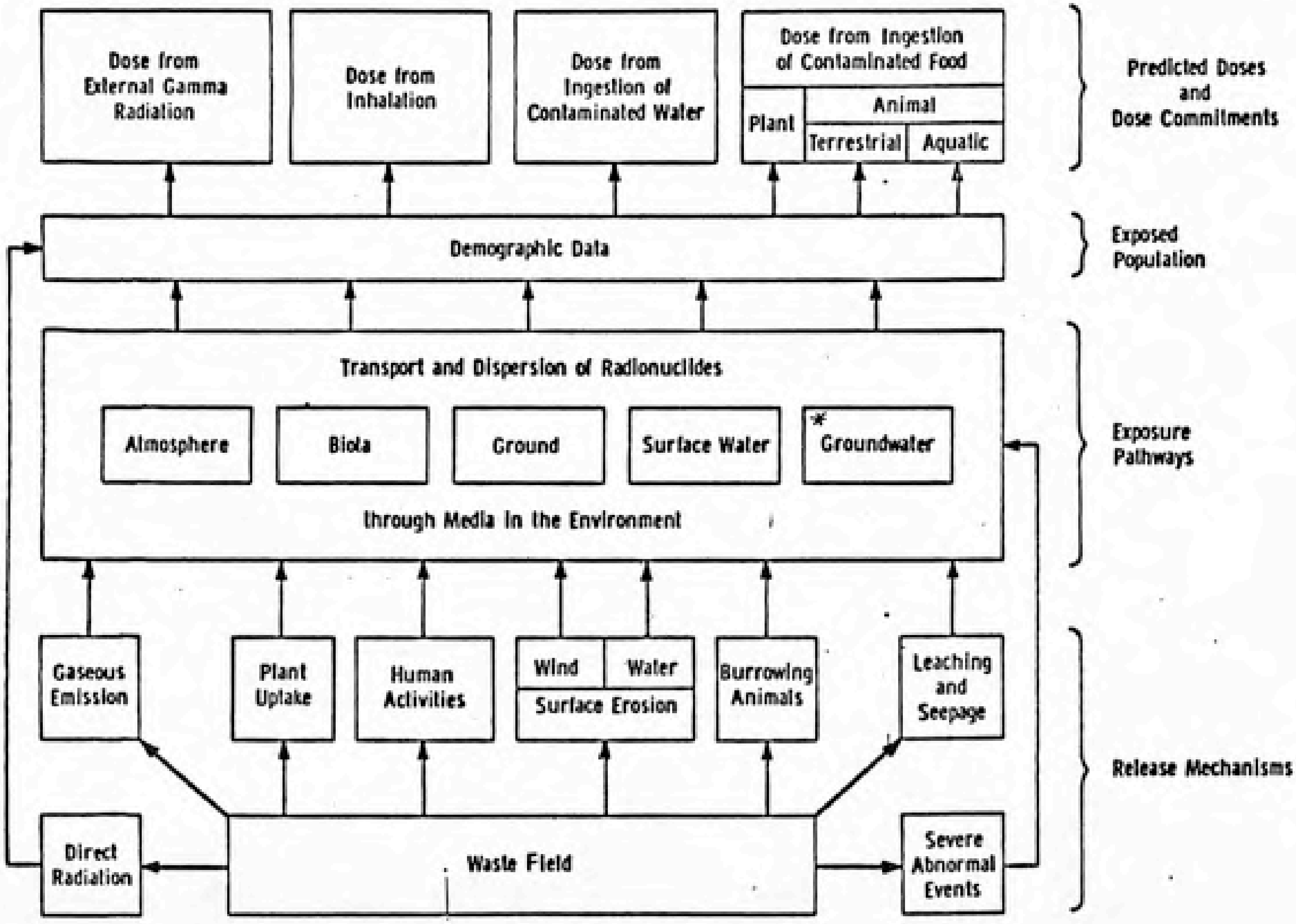
TABLE 8.2

RADIONUCLIDE CONCENTRATIONS FOR A REPRESENTATIVE COMMERCIAL INTERMEDIATE-ACTIVITY LOW-LEVEL RADIOACTIVE WASTE STREAM

Radionuclide	Average Concentration (Curies/Cubic Meter)
H-3	535
C-14	7.35×10^{-1}
Fe-55	429
Ni-59	2.68×10^{-1}
Co-60	329
Ni-63	42.9
Sr-90	17.8
Nb-94	1.58×10^{-3}
Tc-99	1.08×10^{-4}
I-129	9.00×10^{-7}
Cs-135	1.08×10^{-4}
Cs-137	16.6
U-235	3.37×10^{-6}
U-238	1.26×10^{-5}
TOTAL	1,370

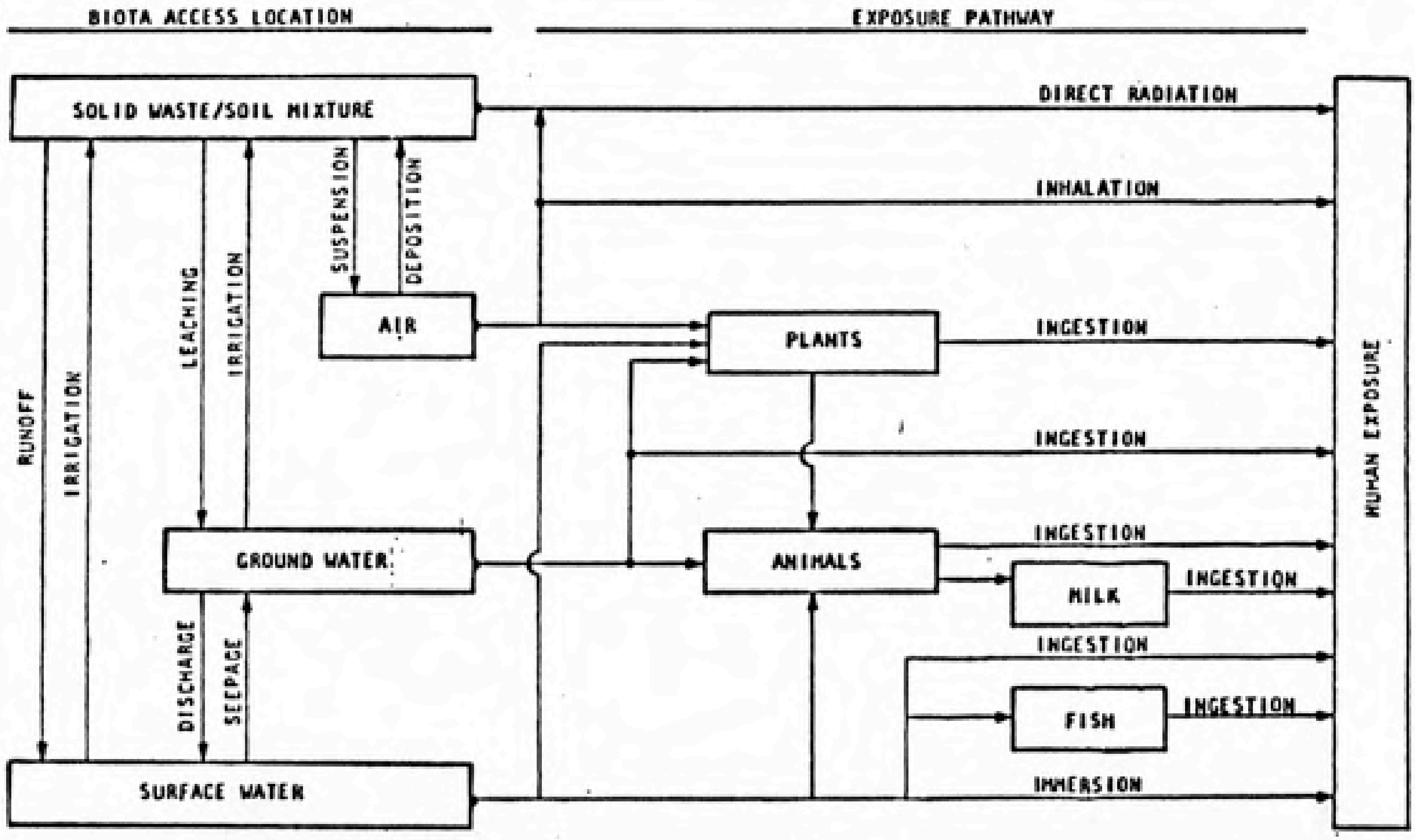
Source: T. L. Gilbert, C. Luner, Alternatives for Greater Confinement Disposal of Low-Level Radioactive Waste, Final Report, November, 1985.

Figure 8.7: SCHEMATIC REPRESENTATION OF ELEMENTS INVOLVED IN THE SOURCE-TO-DOSE ANALYSIS FOR EMPLACED WASTE



Source: T. L. Gilbert, C. Luner, Alternatives for Greater Confinement Disposal of Low-Level Radioactive Waste, Final Report, November, 1985.

Figure 8.8: SIMPLIFIED PATHWAY DIAGRAM ILLUSTRATING BIOTA ACCESS LOCATIONS



Source: T. L. Gilbert, C. Luner, Alternatives for Greater Confinement Disposal of Low-Level Radioactive Waste, Final Report, November, 1985.

8.4.3 Scenarios

The radionuclide releases and human exposure that determine the doses received by exposed individuals are critically dependent on human activities (e.g. use of the site for industrial, commercial or agricultural purposes). Population distributions in the vicinity of a waste disposal facility and accident scenarios are to be considered also. In general, four types of scenarios are to be considered. They include (1) accident scenarios, (2) occupational scenarios, (3) intruder scenarios, and (4) population scenarios. Accident scenarios were examined, but are not a significant part of the Nuclear Regulatory Commission analysis because it was determined that the public doses from accident scenarios were orders of magnitude smaller than intruder doses (Ref. 4). For the purposes of this analysis, occupational dose contributions were excluded. The results of the analysis to be presented are primarily based on intruder and population scenarios. The scenarios in use are thus separated into seven components which are identified in Table 8.3. Intruder doses are designated as being construction or agriculture related. Population exposures are considered to be a result of leaching, migration, surface water runoff or atmospheric transport. Accidental doses are a result of off-site atmospheric transport, which differs from population atmospheric transport, in that the population atmospheric transport component includes a dose contribution from food contaminated from airborne radionuclides. The accident component does not. A more detailed discussion of the scenarios and pathways may be found in the Environmental Impact Statement, U.S. Nuclear Regulatory Commission 10 CFR 61.

8.4.4 Transfer Factors

Transfer factors are mathematical expressions designed to link radiation exposure, exposure pathway and exposure scenario in order to determine a radiation dose. Transfer factors were constructed for the Nuclear Regulatory Commission analysis which resulted from components given in Equation 8.1. In order to rank the alternatives to shallow-land burial, based upon radiological impact, it is necessary to express Equation 8.1 in a form that will allow the factoring in of technology specific barriers to the migration of radionuclides. Equation 8.1 can thus be expressed as follows:

Equation 8.2

$$H = \Sigma (f_o f_d f_w f_s) C_w \text{ PDCF-N}$$

where the summation is over all radionnuclides and pathways (N). H is equivalent to D(x,y,t) in Equation 8.1, and is the 50 year effective whole body dose equivalent commitment in millirem. The components D/E, E/C and C/R in Equation 8.1 combine to yield the pathway dose conversion factors (PDCF-N) in Equation 8.2. S_i in Equation 8.1 is equivalent to C_w, which is the radionuclide concentration. R/S in Equation 8.1 is equivalent to (f_o f_d f_w f_s), which is expressed as I in the Nuclear Regulatory Commission Analysis. In other words, the product of (f_o f_d f_w f_s) is equal to the release rate per unit source term and is equal to I. I is an "interaction factor" which attempts to characterize the various barriers to the migration of waste from the source to biota access locations as follows:

f_o = **time-delay barrier factor:** a factor that accounts for all the control mechanisms that increase the time period between termination of waste disposal at the site and the initiation of contact between the transport agent and the waste.

f_d = **site-design barrier factor**: a factor that includes the effects of any engineered barriers designed into the waste disposal facility, plus any site operational practices that may reduce transport.

f_w = **waste-form and package barrier factor**: a factor that accounts for the physical and chemical characteristics of the waste at the time of the initiation of the release/transport scenario, which may inhibit contaminant transfer to the transport agent.

f_s = **site-selection barrier factor**: a factor that includes the effects of the natural site environment, which contributes to reducing radioactivity concentrations at the biota access location.

These form factors may be used to represent the control mechanisms. They are not the barrier criteria themselves, but may be used to help determine the barrier criteria. Use of these factors may be accomplished by either specifying the value required for a given barrier factor, or by defining the characteristics of the barrier needed to achieve the desired effect.

The determination of appropriate values for the barrier factors for the different alternatives is the heart of the analysis. In the Nuclear Regulatory Commission analysis, these are related to sets of indices called (1) waste-form, (2) waste-processing, and (3) disposal-technology indices. Differences in radiological impact are primarily determined by the disposal-technology indices. Ultimately, the barrier factors are expresed as unity or fractions thereof.

The disposal technology indices used in the Nuclear Regulatory Commission analysis for assessing the effect of different facility designs and operating practices are summarized in Table 8.4. The significance of the given values for these parameters is given in Table 8.5. The reader should consult with individuals named in reference no. 4 for information on the use of parameter values used in Equation 8.2.

The alternatives described in this report rely on two mechanisms of waste isolation. First, aboveground vaults, belowground vaults, and earth-mounded bunkers rely on engineered structures for waste isolation. The selection of materials and thickness of materials is important. Criteria used in selecting a material to construct an aboveground vault or to line and cap belowground vaults and earth-mounded bunkers include the expected service life and associated costs. Past experience indicates that synthetic membranes, in general, have an expected life of around 25 years (Ref. 7). Although the membranes may provide a temporary solution to the containment of radioactive waste, they do not appear to provide optimum containment (Ref. 7). In addition, they are costly. Much more experience is associated with the use of concrete and asphalt. Asphalt appears to be more cost effective in retaining radioactive waste than is concrete (Ref. 7). The life expectancy of exposed asphalt is only on the order of 20 years. Concrete has a life expectancy of approximately 40 years. Major disadvantages associated with the use of asphalt, as opposed to concrete, as a cap or liner include the possible degradation of asphalt by organic compounds in the waste and cracking if it is exposed to differential settlement.

Mined cavities and augered holes would rely on soil or salt compounds for waste isolation. At present, soil barriers appear to offer the most economic solution for a given waste containment time (Ref. 7). Unlike man-made materials that deteriorate with time, soils are considered to be extremely stable.

Leaching of radioactive contaminants from a site by groundwater is considered to be the more probable means of radiation exposure to the population. First and foremost, an effective groundwater management and monitoring program is essential. Migration barriers such as natural or artificial materials can be considered to be a second line of defense against radionuclide migration. The selection of certain soils can provide the same degree of retardance as man-made materials. This is why some individuals still believe that traditional shallow-land burial is the best means of disposing of low-level radioactive waste. However, public perception of traditional shallow-land burial does not appear to be favorable at this time.

Intrusion into an abandoned disposal site is the more probable means of radiation exposure to an individual from an accident scenario.

Using Equation 8.2 as a base, the U.S. Department of Energy has published dose estimates for different waste disposal options (Ref. 4). The technology index values that were used in the analysis for estimating the doses for the different alternatives are given in Table 8.6. Refer to Table 8.5 for an explanation of index values.

8.4.5 Dose Calculations

The algorithms used in the Nuclear Regulatory Commission codes for calculating doses combine in complex ways that are not readily understood. Unless one has been intimately involved in developing the algorithms and writing such codes, it is difficult to gain the kind of familiarity with the logic and construction that enables one to judge when the results of a particular calculation are useful or when they are not. No attempt will be made to describe the calculations in full detail. Various codes, which set forth indices and parameters for the scenarios previously described were used. Maximum individual dose estimates, (both on-site and off-site) for the alternatives are given in Table 8.7. It should be noted that these are generic numbers and are subject to a high degree of variability, depending upon site design and location. In addition, these figures are based on emplacement of 10,000 m^3 of intermediate low-level radioactive waste and 100 m^3 of high activity low-level radioactive waste. Also, the maximum individual on-site dose estimates are based upon the Nuclear Regulatory Commission intruder computer model, which includes intruder construction and intruder-agriculture scenarios. Off-site doses were constructed from groundwater migration codes.

Intruder-construction includes: (1) inhalation of contaminated dust and direct gamma exposure from a contaminated dust cloud, (2) consumption of food grown nearby upon which the airborne contamination is assumed to settle, and (3) direct gamma exposure from the waste during excavation.

TABLE 8.3

SCENARIOS AND UPTAKE PATHWAYS USED IN THE NRC PATHWAY ANALYSIS

Scenario	Biota Access Location	Uptake Pathways		PDCF Symbol[1]
Accident (Acute)	Offsite Air	Soil	Inhalation (soil)	PDCF-1
		Soil	Direct Radiation (area)	PDCF-1
		Soil	Direct Radiation (air)	PDCF-1
			Inhalation (air)	PDCF-1
			Direct Radiation (air)	PDCF-1
Intruder-Construction (Acute)	Onsite Soil	Air	Inhalation (air)	PDCF-2
		Air	Direct Radiation (air)	PDCF-2
		Air	Food (air)	PDCF-2
			Direct Radiation (volume)	PDCF-5
Intruder-Agriculture (Chronic)	Onsite Soil	Air	Inhalation (air)	PDCF-3
		Air	Direct Radiation (air)	PDCF-3
		Air	Food (air)	PDCF-3
			Food (soil)	PDCF-4
			Direct Radiation (volume)	PDCF-5
Leaching & Migration (Chronic)	Well Water	Soil	Inhalation (soil)	PDCF-6
		Soil	Direct Radiation (area)	PDCF-6
		Soil	Direct Radiation (air)	PDCF-6
			Food (water)	PDCF-6
Leaching & Migration (Chronic)	Open Water	Soil	Inhalation (soil)	PDCF-7
		Soil	Direct Radiation (area)	PDCF-7
		Soil	Direct Radiation (air)	PDCF-7
			Food (water)	PDCF-7
			Ingestion (fish)	PDCF-7
Surface Water Runoff (Chronic)	Open Water	Soil	Inhalation (soil)	PDCF-7
		Soil	Direct Radiation (area)	PDCF-7
		Soil	Direct Radiation (air)	PDCF-7
			Food (water)	PDCF-7
			Ingestion (fish)	PDCF-7
Atmospheric Transport (Chronic)	Offsite Air	Soil	Inhalation (soil)	PDCF-8
		Soil	Direct Radiation (area)	PDCF-8
		Soil	Direct Radiation (air)	PDCF-8
			Inhalation (air)	PDCF-8
			Direct Radiation (air)	PDCF-8
			Food (air)	PDCF-8

Source: U.S. Nuclear Regulatory Commission, NUREG 0945, November, 1982.

TABLE 8.4

DISPOSAL - TECHNOLOGY INDEX DESCRIPTIONS

Property	Index	Description
Design	ID	Two options are considered: regular trenches and the so-called "concrete-walled" trenches.
Cover	IC	Three options for the cover between the waste and the atmosphere are considered: regular, thick, and intruder barrier.
Stabilization	IX	Three options for the stabilization program applied to disposal cells, which may contain structurally unstable wastes, are considered: regular, moderate, and extensive.
Emplacement	IE	Three options for the emplacement of the waste are considered: random, stacked, and random combined with decontainerized disposal for compressible low-activity wastes.
Segregation	IS	Option for segregating and separately disposing of wastes that are combustible/compressible and those that could contain complexing agents.
Layering	IL	Option for separating and putting selected waste streams (usually with higher external radiation levels) at the bottom of the disposal cell.
Grouting	IG	Option for filling the interstitial spaces between the wastes with grouting material.
Hot waste facility	IH	Option for having a special area within the disposal facility with special procedures to handle high-activity wastes.
Closure index	IQ	Indicates the activities during the closure period (regular or extensive).
Care level index	ICL	Indicates the care level anticipated during the active institutional control period (low, moderate, and high).
Postoperational period (years)	IPO	Duration of the period between the cessation of active disposal and the transfer of title from site operator to site owner.
Institutional control period (years)	IIC	Duration between transfer of title to site owner and assumed time for loss of institutional controls over the site.

Source: U.S. Nuclear Regulatory Commission, NUREG 0945, November, 1982.

TABLE 8.5

DISPOSAL - TECHNOLOGY INDEX VALUES

Variable	Parameter	Optional Values	Explanation
ID	DESIGN	1	Regular shallow-land burial trenches "Concrete-walled" trenches
IC	COVER	1 2 3	Regular cover "Thick" cover "Intruder barrier" cover
IX	STABILIZATION	1 2 3	No special procedures Moderately extensive procedures Very extensive procedures
IE	EMPLACEMENT	1 2 3 4 5	Random Stacked Decontainerized Random with sand backfill Stacked with sand backfill
IS	SEGREGATION	0 1	No segregation Segregation of unstable waste and waste containing chemical agents
IL	LAYERING	0 1	No layering Layering of waste streams
IG	GROUTING	0 1	No grouting Grouting of interstices between disposed waste packages
IH	HOT WASTE FACILITY	0 1	No special disposal of high-activity waste Special disposal operations for high-activity waste
ICL [1]	CARE LEVEL	11 12 13 21 22 23	2-year modest closure with low care level 2-year modest closure with moderate care level 2-year modest closure with high care level 4-year complete site restabilization with low care level 4-year complete site restabilization with moderate care level 4-year complete site restabilization with high care level
IPO	POSTOPERATIONAL PERIOD	2-99 [2]	Number of years between cessation of disposal of waste and transfer of title to site owner
IIC	INSTITUTIONAL CONTROL PERIOD	0-999	Number of years between transfer of title to site owner and the assumed loss of institutional controls

Source: U.S. Nuclear Regulatory Commission, NUREG 0945, November, 1982.

TABLE 8.6

DISPOSAL - TECHNOLOGY INDEX VALUES
USED FOR DOSE ESTIMATES FOR ALTERNATIVES

Alternatives	ID	IC	IX	IE	IS	IL	IG	IH	ICL	IPO	IIC
Traditional Shallow-Land Burial Facility	1	1	1	1	1	1	0	0	13	2	98
Belowground Vault	2	1	1	2	1	1	1	0	13	2	98
Aboveground Vault	-	-	-	-	-	-	-	-	-	-	-
Earth-Mounded Concrete Bunker	-	-	-	-	-	-	-	-	-	-	-
Mined Cavities	-	-	-	-	-	-	-	-	-	-	-
Augered Holes	1	2	3	2	1	1	1	0	13	2	98

Note: Refer to Table 8.5 for an explanation of the disposal-technology index values presented in this table.

Source: T. L. Luner, G. Gilbert, Alternatives for Greater Confinement Disposal of Low-Level Radioactive Waste, Final Report, November, 1985.

Intruder-agriculture includes: (1) inhalation of contaminated dust suspended due to tilling activities as well as natural suspension, (2) direct gamma exposure from standing in the contaminated cloud, (3) consumption of food contaminated by fallout, (4) consumption of food grown in contaminated soil, and (5) direct gamma exposure from the disposal waste volume.

In order to generate the estimates presented in Table 8.7 it was necessary to express the variables given in Equation 8.1 in a different manner. The 50 year dose commitment in millirem, formerly D(x,y,t) was changed to H in the Nuclear Regulatory Commission code. The intruder-construction dose is given by the terms:

Equation 8.3

$$H = \Sigma (f_o\ f_d\ f_w\ f_s)air\ \ C_w\ \ PDCF\text{-}2 + \Sigma (f_o\ f_d\ f_w\ f_s)_{DG}\ \ C_w\ \ PDCF\text{-}5$$

where the summation is over all radionuclides. The interaction factors (f_o f_d f_w f_s) and pathway dose conversion factor (PDCF-5) are as previously described in this report, and where the subscript DG refers to "direct gamma" exposure. C_w is the radionuclide concentration in the waste, indicated earlier in this section. Numerical values given to the interaction factors and pathway dose conversion factors are presented in the environmental impact statement for 10 CFR Part 61, Appendices G-Q. It should be noted that whole body doses are considered for 23 separate radionuclides assumed to be present in the waste stream. The intruder-agriculture dose is given by the terms:

Equation 8.4

$$H = \Sigma (f_o\ f_d\ f_w\ f_s)air\ \ C_w\ PDCF\text{-}3 + \Sigma (f_o\ f_d\ f_w\ f_s)food\ C_w\ PDCF\text{-}4 +$$

$$\Sigma (f_o\ f_d\ f_w\ f_s)DG\ \ C_w\ PDCF\text{-}5$$

The individual components presented in the previous equations represent a summation of the separate components by which radiation exposure can occur.

The dose for the groundwater scenario is given by the following single sum:

Equation 8.5: $H = \Sigma (f_o\ f_d\ f_w\ f_s)C_w\ \ PDCF\text{-}N$

where N = 6 for a well access location and N = 7 for a surface water access location, and the summation is over all radionuclides.

As can be seen from Table 8.7, shallow-land burial has the greatest potential for individual radiation exposure. Among the alternatives, augered holes are shown to posses the least potential for individual radiation exposure. Below-ground vaults fall in the middle. Aboveground vaults, mined cavities and earth mounded bunkers were not considered in the study.

TABLE 8.7

MAXIMUM INDIVIDUAL DOSE ESTIMATES FOR ALTERNATIVES AND TRADITIONAL SHALLOW-LAND BURIAL (SLB)

Facility Type	Maximum Individual Dose (mRem/yr)(A)			
	Intermediate-Activity LLRW(B)		High-Activity LLRW(C)	
	On-site(D)	Off-site	On-site(D)	Off-site
Traditional SLB(E)	20,000	30	10^5	7
Belowground Vault	0.0007	0.003	12	0.0007
Aboveground Vault	---	---	---	---
Mined Cavity	---	---	---	---
Augered Holes(F)	5×10^{-5}	0.05	0.9	0.01
Earth-Mounded Concrete Bunkers	---	---	---	---

A. Estimated maximum annual dose that would be incurred by an inadvertent intruder on-site or by an individual residing off-site as a consequence of normal releases to the environment.

B. Based on 10,000 m^3 of intermediate-activity low-level radioactive waste (LLRW).

C. Based on 100 m^3 of high-activity LLRW.

D. For intrusion immediately following cessation of active institutional controls, assumed to be 100 years after site closure.

E. Eight meter deep trench.

F. Southeast region.

Source: T. L. Gilbert, C. Luner, Alternatives for Greater Confinement Disposal of Low-Level Radioactive Waste, Final Report, November, 1985.

8.5 Licensing

Licensing of disposal alternatives described in this section is governed by Title 10 Code of Federal Regulations, Part 61, promulgated by the U.S. Nuclear Regulatory Commission, or by equivalent state Regulations. The regulations in Part 61 establish (for land disposal of radioactive waste) the procedures, criteria, and conditions upon which licenses are issued for the disposal of radioactive waste containing by-product, source or special nuclear material received from other persons. These regulations were originally drafted for the licensing of shallow land burial facilities but have been determined to be applicable to the alternative method previously outlined in this section (Ref. 1).

General requirements for licensure can be summarized in certain performance objectives which are: 1) protection of the general population from releases of radioactivity, 2) protection of individuals from inadvertent intrusion, 3) protection of individuals during operations at the site and 4) stability of the disposal site after closure. More specific technical requirements are as follows:

- site geological and hydrological suitability;
- site design which is compatible with land disposal;
- disposal facility operating and site closure procedures;
- environmental monitoring at the site and in surrounding areas;
- acceptable waste characteristics and waste classification;
- proper labeling of waste containers received; and
- long range plans for institutional control of the site.

Each alternative is currently assessed on a case-by-case basis to determine if the criteria presented in 10 CFR 61 can be applied or if additional requirements, not outlined in Part 61, are needed. The Army Corps of Engineers will soon be completing a study for the Nuclear Regulatory Commission which evaluates the applicability of the criteria in Part 61 on an alternative specific basis. It should be noted that all the requirements for licensure may not be binding in States that have entered into an agreement with the NRC to regulate the use and disposal of radioactive material within their own borders; however, the requirements in such states must be compatible with 10 CFR 61 as it relates to performance objectives.

8.6 Cost Comparison

A cost comparison of alternatives to shallow land burial of low-level radioactive waste requires a benefit-cost-risk analysis. This type of comprehensive analysis has not been undertaken to date.

For commercial disposal facilities, a generic formula for total cost may be expressed as follows:

$$C_{TOTAL} = C_{PC} + C_{CT} + C_{OP} + C_{SC}$$

where,

C_{TOTAL} = Total facility costs

C_{PC} = Total pre-construction costs

C_{CT} = Total construction costs

C_{OP} = Total operational costs

C_{SC} = Total site closure costs

Another parameter of interest is the total cost per unit volume of waste disposed, which is expressed as:

$$C_{CPZ} = C_{TOTAL}/V_{DZV}$$

where,

C_{CPZ} = Total cost per unit volume

V_{DZV} = Disposal zone volume

C_{TOTAL} and C_{CPZ} will vary from alternative to alternative and are functions of total capacity desired. Cost comparison figures are not available for the alternatives in question.

In addition, actual costs incurred by those who have already utilized either of the alternatives discussed is not complete. In Sweden, the government has constructed a waste repository in a mined cavity, basically crystalline rock (Ref. 3). Cost estimates average $40.00 United States dollars per cubic foot. It should be noted that the repository was not placed in an existing cavity, but a cavity was created. It has not been ascertained whether or not the excavation of a new cavity is similar in cost to the modification of an existing cavity. Costs are based upon a 1982 price level. Also, Reynolds Electrical and Engineering Company has estimated a cost of $55.00 per cubic foot when applied to the use of augered holes. This work was done for the U.S. Department of Energy at 1984 price levels (Ref. 2). Work performed by EG&G Idaho for the U.S. Department of Energy has provided generic estimates of cost for some of the alternatives discussed in this report (Table 8.8).

TABLE 8.8

GENERIC COST COMPARISON OF ALTERNATIVES(A)

Facility Type	Cost ($\$10^6$)
Traditional shallow-land burial	8
Belowground vault	22
Aboveground vault	--
Mined cavities	--
Augered holes	17
Earth-mounded bunkers	--

Source: T. L. Gilbert, C. Luner, Alternatives for Greater Confinement Disposal of Low-Level Radioactive Waste, Final Report, November, 1985.

From the information presented, it is obvious that shallow land burial is the more economical. Among the alternatives, augered holes are the more economical.

REFERENCES

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3) Proceedings of the Sixth Annual Participants' Information Meeting, DOE Low-Level Waste Management Program, EG&G Idaho for U.S. Department of Energy, CONF-8409115, December, 1984.

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9.0 RECOMMENDATIONS FOR FURTHER STUDY

A final overall comparison of alternatives to shallow land burial should be made to determine if one seems more preferable than another. Each alternative should be compared to shallow land burial based upon the suitability criteria outlined in Sub-section 8.3 of this report. Stated criteria should be expanded to provide more detail, as follows:

A. Simplicity and Feasibility of Design and Operation

- A-1 State of technological development
- A-2 Ease of waste handling and placement
- A-3 Lack of complexity
- A-4 Flexibility in acceptance of waste forms
- A-5 Maintenance requirements
- A-6 Weather vulnerability
- A-7 Visually unobtrusive

B. Greater Confinement Capability

- B-1 Confinement ability

C. Ease of Site Monitoring

- C-1 Ease of performance assessment

D. Period of Institutional Control After Site Closure

- D-1 Long term institutional care
- D-2 Potential need of corrective measures
- D-3 Decommissioning

E. Reduction of Radiation Hazard

- E-1 Ability to handle and shield packages of waste possessing a high external hazard.

F. Resource Exploitation

- F-1 Cost
- F-2 Flexibility in siting requirements

Ideally, the comparison of shallow land burial to those alternatives mentioned previously in this report (based upon the criteria mentioned above) would be expressed in numerical terms. The objective of such quantification would be to assign each criterion a relative number of importance, normalized to unity, for each alternative. The implementation of this quantification technique will pose problems because the assignment of such weighting factors is purely subjective and is dependent upon the attitudes of persons or groups which attempt to implement such a procedure. Thus, the quantification of such criteria is likely to vary from person to person or group to group.

In this report, no attempt was made to quantify alternatives since no standardized method exists and development of such a method is beyond the scope of this report. It is up to each individual body which has the responsibility of deciding what management technique is most desirable to decide what figures of merit should be assigned to each criterion. A final decision can be made based upon this process.

The development of a standardized method of quantifying criteria related to the selection of a particular technology for the disposal of low-level radioactive waste will certainly prove to be a valuable tool for those assigned the responsibility of providing for the paper management of such wastes.