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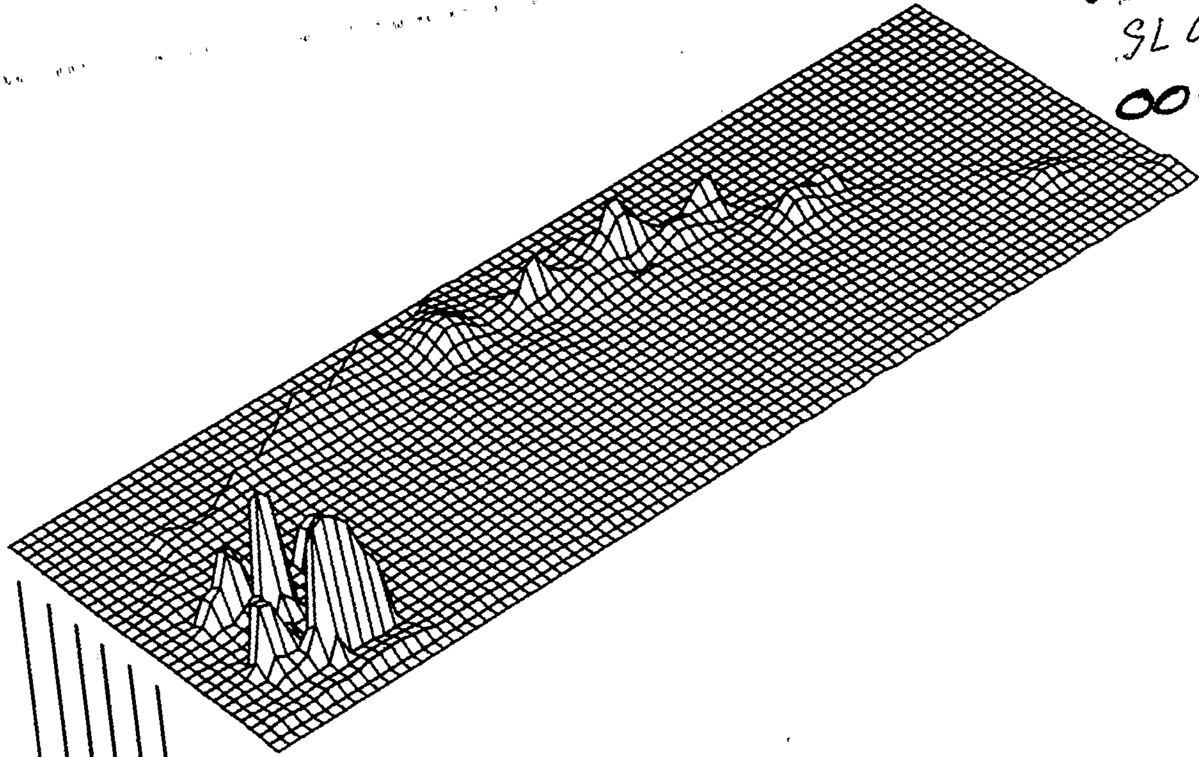

Formerly Utilized Sites Remedial Action Program St. Louis Airport Storage Site (SLAPSS)

SLAPSS Technical Series :

Vol. 2 Engineering

No. 1 Conceptual Design for In Situ Stabilization of Low Level Radioactive Residues.

January 1982

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FORMERLY UTILIZED SITES

REMEDIAL ACTION PROGRAM

ST. LOUIS AIRPORT STORAGE SITE (SLAPSS)

TECHNICAL SERIES

Vol. 2 Engineering

No. 1 Conceptual Design for In Situ Stabilization of Low-Level Radioactive Residues

January 1982

Prepared For

Union Carbide, Nuclear Division, Contract No. 32X70518C
Bechtel National, Inc., Contract No. 14501-5C-2

Prepared By

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FOREWORD

In late 1980, the Department of Energy (DOE) contracted with the Oak Ridge National Laboratory (ORNL) to initiate a research and development program with the ultimate objective of demonstrating in situ stabilization for containment and control of radioactive contaminants at the St. Louis Airport Storage Site (SLAPSS).

The St. Louis Airport storage site project is being conducted as a part of the DOE initiated Formerly Utilized Sites Remedial Action Program (FUSRAP). The St. Louis Airport site is one of several sites, formerly utilized by the Corps of Engineers' Manhattan Engineer District (MED) and the U.S. Atomic Energy Commission (AEC), for storing process residues during the initial production of nuclear materials for national defense and security.

Sites, including SLAPPS, were later decontaminated in accordance with the standards and survey methods then in existence. However, radiological criteria guidelines and proposed guidelines for release of sites for unrestricted use became more stringent as research on the effects of low-level radiation progressed. As a result, FUSRAP was initiated in 1974 to identify these formerly-utilized MED/AEC sites and to reevaluate their radiological status. The ultimate objective of FUSRAP is to decontaminate sites to permit their unrestricted use, or to stabilize and control residual activity to meet current criteria for protection of public health and safety.

One of the steps in the overall FUSRAP management plan is engineering evaluation, including an evaluation of suitable means of stabilizing residual radioactivity, where appropriate, including investigation of pertinent aspects of site geology, hydrology, and meteorology.

This document is part of a technical series to present the results of the ORNL activity and deals with the development of tools and techniques for stabilization of radioactive contaminants at the St. Louis Airport site. Specifically, the information relates to the work being performed, under subcontract to ORNL and to Bechtel National, Inc. by Roy F. Weston, Inc. (WESTON), in providing site characterization, preengineering conceptual evaluation, engineering for peripheral decontamination, conceptual engineering plans for radon and groundwater contamination control, and environmental monitoring plans.

SECTION 1

EXECUTIVE SUMMARY

1.1 INTRODUCTION

The St. Louis Airport storage site (SLAPSS) is located approximately 15 miles northwest of downtown St. Louis, and directly north of the Lambert-St. Louis International Airport. This 21.7-acre fully-fenced site is bounded by highways to the north and east, a railroad mainline to the south, and by Coldwater Creek to the west. Since 1946 this site has been used for storage and burial of radioactive and other residues from uranium processing and other activities.

The residues stored and buried on-site consisted of uranium processing wastes generated by the Mallinckrodt Chemical Corporation's Destrehan Street refinery, pitchblende raffinates, various radium-bearing residues, plus a variety of other materials. Between 1966 and 1977 the stored residues were sold for their mineral content, and ownership of the site was conveyed to the Airport Authority. The site was then razed, the contaminated materials removed, and the site covered with 1 to 3 feet of fill material. As a result of the site's history and the fact that some contaminated materials remained buried on-site, a study was initiated to develop stabilization plans for the buried radioactive residues.

This study commenced with a complete site characterization. The site characterization activity involved the collection and review of all available data, both published and unpublished, as well as field data collection and review. Specifically, data on site history, topography, radiological quality, geology, and hydrogeology were obtained and evaluated.

The radiological quality of the site was evaluated by:

1. Measuring beta-gamma levels 1 centimeter above the ground.

2. Measuring gamma levels 1 meter above the ground.

3. Gamma logging of bore holes.

4. Measuring soil and water radionuclide concentrations.

5. Measuring radon fluxes.

Two areas with relatively high external gamma radiation levels were found within the site fence line. They were in the northern apex of the site on a diagonal following the fence line, and in the lower western end of the site. These results ranged from a high of 240 uR/hr in the northern apex to 300 uR/hr in the western portion of the site. Both of these results are above the U.S. Nuclear Regulatory Commission (NRC) 10 CFR 20 limits. This same pattern appeared for the external beta-gamma levels, as well as for the Ra-226 and U-238 concentrations found in surface soil.

The northern high activity area appears to be in the general vicinity of the AJ-4 storage pile. This raffinate had the highest uranium content (1-2 percent). This was also the area that required further scraping and covering before its release to the Airport Authority. The second high activity area is in the western area where there are strong indications of buried contaminated material. This latter fact was confirmed by the ground-penetrating radar (GPR) scan conducted by WESTON. A strong correlation exists between the high radiation areas on the western end and the areas where buried objects were reported.

In general, with the exception of the two peak areas just discussed, the major central portion appears to be uncontaminated, with only some minor peaks in the southeast corner.

Outside the northern site fence line, contamination was found in the drainage ditches north and south of Brown Road. It was determined, based on elevated beta-gamma and gamma dose rates and radionuclide concentrations in the ditch sediments, that the ditch which lies between Brown Road and the fence is contaminated for a distance of 2,400 feet from Coldwater Creek to the site's east end gate. The ditch north of Brown Road is contaminated for a distance of approximately 1,100 feet from Coldwater Creek to the storm pipe under Brown Road. This contamination was probably due to runoff prior to site decontamination as site cleanup stopped at the fence line. An analysis of the yearly topographical changes does not indicate erosional losses.

Analysis of water samples from these drainage ditches showed Ra-226, U-238, and Pb-210 at concentrations above their respective backgrounds. These results were below the NRC 10 CFR 20 limits in all cases, and, with the exception of U-238, below the U.S. Environmental Protection Agency (EPA) proposed limits in 40 CFR 192. Results of water samples from Coldwater Creek, however, indicated that no meaningful transport of radioactivity was occurring.

The subsurface radiological analysis of the St. Louis Airport site found contaminated materials at depths of 3-12 feet in the western end of the site. In the northern and southeastern areas only surface contamination was found.

Radon flux measurements found values well above background in many areas of the site. The flux rates ranged up to 49 pCi/sq m/s which is well above the EPA proposed standard of 2 pCi/sq m/s (40 CFR 192) for the site annual average. The flux values varied considerably with location; higher fluxes were found in the northern site area both inside and outside the fence line.

In summary, analysis of the site's radiological quality indicates that the contamination is primarily a surface phenomenon with one subsurface area of contamination in the site's western end at depths to 12 feet. It was also determined that the site is contaminated in a heterogeneous fashion. Western, northern, and southeastern sections, as well as the drainage ditches bordering Brown Road, are contaminated while the remainder of the site is relatively uncontaminated.

The site geology and hydrogeology were determined by bore hole, piezometric, ground-penetrating radar, and topographic analyses. It was found that 10 individual soil units in four divisions were present. Division 1, which contains unit 1, is composed of the landfill wastes and soil cover brought to the site; it ranges from a 0 foot thickness at the fence line to 8 feet thick in the western end. Division 2, composed of units 2 and 3, consists of highly compacted silts and clays ranging from 12-19 feet thick. Division 3, composed of units 4 through 7, consists of various clays and ranges from 23-65 feet thick. Division 4 is bedrock and contains units 8 through 10.

Studies of the groundwater hydrology of the site found two separate water-bearing zones. The upper zone is in units 2, 3, and 4 of divisions 2 and 3, while the lower zone is in unit 6 of division 3. Vertical recharge exists between the zones through unit 5.

The predominant groundwater flow pattern is due west towards Coldwater Creek at a rate of 0.33 feet per year. At this rate, approximately 70-80 gallons of groundwater per day can enter the creek.

The regulatory criteria that were used in the design basis were those of NRC and EPA. The NRC is responsible for enforcing Title 10 of the Code of Federal Regulations and the proposed EPA regulations found in 40 CFR 192. While the regulations in 10 CFR are generic with respect to this site and those of 40 CFR 192 apply to uranium mill tailings sites, they were used as a basis for the design of a stabilization plan for the St. Louis Airport site.

The stabilization plan first identified and then considered those goals which should be met for proper site restoration. Four goals were identified:

1. Prevent groundwater and surface-water contamination.

2. Minimize radon emanation from the site due to buried radioactivity.

3. Minimize radiation exposure to persons working or living near or using the site.

4. Apply those feasible engineering techniques so that a 1,000-year life could be reasonably assured for the site after stabilization.

In order to meet these goals, an extensive review of the literature was conducted to establish a design basis and evaluate previous operational experience. As a result of this review and evaluation of the site characteristics, consideration was given to the use of multilayer cover systems, waste fixation techniques, ion exchange methods, subsurface barriers, and liner systems.

1.2 COVER SYSTEM

The purpose of the cover system is to limit water percolation through the residues to groundwater, to prevent any possible exposure of buried wastes to weathering or human contact, and to limit radon emanation from the buried radioactive materials. Based on an analysis of the cover's requirements, engineering feasibility, and availability of materials, a multilayer cover was found to be best suited for this application. The multilayer cover system consists of the following:

1. Top layers of noncompacted soil which support vegetation.

2. A middle layer of coarse gravel or crushed rock.

3. A bottom layer of clay.

The purpose of the noncompacted soil is to support grasses which control water and wind erosion, in addition to promoting water loss through evapotranspiration. The middle layer acts as a porous flow zone which diverts water to seepage pits well below the soil surface. This layer consists of well-graded gravel or crushed rock. The bottom clay layer or cap consists of low permeability and high clay content compacted soil. The clay layer functions as an impermeable barrier to radon emission and water percolation.

The cover system has the benefit of being constructed from entirely natural materials. The use of these materials is the best assurance of extended facility life because of their high resistivity to biochemical degradation and inherent structural stability. As an adjunct to a proper cover system, waste conditioning was then considered.

1.3 WASTE CONDITIONING

Waste conditioning is generally performed to meet one of the following objectives:

1. Improve the handling and physical characteristics of the waste.

2. Decrease the surface area across which transfer and loss of contained contaminants can occur.

3. Limit the solubility of various contaminants within the waste.

After consideration of various waste conditioning methodologies, it was decided not to recommend any of them for application at the St. Louis Airport site. The potential for significant health effects, materials handling considerations, and extensive costs were the primary factors in this decision. As waste conditioning was rejected, other techniques of groundwater protection were investigated, including the installation of an ion-exchange barrier.

1.4 ION EXCHANGE BARRIERS

An ion exchange barrier may be considered a means of controlling the migration of radionuclides in or into groundwater. The ion exchange material may be composed of natural soils, clays, zeolites, and synthetic resins. This type of system could be constructed in two ways, as follows:

1. A curtain or barrier designed to intercept the flow of groundwater.

2. A liner placed under a waste disposal area designed to intercept any leachate that might be generated by the disposal area.

Both types of approaches were investigated for application to the site and both are recommended for certain aspects of the stabilization plan.

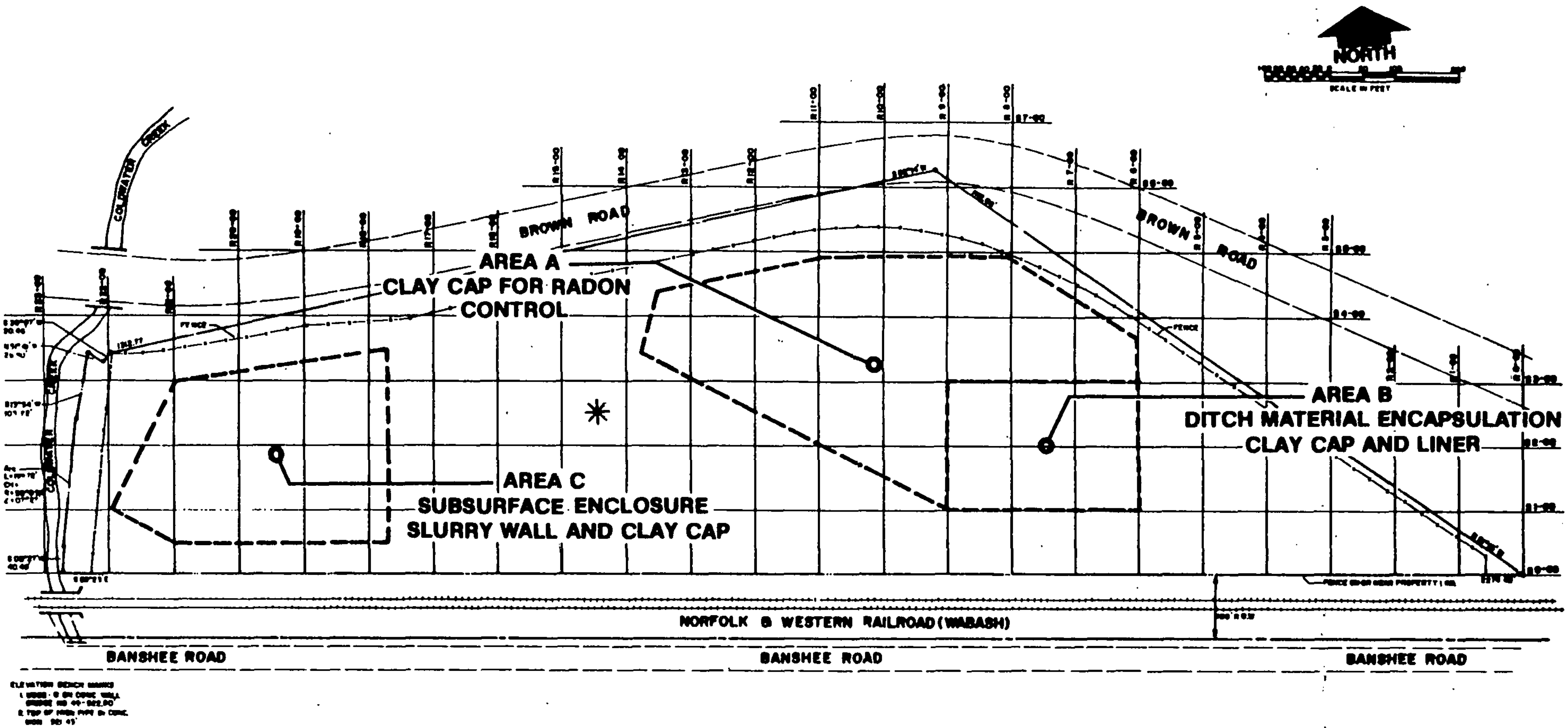
In addition, the ion exchange function of a barrier or liner must be compatible with the other desired functions of that barrier. For example, the primary purpose and function of a liner system is to retard the physical movement of water through the liner. An optimum liner design would address the dual function of restricting water (leachate) movement while treating any leachate that does migrate through the liner by the ion exchange process.

In designing the barrier wall, alternatives were considered for the control of radionuclide species contained in the water leaving the contaminated zone. The incorporation of a material with a high ion exchange capacity in a portion of the barrier wall has been evaluated. A simplified transport model was used to investigate the significance of various design parameters on the control of the radionuclide species.

Due to the high dissolved solids concentration of the groundwater, it is probable that an ion exchange filter, in contact with the groundwater, would become exhausted by saturation within a relatively short time and not be effective as a primary control mechanism. Thus, it was necessary to evaluate other alternative subsurface barriers to augment ion exchange techniques. A groundwater cutoff wall (bentonite slurry trench construction) surrounding the deep deposit (Area C on Figure 1-1) was selected to isolate any groundwater contamination which may now exist or would exist in the future.

1.5 GROUNDWATER CUTOFF WALL

A bentonite-soil slurry wall, surrounding the entire deep deposit and extending from the existing surface into the essentially impervious blue-clay layer underlying the site, was calculated to be the most effective and economical system. Allowing a 5-foot penetration into the clay, the depth of excavation would not exceed 50 feet, which is within the capability of backhoe emplacement. The use of a backhoe would require a minimum trench width of 30 inches which would provide an additional safety factor over competing thin-wall systems. The use of a



* OTHER PARTS OF SITE WITHIN FENCELINE DESIGNATED AS AREA D.

FIGURE 1-1
OVERALL SITE DEVELOPMENT PLAN
ST LOUIS AIRPORT STORAGE SITE

bentonite-soil slurry would minimize the quantity of materials to be imported, and provide an ion exchange capability to reduce the radionuclide content of the small quantity of groundwater that would pass through the wall. The flexible wall would be able to withstand any future soil movement, or settlement of reasonable magnitude, without losing integrity.

The subsurface wall would require an impermeable cap to prevent infiltration from overfilling the enclosure and spilling contaminated water. Simultaneously, the cap would preserve the moisture content of the upper wall, and prevent shrinkage cracks above the groundwater contact zone. Finally, the cap would reduce the downward movement of radionuclides from the unsaturated zone and limit radon emanation from the deposit.

Following completion of the slurry wall, a portion of the western side would be excavated below the existing grade and filled with sand prior to installing the cap. Any flow over the wall would thus be in the interior of the site away from the creek. The bed would be above the groundwater table to minimize the possibility of inflow due to a future extraordinarily high water table.

1.6 LINERS

As further protection against groundwater contamination, some areas of the site should be lined. The use of natural and synthetic materials of low permeability to line waste storage and disposal impoundments has been demonstrated in the field and presented in the literature. It is a feasible method of preventing leachate and waste liquid components from leaking and subsequently polluting ground- and surface-waters.

The control system is viable when the contaminants of concern can be physically contained or attenuated by the lining material or membrane. Such passive barriers can provide excellent radionuclide attenuation; and when properly designed, passive liner systems provide superior pollution control and essentially maintenance-free service lives. Only passive liner systems were considered because of their low maintenance requirements and reasonable expectation of a 1,000-year service life.

Upon reviewing the performance evaluation of various liner materials, it was determined that low permeability native soils, admixtures of soil and bentonite, or bentonite itself have the required characteristics. Selection of the specific liner material must be based on laboratory tests using native soils available in the St. Louis area.

The radionuclide-attenuating capabilities and inherent structural and biochemical stability of soils are the primary reasons for selecting natural soils as the preferred liner material.

1.7 WASTE ENCAPSULATION

A liner system, combined with a multilayer cover, has the additional qualities of providing waste encapsulation. By tying the cover and liner systems together, the buried low-level radioactive wastes can be completely sealed. Encapsulation allows essentially complete isolation of the disposed waste, and therefore, minimizes any potential environmental impacts. The implementation of this system then rests on an evaluation of the actual stabilization methodologies and alternatives.

Selected stabilization alternatives focus on stabilization by in situ containment and on-site encapsulation. In situ containment is accomplished by constructing a multilayer cover system over areas where low-level radioactive materials have been located.

A subsurface barrier may also be used in conjunction with a multilayer cover system in cases where more complete groundwater protection is desired, i.e., the waste materials are in direct contact with groundwater.

On-site encapsulation is accomplished by placing the waste materials on a liner. A multilayer cover is then placed over the waste materials and liner, thus achieving total encapsulation. Encapsulation requires removal and reemplacement of waste materials on a liner, whereas in situ methods employ stabilization without disturbing the emplaced materials. In situ methods thus minimize concerns regarding construction worker exposure and contamination of workers and equipment as well as minimizing the cost of containment.

1.8 SPECIFIC DESIGN CONCEPT FOR THE ST. LOUIS AIRPORT SITE

Given the analyses and considerations presented, the engineering concept for stabilizing the residues at the St. Louis Airport site are shown on Figure 1-1. The concept consists of multilayer soil covers in Areas A, B, and C. The covers serve to control radon emanation, and simultaneously limit water infiltration which may carry radionuclides to the groundwater. Area B has a cover and liner, and Area C has a cover and bentonite slurry wall for additional groundwater protection.

Area D consists of the remainder of the site (about 50 percent of the total site area), approximately 10 acres. It will be covered with an average of 3 feet of soil to properly adjust drainage patterns, and to provide further assurance that beta and gamma dose rates, as well as, radon emanation are controlled.

The multilayer cover system has been designed to attenuate the highest predicted radon flux to 2 pCi/sq m/s (the design objective) from the site in its anticipated future configuration, and to minimize water percolation through the waste materials. The multilayer cover system's configuration consists of the layers shown on Figure 1-2. In order to meet the radon emanation criterion, two multilayer cover systems were designed and evaluated. They differ only in the clay cap thickness to achieve radon control requirements. The ditch material (Area B) and western cover (Area C) systems are identical. Both require a clay cap thickness of 36 inches. The northern cover system requires a clay cap thickness of 48 inches. The clay cap thicknesses were determined using experimental laboratory data and computer modeling which resulted in different cover thicknesses due to differences in contamination levels under the covers and different requirements for radon attenuation.

A water budget analysis was performed on each of the three cover systems used in Areas A, B, and C. The methodology includes the use of a recently developed hydrologic simulation model for solid waste disposal sites (HSSWDS) that was developed by the U.S. Environmental Protection Agency, in conjunction with the U.S. Army Corps of Engineers. It was shown that 1% or less of the water impinging on the site will percolate through to the waste.

Surface runoff and drainage control will prevent the physical transport of contaminated materials away from the site during the construction period, and aid in preserving the final cover integrity in the post-construction years. All final grading on the site will be to levels above the 500-year flood elevation. An erosion control plan must be developed by the construction contractor and submitted to the project engineer before any site activity begins.

The decontamination procedures for construction equipment operating in contaminated areas on-site have been based, in part, on basic decontamination principles contained in USAF T.O. U0-110A-12, "Guidelines for Identification of Aircraft and Material Contaminated with Radioactive Debris" (fallout), 15 February 1979. Dust control during construction is essential to prevent off-site surface and air movement of contaminated dust from exposed soil surfaces.

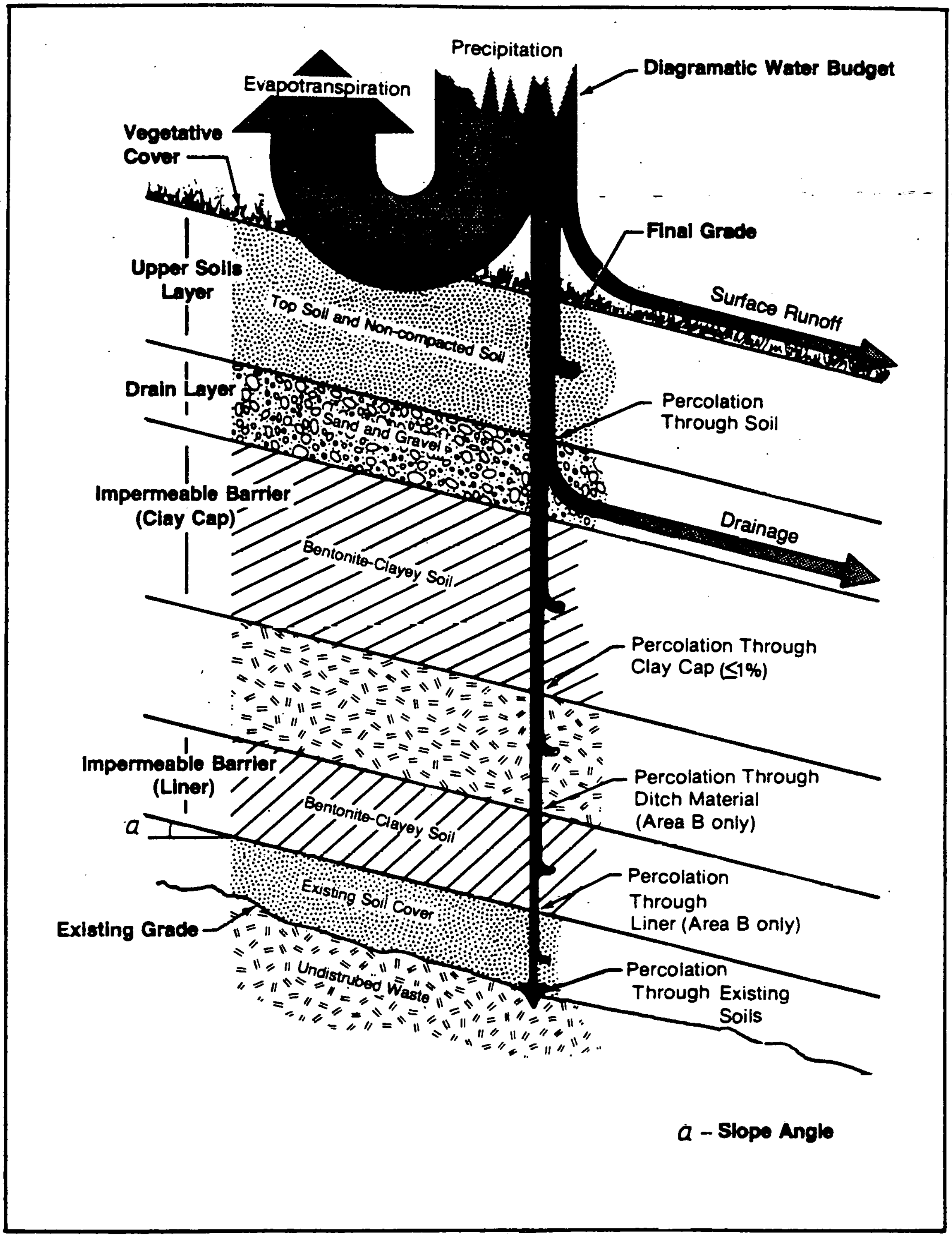


FIGURE 1-2 PROFILE OF RECOMMENDED COVER CONFIGURATION ST. LOUIS AIRPORT STORAGE SITE

Security arrangements are required during the construction phase of the remedial action program to protect the public from coming in contact with the contaminated material, and to protect the site and construction equipment from vandalism.

An integral part of the site stabilization plan involves monitoring the site and surrounding environment both during and after construction. Four distinct monitoring programs were developed. The first program would be implemented during construction, and has as its goals protection of workers and the general public. The second monitoring program would be performed immediately after construction, and would verify that the goals set for site stabilization were met. The third and fourth programs would be implemented post-construction, and their results evaluated to ensure long-term site stability. The third program consists of quarterly and annual surveys for the first five years post-construction. The fourth program would be implemented if the first five years data show no significant off-site transport of radioactivity or construction failure. It requires annual surveys beginning in the sixth year.

Order-of-magnitude cost estimates for in situ stabilization of the St. Louis Airport storage site were prepared and are summarized below. The costs are presented in a modular format to allow each element of the control concept (e.g., cover by itself, etc.) to be reviewed. It should be noted that this cost estimate is based on conservative assumptions. A construction cost estimate should be prepared as part of the detailed engineering phase of this project.

Area A Cover --	$1,240,000
Area B Cover and liner --	758,000
Area C Cover and slurry barrier --	1,367,400
Area D Site preparation and cover --	740,000
Equipment and labor --	850,000
Subtotal Construction Cost --	4,955,400
Engineering and construction management --	1,000,000
Contingency (at 25% of construction cost) --	1,239,000
Total	$7,194,400

1.9 CONCLUSIONS

The study performed by WESTON of the St. Louis Airport site was initiated to develop of stabilization plans for the buried radioactive residues. This study commenced with a complete site characterization from which the following conclusions were drawn:

1. The residues stored and buried on-site through 1966 consisted of uranium processing wastes, pitchblende raffinates, various radium-bearing residues, and a variety of other radiologically-contaminated materials.

2. In 1966 and 1967, the stored, but not the buried, residues were removed and sold for their mineral content. Then the site was covered with from 1 to 3 feet of fill.

3. Subsequent surveys of the site found contamination levels and radiation levels on the site and in the drainage ditches north of the site, as well as radon emanation rates from the site, above current and promulgated regulations, but no evidence of off-site migration of radioactivity in groundwater.

4. The site is in need of stabilization in order to meet various radiation guidelines.

1.10 GOALS

The R&D stabilization of the St. Louis Airport storage site has the following goals:

1. The application of best available, technologically-sound, cost-effective measures for stabilization of this site.

2. The prevention of groundwater and surface-water contamination.

3. The minimization of radon emanation from the site due to buried radioactivity.

4. The minimization of radiation exposure to persons working or living near, or using the site.

5. The application of feasible engineering techniques such that a 1,000-year life could be reasonably assured for the site after stabilization.

1.11 RECOMMENDATIONS

In order to meet these goals for the stabilization of the St. Louis Airport storage site, the following recommendations are made:

1. The site should be divided into four areas, A (approximately 5 acres), B (approximately 1 1/2 acres), C (approximately 3 1/2 acres), and D (approximately 10 acres). Area A is in the north-central section, Area B is in the south-central section, Area C is in the western section, and Area D is the remainder of the site.

2. A multilayer cover should be used in Areas A, B, and C for lowering the external direct dose, groundwater protection, and control of radon emanation. This cover is composed of an upper layer (2 feet of soil), a middle layer of coarse gravel or crushed rock (1 foot), and a bottom layer of a clay-soil mixture (4 feet in Area A and 3 feet in Areas B and C).

3. Area B which should be used for burial of the contaminated ditch material, in addition to the cover, should be fully lined and encapsulated using a clay-soil mixture (3 feet) for further groundwater protection.

4. Area C, in addition to the cover, should be surrounded by a bentonite-soil slurry wall (approximately 30-inches wide and 50 feet deep) extending from the surface into the soil-clay layer for further groundwater protection.

5. Area D, the remainder of the site, should be covered with an average of 3 feet of soil to properly adjust drainage patterns and further ensure site integrity.

6. Waste conditioning is not necessary or recommended for the buried residuals.

7. All final grading on the site should be to levels above the 500-year flood elevation; in addition, riprap will be required at the western edge of the site adjacent to Coldwater Creek.

8. An erosion control plan should be developed in detail and implemented by the construction contractor.

9. Security measures should be taken during the construction phase to protect the public health and safety.

10. The site and worker personnel should be routinely monitored during construction in order to protect worker and public health and safety.

11. The site should be rigorously monitored immediately post-construction to assure that the stabilization goals have been met.

12. The site should be routinely monitored post-construction in order to assess and ensure long-term stability.

The recommendations made above were carefully evaluated for feasibility and cost-effectiveness; however, there are two remaining technical uncertainties which should be addressed prior to implementation of the detailed stabilization plan. Therefore, it is recommended that the following items be analyzed in depth:

1. The composition of the soil/bentonite backfill composition for the barrier must be determined by laboratory testing to optimize the mixtures of site soil and bentonite to bring about the desired permeability. In order to control groundwater movement through the barrier area, the permeability must be in the range of 10^{-6} to 10^{-8} cm/s.

2. Refinements of the cover and liner composition to ensure the desired performance are needed. Detailed testing and evaluation of cover and liner materials are required to determine properties which control water movement into and out of the system.

Of course, numerous other design and construction details will need to be resolved prior to implementing the final engineering design, such as:

1. Preconstruction monitoring to verify the final engineering design.

2. Analysis of the indigenous soils to be used as fill and cover materials for radon flux rates.

3. Final construction cost estimates.

SECTION 2

SITE DESCRIPTION

2.1 LOCATION

The St. Louis Airport Storage Site (SLAPSS) is located approximately 15 miles northwest of downtown St. Louis and directly north of the Lambert-St. Louis International Airport (see Figure 2-1). The 21.7-acre site is bounded by Brown Road to the north and east, the Norfolk and Western Railroad main line on the south, and Coldwater Creek on the west, which is also the property line of the McDonnell Douglas Corporation. A fence runs around the periphery of the site, well within the property line, with two gates providing access to Brown Road.

2.2 SITE HISTORY

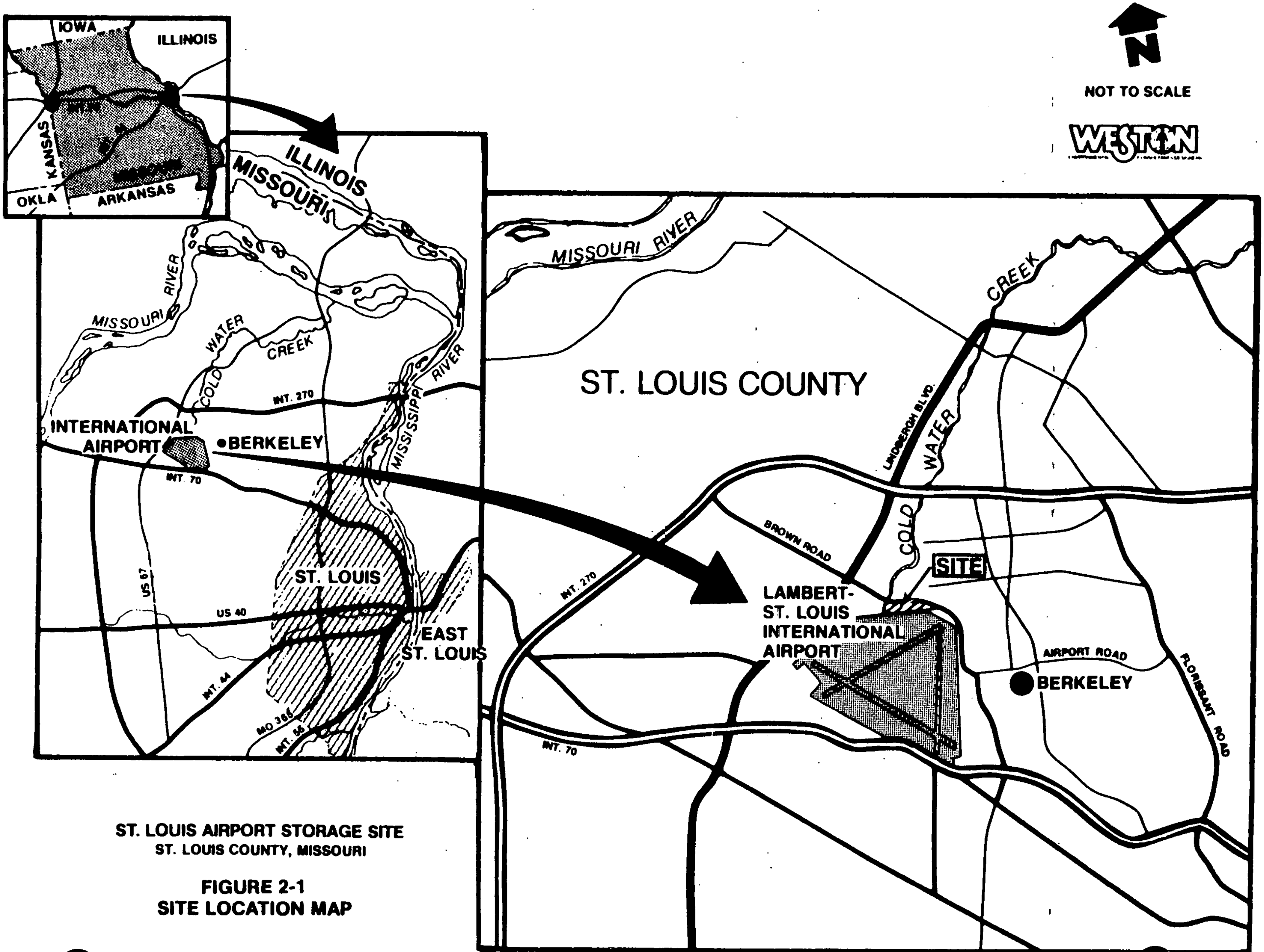
Title to the site was obtained by the Manhattan Engineering District (MED) in 1947 for the purpose of storing residues generated by the Mallinckrodt Chemical Corporation, Destrehan Street Plant, uranium processing operations. The site was operated by the MED and later by the Atomic Energy Commission (AEC) until 1953, when it was turned over to Mallinckrodt Chemical Works.

The Destrehan Refinery used pitchblende ores until 1955. The procurement contract with African Metals required the government to store the pitchblende raffinate (AM-7) and radium-bearing residues (K-65). The AM-7 was stored at the site on the ground and in the open; the K-65 was stored on the site in drums. A barium sulfate cake residue (AJ-4) and Colorado raffinate residues (AM-10) generated from later operations at the Destrehan Refinery using nonpitchblende feedstock were also stored at the site on the ground and in the open. Other wastes stored on-site included:

1. Used dolomite liner and recycled magnesium fluoride liner generated as slag.

2. Tailings from an interim residue plant built in 1955 to recover uranium from the magnesium fluoride slag.

3. 50,000 empty drums.



ST. LOUIS AIRPORT STORAGE SITE
ST. LOUIS COUNTY, MISSOURI

FIGURE 2-1
SITE LOCATION MAP

4. 3,500 tons of contaminated steel and alloy scrap.

5. 2,400 drums containing miscellaneous residues, Japanese uranium-containing sand, and contaminated scrap materials.

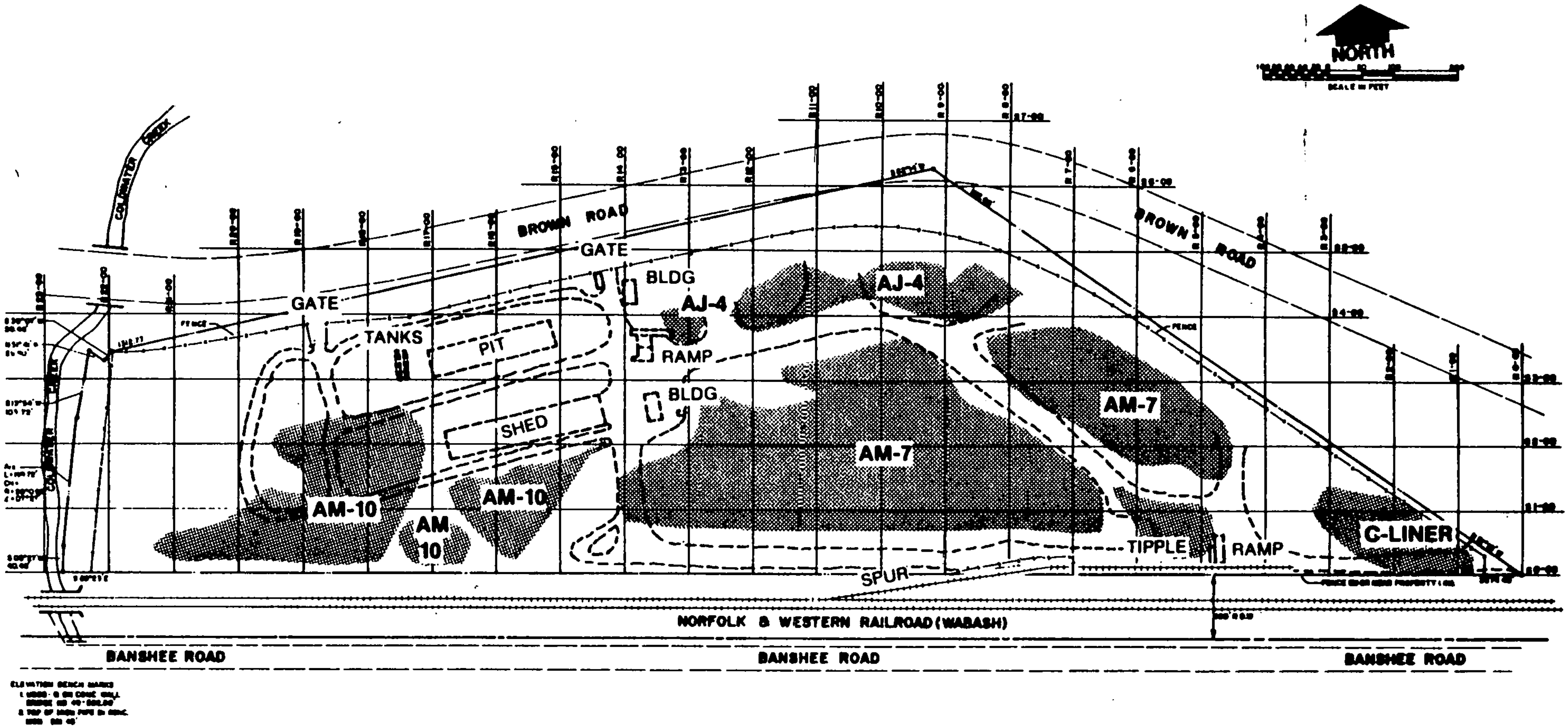
The tailings from the interim residue plant (C-101) were stored in a large concrete pit originally built to store the K-65. In addition, a contaminated vehicle and 50 to 60 truckloads of contaminated metal scrap were buried in low areas at the western end of the property and later covered with clean fill. Figure 2-2 shows the location of these and other waste piles.

In 1966, the AEC transferred the ore residues stored at the airport storage site to Continental Mining and Milling Company. The residues were removed from the site to a former Nuclear Regulatory Commission (formerly AEC) licensed site at 9200 Latty Avenue, Hazelwood, Missouri (hereafter called the Latty Avenue site), approximately three-fourths of a mile northeast of the airport storage site. After removal of these residues, on-site radiation at ground surface was less than 1.0 mrad/hour, except for the area where AJ-4 was stored. In this area, residual contamination at the ground surface was about 3.0 mrad/hr.

In fulfillment of an agreement between the U.S. Government and the St. Louis-Lambert Airport Authority (acquisition permit, 10 November 1969), the AJ-4 was removed. All on-site structures except the perimeter fence were razed and buried on-site, and 1-3 feet of clean fill was spread over the entire site to achieve acceptable radiation levels. Topographic and radiation surveys of the site were conducted in November 1971 to document grade elevation and radiation levels over the entire site. After the cleanup was completed, on-site ground surface dose rates were generally less than 0.05 mrad/hr. Isolated areas exceeded 0.2 mrad/hr; however, no area exceeded 1.0 mrad/hr.

Since 1971, additional fill has been placed on-site to level off low spots for possible future use as a driver training facility for the St. Louis Police Academy. Otherwise, the property has not been used and little maintenance has been done by the Airport Authority. Radiological surveys of the site and its environs were conducted in 1976,(1) 1977,(2) and 1978.(3) These surveys included:

1. Sampling ground and subsurface soils and ground- and surface-water.



NOTE: THIS MAP IS BASED ON SITE SURVEYS BY ROWLAND SURVEYING CO., DATED 25 AUGUST 1979, AND VARIOUS OTHER EARLIER SURVEYS.

FIGURE 2-2
WASTE PILES (AS OF 1965), BUILDING AND ROAD LOCATIONS ST. LOUIS AIRPORT STORAGE SITE

2. Measuring external beta-gamma dose rates and external gamma radiation.

3. Conducting an aerial gamma radiation survey.

4. Evaluating radon emanation and particulate resuspension.

In addition, the topography of the site was surveyed by Rowland Surveying Company in 1969,[4] 1971,[5] 1977,[6] and 1979.[7] Table 2-1 lists the key events occurring at the St. Louis Airport site.

2.3 SITE CHARACTERIZATION

Characterization of the St. Louis Airport site had a twofold purpose. First, all currently available data relative to the site were collected and evaluated for content and sufficiency. This evaluation was performed relative to the data needs associated with in situ control, and the subsequent program necessary to monitor the success of any control options implemented. Secondly, these data were used to describe, to the extent possible, the specific characteristics of the airport site. The resultant characterization thus provided a base for control option evaluation and program development.

2.3.1 Background

Data on-site were obtained from several primary sources. Copies of all previously published reports and correspondence were obtained from both WESTON's and Oak Ridge National Laboratory's (ORNL) project files. Copies on record of all topographic surveys performed at the site since 1955 were obtained from the Rowland Surveying Company of Clayton, Missouri. Aerial photographs detailing the changes due to the site's operation and activities since 1958 in approximate two-year increments were also obtained from ORNL and local sources. These photographs were subsequently enlarged for further comparison and analysis. Finally, copies of all pertinent detailed field data were obtained through a visit to the Health and Safety Research Division, ORNL.

Specific data areas that were addressed include the following:

1. History of site activities and operations.

2. Topographic changes including erosion.

Table 2-1

Chronology of Key Events

Date	Event
1946-1965	Waste storage area - Mallinckrodt Chemical (uranium processing) and the Manhattan Engineering District
Sept. 1965	Topographical survey - Rowland Surveying Company
Nov. 1965	Radiological survey waste inventory -- AEC
1966	Residual piles removed by Continental Mining & Milling Company
Dec. 1966	Surface radiological survey (beta-gamma only) -- AEC
1969	Removal of AJ-4 residue to Weldon Spring and razing of all structures -- St. Louis Airport Authority
Dec. 1969	Radiological survey -- AEC-Oak Ridge Operations
Dec. 1969	Prefill topographical survey -- Rowland Surveying Company
1970	Fill dirt dumped on site (minimum of 1 foot with 2-3 feet on "hot spots") -- St. Louis Airport Authority
Oct. 1971	Postfill topographical survey -- Rowland Surveying Company
Nov. 1971	Postfill surface radiological survey (cleanup complete) -- AEC-Oak Ridge Operations
Nov. 1976	Radiological survey -- Oak Ridge National Laboratory
Jan. 1977	Topographical survey -- Rowland Surveying Company
Late 1977-1978	Additional fill/rubble dumped on-site in several areas -- St. Louis Airport Authority
Aug. 1977	Aerial gamma radiation survey -- EG&G
Aug. 1978	Radiological survey -- Oak Ridge National Laboratory
Aug. 1979	Topographical survey -- Rowland Surveying Company

3. Surface radiation levels.

4. Surface radionuclide activities.

5. Subsurface radionuclide activities and concentrations of buried materials.

6. Radon gas emanation.

7. Site geotechnical descriptions.

8. Groundwater kinetics.

Once all available data were obtained for each of these areas, an evaluation was performed and a determination made of the sufficiency of the data for site characterization.[8] As previously mentioned, this evaluation was performed relative to data requirements associated with any feasible in situ control measures.

2.3.2 <u>Topographic Characteristics</u>

The goals for the temporal topographic analysis were to verify the amount of fill placed on the site during and after the cleanup operations, and to determine the effects, if any, of erosion on the fill cover placed on the site. To accomplish this, topographical data for surveys conducted in December 1969,[4] October 1971,[5] January 1977,[6] and August 1979[7] were digitized and stored in a computer data base. Differential contours were calculated and plotted for the following periods: 1969-1971, 1971-1977, 1977-1979.[8]

These contours showed the changes in surface topography which took place between surveys. A discussion and interpretation of each differential contour follows.

1. <u>1969-1971</u>.

   The 1969 survey serves as the prefill ground level for the site. The survey was taken after the residual storage piles had been removed and prior to any fill being placed. The 1971 survey was performed after the fill operation was completed and is the post-fill ground level. Analysis of the differential between these two surveys indicated that a minimum of 1 to 1 1/2 feet of fill was placed over the entire site. Also indicated are the areas that were identified by a 1969 ORNL radiological survey as "hot spots" and that required an additional 2 to 3 feet of cover. Several of these areas were cross checked and confirmed with original drawings annotated at the time of the survey. It is interesting to note that the "hot spots" seem to correspond to the specific problem areas currently being identified.

2. 1971-1977.

The changes over the 1971-1977 period represent those caused by natural effects such as erosion and settlement, as no activity was recorded on the site for this period. The most significant changes seem to be near the location of the gate closest to Coldwater Creek (S4-0, R18-0 to R19-0; see Figure 2-2 for these locations), where increases in elevation of from 1 to more than 3 feet were found. Based on the location and pattern of increases in this area, there is reason to believe that at some point during the latter part of the period, additional loose material was deposited just inside the gate.

There are also several areas where settlement appears to have been significant. These areas are located at grid points (S1-0, R20-0), (S0-5, R21-5), and (S4-0, R7-0 to R8-0). Comparison with the 1969-1971 topography, however, shows that these areas of high settlement correspond to the areas with high fill. The remaining settlement of approximately one-half foot or less is considered reasonable. Some minor erosion apparently occurred around the perimeter of the site, but none significant enough to cause any appreciable loss of contaminated material.

3. 1977-1979.

The 1977-1979 differential contour shows the effects of dumping additional fill material. A considerable amount of fill was dumped along a ridge line in the southwestern corner (S0-0 to S1-0, R17-0 to R22-0), as well as at grid points (S4-0, R12-0) and in the area of grid points (S0-0 to S2-0, R11-0 to R12-0). This additional fill apparently changed the ground flow characteristics near the gate closest to Coldwater Creek. There appears to be a major reduction in elevation in the area along the northern fence line between R16-0 and R20-0. This area, however, also recorded a high level of increase during the 1971- 1977 period, suggesting that a major portion of the reduction might be due to settlement of loose fill, coupled with possible runoff erosion.

In summary, the following can be said regarding the temporal topographic changes through 1979:

1. There appears to be a high settlement rate in the well built-up areas.

2. There is a continual decline in elevation along the southeastern boundary.

3. The remainder of the site, primarily the central portions, has remained relatively stable.

2.3.3 Radiological Characteristics

The radiological characteristics of the site required for the engineering concept were determined by the following techniques:

1. Measuring external gamma radiation levels at 1 meter.

2. Measuring external beta-gamma radiation levels at 1 centimeter.

3. Determining surface soil radionuclide concentrations.

4. Gamma logging of bore holes.

5. Measuring Rn-222 flux.

6. Measuring radionuclide concentrations in surface and groundwater.

A discussion and analysis of these results follows.

2.3.3.1 Surface Radiological Characteristics.

These data were generated by ORNL during their 1976 and 1978 surveys.[1,3] The 1976 survey was conducted primarily on-site, within the fenced-in area, while the 1978 survey was conducted primarily outside the fenced-in area. In order to analyze the 1976 data, contour plots were generated which showed the following:[8]

1. External gamma radiation levels at 1 meter.

2. External beta-gamma radiation levels at 1 centimeter.

3. Surface concentrations of Ra-226.

4. Surface concentrations of U-238.

Corresponding three-dimensional representations were also presented.[8] A discussion of these results (refer to Figure 2-2 for grid locations) follows.

Two areas with relatively high external gamma radiation levels were found. The area in the northern apex of the site is on a diagonal following the fence line from S3-0, R4-0 to S5-5, R11-0, and in the lower western end (S0-0 to S3-0, R18-0 to R20-0). This same pattern appeared for the external beta-gamma levels, as well as in the Ra-226 and U-238 concentration contours. When this information is correlated with the results of the site history previously discussed, the following conclusions can be drawn.

The northern high activity area appears to be in the general vicinity of the AJ-4 storage pile. This raffinate had the highest uranium content (1-2 percent). This was also the area that required further scraping and covering before its release to the Airport Authority in 1969. The second high activity area is in the western area where there are strong indications of buried contaminated material. This latter fact was confirmed by the recent ground-penetrating radar (GPR) scan conducted by WESTON (see subsection 2.3.4.2). A strong correlation exists between the high radiation areas on the western end (S1-0, R18-0 to R20-0) and (S1-0 to S2-0, R19-0 to R20-0), and the areas where buried objects were reported.

In general, with the exception of the two peak areas just discussed, the major central portion appears to be reasonably clean by every measurement, with only some minor peaks in the southeast corner.

The 1978 survey was conducted outside the fenced-in area, and allowed a determination of the degree of contamination at the ditches located north and south of Brown Road. Beta-gamma dose rates at 1 centimeter were measured in the drainage ditches outside the fenced confines between the fence and Brown Road and north of Brown Road. The dose rates were elevated in the ditches north and south of Brown Road; they ranged up to 0.34 and 1.6 mrad/hr, respectively. Gamma dose rates at 1 meter were measured in the same areas and generally followed the same elevated pattern as the beta-gamma dose rate measurements. Gamma levels between the fence and Brown Road averaged 65 μR/hr, and ranged up to 330 μR/hr; measurements made in and near the ditch north of Brown Road averaged 59 μR/hr and ranged up to 90 μR/hr.

Based on these results, the ditch which lies between Brown Road and the fence is contaminated for a distance of approximately 2,400 feet, starting at the site's east end gate and extending to Coldwater Creek. The ditch on the north side of Brown Road is contaminated for a distance of approximately 1,100 feet, starting at the existing 24-inch RCP storm pipe under Brown Road at R11 (see Figure 2-2) and extending to Coldwater Creek.

Thirty-five surface soil samples were collected from the drainage ditches located north and south of Brown Road. Practically all of these samples had elevated levels of Ra-226, U-238, and/or Ac-227. The range of Ra-226 in samples outside the fence and south of Brown Road ranged from 105 to 460 pCi/g; U-238 ranged from 2.6 to 890 pCi/g; and Ac-227 ranged from less than detectable to 120 pCi/g. The drainage ditch north of Brown Road had Ra-226 concentrations from 1.4 to 120 pCi/g; U-238 ranged from 3.0 to 72 pCi/g; and Ac-227 from less than detectable to 160 pCi/g. Typical background levels in Missouri for these radioisotopes are 1.0 pCi/g for Ra-226, 1.1 pCi/g for U-238, and less than detectable for Ac-227.

Analysis of water samples from the drainage ditches north of the site, above and below Brown Road, showed Ra-226, U-238, and Pb-210 at concentrations above their respective backgrounds; yet, results of water samples from Coldwater Creek indicated that no meaningful transport of radioactivity was occurring.

Although some migration of material may have occurred through post-fill erosion and other transport mechanisms, it is likely that migration of the major portion of the off-site contaminated material, especially in the ditches to the north, occurred before the decontamination operations. No evidence can be found to support the assumption that on-site erosion and exposure of contaminated material occurred to the degree necessary to displace the magnitude of contaminated material found off-site. If anything, the records and data support the assumption that off-site contamination was caused through runoff prior to cleanup activities. It should be noted that no cover was placed outside the fence line, and no record of measurements taken outside the fence before 1976 has been found.

2.3.3.2 Subsurface Radiological Characteristics.

The subsurface radiological characteristics of the St. Louis Airport site were determined by natural gamma logging 31 bore holes.(3) Data from these loggings were computerized and plotted(8) in order to assess and verify the following:

1. The location of the buried contaminated materials.

2. The effect of fill material on attenuating the subsurface radiation.

Additionally, Table 2-2 was prepared which compares the surface and depth where maximum radiation levels were found (refer to Figure 2-2 for grid locations). The data as previously analyzed and in Table 2-2 suggest the following:

1. In almost all instances, the depth of maximum radiation occurs at the prefill surface elevation as represented by the 1969 elevations.

2. In the northern, southern, and eastern areas, only surface activity was observed, confirming the assumption that only prefill surface contamination was present in these areas.

3. In the western area, several loggings show activity below the prefill surface interface, indicating contaminated material buried below the prefill surface.

4. In some instances in the western area, single peaks are located below the prefill surface indicating that surface storage was not done in that location. These holes appear to lie along the perimeter of the site.

Table 2-2

Comparison of Surface Elevations and Elevations Where Maximum Radiation Readings Occurred[1]

Area	Hole No.	Grid Location	Elevations[2] (feet above sea level) 1978 Surface	Maximum Reading	1969 Surface	1965 Surface
North	2	S3-5/R10-0	529	527	526.9	527.4
	3	S4-0/R8-0	529	527.5	527.1	527.3
	12	S4-0/R12-0	527	524.5	524.7	528.9
	31	S4-25/R13-25	528	525.5	526	526.3
South	4	S2-0/R8-0	528.3	526.8	526.8	529
	5	S1-0/R6-0	533.8	529.4	532.2	531
	8	S3-0/R6-0	529.3	527.3	527.1	528
	9	S1-0/R10-0	529	526	527.7	528
	10	S0-0/R12-0	528.7	526.7	527.8	527.8
	11	S2-0/R12-0	527.1	525.6	525.5	527
	24	S0-0/R8-0	533	531.5	530	532
East	6	S1-0/R2-0	537.1	535	535.6	546.9
	7	S2-0/R4-0	532.9	529.4	529.5	529.2
	25	S0-0/R4-0	532.7	530.7	531.3	530.9
West	1	S3-0/R14-0	527.1	526	526.1	525.5
	13	S0-0/R14-0	526.5	524	523.4	525
	14	S0-0/R16-0	523.8	523.3	522.7	522.7
			523.8	518.8	522.7	522.7
	15	S2-0/R16-0	527.9	523.9	523.5	523.9
	16	S4-0/R16-0	527.3	526.3	525.9	526.4
	17	S3-0/R18-0	525.5	520.5	523.1	522.7
	18	S1-0/R18-0	525.5	521	521	519
			525.5	518.5	521	519
	19	S0-0/R20-0	519.3	511.3	518.5	518.5
	20	S2-0/R20-0	527.7	524.2	523.9	523.7
			527.7	512.7	523.9	523.7
	22	S1-0/R22-0	524.3	518.3	520.4	520.4
			524.3	515.8	520.4	520.4
	23	S3-0/R21-5	523.1	521.1	521.6	521

[1] These results relate only to the elevation for the maximum reading for that bore hole and not to any need for remedial action.

[2] Surface elevation data obtained from Rowland Surveying Co. surveys for appropriate dates.

In summary, this analysis corroborates the assumption that the original contamination was predominantly a surface phenomenon. It also confirms that contaminated material had previously been buried in the western end at depths ranging from 3 to 12 feet below the prefill surface. Finally, a review of the logging plots indicates that, in most cases, a minimum cover of 2 feet attenuated the radiation levels by approximately a factor of 10.

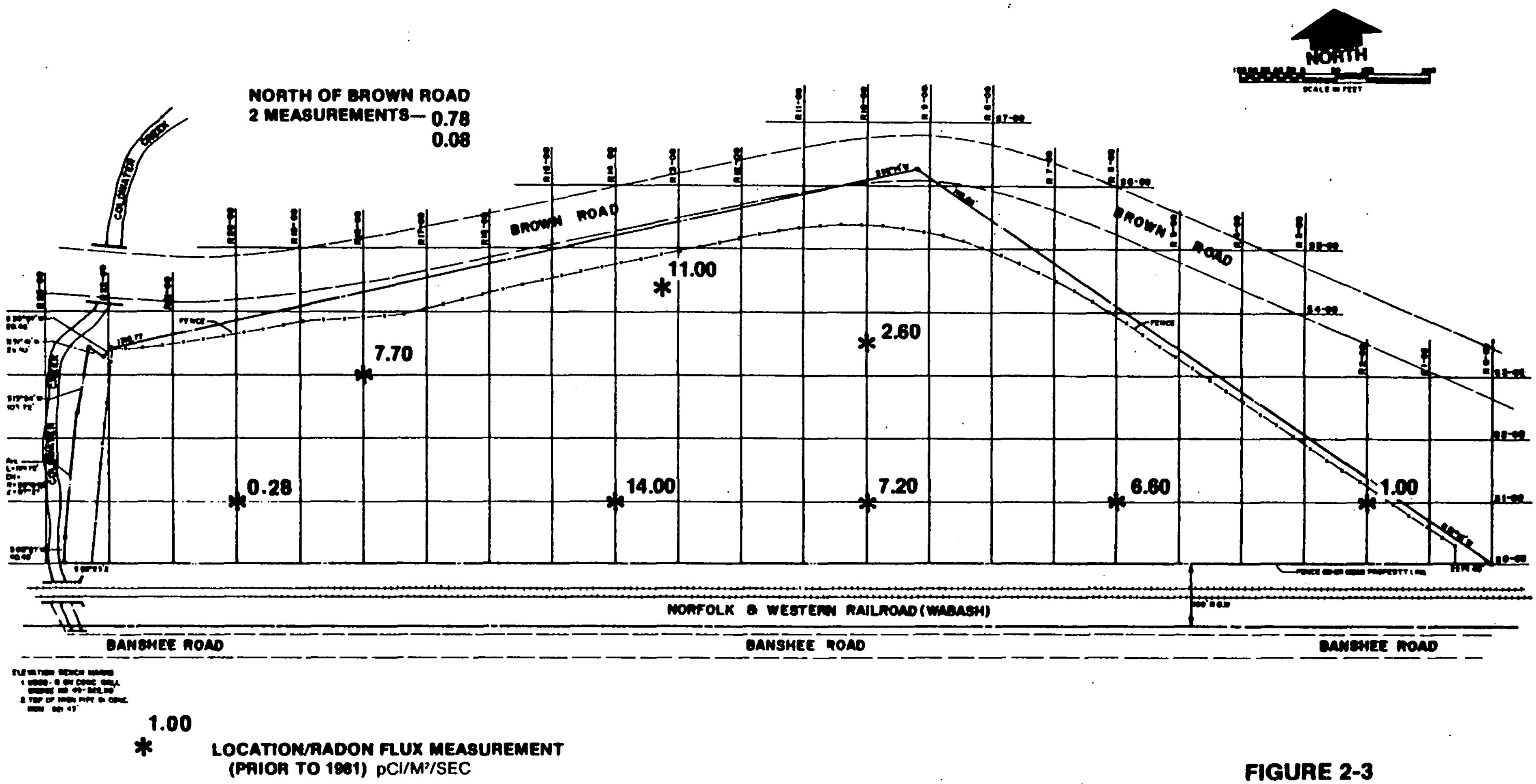
2.3.3.3 Radon Flux Measurements.

Radon flux measurements at the St. Louis Airport site were made in 1978,[3] and in May, June, and August of 1981. The 1978 measurements, eight on-site and two off-site ranged from 0.08 to 14 pCi/sq m/s. The highest value (14 pCi/sq m/s) was found at S1:R14 (refer to Figure 2-2 for grid location), and the second highest value (11 pCi/sq m/s) was found at S4-5:R13-5. In May 1981, 21 locations were measured, 17 inside the fence and four outside; the results ranged from 0.3 to 49 pCi/sq m/s. The highest value found (49 pCi/sq m/s) was at S5:R10, and the second highest (31 pCi/sq m/s) was outside the fence at S5-5:R12. Follow-up measurements taken in June 1981 at 19 locations, 15 inside the fence and four outside, ranged from < 0.09 to 14 pCi/sq m/s. The highest value found (14 pCi/sq m/s) was at S5:R10, and the second highest, 4.8 pCi/sq m/s, was outside the fence at S5-5:R7-5. Measurements taken in August 1981 at 19 locations ranged from 0.3 to 32.9 pCi/sq m/s. The highest value (32.9 pCi/sq m/s) was at S1:R6, and the second highest (24.6 pCi/sq m/s) was at S5:R10.

In general, radon fluxes varied considerably with location; higher fluxes were found in the north-central area, both inside and outside the fence. The fluxes were also appreciably lower in June 1981 than in May or August 1981. Figures 2-3, 2-4, 2-5, and 2-6 summarize these data.

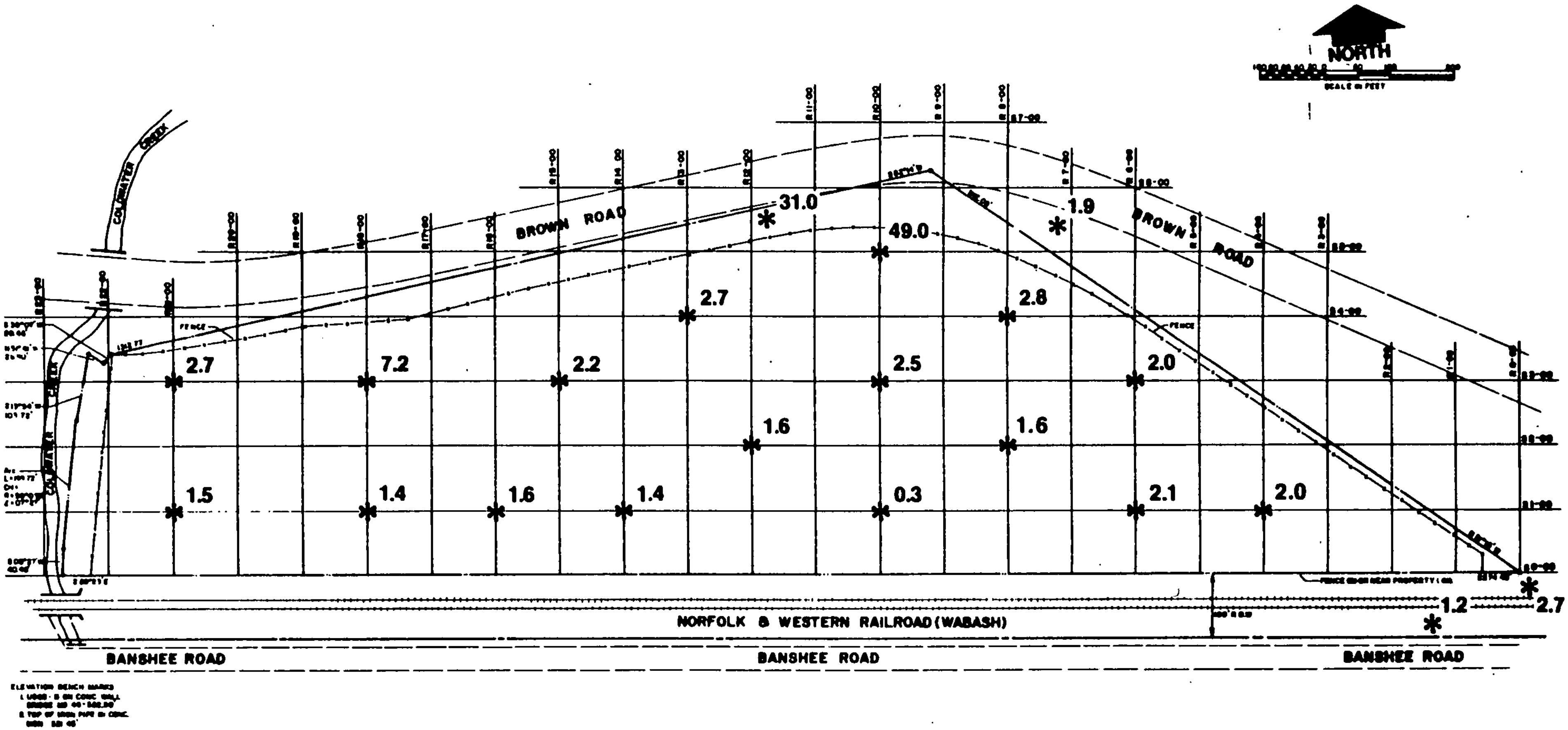
It is believed that the flux differences found in May and June 1981 were due to soil moisture. The soil at those times was very wet due to recent rainfall and a generally higher than normal precipitation rate for the spring and early summer of 1981. Standing water was observed at the site during the June measurements, and some of the measurement locations were moved slightly to avoid puddles.

Moisture measurements for soil grab samples taken at the time of the radon flux measurements reflect the absolute and relative moisture conditions. The samples were both taken at coordinates S2:R16. In May, the moisture content of the sample was 0.16 g water/g dry soil. In June the moisture content was 0.20. Both



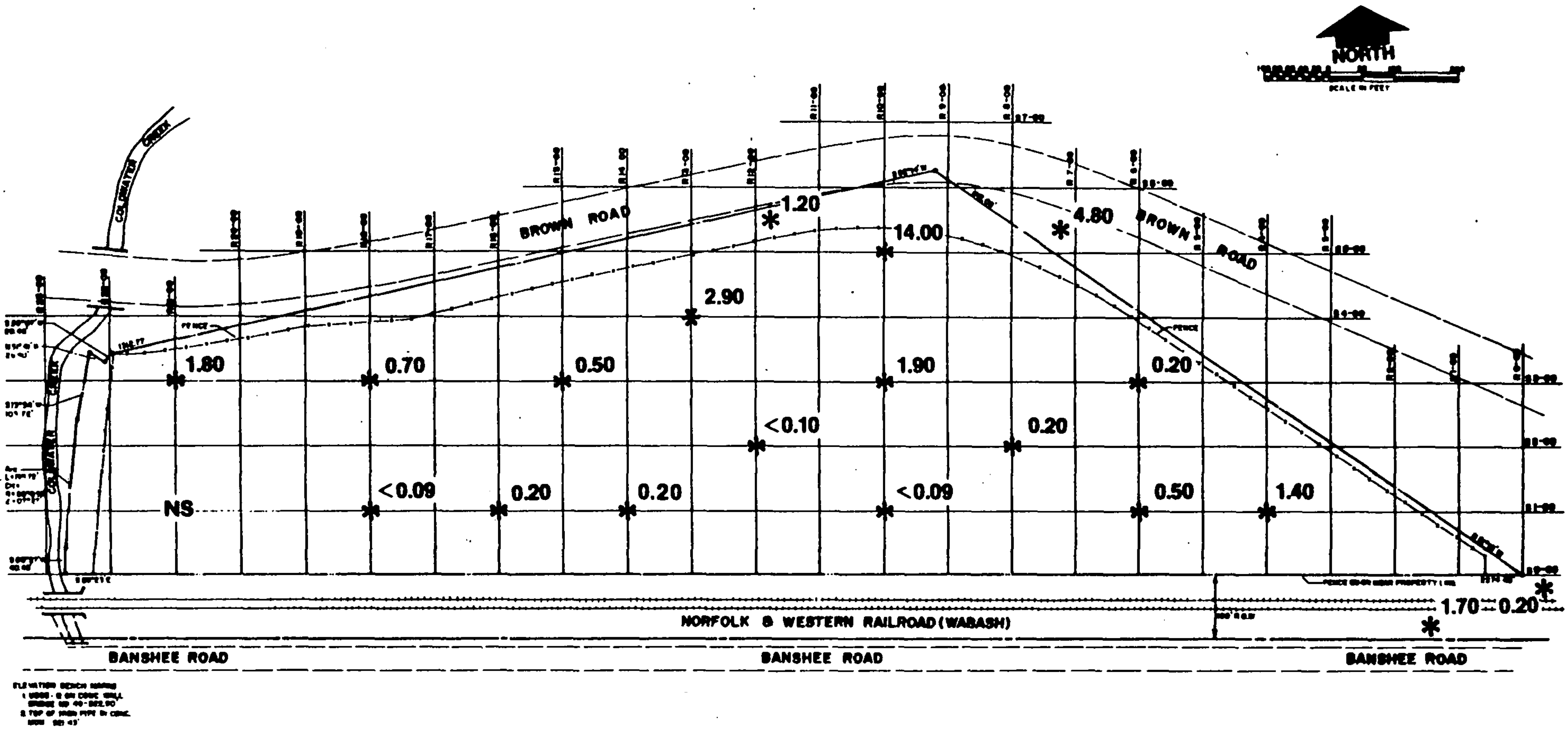
SOURCE: RADIOLOGICAL SURVEY OF THE ST. LOUIS AIRPORT STORAGE SITE, ORNL FINAL REPORT, SEPTEMBER 1979, DOE/EV-005/16, VC-70.

FIGURE 2-3
LOCATION AND MEASUREMENT OF RADON FLUX-PREVIOUS STUDIES
ST. LOUIS AIRPORT STORAGE SITE



* 1.0 LOCATION/RADON FLUX MEASUREMENT (MAY 1981—WESTON) pCi/M²/SEC

FIGURE 2-4
LOCATION AND MEASUREMENT OF RADON FLUX—MAY 1981
ST. LOUIS AIRPORT STORAGE SITE



0.50
* LOCATION/RADON FLUX MEASUREMENT
(JUNE 1981—WESTON) pCi/M²/SEC

FIGURE 2-5
LOCATION AND MEASUREMENT OF RADON FLUX—JUNE 1981
ST. LOUIS AIRPORT STORAGE SITE

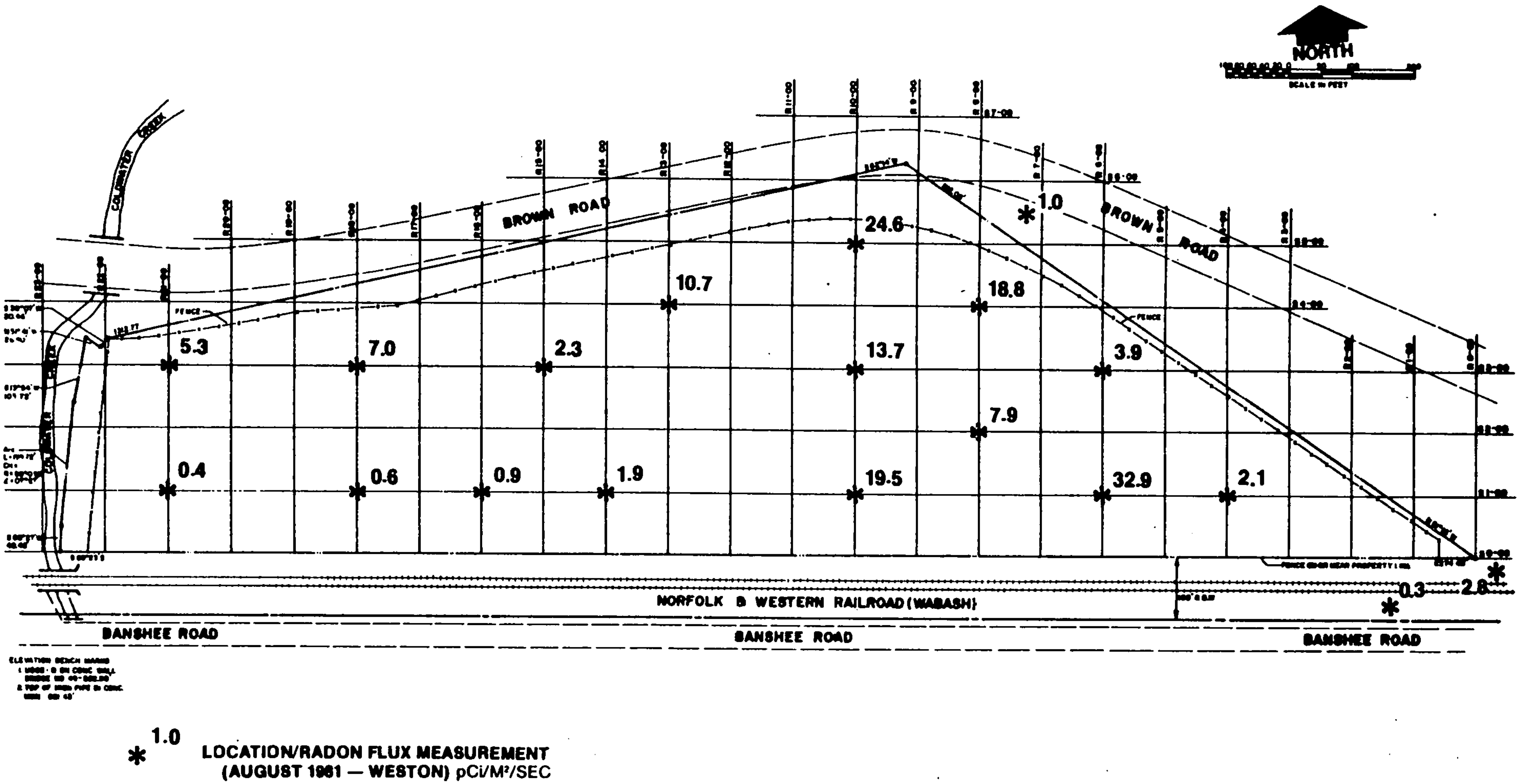


FIGURE 2-6
LOCATION AND MEASUREMENT OF RADON FLUX—AUGUST 1981
ST. LOUIS AIRPORT STORAGE SITE

values are high for surface soil, and the increase in moisture from May to June correlates well with the general decline in measured fluxes over that period.

The proposed EPA criteria for a radon flux <2 pCi/sq m/s for inactive uranium processing sites, which we use here as a guideline, have been interpreted to be the average flux over an annual cycle. The flux monitoring program at the airport site was performed to obtain flux measurements during different times of the year. This then permits the design and construction of radon attenuation covers that will meet the 2 pCi/sq m/s requirement at all times in the annual weather cycle.

2.3.4 Geological Characteristics[8]

The geology of eastern Missouri is one of unconsolidated Pleistocene sand, silt, and clay sediments which have been deposited on Paleozoic bedrock. These deposits represent glacial-derived outwash or loess, and alluvial deposits of the Mississippi and Missouri River systems. The bedrock on which these deposits lie is composed primarily of massive limestones, dolomites, and interbedded sandstone and shale formations. Based on this geological formation and other information, it can be concluded that minor to moderate tremors can be expected in the east-central region of Missouri, However, permanent alteration of the cur'ent site from seismic activity can be considered highly unlikely. More detailed information on the geology of Missouri can be found in reference 8.

2.3.4.1 Geology of the St. Louis Airport Site.

The geology of the site follows the general patterns described for eastern Missouri. Stratigraphic mapping of the site found 10 individual units which may be separated into four major divisions. These divisions and their units are described as follows and shown on Figure 2-7:

1. Division 1, Unit 1 -- Anthropogenous Material -- This material is composed of the landfill wastes and soil cover brought onto the site. The unit ranges from 0-foot thickness at the fence line to 8 feet in areas of buried materials.

2. Division 2, Units 2 and 3 -- Loess -- The Pleistocene and Pliocene sediments comprising these units were derived from glacially-related materials. Variable in color, they are highly compacted silt and clay deposits characterized by mineralization of root channels, low moisture content, and abundant mottling. This division varied in thickness between 3 and 4 feet for unit 2, and from 9 to 15 feet for unit 3.

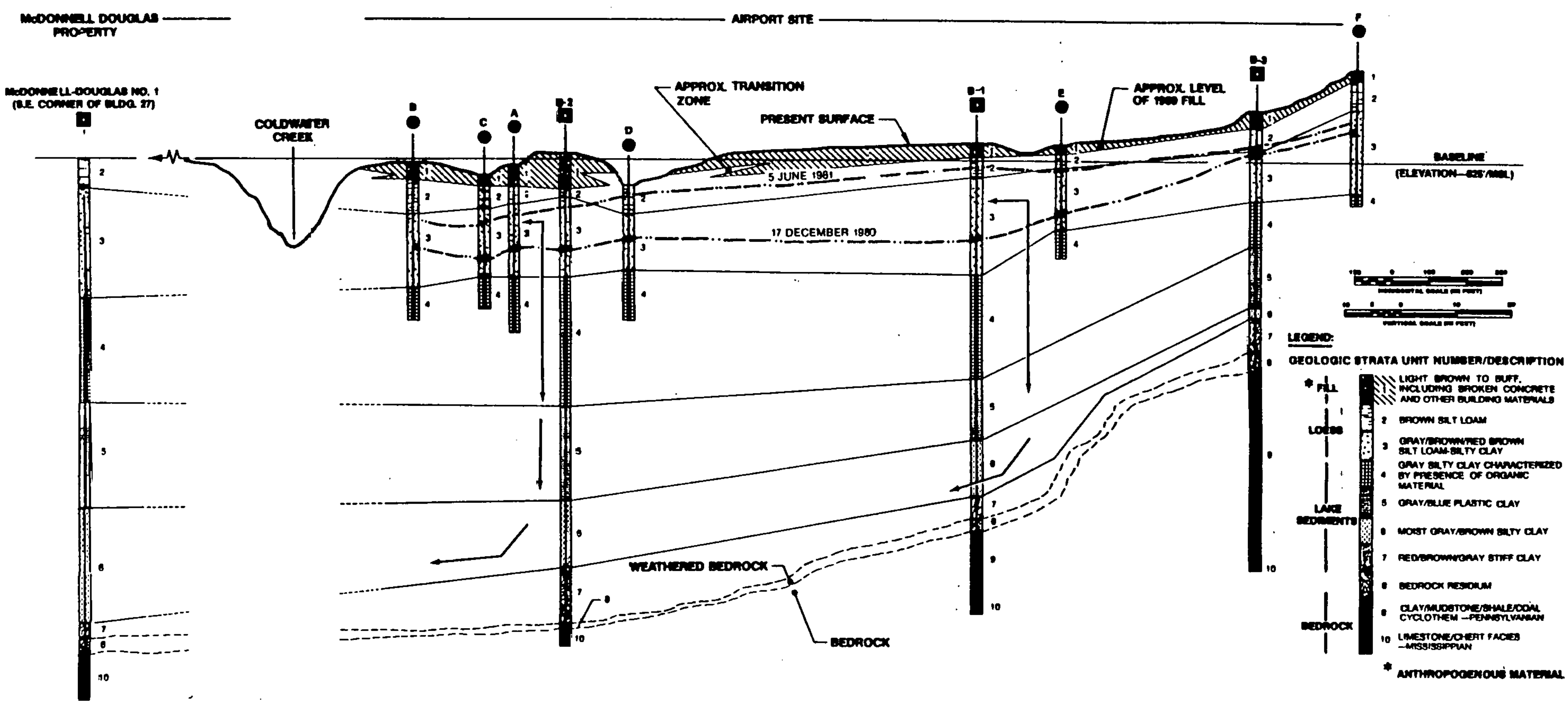
3. Division 3, Units 4, 5, 6, and 7 -- Lake Sediments -- This division is representative of the lacustrine sediments which were deposited in the structural basin when the Mississippi/Missouri River system flooded the area. The contents of the units in this division range from silty clay to plastic clay to stiff clay. This division varied in thickness between 23 and 65 feet.

4. Division 4, Units 8,9 and 10 -- Bedrock -- There were three bedrock formations found at the site. These bedrock units lie virtually flat and no evidence of displacement or developed fractures was found.

The geomorphology of the St. Louis Airport Site was determined from the 1979 topographic survey.(7) The ground surface generally slopes east to west toward Coldwater Creek. A total elevation difference of 25 feet exists across the site. The majority of gradient change is within the eastern quadrant of the site.

North to south across the site, there is little change in elevation. Ten to 20 feet within the fence line along the northern perimeter, the ground surface begins to slope downward from the fill surface into the concrete storm drain downgradient of Brown Road. This ditch trends west between the enclosure and Brown Road before discharging directly into Coldwater Creek.

Just beyond the fence to the west, a sharp drop of 15 to 20 feet exists from the site to the bed of Coldwater Creek. This perennial stream, the only surface-water body in the area, flows north and east before discharging into the Mississippi River tributary system.



WATER TABLE/DATE
GROUNDWATER FLOW
BORE HOLE LOCATION/DESIGNATION (WESTON)
A ● SHALLOW
B-1 ■ DEEP

FIGURE 2-7
GEOLOGIC CROSS-SECTION OF THE ST. LOUIS AIRPORT STORAGE SITE

2.3.4.2 Ground-Penetrating Radar Survey.

In an attempt to further clarify the site geology and to more clearly evaluate the distribution of contaminants buried at the St. Louis Airport site, two ground-penetrating radar (GPR) surveys were conducted. The first was a shallow or near-surface survey that was conducted to locate areas where residues had been buried and to help characterize the fill material. The second, deep survey was conducted to assist in characterizing the site's stratigraphy.

As a result of these surveys it is reasonable to conclude that:

1. The western third of the site had been used for the disposal of drums, rubble, and large block material.

2. The western third of the site may have had a second covering layer of fill and sludge.

3. At depths up to 15 feet the subsurface showed signs of alteration or influence by surface activities.

2.3.5 Groundwater Hydrology[8]

The groundwater hydrology of the site was determined from field studies conducted from November 1980 to July 1981. These field studies included:

1. Installation of three deep bore holes and construction of monitor wells at these sites.

2. Size and permeability analyses from Osterburg cores obtained at the boring sites.

3. Field measurements of water levels from all resurveyed monitor wells.

4. Installation of piezometer nests at three deep bore holes.

Data obtained from these studies was analyzed and led to the following conclusions (refer to Figure 2-7 which shows the direction of groundwater flows):

1. Two separate water-bearing zones can be identified. An "unconfined" water table system exists within surface sedimentary units 2, 3, and 4. A partially-confined system exists in unit 6. Vertical recharge to the partially- or "semi-confined" system is through unit 5, a thick continuous sequence of lacustrine clay (K x 1 x 10^{-7} cm/s).

2. The predominant direction of groundwater flow is due west, toward Coldwater Creek at a rate of approximately 0.33 ft/yr. As such, 70 to 80 gallons of groundwater/day can enter the creek.

3. Water level data from vertical piezometer nests indicate that recharge to the shallow groundwater regime is principally accomplished through infiltration subsequent to percolation of on-site precipitation. A minor component of recharge from off-site is generated in topographically-high areas directly south and southeast near the St. Louis Airport perimeter.

4. Application of Darcy's principles for flow through a porous medium indicates a 2:1 ratio exists in terms of total discharge vertically and horizontally over the western third of the site. In the central portion, the vertical component of groundwater movement is 10 times greater than the horizontal component.

5. The ratio of the directional vectors is a function of the sloping bedrock interface and stratigraphic position of unit 5 as the limiting unit or aquatard in vertical flow.

6. Vertical permeability through the fine-grained materials is enhanced by the presence of well-developed secondary permeability features, primarily extensive root channels in units 3 and 4.

7. Composite water level data collected over a six-month period show wide fluctuations in the position of the shallow groundwater table (units 2, 3, and 4) in response to unusually heavy precipitation. Depth to the zone of saturation in the central portion of the site has been less than 3 feet.

8. While the relative position of the water table in units 2, 3, and 4 has fluctuated over a span of 6 to 8 feet, the vector direction of groundwater movement is essentially constant.

2.4 SUMMARY OF SITE CHARACTERISTICS

The St. Louis Airport storage site is located approximately 15 miles northwest of downtown St. Louis and directly north of the Lambert-St. Louis International Airport. The 21.7-acre site is bounded by highways to the north and east, a railroad mainline on the south, and Coldwater Creek on the west.

Between 1946 and 1966, this site was used for storage of waste residues from uranium processing and other activities. In addition, approximately 60 truckloads of contaminated scrap metal and a contaminated vehicle were buried in the site. In 1966 and 1967, the stored residues were sold for their mineral content, and the site was conveyed to the Airport Authority. The site was then razed except for the boundary fence, the contaminated materials removed, and the site covered with 1 to 3 feet of clean fill.

Site characterization involved the collection and review of all available data concerning the site, both published and unpublished. Specifically, data on site history, topography, radiological characteristics, groundwater kinetics, and geological characteristics were obtained and evaluated.

The geology of eastern Missouri is that of unconsolidated Pleistocene sand, silt, and clay sediments which have been deposited on Paleozoic bedrock. These deposits represent glacial-derived outwash or loess, and alluvial deposits of the Mississippi and Missouri River systems. The bedrock on which these deposits lie is composed primarily of massive limestones, dolomites, and interbedded sandstone and shale formations. Based on this geological formation and other information, it was concluded that minor to moderate tremors can be expected in the east-central region of Missouri, centered within the Mississippi embayment.

However, permanent alteration of the current site from seismic activity can be considered highly unlikely.

The site geology and geohydrology was determined by bore hole, piezometric, ground-penetrating radar (GPR), and topographic analyses. It was found that the predominant direction of groundwater flow is due west toward Coldwater Creek at a rate of approximately 0.33 ft/yr. At this rate, 70 to 80 gals groundwater/day from the site can enter Coldwater Creek. The ground surface slopes to the west with an elevation difference of 25 feet across the site. Ground-penetrating radar surveys found that the site had probably been used for disposal of barrels and sludges. Additionally, the GPR helped to characterize the depth and extent of rubble fill.

The radiological quality of the site was evaluated by measuring beta-gamma levels 1 centimeter above the ground, gamma levels 1 meter above the ground, gamma logging of bore holes, measuring soil and water radionuclide concentrations, and measuring radon fluxes. Based on these data, it appears reasonable to conclude that the contaminated material was initially buried in the western end of the site at depths of 3 to 12 feet. Contaminated areas were also found along the site's northern fence and in the ditches outside this boundary. A review of the logging plots also indicated that a 2-foot thick fill cover attenuated the radiation levels by a factor of 10. The radon flux measurements found values well above background in many areas of the site.

REFERENCES

SECTION 2

SITE DESCRIPTION

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SECTION 3

CONTROL REQUIREMENTS AND OPTIONS

3.1 REGULATORY CONSIDERATIONS

3.1.1 Background

Under the Formerly Utilized Sites Remedial Action Program (FUSRAP), the U.S. Department of Energy (DOE) has the project management responsibility to ensure that remedial action takes place at the selected sites. The U.S. Environmental Protection Agency (EPA) advises the Department of Energy on potential health hazards, and establishes environmental standards. As part of its role to provide radiation protection standards to other Federal agencies, the EPA provides general criteria for control of radioactivity in the environment. The agency has issued interim and proposed final standards for the uranium mill tailings project (40 CFR 192). These standards will provide temporary guidance under FUSRAP for uranium residues containing radium until EPA criteria standards specifically applicable to FUSRAP are promulgated.

A third regulatory entity, the Nuclear Regulatory Commission (NRC), will review the remedial action programs under FUSRAP. In its approval review, NRC will be primarily concerned with ensuring that the health and safety of the public is protected, and that the quality of the environment is preserved. The NRC is responsible for enforcing both its own criteria and standards (10 CFR 61) and the standards established by the EPA for controlling radiation in the environment.

3.1.2 Containment Concept

The EPA has a primary responsiblity for developing environmental standards for the disposal of wastes from formerly used sites. The EPA has proposed regulations for inactive uranium processing sites under the Uranium Mill Tailings Radiation Control Act of 1978. However, the EPA has indicated that the use of these regulations will provide temporary guidance under FUSRAP for uranium residues containing radium until EPA criteria and standards specifically applicable to FUSRAP are promulgated.

In the Uranium Mill Tailings Remedial Action Project (UMTRAP) program, Congress has recognized that uranium mill tailings are hazardous for a long time. They directed the EPA to set reasonable standards for their disposal. They further directed that the remedial action taken at each site must be performed correctly. The EPA has proposed a requirement specifying 1,000 years protection. This means there must be a reasonable expectation that site integrity will be preserved for at least 1,000 years. Specific methods to implement the 1,000-year containment standard will be evaluated based on an analysis of the physical properties of the disposal system and the potential effect of natural processes on this system. This, of necessity, will be on a case-by-case basis. Models, theories, and expert judgement will be the major tools in determining whether disposal system will satisfy the standards.

This containment concept will be implemented through radon emission and water protection standards. These guidelines are discussed in the subsections that follow.

3.1.3 Radon Emission Standards

The EPA has proposed an emission rate of 2 pCi/sq m/sec. Analyses of controlling radon emissions by covering the piles with soil indicate that the required cover and thickness, and therefore, the cost, are reasonable at this level. This value will be used in developing and evaluating alternative remedial actions at the St. Louis Airport site.

3.1.4 Groundwater Protection Standards

The performance standard for groundwater protection in 40 CFR 192 provides that selected contaminants in disposed tailings piles will not exceed specified levels. These standards are outlined in Table 3-1.

In addition to the values listed in the table, it was proposed that:

1. If upstream groundwater levels exceed the specified concentration levels and do not result from tailings, then no further degradation is allowed.

2. For existing sites, the EPA is proposing that the groundwater protection standards be applied starting 1.0 kilometer from the pile.

WESTON

Table 3-1

Proposed Groundwater Protection Standards

Contaminant	Level
mg/L	
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Lead	0.05
Mercury	0.002
Molybdenum	0.05
Nitrogen (in nitrate)	10.0
Selenium	0.01
Silver	0.05
pCi/L	
Combined Ra-226 and Ra-228	5.0
Gross alpha particle activity (including Ra-226 but excluding radon and uranium)	15.0
Uranium	10.0

3. The disposal standards for a new site be applied starting 0.1 kilometer from the site.

3.1.5 Surface-Water Protection

The EPA has developed a surface-water protection standard. This standard requires that any contaminant entering a surface water from a disposal site not cause an increase of that contaminant in the surface receiving water. In developing the disposal systems that will meet the radon emission limits and the groundwater protection requirements, the surface-water requirement should also be met.

The site design standards are performance-oriented and related to total containment. They are compatible with the EPA's proposed standards in that after closure, the need for ongoing active maintenance is eliminated, and only minor custodial surveillance and monitoring are required.

3.2 CONTROL REQUIREMENTS

3.2.1 Surface Runoff and Erosion

Surface runoff and erosion are means by which contaminated materials may be carried off-site. During the construction period, stormwater runoff from contaminated areas will be collected by means of temporary drainage ditches and swales and treated, if necessary. Collected stormwater will be channelled to a sedimentation basin, where the water will be tested for contamination. If none is found, the water will be released to Coldwater Creek; otherwise, appropriate treatment will precede its release to the creek. It is not expected, however, that treatment beyond sedimentation will be required. The sedimentation basin will also serve to allow collected sediments to settle out of stormwater. This will minimize the quantity of sediment, particularly contaminated sediment, which migrates off-site. Clean stormwater runoff will be diverted around the site.

As a part of the remedial action strategy, all final cover layers on the site will be vegetated to provide stabilization and encourage evaporation. A well-established vegetative growth will minimize erosion of the final cover due to storm events.

3.2.2 Subsurface Migration

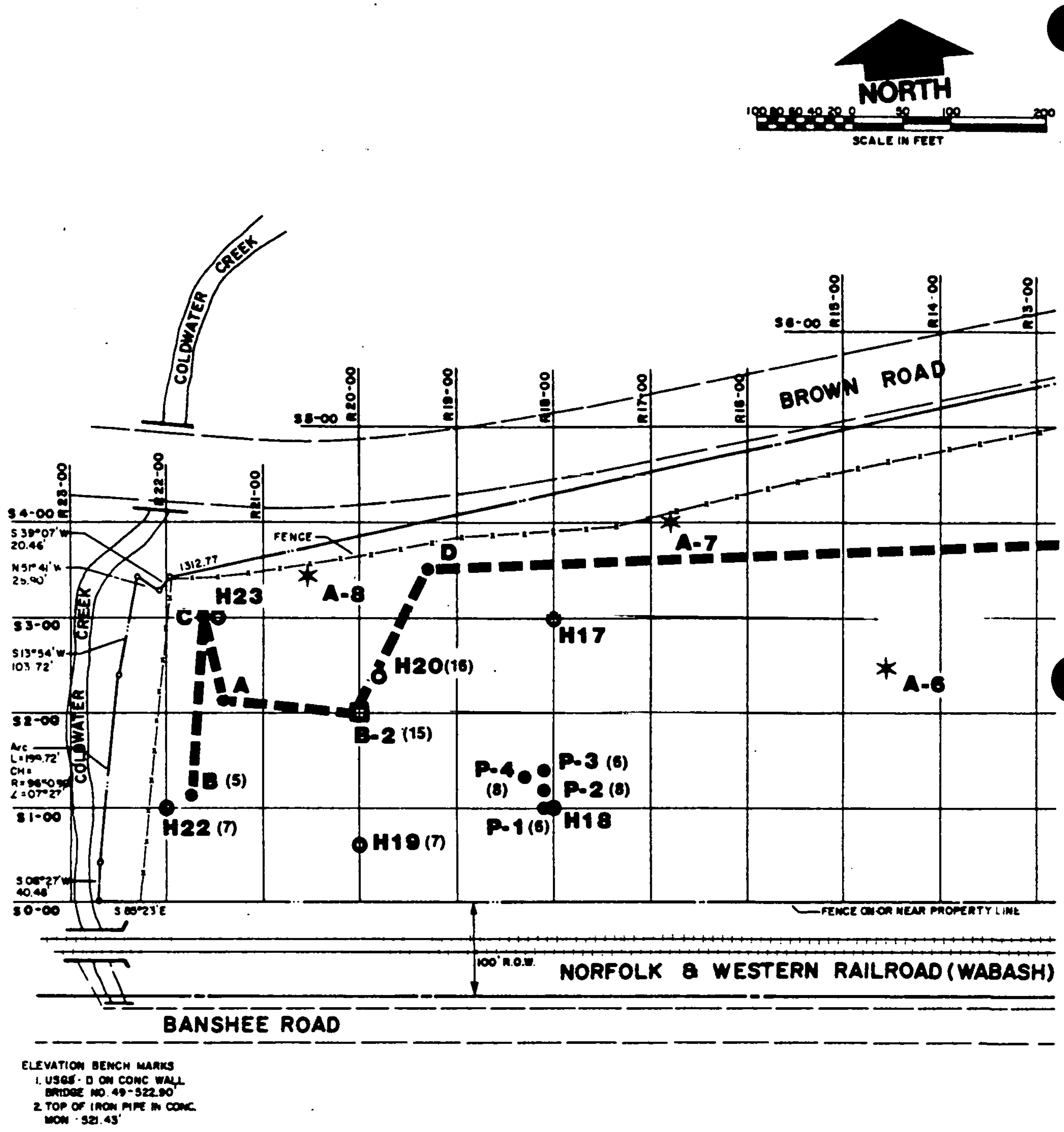
It is known that 50 to 60 truckloads of metal scrap and possibly a contaminated vehicle were buried near the western end of the site and subsequently covered with fill. The presence of this deposit was verified by gamma loggings of wells conducted during the 1978 Oak Ridge National Laboratory study, and has been further documented by additional gamma logging during the current investigation. Gamma peaks have been found up to 15 feet below the current ground surface where it is in contact with groundwater periodically.

Figure 3-1 shows the locations of test borings at the western end of the site. Those borings showing significant subsurface gamma activity are identified. On Figure 3-2, recent observations of water table elevations are combined with gamma logging data to illustrate the extent of contact between groundwater and waste materials. Contact has been observed at bore holes B-2 and D, and undoubtedly occurs periodically at bore hole B. Lacking further data, it must be assumed that the relatively deep deposits at the western end of the site are subjected to cyclical wetting by groundwater. The deposits are, therefore, susceptible to horizontal leaching of radioisotopes into Coldwater Creek.

Over the remaining site area, the data indicate that contamination is confined to the upper few feet. Since there is no direct contact with groundwater, initial migration of radioisotopes must be downward with rainfall seepage prior to possible groundwater contamination. Vertical movement of uranium, thorium, and radium is normally a very slow process. Considering the high clay mineral content of the soil, off-site contamination by materials above the water table is regarded as very unlikely in a 1,000-year time frame. Thus, subsurface controls will be concentrated on those deep deposits at the western end of the site.

Historical evidence and field data indicate that contamination at the site consists of uranium, radium, and their decay products. There is no evidence of significant underground movement of any radioisotopes from their original point of deposition. This is in accordance with previous experience with analogous materials in mine tailings piles where the heavy metals have shown only limited mobility. However, the time since deposition has been short relative to the stabilization goal of 1,000 years or more. Some creep may have occurred within this period without detection by the field measurements performed.

Permeability data from test borings at the site indicate values from 10^{-6} to 10^{-8} cm/sec in subsurface strata. However, it was not possible to determine whether bulk permeabilities in the upper soil layers may be reduced by anomalies such as shrinkage



BORE HOLE LOCATION/DESIGNATION (WESTON)

OH21 BORE HOLE LOCATION/DESIGNATION (ORNL)

(6) DEPTH IN FEET TO SIGNIFICANT SUBSURFACE GAMMA PEAK

CROSS-SECTION AXIS

SOURCES

1. PART OF SURVEY AND GRID SYSTEM FROM ROWLAND SURVEYING CO. MAP DATED 25 AUGUST 1979
2. ORNL DATA—RADIOLOGICAL SURVEY OF THE ST. LOUIS AIRPORT STORAGE SITE, ORNL FINAL REPORT, SEPTEMBER 1979, DOE/EV-005/16, UC-70

FIGURE 3-1
TEST BORE HOLE LOCATIONS AT WESTERN END OF ST. LOUIS AIRPORT STORAGE SITE

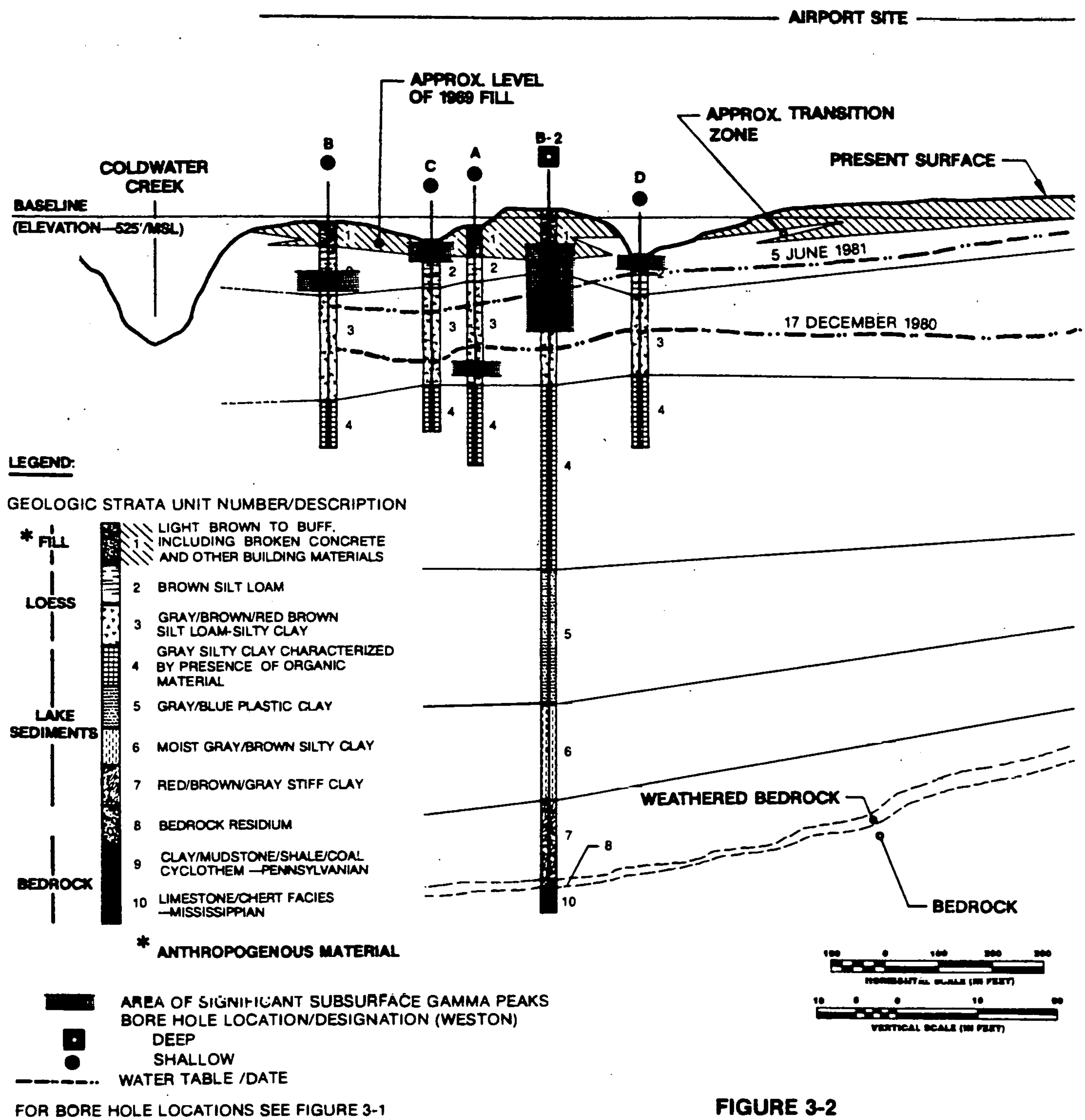


FIGURE 3-2
GEOLOGIC CROSS-SECTION AT WESTERN END OF THE ST. LOUIS AIRPORT STORAGE SITE SHOWING WATER TABLES AND GAMMA LOGGING

or cracks. Allowing for such a reduction by assigning a bulk permeability of 10^{-5} cm/sec would produce a groundwater velocity of 1/3 ft/year at the prevailing hydraulic gradient. Since bore hole B is approximately 100 feet from Coldwater Creek, a flow time of 300 years would be required for any radioactivity to reach the creek.

Figure 3-2 shows that the groundwater table rose approximately 6 feet during the interval from 17 December 1980 to 5 June 1981. A change of this magnitude appears inconsistent with the laboratory-measured permeability of soil samples, and would tend to indicate an increased bulk permeability in the upper soil layers possibly due to flaws and/or anomalies. Since the buried waste is in the zone of fluctuating water table, it must be assumed that the radioisotopes may be considerably more mobile than is indicated by the permeability data, and in fact may be "pumped" to the stream by relatively rapid rises and falls in the water level.

Measured pH values of the groundwater run as low as 6.2. This mildly acidic nature is consistent with the existence of coal-bearing formations located upgradient at the eastern edge of the site. Although not a major factor, the acidic pH would tend to increase cation mobility and enhance any tendency of uranium and radium to leach from the buried wastes.

The soils underlying the entire site consist of fine-grained types containing significant clay fractions. The natural ion exchange capacity would tend to retard movement of any heavy metal cations through groundwater. This factor, however, may not be fully operative in the upper soil layers. If groundwater movement is along flaws, only limited actual contact with clay may occur and the ion exchange capacity might be exhausted relatively rapidly.

In weighing the factors just discussed, the following conclusions have been reached:

1. Some deep waste deposits are located in the zone of fluctuating groundwater table where alternate wetting and draining would tend to increase ion mobility.

2. If the measured permeabilities of the soil are valid in this zone, ion mobility would be very low due to the slow groundwater movement and

ion exchange capacity of the soil. Movement would be enhanced by the mildly acidic nature of the groundwater and also by the very high cation concentration.

3. The relatively rapid observed increase in groundwater elevation indicates that flaws probably exist in the upper soil layers in contact with the waste materials. The existence of such flaws would allow rapid movement of isotopes and largely obviate the ion exchange properties of the soils. There is no adequate way to confirm the presence of flaws within a reasonable time frame, but such flaws would normally be expected in a cohesive soil.

4. If the parent materials, uranium, and radium, are immobilized in place, it is unlikely that radon and its daughters would constitute a problem unless groundwater movement is very rapid. Immobilization by positively blocking groundwater movement would also be effective in preventing migration of all types of radioisotopes expected in the deposit.

5. Any system to block the horizontal movement of wastes should also prevent infiltration through the waste deposit to minimize leaching of radioisotopes into the active groundwater zone.

3.2.3 Radon Diffusion

The nature of the waste formerly and currently in place at the St. Louis Airport site dictates concern for emission of radon from the site. Consequently, permanent protection of humans from elevated radon and radon daughter levels must depend on site barriers that can provide protection at present, and remain effective for long periods of time.

3.2.4 Physical Transport

Physical transport of the waste at the St. Louis site could occur by means of animals, plants, or humans. Burrowing animals in their search for food and water could make their way through cover layers and into the waste material, and then remove and transport this material. This would expose contaminated materials to the elements. To prevent transport of contaminants by animals, cover layers will be designed to discourage burrowing. Fencing the site will prevent access by any larger animals.

Plant roots, especially the roots of large woody-type plants, shrubs, and trees may extend through cover layers into the waste. This could severely diminish the integrity of the cover, providing a direct pathway for radon gas to escape to the atmosphere. In addition, there could be a significant uptake of contamination by plants whose roots extend into the waste material. This would result in leaves, bark, branches, etc. which are contaminated. The growth of woody vegetation on the cover surface can be eliminated with regular mowing. If this type of regular maintenance is not feasible, time-released herbicides might be employed. This would involve placing a layer of time-released herbicide capsules within the cover at a depth where the roots of woody plants would be attacked, but the roots of grasses, etc. would be unaffected.

If the site were to be developed in the future, human transport of contaminated materials could occur. Long-term (1,000 years) controls over development activity are difficult to devise, but deed restrictions will be effective for at least the first 100 years after remedial action is completed. Problems with vandalism in the short term can be addressed with warning signs, lighting, and fencing.

3.3 CONCEPTUAL CONTROL OPTIONS

The basic control options considered in this report are presented in the following sections:

- Section 4 -- Cover Systems
- Section 5 -- Waste Conditioning
- Section 6 -- Ion Exchange Media
- Section 7 -- Subsurface Barriers
- Section 8 -- Liners
- Section 9 -- Development of Selected Alternatives
- Section 10 -- Surface Runoff and Drainage Control

- Section 11 -- Monitoring Program
- Section 12 -- Assessment of Subsurface Pollutant Transport Models
- Section 13 -- Implementation Guidelines

These sections are presented in a modular fashion to allow flexibility of implementation and possible changes in direction due to funding, and institutional and regulatory requirements. The modular approach will allow implementation of parts of the in situ stabilization options as interim or partial measures in response to such uncertainties.

SECTION 4

COVER SYSTEMS

4.1 INTRODUCTION

The cover, as an element of site stabilization, plays a most important role in protecting the environment and public health. A properly selected, designed, and constructed cover system will result in control of potential radioactivity releases through air diffusion, surface and subsurface migration, and other physical transport pathways.

The selection and evaluation of cover systems for low-level radioactive waste is a function of various performance criteria and cover materials. A successful cover system will provide effective control of surface-water infiltration and radon gas emissions, and will remain effective with minimum maintenance for 1,000 years. The control of surface-water infiltration will minimize radionuclide leaching and subsequent transport. Radionuclide transport may lead to contaminant migration in the groundwater to wells or surface streams. Radon gas control is essential for public health protection and waste containment. Finally, long-term containment and control is necessary for public safety and waste stabilization.

An extensive review of the literature was conducted to establish both design criteria and previous operations experience. The types of information reviewed fall into the following five categories:

1. Conference and symposia papers.

2. Current research update reports.

3. Technical journal articles.

4. Federal agency technical evaluation reports.

5. Authoritative technical assessment correspondence.

In reviewing these documents, specific attention was placed on past experience and current research efforts. Useful information was also obtained by reviewing existing technology for cover systems for solid and hazardous wastes. Based on these reviews, it was determined that multilayer cover systems are superior to mono-layer covers. A mono-layer cover consists of a single material emplaced over a residue area. In addition to the limitations inherent in the cover materials themselves, which are different for different materials, all mono-layer covers have the following common disadvantages:

1. Limited protection from wind and water erosion.

2. Susceptibility to surficial cracking during periods of drought.

3. Lack of any back-up protection against sudden failure which might result in a total loss of integrity.

Therefore, consideration has been given to the design of a multilayer cover system.

4.2 FUNCTIONAL COMPONENTS OF A MULTILAYER COVER SYSTEM

A generic multilayer cover system for low-level radioactive residues is shown on Figure 4-1. The system consists of the following:

1. Top layer of noncompacted soil which will support vegetation.

2. A middle layer of coarse gravel or crushed rock.

3. A bottom layer of clay.

The purpose of the noncompacted soil is to support grasses which control water and wind erosion. The middle soil layer acts as a porous flow zone which diverts water to seepage pits well below the soil surface. This layer consists of well-graded granite gravel or crushed rock. The bottom clay layer or cap consists of low permeability and high clay content compacted soil. The clay layer functions as an impermeable barrier against radon emissions and water percolation.

Reduction of water percolation through the cover into the waste is a function of natural permeability and layer thickness. For example, a highly impermeable ($K = 1 \times 10^{-12}$ cm/s) asphalt liner of minimal thickness will provide the equivalent infiltration attenuation of a much thicker (3 to 5 feet) layer of a natural clay with a permeability coefficient of 1×10^{-6} to 1×10^{-8} cm/s.

The functions of the impermeable layer are to control radon emissions and minimize percolation. Typical materials used for such a layer include natural clays, compacted soil ($K = 1 \times 10^{-6}$ cm/ overlaid by a clay or soil/bentonite mixture ($K = 1 \times 10^{-7}$ cm/s), asphalt, or synthetic materials.

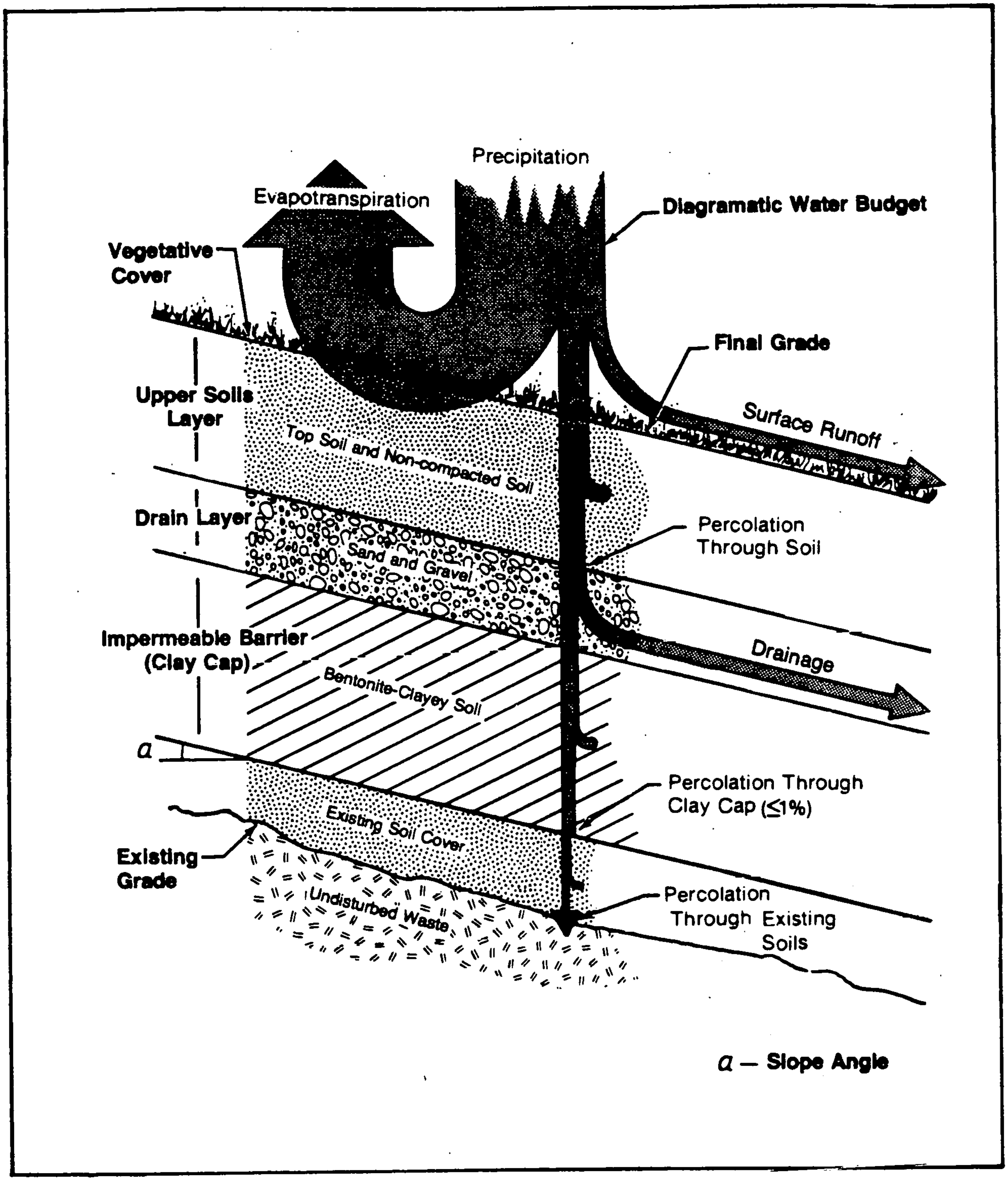


FIGURE 4-1 PROFILE OF GENERIC COVER SYSTEM

The purpose of the drain layer is to laterally divert as much water as possible. The effectiveness will not be great enough, however, to cause a drying-out or desiccation of a clay layer. A very small amount of water will be absorbed to saturate a few millimeters of its upper surface. The degree to which this occurs will depend on the clay moisture content. Less water will be immediately absorbed as clay moisture content increases, which, in turn, decreases capillary tension. Conversely, during prolonged drought periods, greater amounts of water will be absorbed. Over time, the net result of this action will satisfy the minimum moisture contents required to prevent excessive shrinking or cracking, as well as maintaining its effectiveness as a barrier for radon emissions.

The drain layer must be of relatively high permeability. It will usually consist of crushed rock or coarse gravel. "Filter" criteria must be imposed so that fine particles will not migrate into the drain layer, thus, plugging void spaces. As added protection, a filter fabric may be added. Diversion efficiencies of at least 60% are required, i.e., 60% of water vertically impinging on the drain will be laterally diverted. Efficiencies above 90% are desired. Drain thicknesses of 1 to 2 feet are sufficient for permeabilities (K's) of 0.1 cm/s and drainage lengths of several hundred feet at a 5% slope or less.

The purpose of the upper soils (top soil and noncompacted soil) is to protect the low permeability layer below, primarily from erosion and excessive moisture loss; and to attenuate the amount of water available for deep percolation through the entire system.

Principal water losses are due to surface runoff and evapotranspiration. The net difference between water added as precipitation and that lost by runoff and evapotranspiration is percolation through the topsoil. Typically, for upper soils that are 18-inches thick, approximately 75% of water added as precipitation will be lost.

4.3 TYPES OF COVER MATERIALS

Eighteen cover types were systematically evaluated based on 20 performance criteria. The covers were then ranked based on these criteria, and the best performer was identified. Six major classes of covers were evaluated and are as follows:

1. Multilayered.
2. Asphalts.

3. Concrete.
4. Synthetics.
5. Natural soils.
6. Soil admixtures.

Our evaluation has shown two cover systems to be most applicable to the St. Louis Airport site concept. These are:

1. Multilayered soil system.

2. Multilayered asphalt system.

Each cover material has certain advantages and disadvantages. No one cover material possesses all of the attributes that would classify it as an ideal cover. Therefore, it seems logical to use a combination of cover materials, and take advantage of their additive and synergistic effects. A multilayered cover system must account for the following major performance criteria:

1. Minimize surface-water infiltration.

2. Control radon gas emission rates.

3. Provide a reasonable expectation for a 1,000-year, no maintenance life.

These systems are described and evaluated in detail in Appendix A.

In Appendix A.1, general cover classes are discussed, and the associated design strengths and weaknesses highlighted. With proper attention to critical design criteria and the use of a consistent evaluation procedure, the superior covers were readily identifiable.

4.4 COVER SYSTEM EVALUATION

A critical part of the sequence of designing, constructing, and maintaining an effective cover system over low-level radioactive wastes is the systematic evaluation of engineering criteria. First, the individual performance criteria are assessed and standardized. Each cover type is then evaluated based on each of the performance criteria, and the most suitable cover system is selected for further development. Appendix B discusses the individual performance criteria.

Each cover material was evaluated based on the performance criteria discussed in the previous subsection. A systematic performance rating of each cover material is shown in Table 4-1. If a cover material was given a positive performance rating, a plus sign appears in that criteria column. If a negative performance rating was given, a minus sign appears in the criteria column. It is clearly seen that the multilayered cover system shows the best performance. A multilayered cover system was chosen due to the additive and synergistic effects of cover performance criteria. No single cover material meets all of the required performance criteria, and, therefore, a multilayered cover is necessary.

Samples of local soils were obtained and tested in the laboratory to determine their ability to contain radon. Computer codes were then exercised, using the characteristics measured, to design radon attenuation covers that would reduce fluxes from the waste at the airport site to meet the NRC requirements. Specifications for the minimum thickness covers are provided herein. If the NRC requirement for 3 meters of cover is also to be met, additional earthen material can be placed on top of these covers. This report describes these steps in detail.

4.5 FINAL COVER SYSTEM SELECTION

Cover systems have been evaluated based on approximately 20 criteria specific to stabilization of low-level radioactive solid wastes. Multilayered cover systems, consisting of a top layer of uncompacted soil, a middle layer of coarse gravel or crushed rock, and a bottom layer of clay show the highest performance, largely because the layering effect aids in the overall performance of the system. In some instances the performance of each layer is not strictly additive but synergistic. An example of such a synergistic effect is that while gravel alone does not impede water infiltration, when placed above the clay layer, it acts as a drain in removing water which potentially would percolate through the clay layer. Therefore, in the multilayered system gravel does aid in impeding surface-water infiltration.

The only criterion in which this cover system performed poorly was in its inability to impede root penetration. Here it is believed that initial sterilization of the topsoil, along with grass stabilization and periodic mowing, will eliminate this potential problem.

Table 4-1

Cover Material General Performance Criteria Evaluation

Cover Material	Historical Applications as a Cover Material	Trafficability	Impede Water Percolation	Radon Gas Control	Erosion Control	Aid Surface Runoff	Desiccation	Freeze/Thaw Stability	Seismic Stability	Crack Resistance	Side-Slope Stability	Potential for Side-Slope Seepage	Discourages Rodent Burrowing	Supports Vegetation	Ease of Construction	Probable 1,000-Year Life	Cost of Placement	Biological Deterioration	Root Penetration	Wave Radiation Gamma Penetration
Spray Asphalt Emulsion	-	-	+	+	+	+	+	+	-	-	-	+	-	-	-	-	+	-	-	-
Hydraulic Asphalt	-	+	+	+	+	+	+	+	-	+	+	+	+	-	-	-	-	-	-	+
Synthetic -- CSPE	-	-	+	-	+	+	+	+	-	-	-	+	-	-	-	-	-	-	-	-
Synthetic -- PVC	-	-	+	-	+	+	+	+	-	-	-	+	-	-	-	-	-	-	-	-
Synthetic -- Neoprene	-	-	+	-	+	+	+	+	-	-	-	+	-	-	-	-	-	-	-	-
Synthetic -- CPE	-	-	+	-	+	+	+	+	-	-	-	+	-	-	-	-	-	-	-	-
Concrete	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	+	+
Low Permeability Native Soils	+	-	+	+	-	+	-	-	-	-	+	+	-	+	+	+	+	+	-	+
On-site Soils	+	+	-	+	-	-	-	-	-	-	+	+	-	+	+	+	+	+	-	+
Soil Admixtures (Bentonite)	+	-	+	+	-	+	-	-	-	-	+	+	-	+	+	+	+	+	-	+
Bentonite	+	-	+	+	-	+	-	+	-	-	+	+	-	-	+	+	-	+	-	+
Well-Graded Gravel	+	+	-	-	+	-	+	+	+	+	+	-	+	-	+	+	+	+	-	+
Riprap	+	+	-	-	+	-	+	+	+	+	+	-	+	-	+	+	+	+	-	+
Silty-Sand (Soil)	+	+	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	-	+
Clayey-Sand (Soil)	+	-	+	+	-	+	-	+	-	-	+	+	-	+	+	+	+	+	-	+
Soil Cement	-	-	+	+	+	+	+	+	-	+	+	+	+	-	-	-	-	+	-	+
Soil Asphalt	-	-	+	+	+	+	+	+	-	+	+	+	+	-	-	-	-	-	-	+
Multilayered -- Grass/Topsoil/Gravel/Clay/Soil	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	-	+

Finally, the cover system must be considered from a historical application viewpoint. Earthen covers have been used for waste impoundments for many centuries. The trench design for low-level radioactive waste disposal is in use in several disposal sites across the country, and earthen covers are also utilized. The Bear Creek Uranium Tailings Disposal Project, begun in 1974, in Converse County, Wyoming currently utilizes a multilayered earthern cover system similar to the one proposed in this report.(1)

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COVER SYSTEMS

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SECTION 5

WASTE CONDITIONING

5.1 INTRODUCTION

Waste conditioning is generally performed to meet one of the following three objectives:

1. To improve the handling and physical characteristics of the waste.

2. To decrease the surface area across which transfer and loss of contained contaminants can occur.

3. To limit the solubility of various contaminants within the waste.

After consideration of various waste conditioning methodologies, it was decided not to recommend any of them for application at the St. Louis Airport site. The potential for significant health effects, materials handling considerations, and costs were the primary factors in this decision.

Fixation could be considered for handling the material excavated from the ditches. It is necessary to excavate and handle this material as part of the closure, and therefore, the fixation processing steps would not involve as much additional handling as that which is already required. Due to the uncertainties involved with the long-term stability and weathering characteristics of the fixed material, it must be placed in a controlled area. Engineering controls that would be needed are a liner and a cover system. The additional cost for waste fixation is probably not justified because it cannot be viewed as a sole control option, and additional engineering controls would be necessary.

Two approaches for waste conditioning may be considered; these are:

1. In situ fixation.
2. Waste excavation, processing, and reburial.

5.2 IN SITU FIXATION/SOLIDIFICATION

The approach for in situ fixation of waste involves in situ fixing and reacting of the waste with the fixative material. In situ or in-place solidification has been tested in Hanford, Washington for the solidification of liquid radioactive waste in storage tanks. The technique used in this application involved concrete. The objective of this work was to develop a technique for in-place solidification where the risks of removal and treatment were much greater than those of immobilizing the waste in place. At the St. Louis Airport site the approach for in-place solidification could involve the injection of grout into the site to fill the void spaces and surround the buried material to reduce potential leaching of contaminants and to provide a barrier against radon emanation. While the techniques for subsurface grout injection may prove viable, the overall success and effectiveness of this approach are questionable. Major uncertainties include the following:

1. A large number of subsurface injection points would be required to intersect the void spaces which are of a localized nature.

2. It is not possible to guarantee that all void spaces will be filled and a large proportion of the buried waste will be encapsulated. Surface material cannot be handled with grout injection, and as a result, a surface cover system will still be required as part of the final control strategy.

In-place solidification and fixation will not be considered further as a primary alternative due to the uncertainties noted in addition to the fact that it will involve a considerable cost and will only be one component in the overall closure plan. This approach cannot be considered as the sole technique for completing closure of the St. Louis site.

5.3 WASTE EXCAVATION, PROCESSING, AND REBURIAL

The other approach that may be considered for the stabilization of the St. Louis site is excavation of all radioactive waste material, followed by processing through a fixation system. The high cost of thermoplastic and thermosetting resin techniques makes these lower priority options than cement, lime-based, or thermal techniques.

Lime or cement stabilization of the waste material at the St. Louis site can be considered the primary fixation options for closure of this site. The basic fixation process for handling these wastes would involve the following steps:

1. Waste excavation and storage.

2. Pulverization or size reduction of the waste material.

3. Processing the waste material and mixing it with the fixation additive.

4. Temporary strorage of the mixture to allow preliminary curing.

5. Reburial and disposal of the fixed material.

The excavation and size reduction/pulverization steps involve a significant risk of environmental impact due to airborne migration of radioactive contaminants, in addition to exposure of the workmen. Expensive control measures could be implemented to address these exposure pathways, however, this would involve additional costs. Due to the potential adverse environmental impacts, this is not considered a primary option for handling the buried waste material.

5.4 WASTE PROCESSING (FIXATION) METHODOLOGIES

Waste processing (fixation) is a process that has been studied and tested extensively for stabilization and disposal of radioactive waste. This effort has primarily been directed for the management of high-level radioactive waste material. Due to the relatively high costs, this technology has not been evaluated and tested extensively for the stabilization and disposal of low-level radioactive waste material.

In general, waste fixation or solidification will produce a monolithic solid material of low permeability. The success of the various waste fixation processes is highly dependent on the specific chemical composition and physical characteristics of a particular waste and the environment where the fixed waste will be placed for disposal.

Fixation processes may be categorized within the following groups:

1. Cement-Based Techniques.

   This fixation technique normally uses portland cement to form a solid matrix to bind contaminants within the waste. The processing approach utilizes a waste slurry which is mixed directly with the cement so that the suspended solids will be incorporated into a rigid matrix of the hardened concrete. It should be noted that certain compounds which may be present within the waste may have an adverse effect on the setting and curing of common portland cement, and therefore, impact the success of chemical fixation using this technique. Compounds which may affect the waste/concrete mix include metallic salts, silts, clay, organic materials, sodium salts, sulfates, and phosphate. To address this problem, special types of cement may be formulated such as low alumina cement to improve the physical characteristics and decrease the potential leaching losses from the fixed waste. The primary advantages of the cement-based waste fixation techniques are that the technology and management of cement mixing and handling is well known and the resulting fixed material can produce a very high bearing strength product.

2. Lime-Based Techniques.

   Fixation techniques using lime-type products usually depend on the reaction of lime with a pozzolanic[1] material, water, and the waste to produce a concrete-type material. The most common pozzolanic-type materials used in waste fixation are cement kiln dust, fly ash, and pulverized slag. The availability of these materials in the St. Louis area, along with their associated cost, will have a large bearing on the overall economics of this option. The ef-

[1]The term pozzolanic applies to silicate-type material.

fectiveness of chemical fixation using this technique must also be demonstrated through bench-scale tests to simulate the actual process.

The advantages of the lime-based techniques include the use of a well-known chemistry involving lime-pozzolanic reactions, in addition to the fact that no specialized equipment would be required for this type of processing.

3. Thermoplastic Techniques.

Thermoplastic fixation techniques have been utilized in radioactive waste disposal, primarily for high-level radioactive waste processing. Thermoplastic fixation includes the use of asphalts, polyethylenes, waxes, and polypropylenes for solification of the waste material. In processing, the radioactive waste is combined with the thermoplastic material and the waste is dried, heated, and dispersed throughout the heated plastic matrix. The mixture is then cooled to solidify the mass, and is usually placed in a secondary containment system, such as a steel drum or rigid container, for disposal.

The process requires some specialized equipment to heat and mix the waste in the plastic matrix. The matrix and dry waste must be mixed at temperatures ranging from 130° to 230°C, depending on the melting characteristics of the material and type of material used. The ratio of thermoplastic matrix to waste is generally on the order of 1:1 to 1:2, fixative to waste. The advantages of the thermoplastic techniques are that the final product is a solid matrix with low leachability rates, and generally long-term stability.

4. Thermosetting Resins.

Thermosetting fixation techniques generally use organic polymers for waste solidification. Polymer that has been tested involves urea-formaldehyde (UF); this material has been studied and used for managing radioactive wastes. The polymer is generally formed in a batch process where the wastes are then blended with a prepolymer in a processing tank. A catalyst is then added and mixed which leads to formation of the polymer. The polymerized material does not chemically combine with the waste, but forms a spongy mass that traps the solid particles. Any liquid associated with the waste will remain after polymerization; this is a disadvantage of this particular technique. In addition to the urea-formaldehyde polymer, a final esterstyrene polymer system has also been tested for use with radioactive wastes. The primary advantage of this technique is that less fixative is required for solidifying a unit quantity of waste. The primary drawback is that no chemical fixation occurs using this technique.

5. Encapsulation Techniques.

Encapsulation techniques are being tested for handling radioactive wastes, primarily high-level materials. These techniques generally involve processing the waste material with a chemical binder that forms an impervious jacket around the waste material after it cures. Various resins have been tested for producing this encapsulating layer around the waste material. The primary advantage of this option is that the impermeable layer prevents any contact between water and waste materials. The unit cost for this technique is extremely high, and is a major disadvantage for processing large quantities of low-level radioactive waste materials.

6. Glass and Ceramic Fixation Techniques.

The use of glass and ceramic techniques for the solidification, fixation, and disposal of high-level radioactive wastes has been extensively tested and researched. These techniques are currently in commercial use for radioactive waste management by the French. The glassification technique combines the radioactive waste with silica and fuses the mixture into a solid glass matrix. Glasses are only very slowly leached by water so that this approach is generally assumed to produce a safe material for disposal without a high level of secondary containment.

The ceramic techniques involve mixing the waste material with a fire clay, aluminum silicate, or clay such as, bentonite. The resulting material is then fired to produce a ceramic-type material. This process is similar to gasification in which the waste materials are fused into a ceramictype matrix. This type of process has shown promising results with respect to reducing radon emanation from the waste material.

The glassification process will produce a solid matrix with a high degree of stability with respect to weathering. It does involve the use of specialized equipment and is energy-intensive which results in a high processing cost. The ceramic fixation technique offers a lower cost, however, questions remain regarding the long-term stability of the thermally-processed waste material.

7. Thermal Stabilization.

Thermal stabilization for mill tailings sites may be an attractive option for stabilization due to the presence of silicates in the mill tailings which will be beneficial in the sintering process. Due to the fact that the St. Louis site does not contain mill tailings materials, the quantity of silicates would be substantially less. This will likely affect the overall success of thermal stabilization, and therefore, it is not considered a primary alternative.

Tailings subjected to thermal stabilization at 1,200°C have greatly reduced (factors of 22 to 1,400) radon emanations.[1] However, there are still questions concerning the long-term stability of thermally-stabilized tailings (weathering) and material behavior in a production-scale process. Detailed experimental results are presented in reference.[1]

8. Acid Extraction of Contaminants.

Substantial removal of Th-230 and Ra-226 from tailings has been experimentally accomplished using concentrated sulfuric acid (70 to 90%).

In addition, 10N acid (55 to 65%) has been used to remove Th-230. Extrapolation of initial results on radionuclide removal to a conceptual process will require much more extensive examination of technical feasibility. However, these data are encouraging enough to justify a much more detailed examination. The use of concentrated (or near concentrated) sulfuric acid in a full-scale process poses some technical difficulties. The possibility of developing a process that could simultaneously extract and separate valuable metals and hazardous radionuclides, however, seems a realistic expectation in light of these results.

It is possible that a more extensive investigation of leaching by acids in the range 10N to concentrated H_2SO_4 might reveal conditions providing satisfactory decontamination of radionuclides with lesser loading of the extractant by innocuous substances.(1) It is recognized, however, that acid extraction, although having the potential for conditioning some uranium mill tailings, is not applicable to the specific contaminated material at the St. Louis Airport site.

5.5 WASTE FIXATION EVALUATION

Many of the waste fixation techniques discussed in the previous subsection may be viable for solidification/fixation of low-level radioactive wastes. Prior to recommending a fixation technique, of course, extensive laboratory and bench-scale testing would be required in order to develop the details for the process, establish the ratio of fixative material to waste, and determine the effectiveness of this approach. This type of testing would be ultimately required to confirm the technical viability of a fixing technique, in addition to the final economics of the approach. For the purposes of this evaluation, several factors must be considered when evaluating fixation as a primary control alternative. These factors include:

1. Pulverization or grinding of the radioactive waste material may be required as a first step for preprocessing. This step is generally required to maximize the reaction between the waste material and the fixative material. Grinding and pulverization of the waste would result

in a very strong potential for airborne migration of radioactive particles. Special controls would be required in this area, along with arrangements for personnel protection.

2. Effectiveness of the fixation process with respect to chemical fixation and reducing the emanation of radon gas cannot be predicted. As a result, the fixed waste material cannot remain exposed at the disposal site, and additional engineering controls would be needed to bury and secure the waste.

3. The effects of long-term weathering of the fixed material cannot be predicted, and, as a result, it cannot remain exposed at the disposal site. Weathering may affect the structural stability, chemical leaching, and radon emanation characteristics of the fixed waste matrix.

4. Following fixation, the total quantity of waste material requiring disposal will generally increase due to the presence of the fixative material.

5. Economics of the fixation processes will generally depend on the availability of the fixative or additive material. In addition to the costs for handling and processing the waste, the costs for final covering, securing, and disposal of the fixed material must be added to the cost for fixation processing.

6. Waste fixation techniques may be viewed as a means for reducing the chemical leaching and radon emanation characteristics of the waste, in addition to improving its physical and structural characteristics. The degree to which fixation achieves these objectives must be determined through a thorough laboratory testing step.

7. Due to the requirement for bench-scale and laboratory testing to evaluate the success of fixation, this option will require lead time to perform this work prior to implementation. The lead time should also include testing the fixed matrix with respect to weathering effects and possible degradation.

5.6 APPLICATION OF CONDITIONING TECHNIQUES

Since most of the material is already buried on the existing site, and it is agreed that containment techniques (liner, cover, and barrier) are effective for in situ stabilization, conditioning techniques are not recommended. However, for other applications where large volumes of waste are to be removed for off-site disposal, conditioning could be evaluated for possible improvement of waste characteristics prior to disposal.

REFERENCES

SECTION 5

WASTE CONDITIONING

1. "Draft Preliminary Evaluation of Uranium Mill Tailings Conditioning," Los Alamos National Laboratory, Environmental Science Group, LS-6, April-June 1981.

SECTION 6

ION EXCHANGE MEDIA

6.1 INTRODUCTION

An ion exchange barrier may be considered a means of controlling the migration of radionuclides in or into groundwater. This type of system could be constructed as follows:

1. A curtain or barrier designed to intercept the flow of groundwater from a contaminated area.

2. A liner to be placed under a waste area designed to intercept any leachate that may be generated.

Ion exchange material may be comprised of:

1. Natural soils (clays generally have a high cation exchange capacity).

2. Synthetic resins (zeolites, macroreticular polymers, gels, etc.).

Selection of the type of ion exchange material will generally depend on the following factors:

1. Characteristics of the water or leachate that will be handled.

2. Presence and concentration of other ionic species.

3. Type of ionic species that is desired to be removed.

4. Economic considerations.

5. Effective life.

6. Construction viability.

In addition, the ion exchange function of a barrier or liner must be compatible with the other desired functions of that barrier. For example, a primary purpose and function of a liner system is to retard the physical movement of water through the liner. An optimum liner design would address the dual function of restricting water (leacnate) movement while treating any leachate that does migrate through the liner by the ion exchange process.

The placement of a barrier wall in the western portion of the site to prevent groundwater from moving through the contaminated materials found in that area will require the interception of the gray/blue clay layer located approximately 45 feet below the present ground-level surface. During the course of field investigations, the height of the water table in this area was found to vary. In December 1980, the water table level was found to be approximately 510 feet MSL; in June 1981, the water table level was approximately 515 feet MSL. In an area with varying groundwater levels, imperfections or cracks in the barrier wall could cause the isolated area to "pump" with varying levels of groundwater, periodically allowing the release of contaminated materials.

In designing tne barrier wall it was decided to consider alternatives for the control of radionuclide species contained in the water leaving the contaminated zone. The incorporation of a material with a hign ion exchange capacity in a portion of the barrier wall has been evaluated. A simplified transport model was used to investigate the significance of various design parameters on the control of the radionuclide species.

6.2 LITERATURE REVIEW

The use of ion exchange materials for control of radioactive wastes has been proposed in the literature.[1,2] The performance of various natural materials, e.g., expandable clays and zeolites, for adsorbing specific radioactive species has been reported. The bulk of the data reported have been in the form of distribution coefficients (K_d) which are defined as:

$$K_d = \frac{\text{Solid-phase equilibrium concentration}}{\text{Solution-phase equilibrium concentration}} \qquad (6\text{-}1)$$

There are numerous reports in the literature of laboratory studies estimating K_d values for various solution/sorbent/radionuclide systems. A recent literature search[1] for ion exchange data associated with clays, zeolites, and basalt identified 92 references to ion exchange data on clays, 22 references for zeolites, and six references on basalt. The values reported are specific to the system and test conditions investigated; variations in solution composition can have a significant effect on the value of K_d. Nowak[3] reported the results of batch equilibrium tests for sorption of $Eu\text{-}152^{3+}$ on samples of soils, clays, and zeolites. These tests were run using different brine solutions, at different pH values, and using different preparation procedures for the sorbent materials. Summaries of the brine compositions used and K_d values for Nowak's experiments are presented in Table 6-1 and Table 6-2. As Nowak points:[3]

> "Radionuclide sorption and retention measurements on clays and soils have been underway for many years, and a ponderous body of literature has been generated. However, those data are not readily generalizable to specific backfill barrier applications."

While there has been a significant amount of laboratory-scale investigations of ion-exchange/radionuclide systems, no reports of actual full-scale applications have been found in the literature.

Various transport models have been proposed for modeling radioactive waste migration through adsorbing media. Lester[4] and Lu[5] have developed similar models for analyzing one-dimensional migration of radionuclides from underground disposal sites. In each case, the model includes terms for local accumulation of a given species, the net change in the inventory of a species due to radioactive decay, and for appearance due to decay of the proceeding members of the decay chain. These models assume that:

1. Flow is one-dimensional (vertical or lateral) in a saturated medium which is not an aquifer.

2. Rate of infiltration and water content are constant.

3. Hydrodynamic dispersion coefficient can be approxmated by a constant.

4. Linear isotherm conditions prevail.

The solutions to these equations, presented elsewhere,[4,5] required automated numerical procedures and resolution of regions where numerical problems existed.

Nowak[6] proposed a simpler model for migration through an ion-exchange backfill barrier system. This model is, in some regards, similar to Lester's and Lu's; however, it was developed

Table 6-1

Representative Brine Compositions (from Nowak[3])

	Major Constituents, Molarity							
	Na^+	K^+	Mg^{++}	Ca^{++}	Cl^-	SO_4^{--}	HCO_3^-	BO_3^{---}
Brine A	1.8	0.8	1.4	0.02	5.4	0.04	0.01	0.02
Brine B	5.0	---	---	0.03	5.0	0.04	----	----

Table 6-2

Batch Equilibrium Results for $Eu\text{-}152^{3+}$ Sorbate at Room Temperature (from Nowak[3])

$C_o = 2 \times 10^{-7}$ $\underline{M}$ Eu^{3+} (~ 0.1 µCi/ml)

	K_d (ml/gm)					
	Brine A			Brine B		
	pH = 5.5	pH = 6.5		pH = 5.5	pH = 6.5	
Getter	----	----	Heated[1]	----	-----	Heated[1]
DLR (soil)[2]	200	1,600	1,800	270	14,000	7,300
Caliche	140	8,000	9,000	220		11,000
Tuff	200	2,500		200	1,400	
Zeolon (zeolate)	50	690	270	60	6,000	1,400
Montmorillonite (SWy-1)[3]	100	850	1,100	6,700	1,300	3,500
Hectorite (SHCa)[3]			5,500			7,200
Kaolin (DGa-1)[3]	60	1,100		200	1,600	

[1]Heated six hours in air at 300°C before sorption measurement at room temperature.

[2]Dewey Lake Redbeds, and outcropping in the Los Medanos area, Carlsbad, New Mexico.

[3]Samples from Source Clay Mineral Repository, University of Missouri, Columbia, Missouri.

for a single radionuclide and did not include terms for creation or decay of the species. Nowak has also assumed a linear equilibrium relationship in his model. He states, however, that there is no parameter in radionuclide migration studies which seems to have been the focus of more controversy, uncertainty, and misunderstanding. K_d is not a single equilibrium constant, rather, it is a function of some or more equilibrium constants and the chemical potentials for some of the dissolved species. It is nearly constant only under special conditions and for single uptake mechanisms and chemical reactions. The value calculated for K_d from a set of data for a single radionuclide-solid phase pair can be a function of the concentrations of all species in solution, including radiolysis products. It can be changed by changes in pH, eH, the quantity of dissolved CO_2, total dissolved ions and their charge and molecular weights, extent of competing reactions, and trace impurity concentrations in both phases. Consequently, literature values span a wide range.

Although values of K_d are given for a wide variety of systems, seldom is it firmly established that the uptake mechanism is ion exchange for which linear equilibrium is a reasonable approximation. There is often doubt as well about the composition and chemistry of the sorption sites in the solid phase where uptake occurs. With these cautions in mind, values of K_d can be chosen for calculated estimates of getter (sorbent) performance. It must be recognized that, as it is used here, K_d is an empirical parameter rather than a basic chemical property of the system.

Due to the uncertainty in the estimates of K_d, Nowak[7] has stated that omission of the creation/decay terms may not substantially affect the intended use of the model, which was to permit an order-of-magnitude evaluation of the radionuclide/barrier wall system.

Nowak presented his model,[6] beginning with its differential form, as follows:

$$\epsilon \frac{\partial C}{\partial t} + \frac{\partial S}{\partial t} + \epsilon v_g \frac{\partial C}{\partial x} - \epsilon D_L \frac{\partial^2 C}{\partial x^2} = 0 \qquad (6\text{-}2)$$

Where: C = Liquid phase concentration, quantity of sorbing species per unit volume of liquid.

S = Concentration of species sorbed on the solid phase (quantity of sorbed species per unit volume of bed liquid plus solid volumes).

ϵ = Effective porosity of bed (fraction of bed volume containing flowing liquid).

v_g = Average <u>interstitial</u> velocity of flowing liquid.

x = Distance in bed along direction of flow and longitudinal diffusion.

D_L = Coefficient of longitudinal dispersion and diffusion combined.

t = Time.

The first two terms are the rates of accumulation (or depletion) of sorbing species in the liquid and on the solid per unit volume of bed. The third term is the net transport of liquid phase species by convection. The fourth term is the net transport of liquid phase species by dispersion and diffusion.

The first two terms are related by rate expressions for local mass transport in the liquid and solid phases and an equilibrium sorption isotherm at the interface. It can be shown[8,9] that the application of linear sorption isotherm and "linear-driving-force" mass transport rate relation approximations yield the following simplified differential mass balance:

$$\left(1 + \frac{\rho b K_d}{\epsilon}\right) \frac{\partial C}{\partial t} + v_g \frac{\partial C}{\partial x} - D_L^* \frac{\partial^2 C}{\partial x^2} = 0 \qquad (6\text{-}3)$$

Where $\rho b K_d$ = S^*/C, a linear sorption isotherm (S^* = S at equilibrium with C).

ρb = Bulk packing density of solid sorbent, mass of solid per unit bed volume.

K_d = Distribution coefficient for a linear sorption isotherm, the ratio of quantity of sorbed species per unit mass of solids to quantity of mobile species in the liquid phase per unit volume of liquid.

D^*_L = Modified coefficient of longitudinal dispersion and diffusion which includes separate terms for local liquid and solid phase mass transport rate effects, as well as for dispersion due to finite particle size and for molecular diffusion in the x- direction.[8]

Convection, longitudinal molecular diffusion, and longitudinal dispersion remain as the significant processes which determine breakthrough for the chosen set of parameters. These processes are described by the following modification of equation (6-3):

$$\frac{\delta C}{\delta t} + \frac{v_g}{R_f} \frac{\delta C}{\delta x} - \frac{D_L}{R_f} \frac{\delta^2 C}{\delta x^2} = 0 \qquad (6\text{-}4)$$

Where $R_f = 1 + \left(\frac{\rho b^{K} d}{\epsilon} \right)$. (6-5)

When the interstitial velocity, v_g, and the particle size, d_p, are small enough, convection and dispersion are small compared with molecular diffusion. Longitudinal transport is by diffusion alone. In that case, equation (6-4) becomes:

$$\frac{\delta C}{\delta t} - \frac{1}{\sqrt{2}} \frac{D_f}{R_f} \frac{\delta^2 C}{\delta x^2} = 0 \qquad (6\text{-}6)$$

Where: D_f = Liquid phase molecular diffusivity.

and $\frac{1}{\sqrt{2}}$ = A tortuosity factor to account for the tortuous diffusion path through the porous bed.

The boundary condition is:

$C = C_o,\ x = 0,\ t > 0.$

The initial condition is:

$C = 0,\ x > 0,\ t = 0.$

Crank(10) gives the following solution for equation (6-4):

$$\frac{C}{C_o} = 1 - \text{erf} \left\{ \frac{x}{2 \left(\frac{D_f t}{\sqrt{2R_f}} \right)^{1/2}} \right\} \qquad (6\text{-}7)$$

At interstitial groundwater velocities equal to 0.1 - 1.0 ft/year, transport is mostly by diffusion.[6] The convective and dispersion terms are small, therefore, the estimated breakthrough time, t_b, can be calculated using equation (6-7) for diffusion alone.

6.3 EVALUATION OF DESIGN PARAMETERS FOR ION EXCHANGE MEDIA

Typical values for the parameters used in equations (6-5) and (6-7) are presented in Table 6-3. Representative values from this table were used, with a numerical solution of equation (6-7), to estimate the time to "breakthrough" for barrier walls with various characteristics. In developing these estimates, "breakthrough" was defined as $C/C_o = 0.01$. A summary of these solutions is presented in Tables 6-4 and 6-5, and Figure 6-1.

As Figure 6-1 indicates, for those parameter values used, a barrier thickness ranging from less than 1.0 foot to approximately 6.5 feet would be necessary to attain a 1,000-year design life for the barrier (i.e., at 1,000 years of barrier life, the breakthrough concentration ratio, C/C_o would be less than or equal to 0.01. The minimum barrier wall thickness necessary to satisfy the 1,000-year design life, $C/C_o \leq 0.01$, for each of the systems presented in Figure 6-1 are summarized in Table 6-6.

6.4 IMPACT OF ION EXCHANGE BARRIER WALLS ON GROUNDWATER QUALITY AT THE ST. LOUIS AIRPORT SITE

Samples of groundwater from various wells at the St. Louis Airport site were analyzed for radioactivity. The average value of radioactivity found in the samples was 50 pCi/L. Using this value as C_o in equation (6-7), the breakthrough concentration of radioactivity from the barrier wall (whose characteristics are shown in Table 6-6) would be 0.50 pCi/L.

Limits have been set for various types of radioactivity for groundwater used as drinking water in the Federal Drinking Water Standards (PL 93-523). These include:

1. Gross α, including Ra-226, but excluding radon and uranium, limited to 15 pCi/L.
2. Allowable uranium limited to 10 pCi/L.
3. Combined Ra-226 and Ra-228 limited to 5 pCi/L.

Thus, comparison between the forecasted breakthrough concentrations for the barrier wall systems summarized in Table 6-6, and the standards listed indicates that these systems should provide adequate performance over the 1,000-year design life.

Table 6-3

Typical Values of Physical and Chemical Properties
for the Ion Exchange Barrier Wall

K_d = 100 to 5,000 gm/ml

ρB = 2 gm/cu cm

D_f = 10^{-4} to 10^{-6} sq cm/s

ϵ = 0.25 to 0.40

X = 1 to 10 feet

Table 6-4

Breakthrough Time as a Function of Barrier Wall Characteristics

For: $C/C_o = 0.01$ $\rho B = 2$ gm/cu cm, $D_F = 10^{-4}$ sq cm/s, $\epsilon = 0.25$

K_d gm/ml	X ft	T Years
100	1	30
	3	200
	5	600
	10	3,000
500	1	100
	3	1,000
	5	3,000
	10	10,000
1000	1	300
	3	2,000
	5	6,000

Table 6-5

Breakthrough Time as a Function of Barrier Wall Characteristics

For: $C/C_o = 0.01$, $\rho B = 2$ gm/cu cm, $D_F = 10^{-5}$ sq cm/s, $\epsilon = 0.25$

K_d gm/ml	X ft	T Years
100	1	300
	3	2,000
	5	6,000
	10	30,000
500	1	1,000
	3	10,000
	5	30,000
1000	1	3,000
	3	20,000
	5	60,000

Table 6-6

Minimum Thickness of Barrier Walls, with Various Characteristics, to Achieve 1,000-Year Design Life[1]

Thickness Ft	K^d gm/ml	ρB gm/cu cm	D^f sq cm/s	ϵ (-)
6.4	100	2	10^{-4}	0.25
2.8	500	2	10^{-4}	0.25
2.0	1,000	2	10^{-4}	0.25
1.9	100	2	10^{-5}	0.25
1.0	500	2	10^{-5}	0.25
<1.0	1,000	2	10^{-5}	0.25

[1]To achieve 1,000-year design life means that the breakthrough concentration ratio $C/c_o \leq 0.01$ at 1,000-year barrier life.

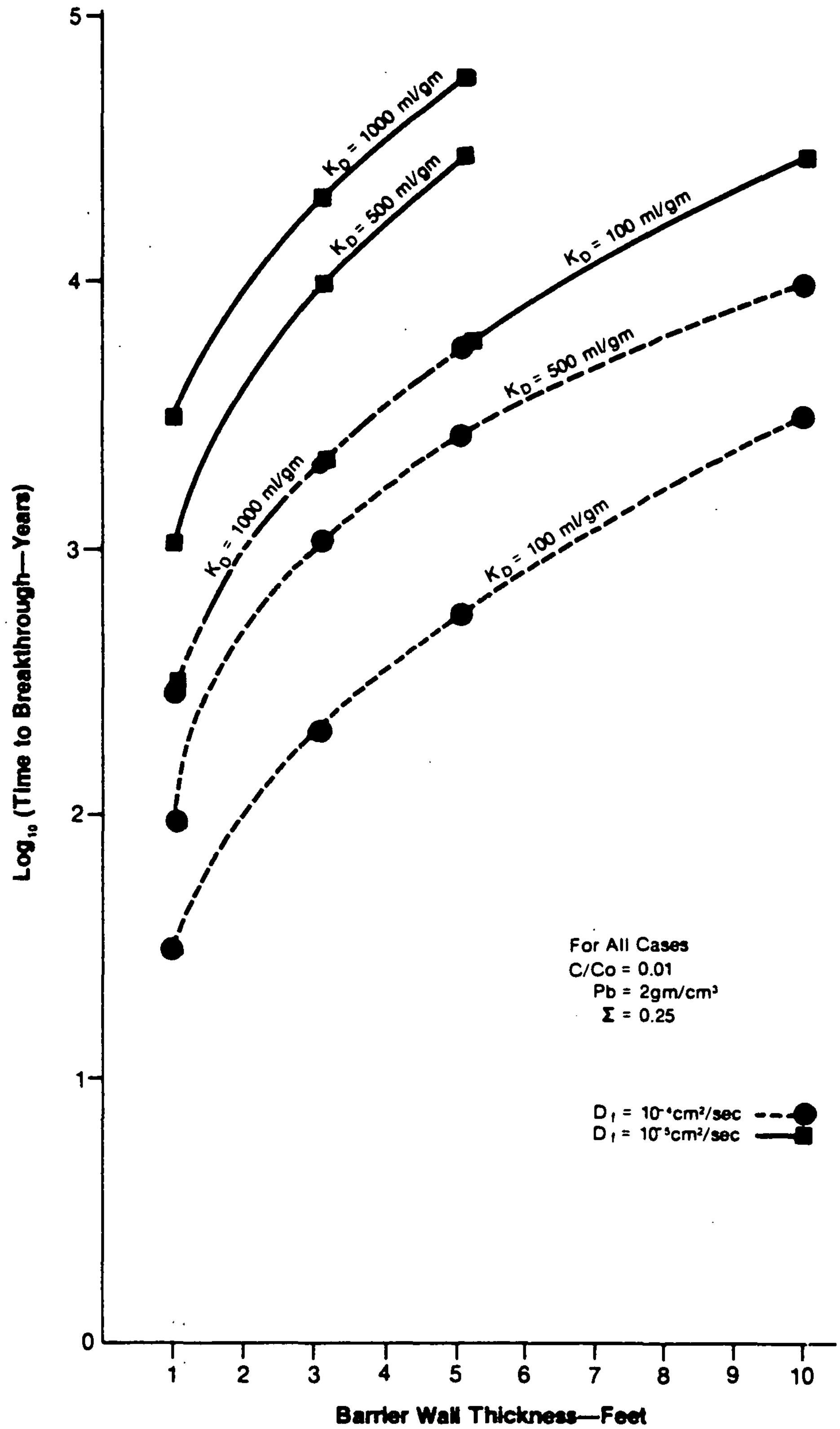

FIGURE 6-1 GRAPH OF BREAKTHROUGH TIME AS A FUNCTION OF BARRIER WALL CHARACTERISTICS—HIGH AND LOW DIFFUSION RATES (D_f)

6.5 DISCUSSION OF RESULTS

The results of this investigation indicate that an ion exchange barrier of proper design will tend to retard the migration of radionuclides buried in certain areas at the St. Louis Airport site. Before any firm conclusions are drawn or decisions made regarding the final design and construction of an ion exchange barrier, however, certain factors should be evaluated further.

As discussed in subsection 6.2, in any specific applications, the chemical characteristics of the groundwater can have a significant effect on the ion exchange relationships, e.g., equilibrium distribution coefficients, K_d, of importance. Presented in Table 6-7 are certain analytical results for samples taken from three monitoring wells at the St. Louis Airport site. Comparison of these results with those presented in Table 6-1 indicates that the concentration of dissolved species is high and comparable to a brine-type solution. The high concentrations of calcium and magnesium, would likely result in fouling the ion exchange material, and result in a significant reduction in its effectiveness in attenuating the levels of radionuclides. In general, these high levels of dissolved solids will adversely affect the ion exchange relationships for the radioactive species, by increasing the driving forces for these other dissolved species.

It is important to note that these high concentrations of dissolved species may, in part, be due to the slow groundwater movement through the site. This slow movement would tend to minimize migration of the species, causing a build-up in their concentrations. To the extent that this mechanism is valid, the need for barrier walls, i.e., to minimize migration, would be mitigated.

Another factor which should be considered is the natural ion exchange capacity of the existing soils which surround the contaminated waste materials. As shown on Figure 6-2, the minimum value of K_d, the ion exchange distribution coefficient, for an ion exchange material or natural soil which will ensure the isolation of the contaminated wastes for the 1,000 year design life, is inversely related to the thickness of the material or soil.

The nominal distance from the buried waste materials to Coldwater Creek, where migration of radionuclide species in the groundwater would first manifest themselves as a surface-water contaminant, is between 100 and 200 feet. Therefore, the natural exchange capacity of the soils lying in this pathway may have a significant effect on mitigating this migration.

Table 6-7

Results of Groundwater Sampling of Three Wells
at the St. Louis Airport Site
(WESTON, 1981)

	Well B mg/L	Well A-8 mg/L	Well A-2 mg/L
Na^{+}	172	80	20
K^{+}	1	10	1
Mn^{+2}	1	1	1
Mg^{+2}	430	150	50
Ca^{+2}	2,400	460	120
Cl^{-}	58	60	68
$SO_4^{=}$	285	475	150
NO_3^{-}	1.0	2.3	9.6
pH	---	---	---

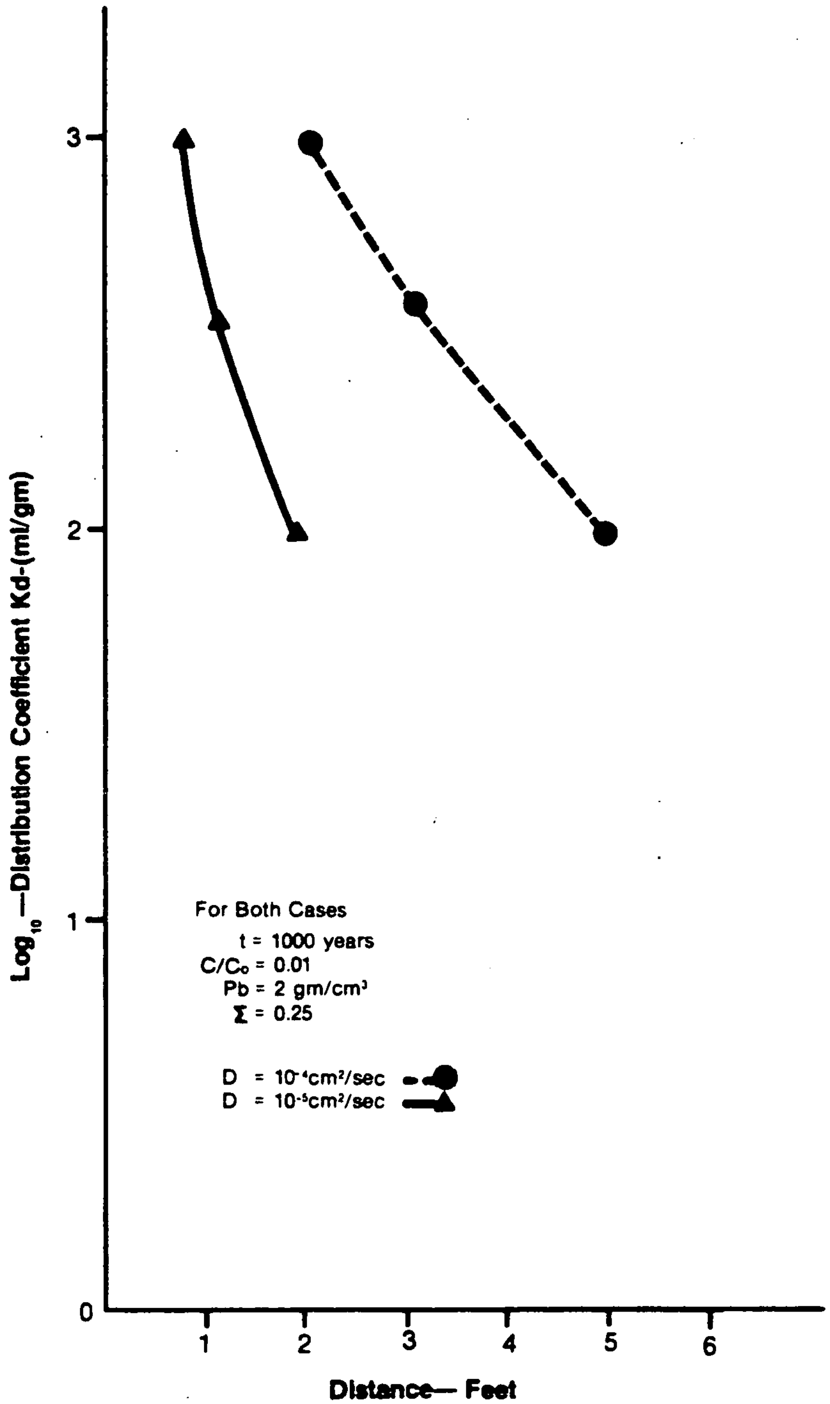

FIGURE 6-2 GRAPH OF MINIMUM DISTRIBUTION COEFFICIENT VERSUS BARRIER WALL THICKNESS FOR 1,000 YEAR DESIGN LIFE—WITH HIGH OR LOW DIFFUSION RATE (D_f)

6.6 APPLICATION OF ION EXCHANGE

The use of an ion exchange filter for isolating the buried radioactive wastes at the St. Louis Airport site cannot be viewed as the primary control mechanism due to the probable fouling caused by the high dissolved solids concentration of the groundwater. The proper design of the media would include specifications for thickness, ion exchange capacity (K_d), bulk density (ρB), molecular diffusivity (D_f), and porosity (ϵ) for the barrier material to be used. Sets of possible values for these design parameters have been developed and presented (in subsection 6.3). The final design values for these parameters can best be determined through column-exchange studies using samples of groundwater from the site.

It is probable that the exchange capacity of the natural soils surrounding the buried wastes may also be adequate to reduce the migration of the radionuclides to an acceptable level. This is supported by the results of groundwater analyses which do not show any significant migration of radionuclides in the groundwater. The use of natural clay soils for slurry walls and liners as other control mechanisms will also perform a cation exchange function due to the high cation exchange capacity of these materials.

A separate ion exchange filter is not a part of the initial clean-up strategy; it would be possible to retrofit the site with a filter wall if future monitoring data warrant it. In view of this possibility, determination of the proper design criteria through testing the actual wastes may be justified.

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SECTION 6

ION EXCHANGE MEDIA

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SECTION 7

SUBSURFACE BARRIERS

7.1 INTRODUCTION

A variety of subsurface barriers to divert, cut off, or passively treat groundwater flow in the vicinity of the major deep deposit were considered. These include:

1. Neutralization of groundwater.
2. In situ solidification.
3. Ion exchange filter.
4. Diversion walls.
5. Barriers.

Groundwater diversion and passive treatment were eliminated due to excessive cost and limited applicability and feasibility. A groundwater cutoff wall (bentonite slurry trench construction) surrounding the deep deposit was selected to isolate any groundwater contamination which may now exist or would exist in the future.

7.2 NEUTRALIZATION OF GROUNDWATER

Cation mobility tends to increase with the acidity of the groundwater. Since the groundwater under the site tends to be acidic, cationic radioisotope movement could be retarded somewhat by neutralization. Disregarding groundwater extraction becasue of its continuing nature, the only realistic passive neutralization system would involve trenching and placing limestone at the groundwater level. This would be extremely expensive for the benefit derived and has been rejected on that basis. However, the concept of a surface layer of limestone over the deposit to reduce the leaching rate of acid rain on the deposits above the groundwater table has some merit and may be retained as a potentially-viable alternative.

7.3 IN SITU SOLIDIFICATION

To prevent the ingress or egress of water and the potential leaching of contaminants, total solidification of the waste deposit in place may be attempted. Solidification would be achieved by filling all fissures and voids in the mass, thus, totally entrapping the contaminant and preventing its movement. This control technique has been discussed earlier in subsection 5.2 as in situ fixation/solidification.

Successful saturation of the soil voids is dependent on the porosity of the deposit. An ideal mass is that in which the injected material can radiate out a significant distance from the point of injection, thus minimizing the number of vertical injection wells needed. Typical ideal soils are sands and gravelly sands. The success of solidification is also dependent on minimal water flow across the mass during the injection process.

Materials used for injection are cement, bentonite, asphalts, and solidifying chemicals. The relative costs and equipment needs to perform these injections favor cement and bentonite, with the cost increasing considerably for asphalts and chemicals. This is especially true as the quantities required increase.

Since the site contains loess, clayey silts, and clays, the injection process is not considered a viable alternative due to the low permeabilities and the necessity for numerous, closely-spaced injection wells. High injection pressures would be required, and the result would be soil fractures producing ribbons of the solidifying agent, rather than filling the soil voids.

7.4 ION EXCHANGE FILTER

The concept of installing a permeable, subsurface filter of ion exchange media downgradient of the contaminated areas is presented in Section 6 of this report. Such a filter could entrap any radioisotopes migrating from the deep deposit by means of groundwater, as well as any contamination carried by infiltration. However, a complete ion exchange filter extending along the northern and western boundaries of the site is not recommended as a part of the overall plan for site control. The principle of ion exchange is potentially important in several other control options applicable to the subsurface deposits. However, the extremely high calcium and magnesium concentrations found in the groundwater (Table 6-7) would severely limit any capture or deterrent effects on radioisotope movement.

7.5 GROUNDWATER DIVERSION WALLS

The concept of an impervious groundwater diversion wall placed either upgradient or downgradient of the deep waste deposit has been considered as a means of reducing the flow of groundwater through the area. Such a wall could be constructed economically through techniques to be discussed in subsection that follows. This option has been rejected because the waste deposit is located in a zone of fluctuating groundwater level. If it is assumed that the true permeability in the upper soil layers is higher than indicated, the rise and fall of the water table will cause a "pumping" effect which will be very significant in the areas which are most heavily contaminated. As the water table drops, contaminated water will be rapidly drained independently of the retarded movement of deeper groundwater layers. Radioisotope mobility would be almost impossible to predict. For this reason, groundwater diversion walls are not regarded as viable barriers within a 1,000-year life context.

7.6 TYPES OF BARRIERS

Since the major buried waste deposit is confined to a small portion of the site, it is technically and economically feasible to construct an impervious underground wall around the entire deposit. Such a wall, extending from the surface to an impermeable layer underground, will completely isolate the wastes from adjacent groundwater and prevent significant movement of radioisotopes. Radon may pass through the wall in small quantities, but the combination of its short half-life and the slow groundwater movement outside the wall will prevent measurable quantities of even Pb-210 from reaching the site boundaries. In order to prevent the isolated area from filling with rainwater, an impervious cap will be required over the entire enclosed area.

In the event that seepage through the cap is higher than anticipated, the enclosed area may fill and overflow. Alternatively, an abnormally high groundwater elevation brought about by wet climatic cycles may fill the enclosure. To ensure against radioisotope leakage during such an event, a portion of the wall could be excavated to provide a "spillway" leading to an ion exchange bed, or simply to an interior zone of the site. Since the ion exchange or seepage bed would be small, the cost of such a back-up system would be small in relation to the overall project.

Cutoff walls are most often classified according to the degree of stiffness, the type of backfill materials, and the construction methods. Systems used previously can be divided into the five main groups discussed in the following paragraphs:

1. Earth-Filled Slurry Trench.

   In this case, a trench is excavated by backhoe using bentonite slurry to stabilize the trench during construction. As the trench reaches the intended depth, the trench is backfilled with a selected blend of soil materials, consisting of those excavated along with suitable proportions of fine-grained soils and bentonite. Once in place, the backfill has a low permeability, and thus, serves as a cutoff.

2. Cement/Bentonite Slurry Wall.

This type of wall is also known as solidified bentonite slurry. The wall consists of cement/bentonite mixes containing no aggregates other than some soil that mixes with the slurry during excavation. The bentonite slurry in the excavated trench becomes the final construction material by adding a specified amount of cement. When the cement/bentonite/water slurry is placed in the trench, it gradually hardens and gains strength, yet remains essentially elastic to allow deformation without cracking.

3. Injected Slurry Wall.

This type of wall is constructed by driving a group of H piles with the flanges back-to-back until their tips reach the impermeable layer. The piles are extracted one at a time as the void beneath them is filled by injection of a grout under pressure. This is a continuing process of driving and pressure grouting during extraction until the screen is developed.

4. Plastic/Concrete Cutoffs.

As the name implies, these are concrete walls, usually unreinforced, of low strength and high flexibility to withstand settlement and ground movement without failing, and in addition, provide seepage control. Situations favoring plastic/concrete walls include:

a. Those where an additional overburden load is applied.

b. Those where considerable hydraulic pressure will exist along the wall.

c. Areas of loose or settling ground.

d. Areas where extreme alterations of the stress conditions within the surrounding soil masses will occur during the operational life of the project.

A high slump concrete is blended with bentonite to effect the desired stress/strain characteristics.

5. Rigid Cutoff Walls.

These walls are used many times as a structural feature, as well as in areas where the depth is too great to allow placement of other types of barriers, and in areas where the site and subsoil conditions are erratic and restrict the construction to special techniques. The construction is performed by excavating with a slurry in alternating panels, and then backfilling the excavation with concrete. These walls can be reinforced to provide any needed strength.

7.7 SUMMARY OF ALTERNATIVES

In order to facilitate the comparison of the alternatives discussed, a summary of the major concepts is contained in Table 7-1. The major advantages and disadvantages of each concept are also listed.

7.8 CONCEPT SELECTION

In reviewing the alternatives for isolation of the buried waste deposit, it appears that the most effective and economical system would consist of a bentonite slurry trench surrounding the entire deposit, and extending from the existing surface to the essentially impervious blue clay layer underlying the site. Allowing a 5-foot penetration into the clay, the depth of excavation will not exceed 50 feet, which is within the capability of backhoe emplacement. The use of a backhoe will require a minimum trench width of 30 inches which provides an additional safety factor over competing thin-wall systems. The use of a bentonite/soil slurry will minimize the quantity of materials to be imported, and will provide an ion exchange capability to reduce the radionuclide content of the small quantity of groundwater which will pass through the wall. The flexible wall will be able to withstand future soil movement, or settlement of reasonable magnitude without losing integrity.

Table 7-1

Comparison of Alternative Concepts

Concept	Specific Systems	Advantages	Disadvantages
Groundwater neutralization	Underground limestone wall	Reduced cation mobility. Long life.	Poor quality control. Expensive. High bicarbonate. Possible cementing and channeling.
	Limestone on surface	Neutralize acid rain. Long life. Economical.	Life uncertain. Possible plugging and channeling.
Solidification	Cement grout Asphalt emulsion Chemical grout	Immobility for geologic time.	Almost impossible in fine-grained soil. Very expensive. Quality control difficult.
Ion exchange filter	Downgradient,subsurface wall	Off-site protection independent of upstream controls.	Hard, acidic groundwater. Quality control difficult. Life uncertain. Very expensive.
	Bentonite	Long life.	Lowest capacity.
	Zeolite	Long life. Good capacity.	Expensive.
	Resins	Highest capacity.	Life uncertain. Expensive.
Groundwater diversion wall	Upgradient Downgradient	Reduce groundwater flow through site. Economical.	"Pumping" at groundwater surface.
	Bentonite	Economical. Long life.	None.
	Cement/bentonite	Long life.	Economical.
	Asphalt emulsion	Very impervious.	Life uncertain.
	Chemical grouts	Very impervious.	Expensive.

Table 7-1
(continued)

Concept	Specific Systems	Advantages	Disadvantages
Groundwater cutoff	Circular wall around waste deposit	Almost complete isolation. Can enhance ion exchange. Economical materials and construction.	Requires surface cap.
	Bentonite	Low cost. Long life. Ion exchange.	No structural strength.
	Cement/bentonite	Moderate cost. Ion exchange.	Life uncertain. Some strength.
	Asphalt emulsion	Very impermeable.	Expensive. Life uncertain.
Construction -- grouting		No excavation.	Soil too fine. No quality control. Expensive.
	Pile slurry wall	Inexpensive.	Thin wall. Limited quality control.
	Slurry trench	Proven. Thick wall. Economical. Good quality control.	None.

The area surrounded by the subsurface wall will require an impermeable cap to prevent the infiltration from overfilling the enclosure and spilling contaminated water. Simultaneously, the cap will preserve the moisture content of the upper wall, and prevent shrinkage cracks above the groundwater contact zone. Finally, the cap will reduce the downward movement of radioisotopes from the unsaturated zone and limit the radon flux from the deposit.

The most likely mode of system failure, involves future leakage of the cap due to root penetration, extreme drought with the formation of shrinkage cracks, or erosion or disturbance of the cap. A back-up system is proposed to protect against such an eventuality by placing a sand layer over the enclosed area to lead seepage to a shallow seepage bed.

Following completion of the slurry wall, a portion of the western side will be excavated below the existing grade and filled with sand prior to installing the cap. Any flow over the wall will thus be in the interior of the site away from the creek. The bed will be above the groundwater table to minimize the possibility of inflow due to a future extraordinarily high water table.

SECTION 8

LINERS

8.1 INTRODUCTION

The use of natural and synthetic materials of low permeability to line waste storage and disposal impoundments has been demonstrated to be a feasible method of preventing leachate and waste liquid components from leaking and subsequently polluting ground- and surface-waters. These liner materials can also be used to prevent the migration of dangerous concentrations of radon and other gases from a waste containment site. Many materials are available from which the containment for specific wastes may be chosen.

Considerable information exists regarding the water resistance of lining materials, regardless of whether they are soils, asphalts, or polymeric membranes. The wastes also contain many other ingredients which have varying effects on lining materials. Waste leachates are generally not the aggressive agents in waste liquids and usually are of relatively low concentrations. In assessing a liner material for a given application, the chemical composition of both the waste and the lining material must be considered.

Two types of liner systems exist, both active and passive. Active liner systems employ the use of leachate collection, and generally require considerable post-closure maintenance. An active liner system also must be constructed of highly impervious materials and double lined for quality assurance. Finally, active liner systems have restricted life expectancies and typically cannot be expected to provide a low maintenance 1,000-year life.

Passive liner systems allow controlled liquid flux through the lining membrane. This system is only viable when the contaminants of concern can be physically filtered or chemically attenuated by the lining membrane. Such passive barriers can provide excellent radionuclide attenuation. When properly designed, passive liner systems provide superior pollution control and essentially maintenance-free service lives.

This section will only consider passive liner systems because with their use, a low maintenance 1,000-year service life, can reasonably be expected.

8.2 LINER TYPES

Twelve liner types were systematically evaluated based on 11 performance criteria. The liners were then ranked based on these criteria and the best performer selected for design. Five major classes of liners were evaluated and are as follows:

1. Asphalts.
2. Concrete.
3. Synthetics.
4. Natural soils.
5. Soil admixtures.

Each general liner class will be discussed and the associated design strengths and weaknesses highlighted. With proper attention to design criteria and the use of a consistent evaluation procedure, the superior liner should be readily identifiable.

8.2.1 Asphalts

A detailed discussion of asphaltic membranes, including asphalt emulsion and asphalt concrete, is contained in Appendix A. Asphaltic lining materials are generally poor passive barriers because they do not allow controlled hydraulic flux through the lining membrane. This critical deficiency, combined with long-term biochemical deterioration, makes asphaltic barriers poor candidates for liner materials.

8.2.2 Concrete

Concrete and its performance as a construction material for waste containment structures is discussed in Appendix A. Concrete is a victim of the same fatal flaw as asphaltic membranes because of its inability to provide controlled hydraulic flux of the impoundment fluids. For these reasons, concrete is also a poor candidate for a liner material.

8.2.3 Synthetics

While their applications are numerous in active liner systems, synthetic membranes are not applicable in passive barrier systems. Due to their impervious nature and subsequent inability to control hydraulic flux, synthetic liners perform poorly in passive liner systems. In addition, long-term biochemical deterioration makes synthetic membranes poor candidates for liner materials.

8.2.4 Soils

Soils can provide controlled hydraulic flux through the liner system. Additionally, due to long-term biochemical stability and contaminant attenuation properties, soils become an attractive option. Soil liners can also be constructed with relative ease and designed to withstand minor seismic disturbances.

Soils to be used as liners at waste disposal facilities must contain a relatively large proportion of fines, i.e., particle size of less than 2 µm. For a broad range of soils, a close correlation between soil permeability and clay (less than 2 µm) content has been observed; soils exhibiting low permeability generally contain a large proportion of fines. The minimum amount of clay particles required in soil to yield a good soil liner is 25 to 28% by weight.(1) The distinction between clay and nonclay made at a particle size equal to 2 µm is based on the observation that clay minerals are heavily concentrated below this size, while nonclay minerals constitute the bulk of soil solid phases above this particle size.

8.2.4.1 Attenuation Properties of Soil Liners.

A clayey soil liner below a low-level radioactive waste can attenuate radionuclides, by:

1. Effectively reducing the level of contamination (if present).

2. Spreading the contamination over a much longer period.

3. Considerably lowering the maximum value of contamination, i.e., highest discharge rate of contaminants per unit area during the operation period.

The term "attenuation" at the same time implies that a soil liner cannot be an "absolute" liner. This point is illustrated schematically by Figures 8-1 and 8-2 for which the following assumptions were made:

1. The rate of contamination is defined as the amount of polluting species passing through a unit area per unit time, e.g., grams per square meter per day.

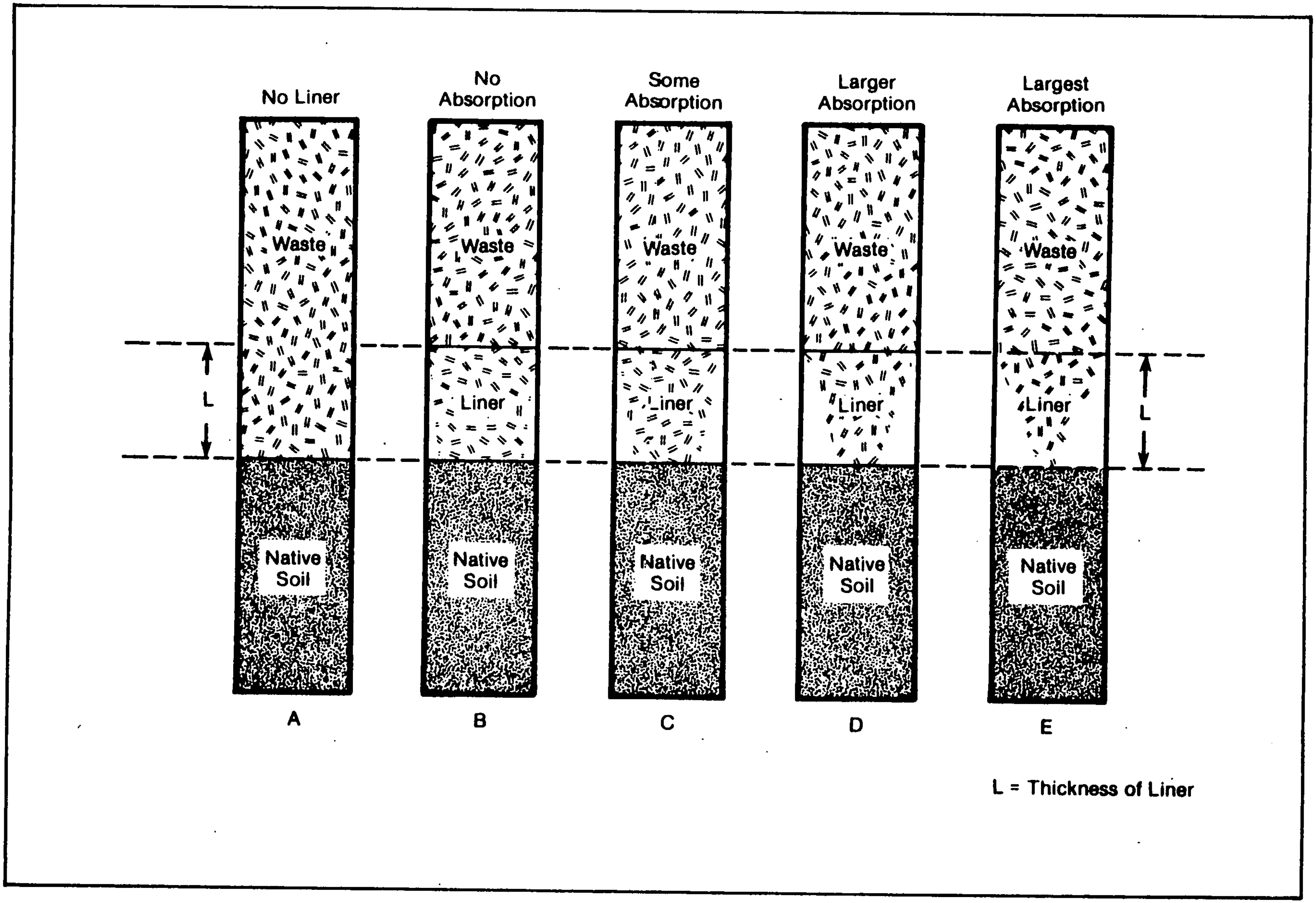
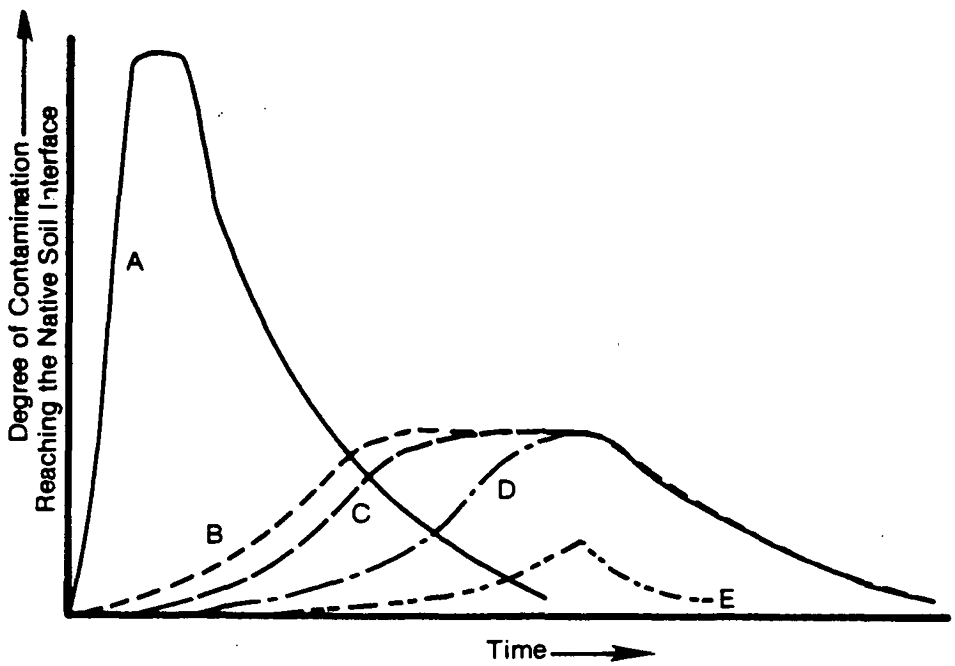


FIGURE 8-1 SCHEMATIC REPRESENTATION OF THE ATTENUATION OF POLLUTING SPECIES BY SOIL LINERS OF DIFFERENT ABSORPTIVE CAPACITIES.



Note: Letters A, B, C, D, & E refer to the five cases shown in Figure 8-1.

FIGURE 8-2 GRAPH OF RATES OF CONTAMINATION OF SOIL LINERS AT DEPTHS EQUAL TO THE THICKNESS OF THE LINERS.

2. The rate of contamination is evaluated in all cases at a depth, L, from the waste interface. The depth L is also taken as the thickness of the liners in cases B through E (Figure 8-1), inclusive.

3. The permeability of the liners in cases B through E, inclusive, is assumed to be the same.

4. The permeability of the native soil is assumed to be greater than that of the clayey soil liners.

5. The absorptive capacity for the polluting species in case C is less than for the corresponding capacity in case D.

6. The absorptive capacity of the liner in case E is greater than the total mass loading of the polluting species of the single load situation.

7. The single unit load situation is defined as a finite amount of polluting species at a given hydraulic gradient which, over time, will approach zero as the polluting species is leached from the soil and/or liner and is not replenished.

8. The constant, continuous wasteloading is defined as the maintenance of a given constant concentration of polluting species at a given hydraulic gradient over time. This implies replenishment of the polluting species in the waste.

9. The analysis assumes saturated flow.

10. The analysis assumes that the waste does not damage the liner or its structural integrity.

Rate curves shown on Figure 8-2 are for the single unit loading condition defined previously. Analysis of Figure 8-2 reveals that case A, as expected, has the highest flux of pollutant contamination, reached within the shortest relative time period. In a single unit loading situation, a plateau is reached, continues for a period of time, and then drops off as the amount of pollutant remaining decreases. In the situation of constant, continuous loading, the plateau is maintained due to steady-state loading conditions. In case B, a liner is present which functions solely to impede flow by reduced permeability.

The distinction between cases A and B is one of intensity of contamination; the capacity of contamination is the same since the integrals below the two curves for times between 0 and t are assumed to be equal. The factors controlling the degree of contamination are mainly physical (flow properties) inasmuch as absorption is assumed to not affect them drastically. In drawing these two curves, one assumes that the contaminant concentration of any polluting species follows the same pattern; the flat plateau represents the situation of the maximal concentration controlled by the characteristic dissolution/precipitation reactions of the effluent. All in all, the permeability differential has the effect of diminishing the intensity factor, but leaving the capacity of contamination unaltered, thus, only a retardation effect is accomplished.

In examining cases C and D, it can be seen that reaching the maximum rate of contamination is delayed due to the absorptive capacity of the liners. At any time prior to attaining the maximum rate plateau, the difference in the rate curves reflects the magnitude of absorptive capacity of each liner. This absorptive capacity can be defined as alteration of the chemical composition of the waste fluid with respect to the polluting species such that the species is irreversibly retained in the liner. Characteristic curves like cases C and D will be generated, depending on the degree of retention of the polluting species by the liner. If the relationship between a particular contaminant and the liner is so great that the pollutant is almost totally retained, then no plateau will exist for such a curve for single loading, and a situation similar to that described for case E will result. The characteristic curve shown by case E reflects leakage in the system. In the situation where constant continuous loading is applied, the characteristic curve for case E (after a relatively long period) will approach the plateau level of cases B, C, and D.

Further analysis of Figure 8-2 shows the rate differential of the characteristic curve plateaus for the constant, continuous loading situation. This differential, given the assumptions stated previously, is mostly a function of permeability of the soil versus the liner.

8.2.4.2 Attenuation and Cation Exchange Capacity.

The term "attenuation" is sometimes erroneously linked to metallic trace elements through the well-known cation exchange properties of soils. This connection can be grossly misleading on at least two bases:

1. Soil cation exchange properties are revealed by true exchange reactions. A cation can be adsorbed and temporarily stored in the liquid/solid interface. With the decrease of concentration in the liquid phase, it will be released again. Consequently, if an exchange would have been present in soil B, then the degree of contamination versus time relationship should have been a mirror image of curve B, but slightly displaced to the right on the time scale. The picture described by soil C does not correspond to such a situation. Curve C describes the situation in which the retention of the cation was permanent. Although these reactions are known in soil chemistry (for metallic species like K, Li, etc.), the engineer designing a waste disposal site should not rely on them.

2. For the same ionic composition and strength of waste effluent and the same activity of a particular cation, the larger the cation exchange capacity of a soil, the larger the amount of the element temporarily stored. However, this amount is so dependent on the chemistry of the effuent (its purity with regard to the particular element considered, ionic composition, strength, secondary mineral formation (precipitation/dissolution), the presence of chelating agents, complex formation with different than assumed ionic forms, etc.) that the effect of the magnitude of the exchange capacity is almost totally offset.

Modeling of such complex systems has been done in the past. Such an analysis will require an accurate assessment of the interaction between the particular waste and soil considered. This analysis can only be obtained by setting up bench-scale column tests with the materials of concern.

8.2.5 Soil Admixtures

The same soil admixtures have been evaluated for liner materials as were for the cover materials discussed in Appendix A. Bentonite clay is an excellent soil additive due to its low permeability and excellent cationic exchange capacity. Bentonite clay should be used as a soil additive if either soil permeability or radionuclide attenuation properties of readily available soils are found to be insufficient. The effects of increased pollutant attenuation capabilities were previously discussed in subsection 8.2.4 and are achievable by supplemental clay addition.

Both soil cement and soil asphalt could be used as liner materials, however, their pollutant attenuation capabilities and ability to control hydraulic flux are suspect and must be field tested before being used as passive liner materials.

8.3 LINER EVALUATION

A critical aspect of the design and construction of an effective liner system for low-level radioactive wastes is the systematic evaluation of engineering criteria. Such an evaluation is the intent of this subsection. The individual performance criteria will be discussed and standardized. Each liner type will be evaluated based on each of the performance criteria, and the most suitable liner will be selected for further development.

8.3.1 Performance Criteria

The following parameters were considered in evaluating synthetic liner materials:

1. Ability to Provide Controlled Hydraulic Flux -- The ability to provide controlled hydraulic flux is the most essential criteria in selecting a passive liner system. Without this ability an impermeable liner would fill with leachate and risk massive hydraulic failure. With the ability to control hydraulic flux properly, a selected liner material can also provide pollutant attenuation if adequate retention times through the liner are established. Thus, it can be seen that a low permeability liner with proper pollutant attenuating capabilities can be engineered to provide excellent pollution control.

2. Seismic Stability -- Liner materials were evaluated on the same basis as cover materials for seismic stability, and the reader is referred to Appendix B for a discussion of the performance criteria.

3. Crack Resistance -- Liner materials were evaluated on the same basis as cover materials for crack resistance, and the reader is referred to Appendix B for a discussion of the performance criteria.

4. Radionuclide Attenuation -- Radionuclide attenuation is probably the most important aspect of a passive liner system for the containment of low-level radioactive solid wastes. Radionuclide attenuation is directly related to a soil's cationic exchange capacity because radionuclides are predominantly cations. Knowing the radionuclear ionic chemistry of a particular waste, along with the cationic exchange capacity of a particular soil, the proper liner thickness and density can be engineered. Additionally, the cationic exchange capacity of a soil can be increased by the addition of bentonite clay. The very high cationic exchange capacity of bentonite can easily enhance the radionuclide attenuation capabilities of native soils.(2) A detailed discussion of the attenuation properties of soil liners was discussed in subsection 8.3.4.

5. Ability to Impede Root Penetration -- The ability of a liner to impede root penetration is only important in the shallow areas of an impoundment facility where the cover ties into the liner. For this reason, the liner materials were evaluated for their ability to impede root penetration. Liner materials were evaluated on the same basis as cover materials on their ability to impede root penetration, and the reader is referred to Appendix B.

6. Potential for Damage to Liner During Placement -- Damage during placement is an important criteria for both covers and liners. Generally, thinner membranes are more susceptible to damage during placement. Thinner membranes are easily punc-

tured by heavy construction equipment, and therefore, much care must be taken during placement. For these reasons, synthetic membranes and spray asphalt emulsion were given poor performance ratings due to their relatively thin natures.

7. Ease of Construction -- Liner materials were evaluated on the same basis as cover materials for their ease of construction. The reader is referred to Appendix B for a review of the performance criteria in evaluating ease of construction. Here again soils are rated the highest.

8. Probable 1,000-Year Life --Liner materials were evaluated on the same basis as cover materials for the probability of a 1,000-year, low maintenance life, and the reader is again referred to Appendix B. Again, natural materials are preferred over synthetic and biochemically-degraded materials.

9. Cost of Placement -- Liner materials were evaluated on the same basis as cover materials for the cost of placement, and the reader is referred to Appendix B.

8.3.2 Systematic Liner Evaluation

Each liner material was evaluated on the performance criteria discussed in the previous subsection. A systematic performance rating of each liner material is shown in Table 8-1. If a liner material was given a positive performance rating, a plus sign appears in that criterion column. If a negative performance rating was given, a minus sign appears in the criterion column. It can be clearly seen that bentonite as a soil admixture displays the best performance as a liner material. By mixing bentonite with native soils the desired permeability of the liner can be achieved for proper hydraulic flux. The additional cationic exchange capacity added by the bentonite will also increase the radionuclide attenuation capabilities of the liner. Finally, the use of natural materials allows long-term stability of the system.

Table 8-1

Liner Material General Performance Criteria Evaluation

Liner Material	Permits Hydraulic Controlled Flux	Historical Application as Liner Material	Seismic Stability (2)	Crack Resistance (3)	Radionuclide Attenuation (5)	Vegetation Penetration	Potential for Damage to Liner During Placement	Ease of Construction	Probable 1,000-Year Life	Biochemical Deterioration	Cost of Placement
Spray Asphalt Emulsion	-	+	-	-	-	-	+	-	-	-	+
Hydraulic Asphalt	-	+	-	+	-	+	+	+	-	-	-
Synthetic -- Hypalon	-	+	-	+	-	-	-	+	-	-	-
Synthetic -- PVC	-	+	-	+	-	-	-	+	-	-	-
Synthetic -- Neoprene	-	+	-	+	-	-	-	+	-	-	-
Synthetic -- CPE	-	+	-	+	-	-	-	+	-	-	-
Concrete	-	+	+	+	-	+	+	-	+	+	-
Low Permeability/Native Soils (1)	+	+	+	-	-	-	+	+	+	+	+
Soil Admixtures (4) (Bentonite)	+	+	+	-	+	-	+	+	+	+	+
Bentonite (4)	+	+	+	-	+	-	+	+	+	+	-
Soil Cement	+	-	-	-	-	+	+	-	-	+	-
Soil Asphalt	+	-	-	+	-	+	+	-	-	-	-

Note: Numbers in parentheses are reference citations.

8.4 FINAL LINER SELECTION

Upon reviewing the performance evaluation procedure used in the previous subsection, it can be seen that low permeability native soils, bentonite as a soil admixture, and bentonite were given the highest performance ratings. Bentonite is added in two of the three materials to decrease permeability and increase the radionuclide attenuating properties of the soils. The specific liner material can only be selected once the readily-available native soils are tested for permeability and cationic exchange capacity.

It should also be noted that bentonite is susceptible to deterioration in excessively low or high pH environments.[3,4,5] pH effects can only be assessed once the low-level radioactive waste of concern is tested sufficiently. These effects are expected to be minimal because the waste material has been leached by rainwater for many years.

A liner system used with a cover has the additional qualities of allowing waste encapsulation. By tying the cover and liner systems together, the buried low-level radioactive wastes can be completely sealed. Encapsulation allows more complete isolation of the disposed waste, and therefore lessens any environmental impacts.

Finally, the radionuclide attenuating capabilities and inherent structural and biochemical stability of soils aid in their selection. Additionally, no other materials known to man can provide such long-term stability as soils. Relatively simple construction techniques, along with ready availability and accessibility, make soil an obvious choice as a liner material.

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SECTION 8

LINERS

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SECTION 9

DEVELOPMENT OF SELECTED ALTERNATIVES

9.1 INTRODUCTION

In the preceding sections, the principles applicable to the control of the various routes of migration of radioisotopes off-site were presented. The specific components selected for overall site management include:

1. Low permeability soil cover system to reduce radon emanation and simultaneously limit water infiltration which may carry radioisotopes to the groundwater tables (designated Area A).

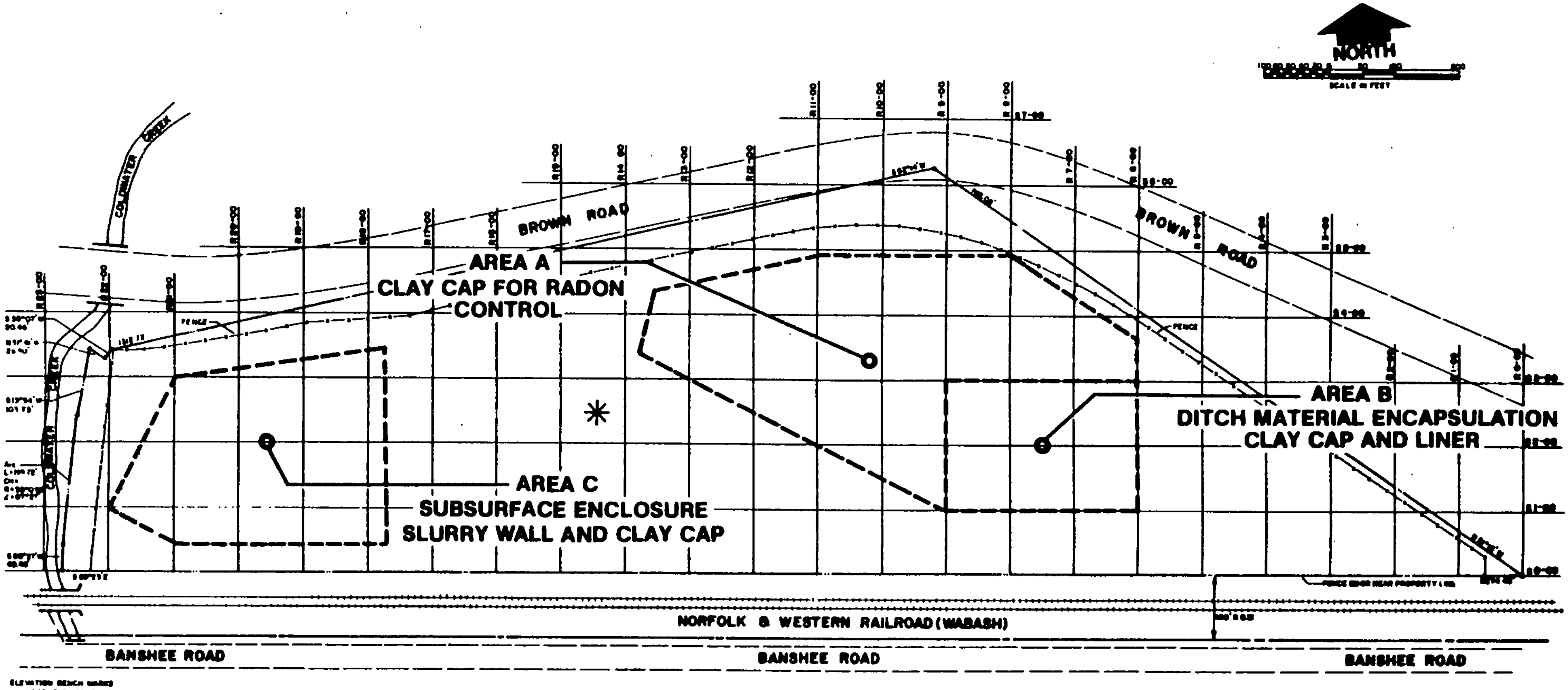
2. Excavation of contaminated soil and burial in a landfill with an impervious liner and cover (designated Area B).

3. Low permeability subsurface cutoff wall (bentonite-soil slurry wall) to reduce migration off-site by horizontal groundwater movement in conjunction with a low permeability soil cover system to reduce radon emanation and simultaneously limit water infiltration into the enclosed area (designated Area C).

4. Topsoil and soil cover to reduce erosion, suppress the surface alpha, beta, and gamma flux, and control water infiltration (designated Area D).

The overall plan for site development is shown on Figure 9-1.

A complex cover is recommended for Area A, to suppress the diffusion of radon. In part, it will abut the encapsulation area, Area B, as shown on Figure 9-2. An additional section through the cover is illustrated on Figure 9-3. The clay cap is 4-feet thick. It is covered by a 1-foot drain layer and 2 feet of soil. The drain layer laterally diverts water into seepage pits well below surface grade elevation so that soils above the drain layer may provide an additional safety factor for the control of radon emanation. The surface slope of the cover varies from a minimum of 1 percent to a maximum of 5 percent. The side slopes range up to 20 percent, and are riprapped to ensure long-term stability.



✳ OTHER PARTS OF SITE WITHIN FENCELINE DESIGNATED AS AREA D.

FIGURE 9-1
OVERALL SITE DEVELOPMENT PLAN
ST. LOUIS AIRPORT STORAGE SITE

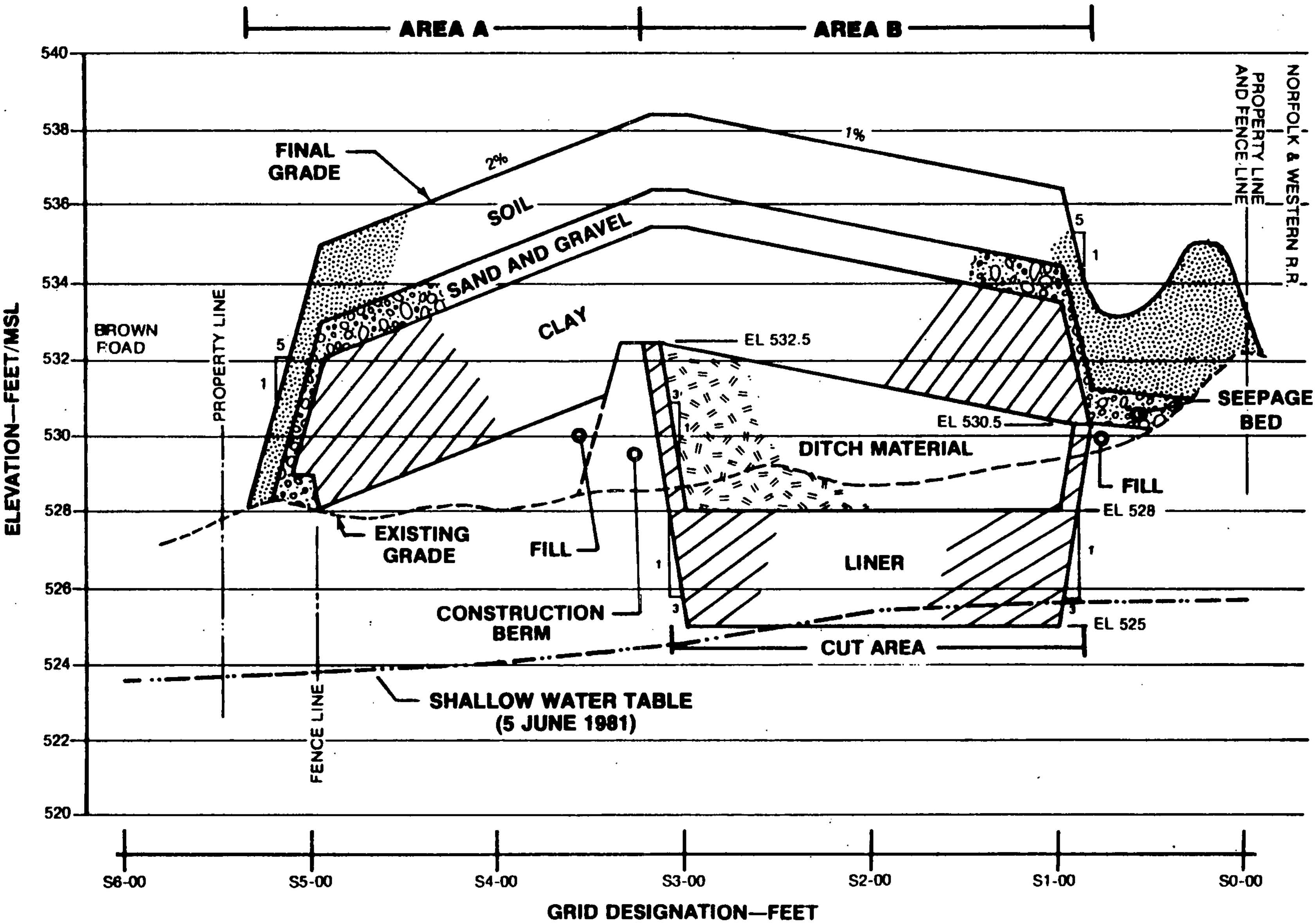


FIGURE 9-2 CROSS SECTION (AXIS R8-00) THROUGH DITCH MATERIAL ENCAPSULATION (AREA B) AND CLAY CAP FOR RADON CONTROL (AREA A)—ST. LOUIS AIRPORT STORAGE SITE

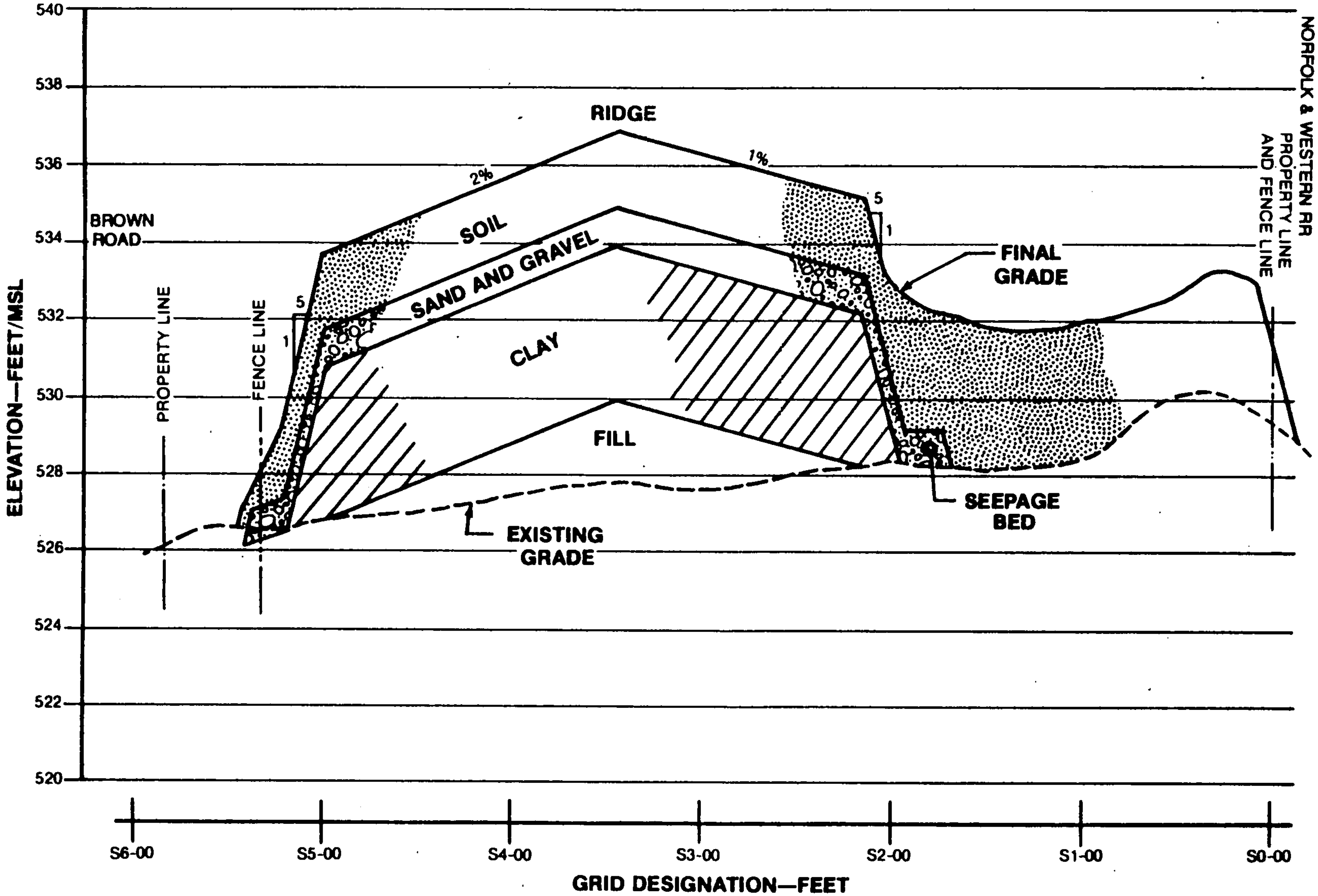


FIGURE 9-3 CROSS SECTION (AXIS R11-00) THROUGH CLAY CAP FOR RADON CONTROL (AREA A)— ST. LOUIS AIRPORT STORAGE SITE

The contaminated material to be removed from the ditch along Brown Road will be placed on a clay liner and covered in the area designated Area B on Figure 9-1. This area was selected due to its very low contamination level. Since the surface material is relatively clean, there will be little risk of off-site contamination during excavation for the liner and emplacement of the soil elsewhere.

The very eastern tip of the site would produce very steep slopes if covered with clean fill. Therefore, some preliminary excavation of this area is required, as noted on Figure 9-1. This material (2,300 cu yds) will also be placed in the lined and capped area. The total capacity of the lined area, as designed, is 8,300 cu yds. This provides an excess over the total projected fill of 5,000 cu yds from the ditches, plus 2,300 cu yds from the eastern tip. If the entire volume is not required, the elevation may be adjusted during construction as long as the 1 percent surface slope is maintained.

The soil removed from the liner pit may be used to grade the surface under the radon cap area to the north. Some excess soil is predicted which may be mounded in the excess soils area near coordinates S2-R15.

At the western end of the site, Area C, the buried waste deposit will be surrounded by a subsurface slurry wall and capped with:

1. A surface drain of 6 inches of sand.

2. A clay cap with a minimum thickness of 3 feet.

3. A drain layer of crushed rock or coarse gravel 12-inches thick.

4. A soil layer 18-inches thick.

5. A topsoil layer of 6 inches.

The remainder of the area, Area D, will be covered with 3 feet of soil (on the average) to properly adjust the site drainage patterns and to provide further assurance that beta and gamma emissions, as well as radon emanation, are controlled. In general, the soil will be placed over existing grades with only minor surface smoothing. However, as will be shown in the grading plan, some surface material must be moved from the vicinity of the sedimentation basin (Figure 9-14) to the excess soil area.

9.2 COVER SPECIFICATIONS FOR RADON CONTROL

The purpose of the cover systems described in this section is to reduce radon fluxes at the surface of the covered St. Louis disposal site to 2 pCi/sq m/sec or less. It is necessary to design the cover to accommodate the highest radon flux anticipated for the site in its present configuration. The site characterization indicates that the highest measured radon flux is 49 pCi/sq m/sec measured in the far northern portion of the site in May 1981.(15)

The peak radon flux of 49 pCi/sq m/sec was measured during a period of extreme soil wetness and is considered to be lower than fluxes that may occur during dry periods and lower than the yearly average maximum flux. To be conservative, a design base radon flux of 150 pCi/sq m/sec was selected.

The design cover thickness to reduce the design base flux to the 2 pCi/sq m/sec specification can be computed using equation (9-1). Equation (9-1) was derived by solving equation (C-2) for x_1 (see Appendix C).

$$x_1 = -\ln\left(\frac{J_1}{J_o}\right)\frac{1}{\sqrt{\frac{\lambda x p}{Dh}}} \qquad (9\text{-}1)$$

Where:

$h = 1$ (dimensionless coefficient)

$J_1 = 2$ pCi/sq m/sec

$J_o = 150$ pCi/sq m/sec

Laboratory measurements were performed on two soils by Rodgers and Associates Engineering Corporation (RAECO) as given in Appendix C. One soil sample, designated Berkeley soil, was taken near the site. It is considered to be representative of soils common to the St. Louis area. The second soil, a clay soil not necessarily common to the St. Louis area, was evaluated. RAECO has found that the clay soil performs very well in attenuating radon.

The following minimum cover thicknesses were calculated from data obtained through laboratory experimentation:

Berkeley: $x_1 = 113$ cm (44.6 in)

Clay: $x_1 = 76.5$ cm (30.1 in)

Experimental procedures and methodologies and an explanation of equation (9-1) are given in Appendix C. It is recommended that these minimum cover thicknesses be increased to 6 feet of Berkeley soil or 4 feet of clay to provide an adequate safety factor for the site area with the highest radon flux levels.

The cover configuration recommended for use in the encapsulation area is shown on Figure 9-4. The clay or special soil layer is sufficient to attenuate the radon to acceptable levels. The sand layer above the clay will act to retard the loss of moisture in the clay from capillary action. The precipitation/evapotranspiration balance indicates that the clay should retain sufficient moisture to be effective in attenuating radon.

The site characterization report indicates that south of the S-3 coordinate at the site, the largest recorded radon flux was 14 pCi/sq m/sec. For this reason, it is suggested that the above minimum cover thicknesses be reduced to 3 feet of Berkeley soil and 2 feet of clay south of the S-3 line.

Table 9-1 summarizes the design parameters for the clay cap at the St. Louis Airport site. The clay caps consist of single layers of soil or clay placed over the current site surface with the thicknesses, compactions, and moistures shown. Additional layers of material, such as those shown on Figure 9-4 should further reduce radon emissions. However, the clay cap design parameters summarized in Table 9-1 are adequate by themselves to meet the 2 pCi/sq m/sec specification.

Table 9-1

Clay Cap Design Parameters

Parameter	Material	
	Berkeley Soil	Clay
Minimum thickness[1] (ft)	6	4
Density (g/cu m)	1.8	1.8
Moisture g water/g dry soil	0.25	0.53

[1]South of S-3 it is permissible to reduce the cover thicknesses to half the values shown.

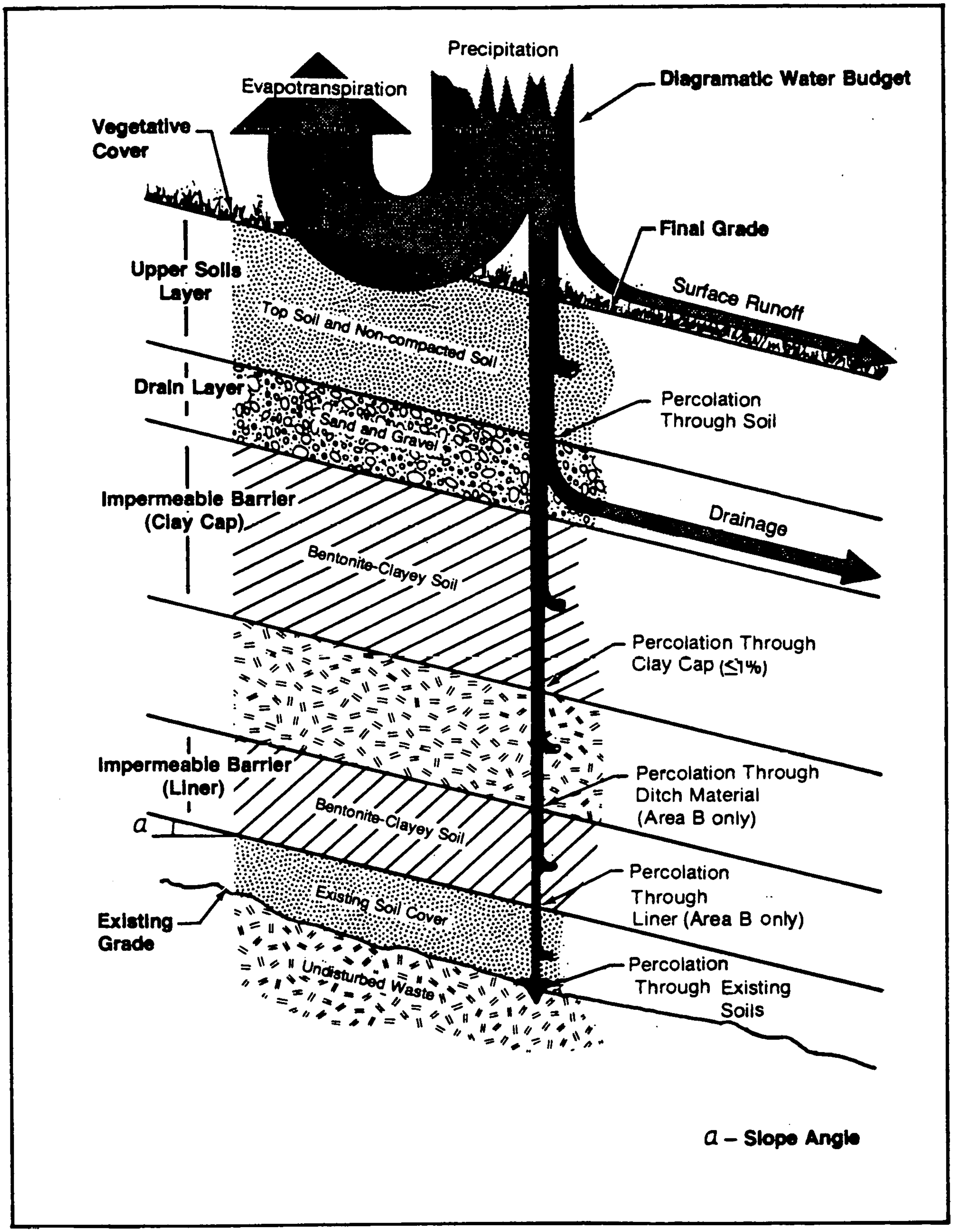


FIGURE 9-4 PROFILE OF RECOMMENDED COVER CONFIGURATION ST. LOUIS AIRPORT STORAGE SITE

Because of the conservatism used in calculating the required clay cap thicknesses, it is believed that the density and moisture content of the clay cap shown in Table 9-1 can vary from the values given by 30 percent without causing radon fluxes to exceed the design goal.

9.3 COVER (SURFACE CONTAINMENT)

The cover systems consist of several layers as shown on Figure 9-5. To accommodate the criteria indicated, two multilayered cover systems were evaluated. They differ only in the clay cap thickness to achieve radon control requirements. The ditch material (Area B) and western cover (Area C) systems are identical. Both require a clay cap barrier thickness of 36 inches. The northern cover system, on the other hand, requires a clay cap thickness of 48 inches. Each system will consist of the following:

1. Top layers of noncompacted soils which support vegetation.

2. A middle layer of coarse gravel or crushed rock.

3. A bottom layer of clay.

The purpose of the noncompacted soil is to support grasses which control water and wind erosion. The soils consist of 6-inches of topsoil, supported by a less expensive soil which lacks the necessary nutrients needed to support vegetation. In addition, they protect the clay cap from direct exposure to weathering. The added safety factor of controlling the escape of radon gas and preventing the clay cap from drying out and cracking are other benefits.

The middle soil layer acts as a porous flow zone. This layer laterally diverts water to seepage pits well below the soil surface. This layer consists of well-graded granite gravel or crushed rock. The purpose of the drain layer is threefold, as follows:

1. Provide a significant reduction in the vertical component of water infiltration flow by diverting it in a horizontal direction.

2. Act as a hydraulic air gap, negating the possibility of upward capillary water flow and subsequent dewatering of the clay layer, which would result in the clay cracking and greatly increasing water infiltration.

3. Impede rodent burrowing and the resulting cover distruction.

The clay cap consists of low permeability and high clay content compacted soil. The clay layer functions as an impermeable barrier against radon emissions and water percolation. The upper 6 inches of this layer will consist of a bentonite/soil mixture (5% bentonite by weight). It will be underlain by clayey soils native to the St. Louis area to the required total thickness of either 36 or 48 inches.

The cover system as described has the benefit of being constructed of entirely natural materials. The use of these materials is the best assurance of extended facility life because of their high resistivity to biochemical degradation and inherent structural stability.

The results of water budget analyses for the ditch material, cover (Area B), and western cover systems (Area C), are given on Figure 9-5. Both cover systems have clay thicknesses of 36 inches, based on radon control requirements. They differ in minimum surface slope only. Greater surface slopes result in greater attenuation of deep water percolation through the cover. Minimization of deep percolation is an objective of surface containment. An annual deep percolation rate for the western cover system was set at 0.1 in./yr so that its efficiency for attenuating water percolation is greater than that of the bentonite/slurry wall. In time, water will accumulate within the subsurface enclosure unless it is permitted to exit at a rate that is equal to or greater than the rate at which it enters.

Water budget results for the northern cover system (Area A) are given on Figure 9-5. Observed radon emission fluxes in the northern area are greater than those for either the ditch material or western areas. In fact, observed fluxes in the northern area are the greatest observed on the entire site. Radon control, therefore, requires a clay cap thickness of 48 inches as described in subsection 9.2. The impermeable barrier for the northern area is 12 inches thicker than that specified for the ditch material and western cover systems.

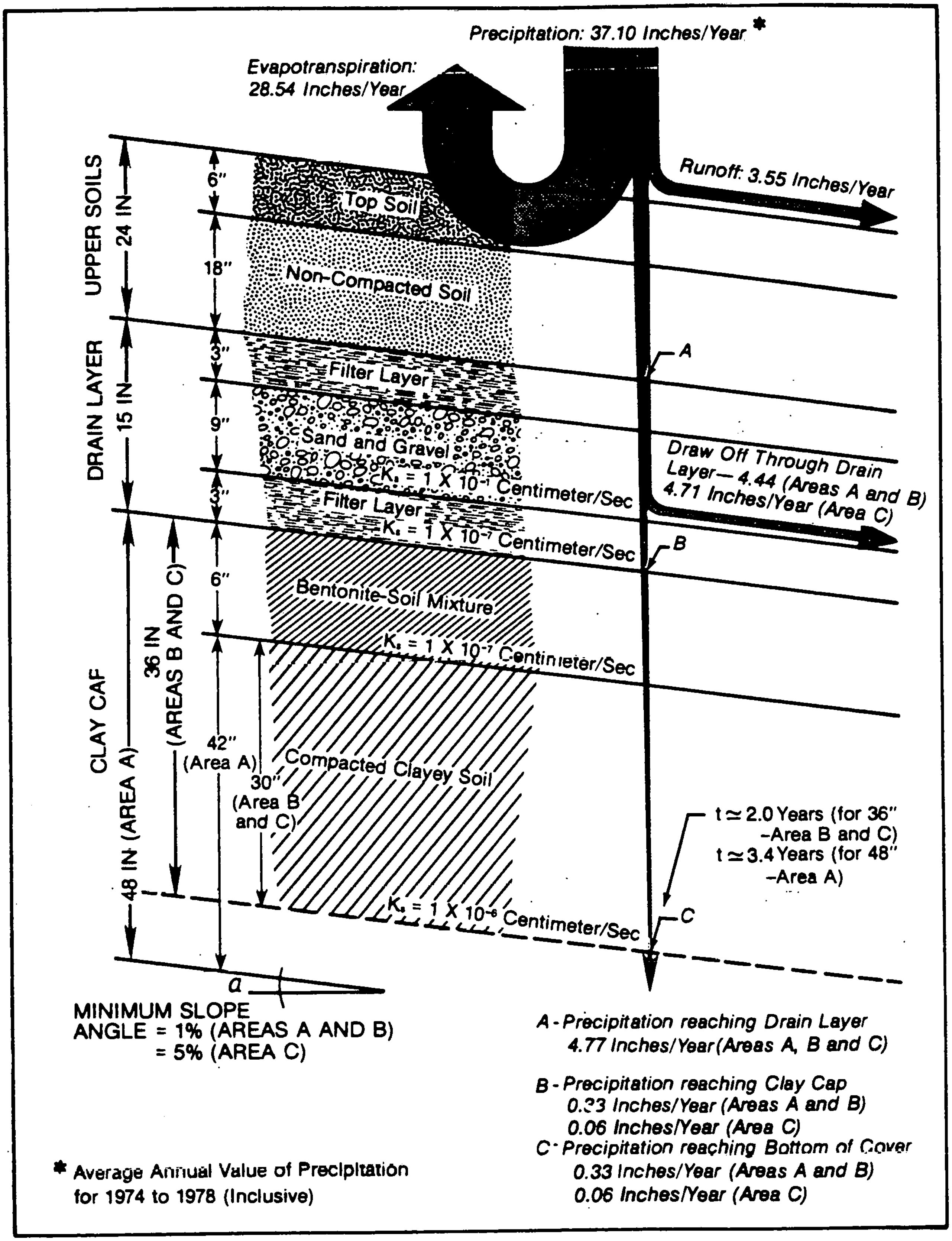


FIGURE 9-5 WATER BUDGET RESULTS FOR RECOMMENDED COVER SYSTEM (AREAS A, B AND C) ST. LOUIS AIRPORT STORAGE SITE.

9.3.1 Vegetation and Upper Soils

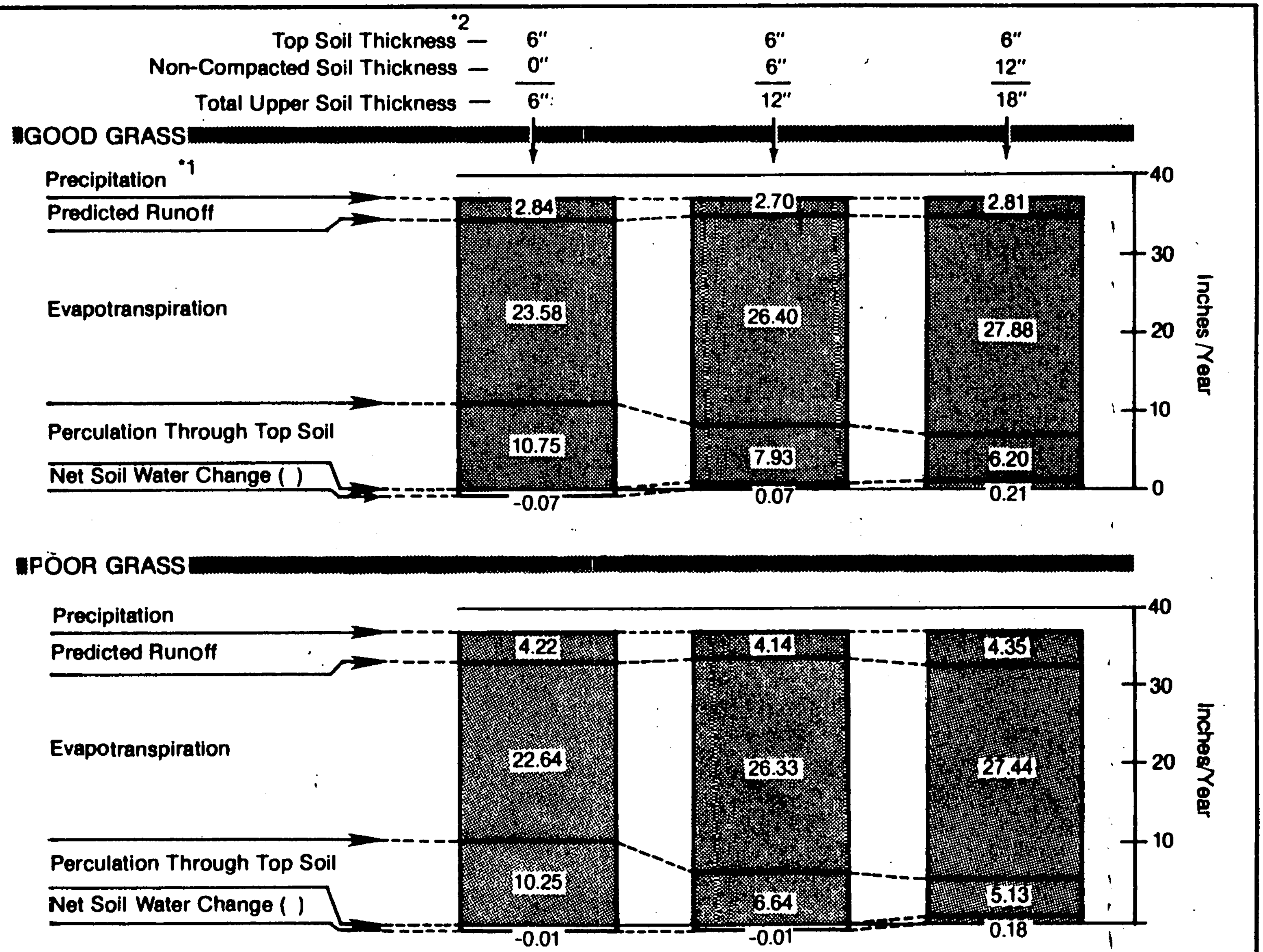
Vegetation controls erosion and encourages soil water loss by evapotranspiration. Otherwise, erosion will ultimately degrade the cover and seriously reduce its effectiveness. A "fair" vegetation rating is used in the concept design as opposed to "good" or "excellent" ratings. The "fair" rating is considered representative of the as-built system.

The effect of vegetation quality on resultant percolation through the topsoil and underlying noncompacted soil was examined. The results for good grasses as opposed to poor grasses are shown on Figure 9-6. Subjectively, good grasses may be defined as grasses that give full, thick cover, with deep root penetration for soil stability, while poor grasses yield patchy, thin cover with shallow root penetration. The results were computed using the Hydrologic Simulation on Solid Waste Disposal Sites (HSSWDS) model developed by the EPA with the U.S. Army Corps of Engineers.[18] This one-dimensional (vertical) model is presently in draft form. It represents a state-of-the-art methodology for performing water budget analyses on complex cover systems. Since it is a one-dimensional simulation, the results are insensitive to surface slope and area. However, for the St. Louis Airport site, all covers are modest in size (less than 3 acres) and surface slope (5 percent or less). Therefore, water budget results are considered the best engineering estimates. A two-dimensional model has been developed as Version II of HSSWDS. The EPA expects to release Version II in late fall 1981.

In Figure 9-6, the dynamic interaction between surface runoff and evapotranspiration is evident. Note that for good grass, evapotranspiration is greater than for poor grass. The benefit of greater transpiration loss is negated, however, because runoff for good grass is less than that for poor grass. Therefore, the resultant percolation for poor grass is less than that for good grass. Due to its adverse water erosion effects, poor grass is unacceptable.

Topsoil thickness will be limited to 6 inches because of its relatively high cost. If adequate quality topsoil is not available, it may be necessary to supplement it with fertilizers, conditioners, etc. Vegetation characteristics which almost universally should be given precedence are:

1. Low-growing and limited penetration of plant roots.



*1. Average Annual Value Precipitation for 1974 to 1978 (Inclusive) — 37.10 Inches/Year

*2. Top Soil—Silt Loam, Non-Compacted Soil—Clay as per USDA Soils Textural Classification

FIGURE 9-6 COMPARATIVE WATER BUDGET RESULTS FOR 'GOOD' GRASS VERSUS 'POOR' GRASS VEGETATIVE COVERING

2. Rapid germination and development.

3. Resistance to fire, insects, and disease.

Rapid establishment and maintenance of vegetation can be accomplished by carefully addressing soil type, nutrient and pH levels, climate, species selection, mulching, and seeding time. Local agronomists or county agricultural agents could provide guidance with respect to specific requirements.

Beneath the topsoil, a noncompacted soil, native to the area, will be used. The noncompacted soil layer supports vegetation primarily through its increased water-holding capacity. This soil layer typically lacks the general silt, sand, and clay composition and macronutrients needed to adequately support vegetation.

Slope stability will be maintained by limiting slopes to a ratio of 1 vertical to 4 horizontal (1V on 4H). This is the maximum slope on which vegetation can be established and maintained, assuming an ideal soil with low erodibility and adequate moisture-holding capacity. For less than ideal soils, maximum vegetative stability cannot be attained on slopes steeper than about 1V on 3H. Optimum vegetative stability generally requires slopes of 1V on 4H or flatter. Wind erosion is insignificant for slopes less than 1 percent, however, it is significant for slopes greater than 10 percent. This can be minimized by adequate vegetation cover.

Annual percolation through the upper soils from 1974 through 1978, inclusive, are given in Table 9-2. Water budget results were computed by HSSWDS.[18] Minimum and maximum percolation values were found in 1977 and 1975, respectively.

A "default" climatological data input option in HSSWDS was used for the analysis. This option permits the use of climatological data for approximately 90 cities across the country. The program used has a second option of manually loading climatological data that may be more specific to a study area. The climatological input includes parameters such as precipitation, solar radiation, and leaf area index (LAI) for the city requested. Climatological data for Columbia, Missouri were felt to be representative of St. Louis.

Greater attenuation of percolation through the upper soils layers is achieved with greater total thickness as shown on Figure 9-7. There is a significant reduction in percolation as a function of increased total thickness. A thickness of 24 inches was selected for the cover systems proposed in the concept design on the basis of:

Table 9-2

Results of Water Budget Computed Using HSSWDS

Vegetation Classification: "Fair" grass

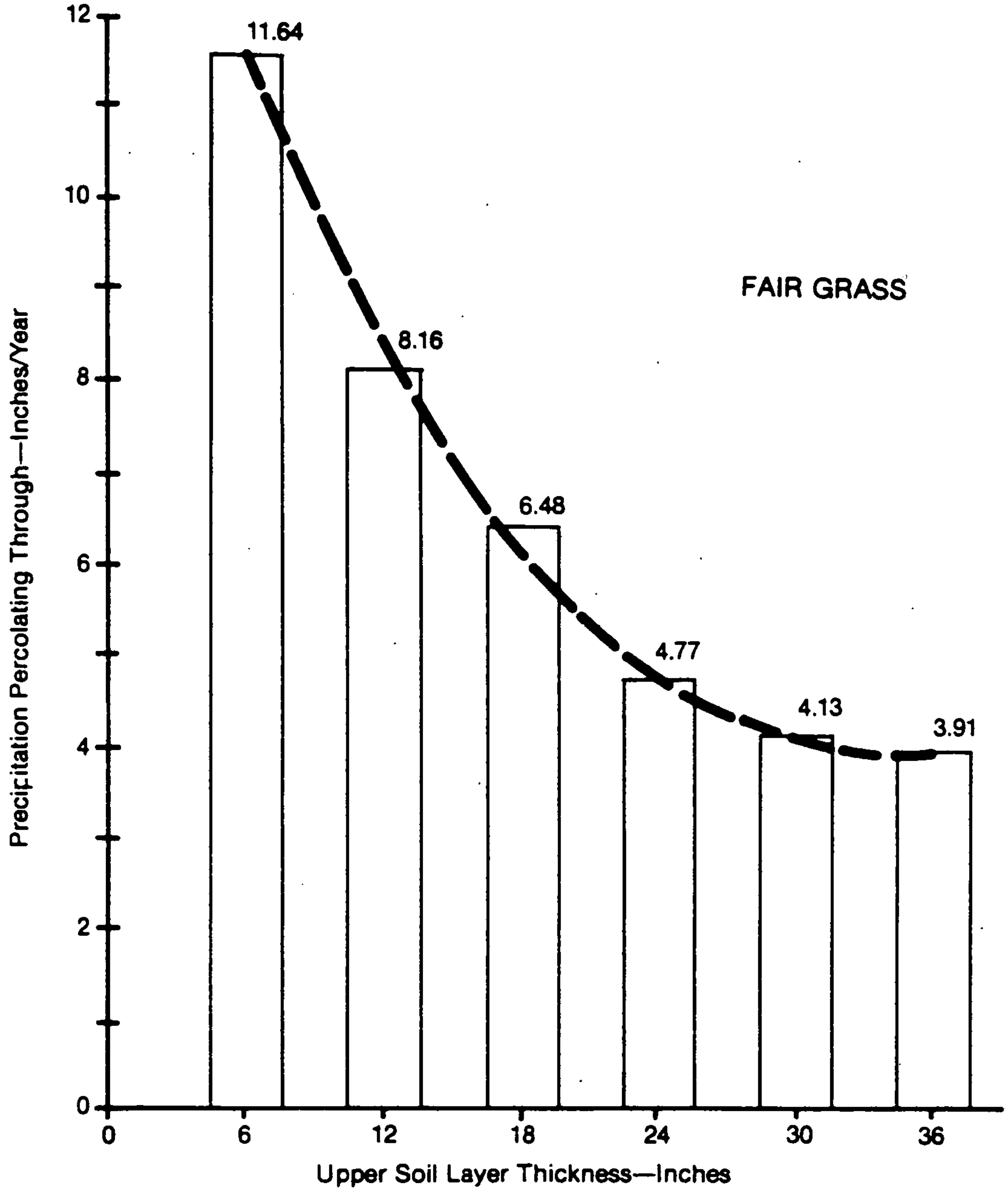
Topsoil: Silt loam[1]

Noncompacted Soil: Clay[1]

Year	Rain in.	Runoff in.	Evapo-transpi-ration in.	Perco-lation in.	Soil Water Initial in.	Soil Water Final in.
1974	43.93	3.15	33.06	6.28	1.45	2.89
1975	44.13	6.78	30.85	6.49	2.89	2.90
1976	23.88	1.93	19.79	3.47	2.90	1.58
1977	36.49	2.82	29.91	3.20	1.58	2.14
1978	37.07	3.36	29.06	4.41	2.14	2.38
Average	37.10	3.61	28.54	4.77		

Note: Topsoil layer thickness: 6 inches
Noncompacted soil layer thickness: 18 inches
Total upper soil thickness 24 inches

[1]U.S. Department of Agriculture textural classification.



1. Upper Soils Layer Consists of top soil (a constant thickness of 6 inches) and non-compacted soils
2. As per USDA Soils Textural Classification
   Top Soil—Silt Loam
   Non-Compacted Soil—Clay
3. Precipitation value (37.10 inches/ year) is the Average Annual Value Precipitation for 1974 to 1978 (inclusive).

FIGURE 9-7 GRAPH OF AMOUNT OF ANNUAL PRECIPITATION PERCOLATING THROUGH INCREASING UPPER SOILS LAYER THICKNESS

1. Attenuation of water percolation.

2. Minimization of total cover thickness which must not exceed FAA specified maximum elevations.

3. Minimization of imported materials.

Significant water percolation attenuation for upper soil thicknesses greater than 24 inches was not found.

Five-year average water budget data, given in Table 9-2, are also found on Figure 9-5. Water budget results for successive layers will follow.

9.3.2 Drain Layer

The drain layer will consist of crushed rock or coarse gravel having a relatively large permeability, K_s, of 1×10^{-1} cm/sec. A drain layer thickness of 1 foot will be used. The thickness requirement is a function of:

1. Annual percolation rate.
2. Drain length.
3. Permeability.
4. Drain slope.

The assumed conditions for calculating flow through the drain layer is given in Figure 9-8. This figure shows a drain layer of thickness d(cm) overlying a low permeability material. The drain layer extends over distance, L. The saturated permeability of the drain layer is given by K_s. The annual percolation rate, e, is the amount of water, annually, that impinges on the drain layer. It is assumed that the percolation rate is constant with time. This is a valid assumption since seepage fluxes do not change rapidly with respect to time.

The shape of the saturated water surface for the limiting case when $\alpha = 0$ is given by:[18]

$$h = \left(\frac{e}{K_s} \quad (L-x) \quad x\right)^{1/2} \qquad (9\text{-}2)$$

The maximum height of water in the drain layer, h_{max}, is given by:

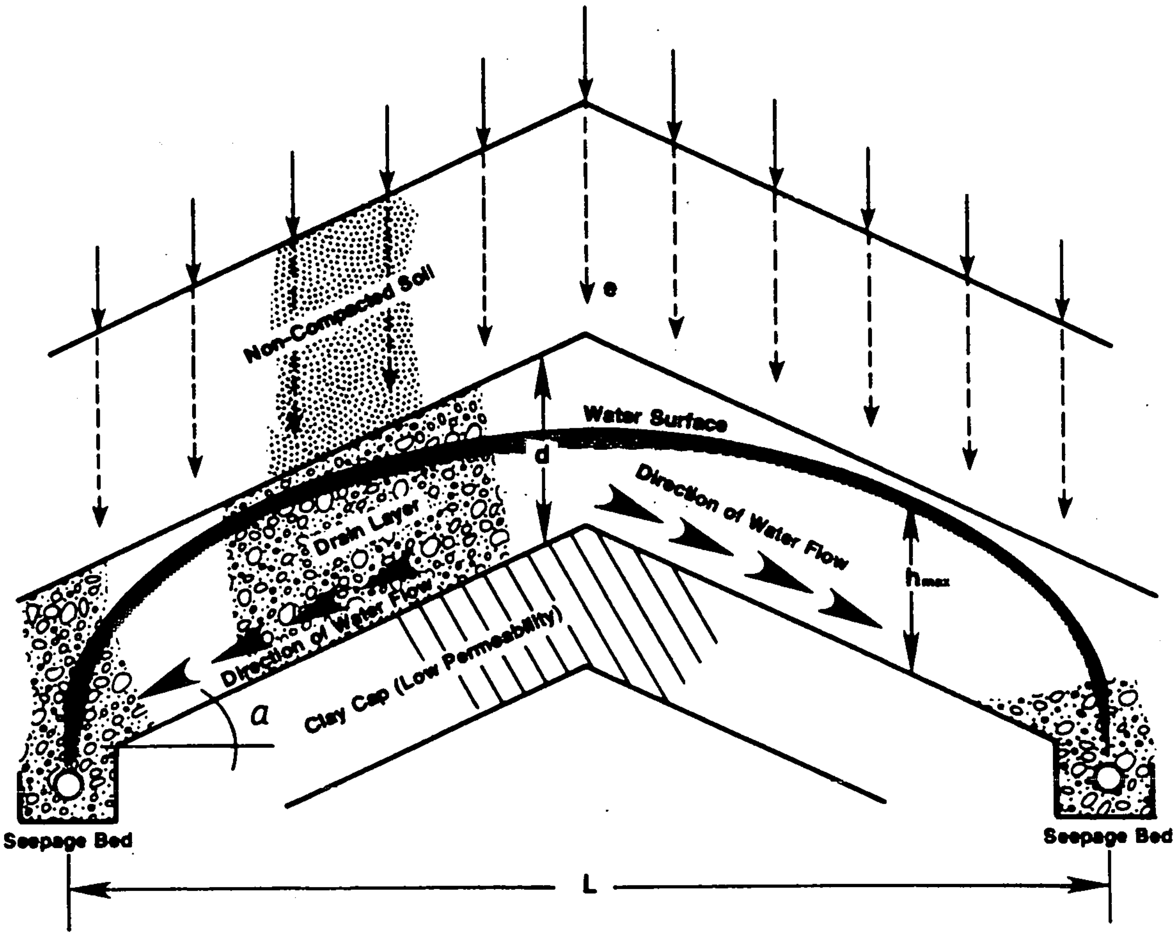
$$h_{max} = \left(\frac{eL}{4K_s}^2\right)^{1/2} \qquad (9\text{-}3)$$

Setting the slope at some value greater than 0 ($\alpha = 0$) will accelerate the flow toward the collector system. h_{max} for $\alpha > 0$ is given by:

$$h_{max} = \frac{L\sqrt{C}}{2}\left[\frac{\tan^2\alpha}{C} + 1 - \frac{\tan\alpha}{C}\sqrt{\tan^2\alpha + C}\right] \qquad (9\text{-}4a)$$

Where:

$$C \equiv \frac{e}{K_s} \qquad (9\text{-}4b)$$



h_{max} — Maximum height of water standing in the Drain Layer

d — Drain Layer thickness

L — Distance between opposing laterals or seepage beds

e — Rate of water flow impinging on drain layer, equal to percolation rate

a — Slope angle

FIGURE 9-8 DIAGRAM OF ASSUMED WATER SURFACE PROFILE IN DRAIN LAYER.

Having a slope α, greater than zero is critical since in this case, if water were to cease impinging on the drain layer, the water would completely drain in a finite amount of time. If $\alpha = 0$ the drainage time is infinitely long.

The results of a sensitivity analysis are given in Table 9-3 to examine the effects of percolation rate, drainage length and slope, and saturated permeability on the maximum height of water standing in the drain layer. Drain thickness requirements will increase as a function of an increase in annual percolation rate and decrease in permeability. Other parameters being equal, drain thickness requirements will decrease as a function of increasing slope. The most critical parameter for a given annual percolation rate is drain permeability. A drain saturated permeability of 1×10^{-1} is specified.

Gradation of particle sizes is required above and below the drain layer to prevent the tendency for fine particles to penetrate the coarser layer.

Equally important, "internal" erosion or differential settlement will result. In time, this will result in deep cracks. Such discontinuities are aggravated by depressions in the vegetated topsoils which provide surface storage of runoff, thus, further encouraging deep percolation. Increased percolation through the upper soils will then overload the hydraulic capacity of the drain layer which, because of its deterioration, is decreasing.

Several filter layers may be used to protect the drain layer. A widely-used criterion for specifying the grain size of a filter layer is:

$$\frac{D_{15}}{D_{85}} < 4 \text{ to } 5$$

Where D_{15} and D_{85} equal grain sizes at 15 and 85 percent by weight of soils that are finer, respectively. A filter fabric may be added to provide an additional safety factor. The details of the required filter layers will be addressed in the final design.

The interaction of particle size and drain slope and length are more critical with respect to drain layer efficiency. Drain efficiency is a measure of the drain's capacity to divert water laterally that is percolating vertically. Efficiencies that exceed 60 percent are recommended.

Table 9-3

Results of Sensitivity Analysis

Drain Layer Length: 325 ft
L = 2 x drainage length = 650 ft = 198.12 m

Vegetation Cover: "Fair" grass

Upper Soil Thickness	Percolation Rate[1]	Slope 1%	5%	10%	15%
		Drain Layer Thickness (in.)			
($K_s = 1 \times 10^{-1}$ cm/sec)					
6 in.	16.02 in./yr 1.28×10^{-8}	7.19	6.99	6.98	6.98
12 in.	11.59 in./yr 9.27×10^{-9} m/sec	6.07	5.94	5.94	5.94
24 in.	6.49 in./yr 5.19×10^{-9} m/sec	4.50	4.45	4.44	4.44
($K_s = 1 \times 10^{-2}$ cm/sec)					
6 in.	16.02 in./yr 1.28×10^{-8} m/sec	26.5	22.3	22.1	22.1
12 in.	11.59 in./yr 9.27×10^{-9} in./yr	21.8	18.9	18.8	18.8
24 in.	6.49 in./yr 5.19×10^{-9} m/sec	15.5	14.1	14.1	14.1

Over 90% of the water impinging on the drain layer, ranging from 3.20 in./yr (1977) to 6.49 in./yr (1975), must be laterally diverted. The drain layer thickness requirement for Areas A and B cover systems is 1.38 inches, using equation (9-4). The drain layers for each area are of the same length, 200 feet, and slope, 1%. For Area C, having a drainage length of 150 feet and a 5% surface slope, the maximum height of water standing in the drain layer is 2.05 inches. A drain layer thickness of 12 inches was selected. This thickness is considered practical from a construction standpoint, and, in addition, provides a safety factor that exceeds several hundred percent. This can be achieved for a very modest additional construction cost.

The approach is based on saturated Darcy flow in both the drain layer and clay cap. The assumed geometry is given on Figure 9-9a, at some time, t.

This approach postulates that at some initial time a rectangular slug of liquid is placed on the saturated liner to a depth, h_o. The liquid flows both horizontally along the slope of the system, and vertically into the clay liner. The fraction of liquid moving into the collector drain system at time, t, is given by:

$$\frac{S}{S_o} = 1 - \frac{t}{t_1} \qquad (9\text{-}5)$$

and the fraction of liquid seeping into the clay liner is given by:

$$\frac{h}{h_o} = \left(1 + \frac{d}{h_o \cos \alpha}\right)e^{-Ct/t_1} - \frac{d}{h_o \cos \alpha} \quad 0 \leq t \leq t_1 \qquad (9\text{-}6)$$

Where:

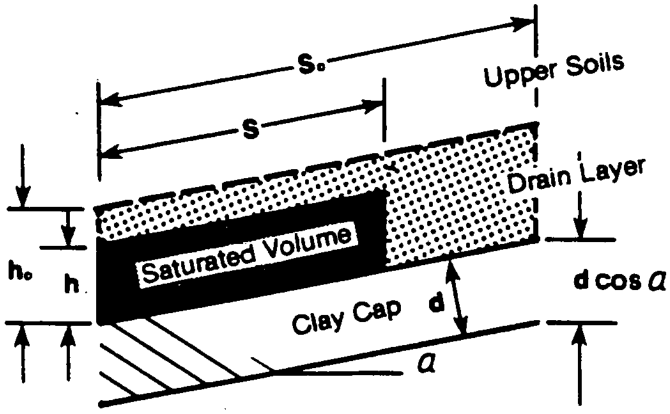
$$t_1 = \frac{S_o}{K_{s1} \sin \alpha} \qquad (9\text{-}7)$$

$$C = \left(\frac{S_o}{d}\right)\left(\frac{K_{s2}}{K_{s1}}\right) \cot \alpha \qquad (9\text{-}8)$$

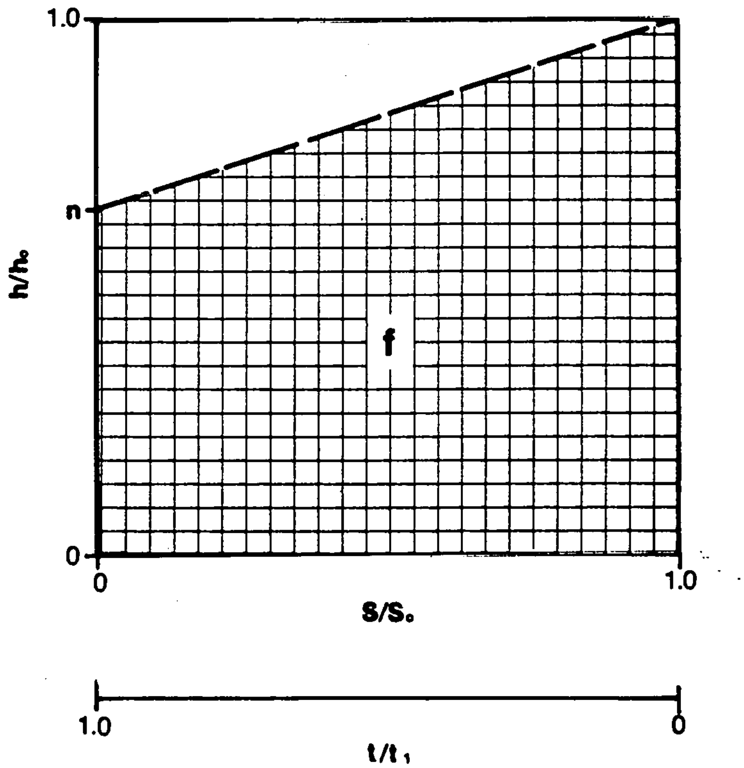
and

S = Length of saturated volume at time, t (cm).

h = Thickness of saturated volume at time, t (cm).



a GEOMETRY FOR CALCULATING EFFICIENCY OF DRAIN LAYER



b DIAGRAM FOR COMPUTING EFFICIENCY OF DRAIN LAYER

FIGURE 9-9 ASSUMED GEOMETRY FOR COMPUTING DRAIN LAYER EFFICIENCY

S_o = Initial length of saturated volume = L/2 sec (cm).

h_o = Initial thickness of saturated volume (cm).

K_{s1} = Saturated permeability of the material above clay liner (cm/sec).

K_{s2} = Saturated permeability of the clay liner (cm/sec).

α = Slope angle of the system (^{o}).

d = Thickness of the clay liner (cm).

The efficiency of the liner is easily determined with reference to Figure 9-9b which plots h/h_o versus S/S_o and t/t_1. Equations (9-5) and (9-6) can be solved parametrically in t/t_1, to yield the line shown on the figure. (The line is actually a curve, however, for practical liner/drain layer configurations it can be approximated as a straight line.) In this case, the efficiency of the system is given by the area labelled "f." This area is most easily determined by calculating the value of h/h_o when t/t_1 = 1.0 (or S/S_o = 0). The term h/h_o is set equal to n and can be obtained by solving equation with t/t_1 = 1.0:

$$n = \left(1 + \frac{d}{h_o \cos \alpha}\right) e^{-C} - \frac{d}{h_o \cos \alpha} \qquad (9\text{-}9)$$

The value of n can be either positive or negative, however, most efficient designs will have $n > 0$. The efficiency is given by either:

$$f = \frac{1+n}{2} \quad \text{for } n > 0 \qquad (9\text{-}10a)$$

or

$$f = \frac{1}{2(1-n)} \quad \text{for } n < 0 \qquad (9\text{-}10b)$$

Thus, the efficiency varies from 0 to 1.0.

The quantity of liquid draining out of the system is given by:

Amount collected in drains = f x h_o

and the quantity of liquid seeping into the clay cap or liner is given by:

Amount seeping into liner = (1-f) x h_o

The amounts of water impinging on the clay cap are summarized in Table 9-4.

Table 9-4

Water Impinging On Drain Layer and Clay Cap

	Precipitation in./yr	Water Impinging on Clay Cap in./yr	Water Impinging on Clay Cap Areas A and B in./yr	Area C
Average 1974 to 1978, inclusive	37.10	4.77	0.329	0.062
Maximum, 1975	44.13	6.49	0.402	0.071
Minimum, 1977	36.49	3.20	0.256	0.048

For the cover system with a bentonite-soil slurry trench (Area C), it is critical that the rate of water passing through the cover not exceed 0.1 in./yr that which can escape through the slurry wall. The cover functions as a lid over the isolated area. If the rate of water through the cover is greater than that which exits through the slurry wall, the contained area will be ultimately filled with water. Groundwater exists around the contained area, but at an elevation well below that of the waste.

Water will be diverted into seepage pits. This was done, as opposed to drainage at the soil surface, to contain radon that may diffuse through the impermeable barrier. Thus, the upper soils provide an added safety factor for radon containment.

9.3.3 Impermeable Barrier (Clay Cap)

The clay cap is constructed either of one layer of compacted soil; or two layers, compacted soil overlaid by a compacted soil-bentonite mixture. The criterion for barrier selection is permeability. Permeabilities of 10^{-6} to 10^{-8} cm/sec are required for attenuation of radon as well as water.

Clay cap thicknesses for the selected concept are 3 and 4 feet. The western and ditch material covers (Areas B and C) will have a thickness of 3 feet. Area A will have a thickness of 4 feet. Measured radon fluxes are greatest in the northern area (Area A) and will require an additional foot of cap thickness.

All water that permeates the clay layer will, in time, ultimately percolate downward through the waste material and the liner (where used). The times required to permeate the barrier are given in Table 9-5 (using equation (9-16)). These time estimates are conservative since they assume a constantly saturated upper boundary. The initial water content will be approximately 15 percent, a water content that is about optimum for soil compaction. During the time that water permeates the cap, the moisture content will increase from 15 to 40 percent. The water holding capacity of the clay soil is approximately 40 percent.

In the early stages, the wetting process is described by equation (9-11) where the first term on the right side dominates,[17] i.e.:

$$\frac{\partial \tilde{\theta}}{\partial t} = D^* \frac{\partial^2 \tilde{\theta}}{\partial Z^2} - K^* \frac{\partial \theta}{\partial Z} \qquad (9\text{-}11)$$

Table 9-5

Time Required for Water to Completely Permeate Clay Cap Consisting of Soil-Bentonite Mixture Plus Compacted Soil

Assumptions:

Diffusivity, D* (sq cm/sec) is from 1 to 2 orders of magnitude greater than in situ permeability.

Compacted soil permeability is one order of magnitude greater than soil-bentonite mixture permeability.

Time Required to Permeate
yrs

Soil-Bentonite Mixture Thickness 0.5 ft			Compacted Soil Thickness 2.5 ft			Total Time yrs
K cm/sec	D* sq cm/sec	Time yr	K cm/sec	D* sq cm/sec	Time yr	
10^{-6}	10^{-4}	0.058	10^{-5}	10^{-3}	0.145	0.203
10^{-7}	10^{-5}	0.578	10^{-6}	10^{-4}	1.446	2.024
10^{-8}	10^{-6}	5.784	10^{-7}	10^{-5}	14.461	20.245

Thus,

$$\frac{\partial \tilde{\theta}}{\partial t} \cong D^* \frac{\partial^2 \theta}{\partial Z^2} \tag{9-12}$$

The D* term represents capillary attraction. During this stage of the wetting process, gravitational forces are negligible as compared to capillary forces.

Imposing the following initial and boundary conditions:

Initial Condition

$\tilde{\theta} = \theta$; for $Z > 0$ and $t = 0$

(Z is positive, downward)

At initial time ($t = 0$), assume that the moisture content is equal to θ, throughout the depth of the liner.

Boundary Condition

$\theta = \theta_s$ for $Z = 0$ and $t \geq 0$

At all times at the boundary ($Z = 0$), the moisture content is held at the saturation moisture content, θ_s.

The solution of equation (9-12) , having the initial and boundary conditions just given is:

$$\tilde{\theta} = \theta_i + (\theta_s - \theta_i) \operatorname{erfc} \frac{Z}{2\sqrt{D^* t}} \tag{9-13}$$

The relationship for the cumulative amount of water entering the barrier soil at time, t, is:

$$M_t = 2 (\theta_s - \theta_i)\sqrt{\frac{D^* t}{\pi}} \tag{9-14}$$

and the quantity of liquid required to saturate the barrier to a depth, d, is given by:

$$M^t = (\theta_s - \theta_i) \quad d \tag{9-15}$$

Equating equations (9-14) and (9-15) yields:

$$t = \frac{\pi d^2}{4D^*} \tag{9-16}$$

9.4 LINER (ENCAPSULATION)

The purpose of a liner is to provide back-up containment in the event of cover failure. In addition to back-up protection, it provides ion exchange capability. Ion exchange capacities of both natural as well as synthetic materials for retention of radionuclides are given in Section 6.

A liner will be used in conjunction with a cover for the ditch material only. The cover and liner components, when used together, form the encapsulation system, as shown on Figure 9-2.

Liners are not recommended in conjunction with the Area A or Area C covers because the materials beneath the Area A and Area C covers can be contained in situ. Risks associated with worker exposure and release into the environment during construction are avoided with in situ containment.

Water that permeates the clay soil will, in time, permeate the waste material and liner. The rate of water movement through the liner will not be less than that of the clay cap. Thus, water will not accumulate above the liner. The time required for water to permeate the liner is given in Table 9-6.

Table 9-6

Time Required for Water to Completely Permeate
a Liner Consisting of Compacted Clayey Soil

Assumptions:

Diffusivity D* (sq cm/sec) is from 1 to 2 orders of magnitude greater than in situ permeability.

Compacted soil permeability is one order of magnitude greater than soil-bentonite mixture permeability.

K cm/sec	D* sq cm/sec	Time yrs
10^{-5}	10^{-3}	0.093
10^{-6}	10^{-4}	0.925
10^{7}	10^{-5}	9.25

9.5 BURIED WASTE ENCLOSURE

In reviewing the alternatives for immobilization of the buried wastes, it appears that the most effective and economical system would consist of a bentonite slurry trench surrounding the entire deposit, and extending from the existing surface to the essentially impervious blue-clay layer underlying the site. Allowing a 5-foot penetration into the clay, the depth of the excavation will not exceed 50 feet. This depth is within the capability of a backhoe. The use of a backhoe will require a minimum trench width of 30 inches which provides an additional safety factor over competing thin-wall systems. The use of bentonite/soil slurry will minimize the quantity of materials to be imported, and provide an ion exchange capability to reduce the radionuclide content of the small quantity of groundwater which will pass through the wall. The flexible wall will be able to withstand future soil movement or settlement of reasonable magnitudes without losing integrity.

The subsurface wall will require an impermeable clay cap to prevent infiltration from overfilling the enclosure and spilling contaminated water. Simultaneously, the cap will preserve the moisture content of the upper wall and prevent shrinkage cracks above the groundwater contact zone. Finally, the cap will reduce the downward movement of radioisotopes from the unsaturated zone and limit the radon flux from the deposit.

The most likely mode of system failure involves future cap leakage due to root penetration, extreme drought with the formation of shrinkage cracks, or erosion or disturbance of the cap. It is proposed to limit the impact of any possible overflow by placing a sand layer over the enclosed area to lead any overflow to a shallow seepage bed located at the interior of the site. The bed will consist of sand of higher permeability than the surrounding soil. Following completion of the slurry wall, a portion of the western side will be excavated 3 feet below the existing grade and filled with sand prior to emplacing the cap. Any flow over the wall will thus be through the sand bed, but the bed will be above the groundwater table to minimize the possibility of inflow due to a future extremely high water table.

9.5.1 Concept Design

9.5.1.1 Subsurface Groundwater Cutoff Wall.

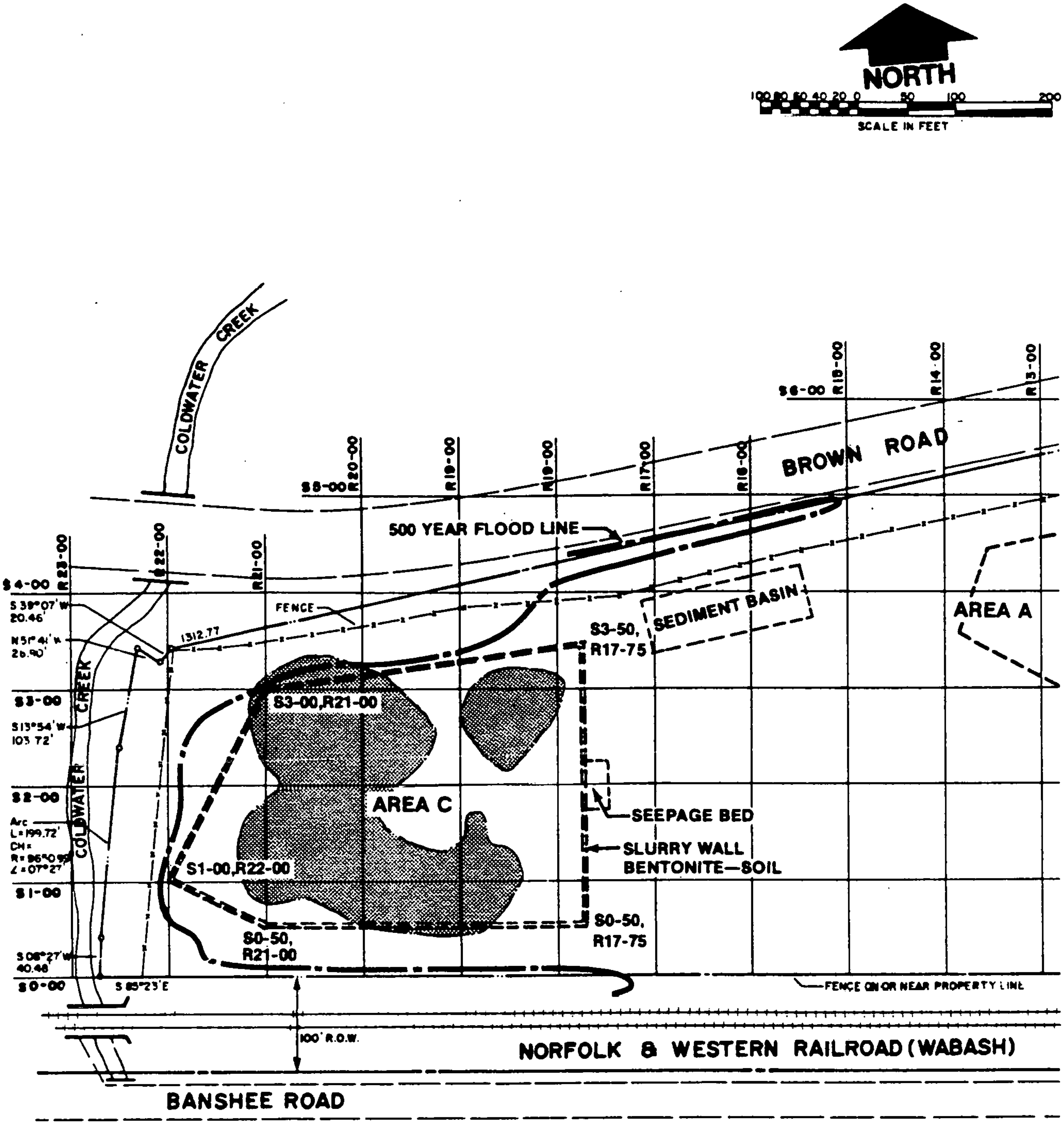
The subsurface cutoff wall should enclose that area known or suspected of containing the buried waste, as well as most or all of the surface contamination observed in the western end of the site. Due to the difficulty of deep excavation of sharp angles with a backhoe, gentle bends or straight segments should be used where possible. The recommended enclosure is shown on Figure 9-10. The periphery constitutes a series of straight lines to facilitate construction. The straight segments should be extended past the corners during construction to ensure hydraulic integrity. The recommended location includes most of the surface and buried activity, avoids the flood plain, and is far enough from the property boundaries to allow acceptable slopes on the clay cap.

A limited amount of surface grading will be required to allow drainage of any overflow to a seepage bed located at coordinates S2+00, R17+75. Since the uppermost surface materials are of limited radioactivity, this can best be accomplished by constructing a leveling berm at elevation 526 around the walls, then grading the existing interior surface to slope toward the top of the seepage bed at elevation 523. Surface grading must be accomplished prior to construction of the wall. The wall should extend from the surface to an elevation of 476 feet. There is sufficient depth to extend approximately 5 feet into the underlying blue-clay layer to ensure a positive seal. The wall will have an average depth of 48 feet. Combined with the length of 1,264.2 feet, the total wall surface area is 60,682 square feet, and the volume for a 30-inch thickness is 5,619 cubic yards. The area enclosed is 2.34 acres.

The composition of the wall must be determined by testing the permeability produced by various mixtures of soil from the site with the actual bentonite to be used during constructon. In order to obtain a significant reduction in groundwater flow through the waste deposit, a design permeability of 10^{-8} cm/s will be required. It is estimated that this value can be achieved with a mixture of bentonite equivalent to approximately 6 percent of the dry weight of soil. The total bentonite requirement will be approximately 455 tons. Due to the clay soils, it will be necessary to mechanically mix the wet bentonite/soil slurry on-site in order to obtain the design permeability.

9.5.1.2 Cover Interaction.

An impervious cover will be required to prevent the slurry trench enclosure from filling and overflowing due to infiltration. Clay caps and the water balance are discussed elsewhere in this report, but it should be noted that a 5 percent surface



ELEVATION BENCH MARKS
1. USGS - D ON CONC WALL BRIDGE NO 49-522.90'
2. TOP OF IRON PIPE IN CONC. MON - 521.43'

AREA ENCLOSED—2.34 ACRES
LENGTH OF SLURRY WALL—1264 FEET
THICKNESS OF SLURRY WALL—30 INCHES
DEPTH OF SLURRY WALL—50 FEET

— AREA DEFINED BY ISOPLETH OF 0.1m RAD/Hr BETA-GAMMA RADIATION LEVEL, 1 CM ABOVE THE SURFACE

SOURCE: RADIOLOGICAL SURVEY OF THE ST. LOUIS AIRPORT STORAGE SITE, ORNL FINAL REPORT, SEPTEMBER 1979, DOE/EV-005/16, VC-70.

FIGURE 9-10 LOCATION OF SLURRY WALL FOR SUBSURFACE ENCLOSURE (AREA C)—WESTERN END ST. LOUIS AIRPORT STORAGE SITE slope is required to reduce infiltration to the point where the subsurface enclosure will not overflow. This requirement dictates an unusual cover configuration. The original ground surface will be graded to flow east, but the upper surface of the clay cap will be ridged along axis S2+00 and sloped to drain surface water north and south. The central ridge provides the desired 5 percent slope without the necessity for extreme fill heights.

9.5.2 Evaluation of System Performance

9.5.2.1 Effect of Cutoff Wall on Groundwater Flow Patterns.

The existing groundwater flow pattern can be visualized from the groundwater contours shown on Figure 9-11. In the area to be enclosed, the flow is predominantly to the west toward Coldwater Creek with a northwesterly trend along the northern boundary. The spacing of the contours indicates a decreased permeability approaching the creek. With the barrier in place, the flow pattern will be altered by diverting flows to the north and south around the wall. Assuming isotropic conditions and two-dimensional flows, the alterations can be estimated by construction of a flow net. On Figure 9-11 the flow net has been superimposed on the groundwater contours of 5 June 1981 to illustrate the impact of the wall.

9.5.2.2 Reduction in Flow through the Deep Waste Deposit.

In order to estimate the reduction in groundwater flow passing through the deep deposit, flows have been estimated before and after construction of the wall.

The 5 June 1981 groundwater contours produced the steepest observed hydraulic gradient. On this date, a 6.0-foot drop in groundwater surface was observed over the 375-foot distance from wall-to-wall following axis S2+00 in a westerly direction. Taking this hydraulic gradient as typical and assuming a bulk permeability of 10^{-5} cm/s through the area to be enclosed by the cutoff wall, a total flow of 14,844 gals/yr would pass through the area.

With the cutoff wall in place, the hydraulic gradient across the enclosure would increase due to backwater effects upstream and a drop downstream. From Figure 9-11, the total head is estimated at 7 feet for the 5 June condition. The same flow path along axis S2+00 would experience a drop of 7 feet in water elevation over a 2.5-foot wall, a 375-foot undisturbed soil area, and a second 2.5-foot wall. The head distribution is illustrated on

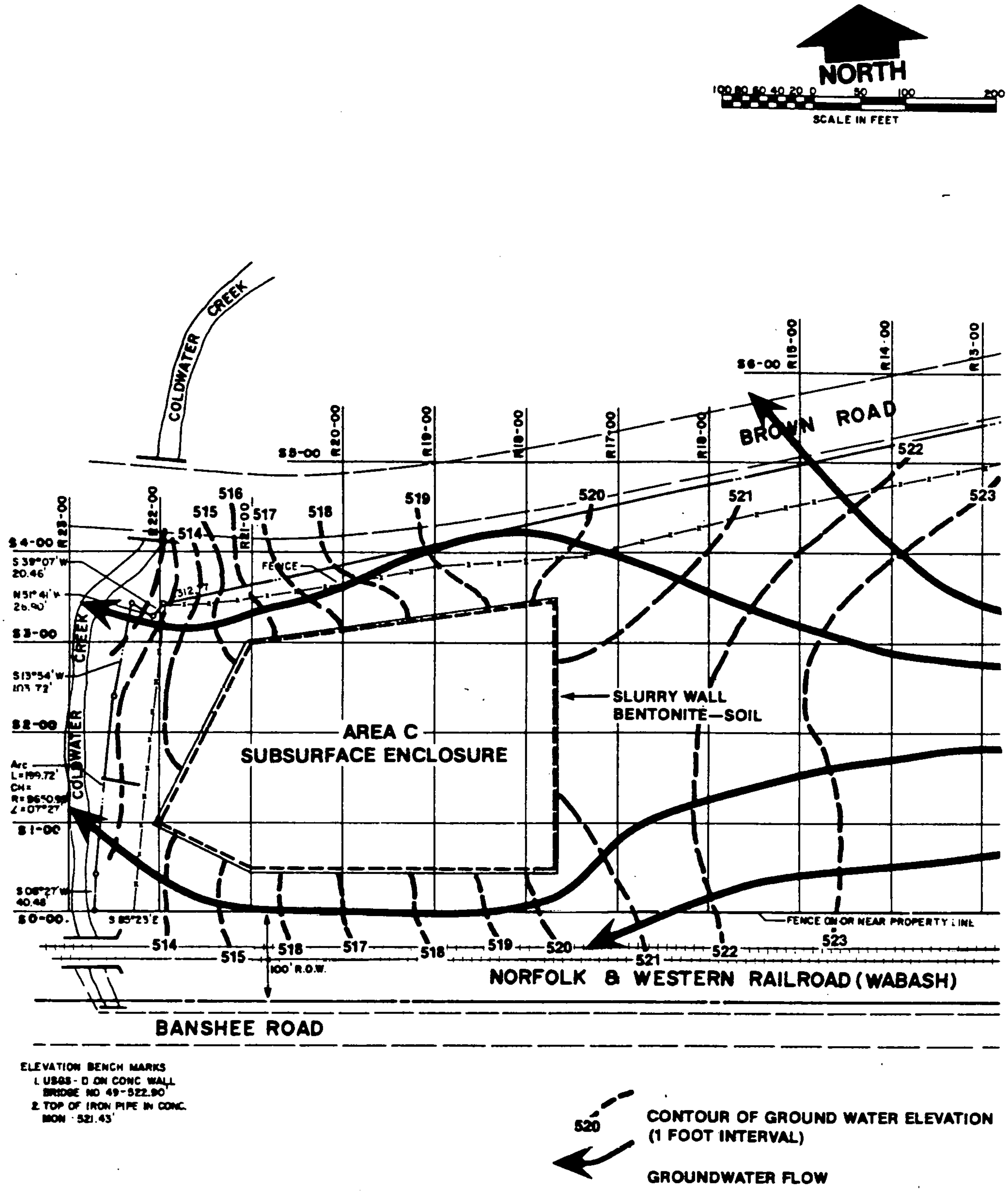


FIGURE 9-11 PREDICTED GROUNDWATER FLOW PATTERN WITH SLURRY WALL ENCLOSURE (AREA C)—WESTERN END ST. LOUIS AIRPORT STORAGE SITE

Figure 9-12. Using permeabilities of 10^{-5} cm/s for the soil, and 10^{-8} cm/s for the walls, a reduction in flow due to the wall can be calculated. Along axis S2+00, the reduction is by a factor of 92 percent. Thus, approximately 1,167 gals/yr per year would pass through the enclosed waste deposit under the groundwater conditions observed on 5 June 1981, if the slurry trench were installed.

Under the condition of a 7-foot total drop in groundwater level across the slurry trench enclosure, the flow times may be estimated using a porosity of 0.33 for the soil:

Flow through one wall: 60 years.

Flow through existing soil within enclosure along axis S2+00 = 8,870 years.

Flow from closest point of enclosure to Coldwater Creek (slope = 0.01) = 320 years.

9.5.2.3 <u>Effect of Infiltration</u>.

Referring to Figure 9-12, if a downward flow due to infiltration is superimposed on the horizontal movement of groundwater, the water level within the enclosure will rise. This will reduce the hydraulic gradient across the upstream wall and decrease the groundwater flow into the enclosure. Simultaneously, the downstream wall will experience an increased hydraulic gradient resulting in leakage of the combined groundwater and infiltration. If the infiltration component becomes sufficiently large, the enclosure will fill and all wall leakage will be outward. The full condition is illustrated on Figure 9-13. Taking an average of 5 gals/yr/lin. ft of wall, the allowable infiltration without overflow is 6,320 gals/yr. This is equivalent to 0.1 in./yr of infiltration over the 2.34-acre surface area.

Based on the analysis of the performance expected of the clay cover presented in subsection 9.3.2, the average infiltration will be 0.062 in. with a clay cap slope of 5 percent. A detailed analysis of the effect of this rate on total leakage would be very complex due to the fact that the hydraulic gradient within the enclosure is affected by the distribution of infiltration and the shape of the enclosure. However, it is obvious that some reduction in groundwater flow will occur. The total leakage is estimated at 3,920 gals/yr from infiltration, plus 600 gals/yr due to horizontal movement of groundwater, for a total of 4,520 gals/yr.

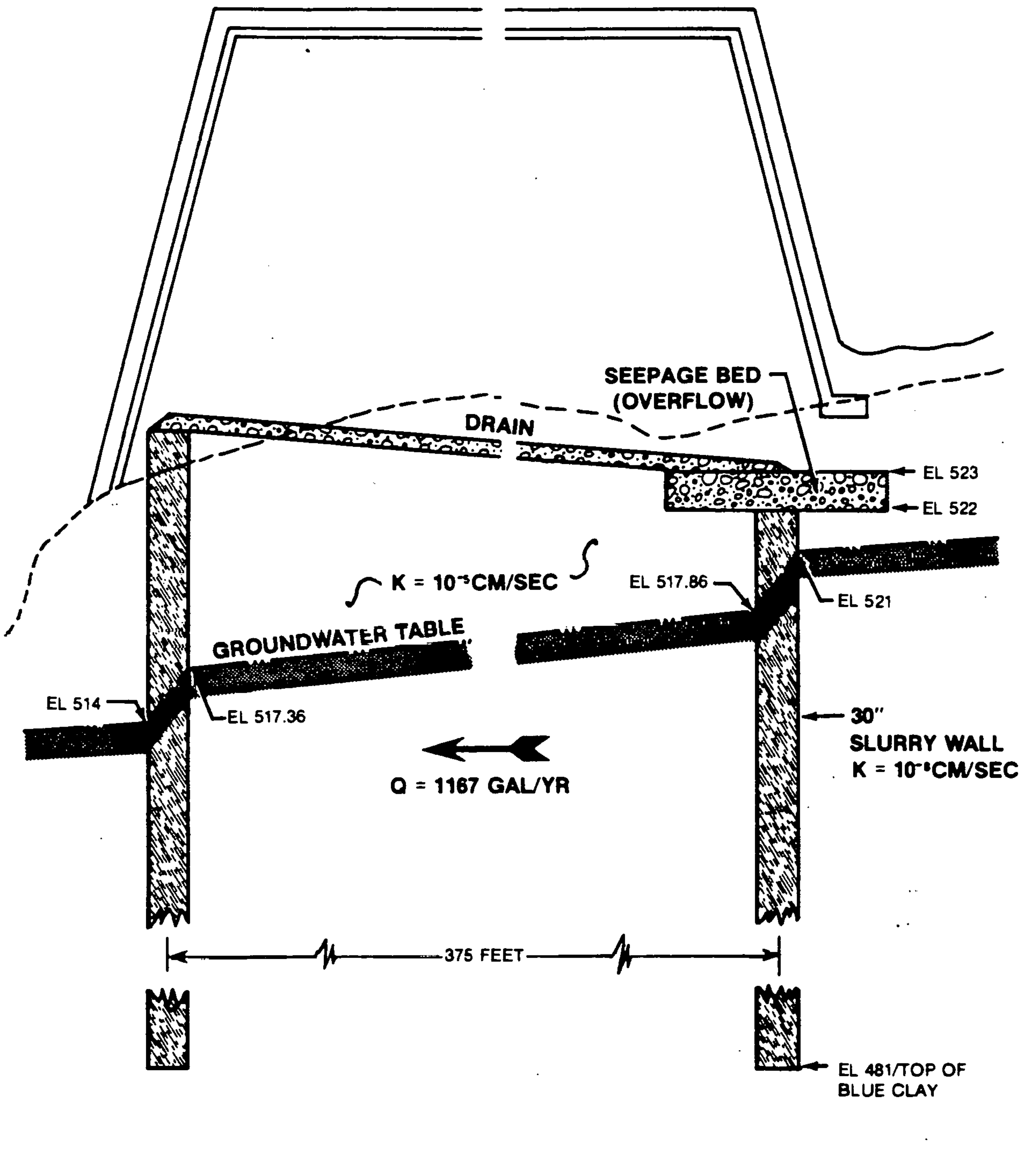


FIGURE 9-12 PREDICTED GROUNDWATER FLOW THROUGH SLURRY WALL ENCLOSURE (AREA C) ST. LOUIS AIRPORT STORAGE SITE.

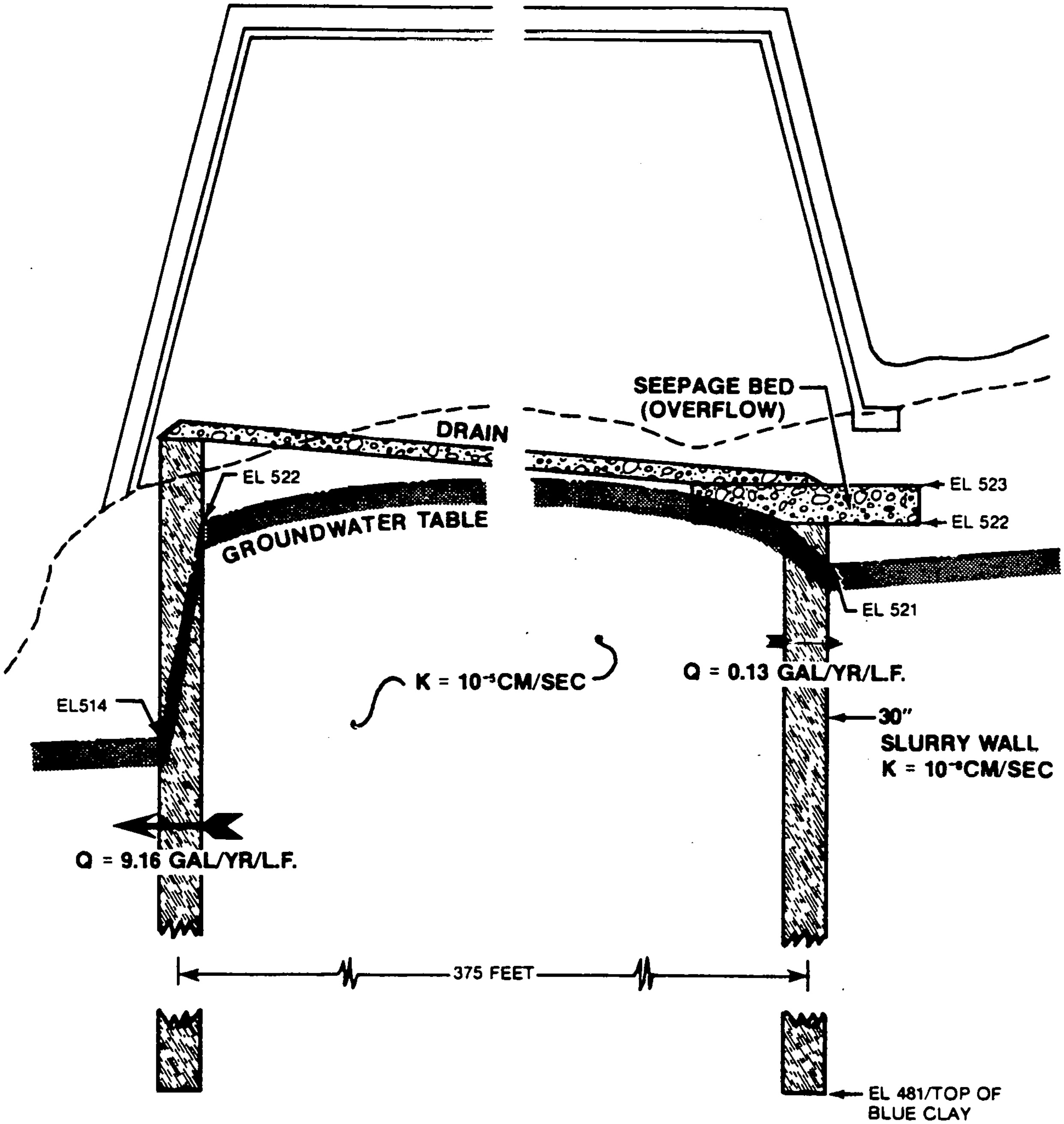


FIGURE 9-13 PREDICTED GROUNDWATER FLOW AT IMPENDING SPILLAGE THROUGH SLURRY WALL ENCLOSURE (AREA C)—ST. LOUIS AIRPORT STORAGE SITE.

In the event that infiltration through the cap is higher than the design value or the cap integrity is impaired in the future, the enclosure will overflow at coordinates S2+00, R17+75. The travel path to the creek will be approximately 650 feet long with a total head of 8 feet. Using a permeability of 10^{-5} cm/s and porosity of 0.33, the total time of travel will be 1,750 years. Radioisotope movement would undoubtedly be slower due to soil interactions.

9.5.2.4 Ion Exchange Retention in the Slurry Trench Wall.

Since the slurry trench wall consists of soil containing approximately 6 percent bentonite by weight, the ion exchange capacity of the bentonite will tend to reduce the rate of motion of any radioactive cations in the groundwater. The mechanism of ion exchange holdup has been discussed in Section 6. Under normal circumstances, cations may move as much as a factor of 10^{-5} slower than the groundwater. However, the groundwater at the site is extremely high in calcium and magnesium, both of which will compete for any ion exchange sites in the bentonite.

A review of the available literature yielded no information directly relevant to natural radioisotope holdup in extremely hard water. Therefore, no specific delay in radioisotope movement to Coldwater Creek will be attributed to either the bentonite in the slurry trench, or to the clay minerals in the in situ soils. Motion will be considered as strictly hydraulic with an intangible safety factor added by the presence of the clay.

9.5.2.5 Summary of Total System Impact on Radioisotope Movement.

The impact of the total system on radioisotope movement is summarized as follows:

1. Time required for groundwater to flow through slurry trench area to:

   Coldwater Creek: Before -- 1,350 years

   After -- 9,310 years

2. Groundwater flow through deep deposit:

   Before -- 14,844 gals/yr.

   After -- Approximately 600 gals/yr.

3. Infiltration through area:

Before -- Approximately 254,000 gals/yr.

After -- 3,920 gals/yr.

4. Total leakage from slurry trench: 4,520 gals/yr.

5. Minimum flow time for seepage to reach Coldwater Creek:

Before -- 110 years

After -- 320 years

6. Time for any future overflow to reach Coldwater Creek: 1,750 years

7. Radioisotope velocity reduction relative to water due to the use of clay minerals -- magnitude unknown.

9.6 CONCEPT DETAILS

The overall plan for site development is shown on Figure 9-14. At the western end of the site, the buried waste deposit will be surrounded by a subsurface slurry wall and capped with:

1. A surface drain of 6 inches of sand.
2. A clay layer with a minimum thickness of 3 feet.
3. A layered sand and gravel drain 12-inches thick.
4. A soil layer 18-inches thick.
5. A 6-inch thick topsoil layer.

Cross-sections showing the relationship of the various units are shown on Figures 9-15, 9-16, and 9-17. Key design parameters are summarized as follows:

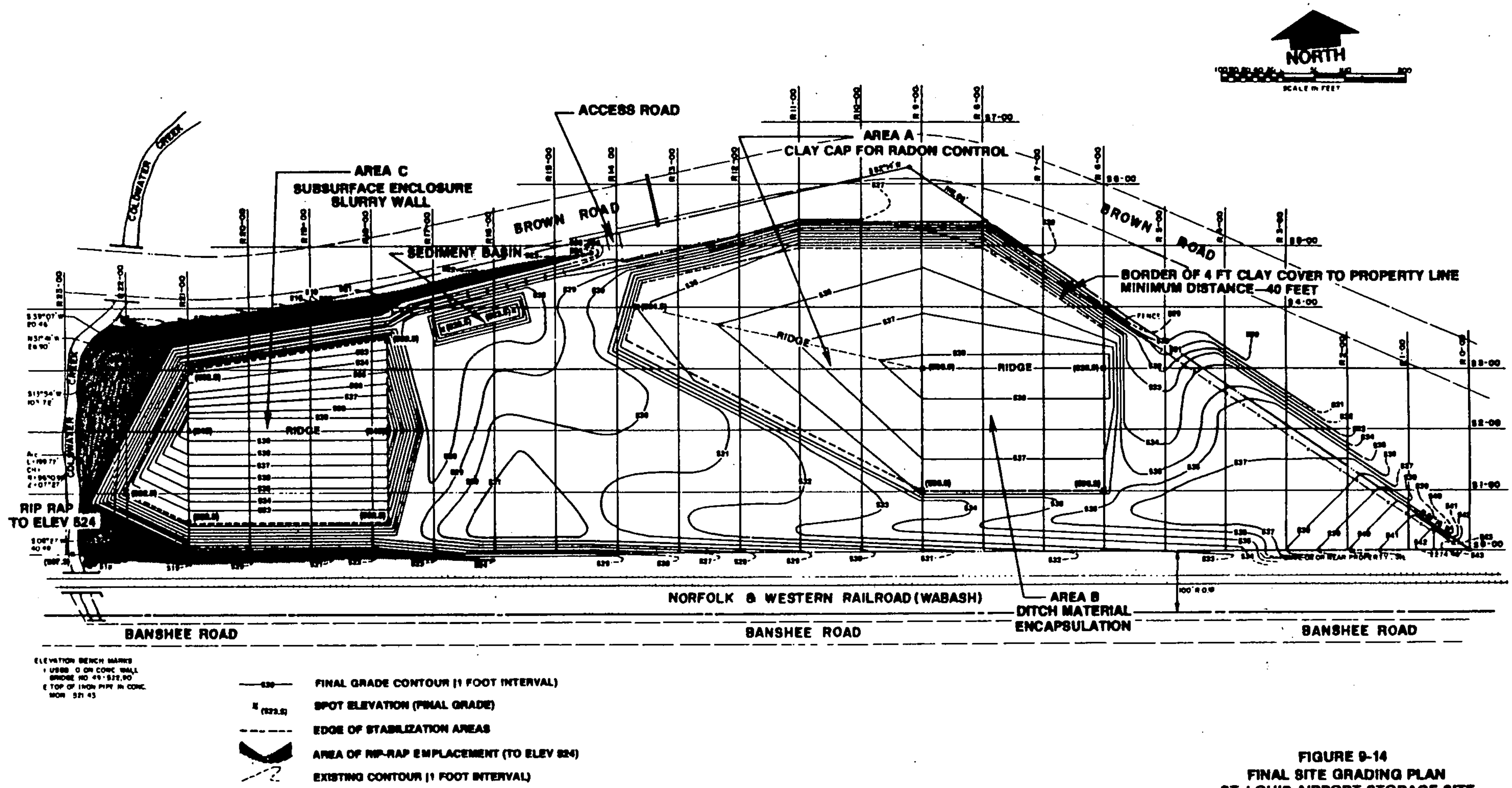
Slurry Wall:	Top elevation	526 feet
	Bottom elevation	476 feet
	Thickness	30 inches minimum
	Permeability (K)	10^{-8} cm/s
	Bentonite content	6% (weight) estimated
	Coordinates of corners	S0+50, R17+75 S0+50, R21+00 S1+50, R22+00 S3+00, R21+00 S3+50, R17+75
Cap System:	Surface slope	5 percent minimum
	Bank slopes	20 percent maximum
	Surface drain -- thickness	6 inches
	Surface drain -- K	10^{-2} cm/s
	Clay cap -- thickness	3 feet, minimum To 13.5 feet maximum
	Clay cap -- K	10^{-7} cm/s
	Drain -- thickness	12 inches

Drain -- K	10^{-1} cm/s
Soil cover -- thickness	18 inches
Topsoil -- thickness	6 inches

Key design specifications for the encapsulation area are as follows:

Size: 200 feet x 300 feet nominal

Coordinates of corners:		S1+00, R6+00 S1+00, R9+00 S3+00, R9+00 S3+00, R6+00
Liner:	Thickness	3 feet
	Permeability (K)	10^{-7} cm/s
	Bottom slope	0
	Side slope	33 percent
Waste soil:	Depth	2.5 to 4.5 feet
	Volume	8,300 cubic yards
Clay cap:	Thickness	3 feet
	Slope	1 percent
	Permeability (K)	10^{-7} cm/s
	Side slopes	20 percent
Drain layer:	Graded sand and gravel	
	Thickness	1 foot
	Permeability (K)	10^{-1} cm/s
	Slope	1 percent
Soil cover:		18 inches
Topsoil:		6 inches



NOTE:
SURVEY AND GRID SYSTEM FROM
ROWLAND SURVEYING CO. MAP
DATED 25 AUGUST 1979

FIGURE 9-14
FINAL SITE GRADING PLAN
ST. LOUIS AIRPORT STORAGE SITE

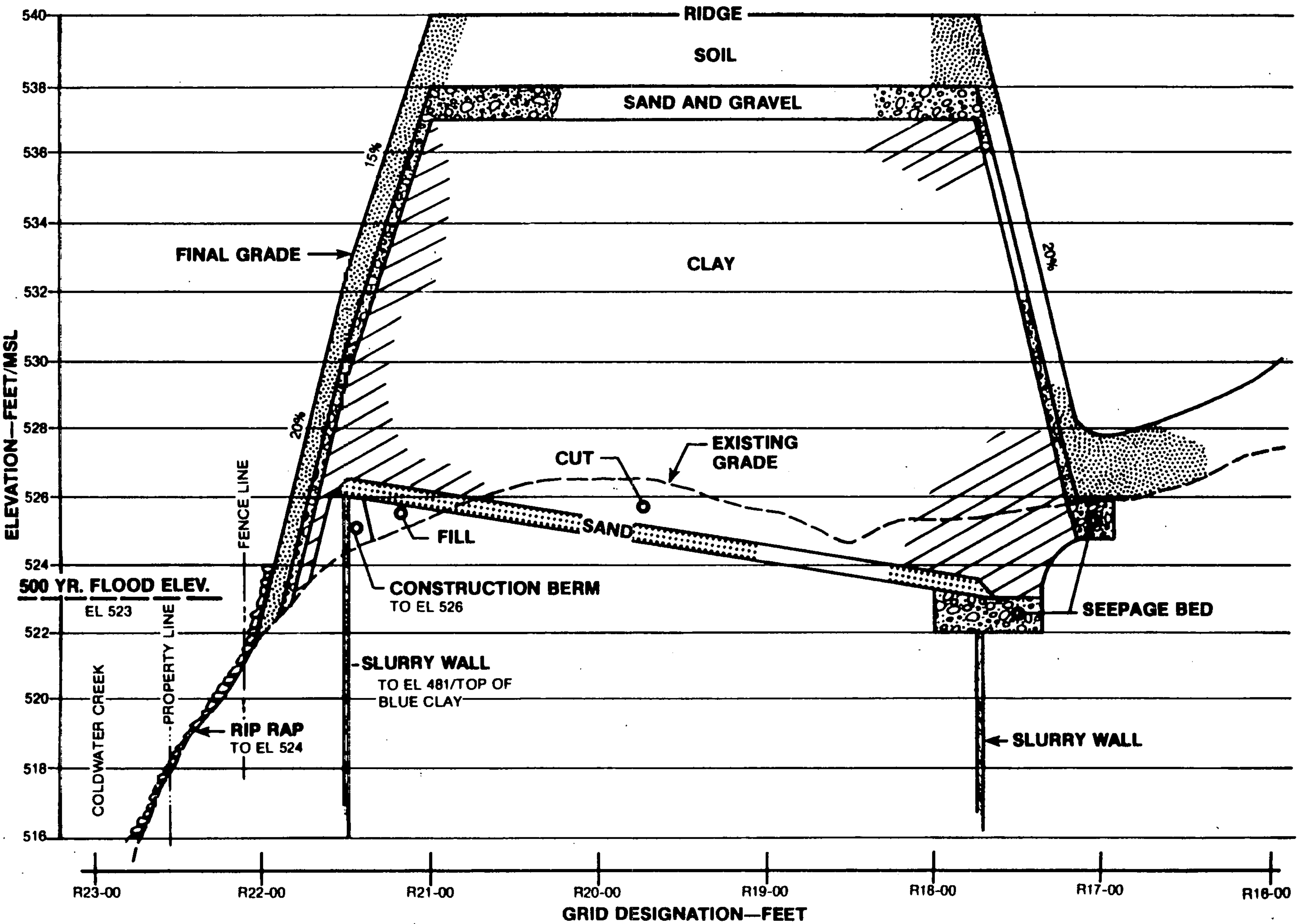


FIGURE 9-15 LONGITUDINAL SECTION (AXIS S2-00) THROUGH SUBSURFACE ENCLOSURE (AREA C) ST. LOUIS AIRPORT STORAGE SITE.

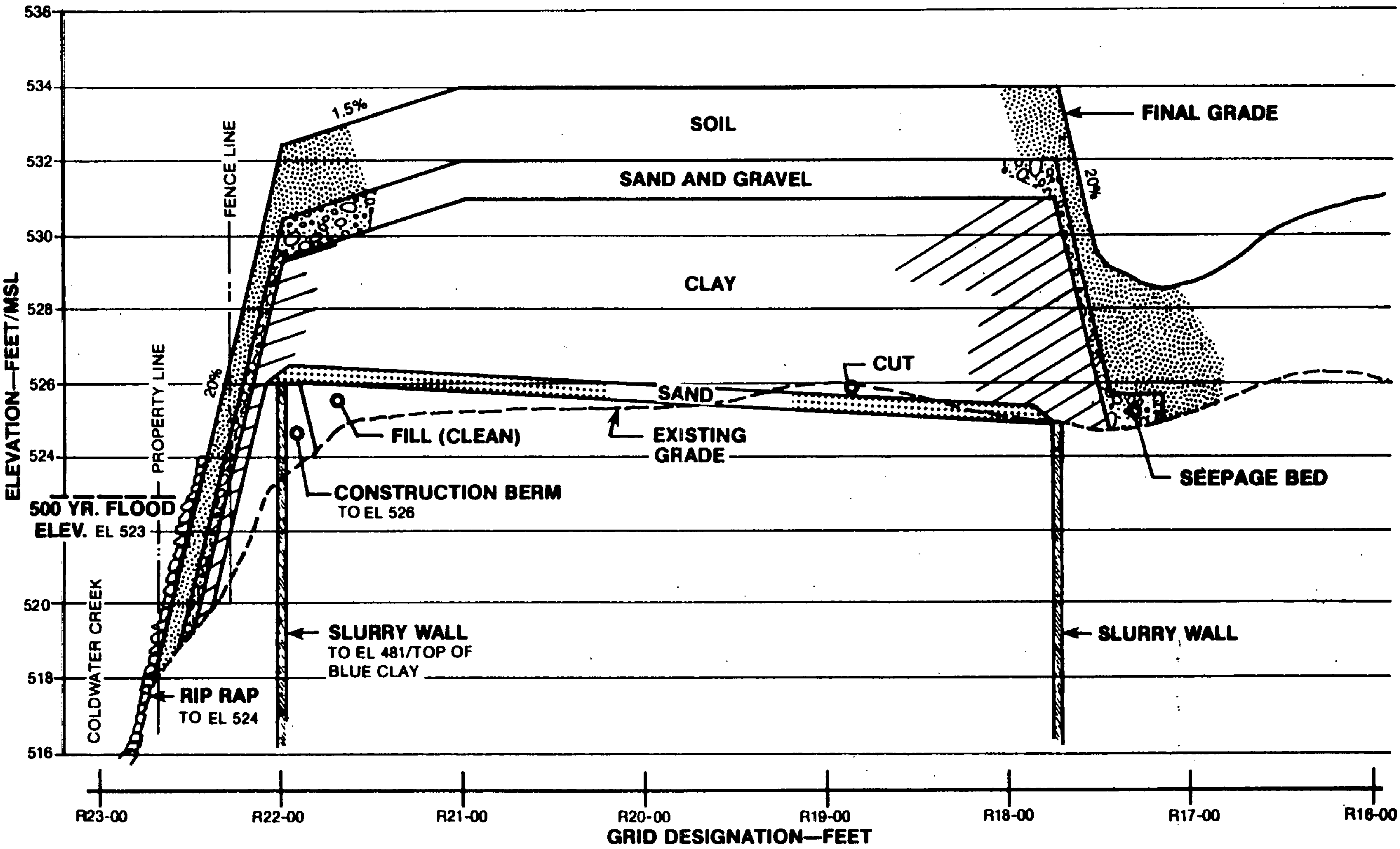


FIGURE 9-16 LONGITUDINAL SECTION (AXIS S1-00) THROUGH SUBSURFACE ENCLOSURE (AREA C) ST. LOUIS AIRPORT STORAGE SITE.

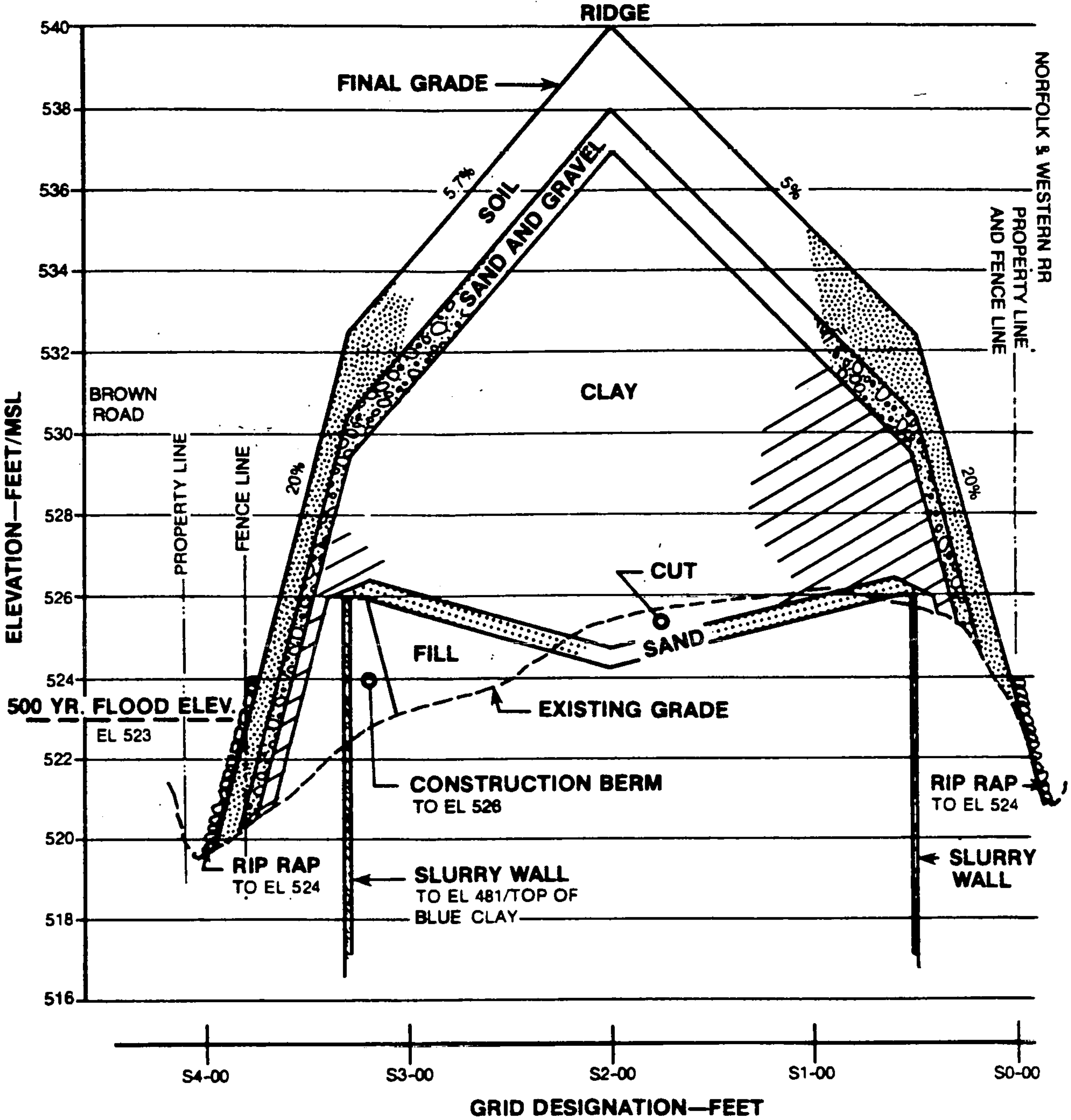


FIGURE 9-17 CROSS SECTION (AXIS R19-00) THROUGH SUBSURFACE ENCLOSURE (AREA C) ST. LOUIS AIRPORT STORAGE SITE.

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The central portion of the site will receive a clay layer 4-feet thick to suppress the diffusion of radon. In part, the cap will abut the encapsulation area and thus, the cap appears on Figure 9-3. An additional section through the cap is illustrated on Figure 9-4. The cap is 4-feet thick, and covered by a 1-foot drain and 2 feet of soil. For economy, the underlying fill is graded from a design ridge elevation to ground level at the edge. The slope of the cap, therefore, varies from a minimum of 1 percent to a maximum of 5 percent. Design specifications are as follows:

Area capped:		5.15 acres
Coordinates of corners:		S1+00, R9+00 S3+60, R13+60 S4+40, R13+60 S5+00, R11+00 S3+60, R6+00 S3+00, R6+00 S3+00, R9+00
Ridge line:	S3+00, R6+00 fill elevation 531.5 S3+00, R9+00 fill elevation 531.5 S4+00, R13+60 fill elevation 528	
Clay cover:	Thickness	4 feet
	Permeability (K)	10^{-7} cm/s, maximum
	Slope	1 percent, minimum
	Edge slope	20 percent, maximum
Drain:	Thickness	1 inch
	Permeability (K)	10^{-1} cm/s, minimum
	Slope	1 percent, minimum
Soil:	Thickness	18 inches
	Slope	1 percent, minimum
Topsoil:	Thickness	6 inches
	Slope	1 percent, minimum

The remainder of the area will be covered with an average of 3 feet of soil to reduce erosion and surface activity. Some reduction in radon emanation will also be attained. In general, the soil will be placed over existing grades with only minor surface smoothing. However, as will be presented in the grading plan, some surface material must be moved from the vicinity of the sedimentation basin (Figure 9-1) to the excess soil area.

The maximum heights achieved are well below the limitations imposed by the Air Navigation Space Regulations, St. Louis County Zoning Ordinance.

9.7 ORDER OF MAGNITUDE COST ESTIMATE

Table 9-7 lists approximate cost estimates for in situ stabilization of the St. Louis Airport storage site. The cost is presented in a modular format to allow the review of each element of the control concept (e.g., cover by itself, etc.). It should be noted that this order of magnitude cost estimate is based on conservative assumptions, and would tend to be on the high side. A preliminary cost estimate should be prepared as part of the detailed engineering phase of this project.

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Table 9-7

Order of Magnitude Cost Estimate

	Approximate Cost $
Area A (approximately 5 acres)	
Clay cap (4 ft deep) at $40/sq yd	970,000
Gravel layer (1 ft deep) at $5/sq yd	120,000
Soil cover (2 ft deep) at $6/sq yd	150,000
	$1,240,000
Area B (approximately 1.5 acres)	
Replacement of fence	48,000
Removal of ditch material	180,000
Clay liner (3 ft deep) at $30/sq yd	220,000
Clay cap (3 ft deep) at $30/sq yd	220,000
Gravel layer (1 ft deep) at $5/sq yd	40,000
Soil cover (2 ft deep) at $6/sq yd	50,000
	$ 758,000
Area C (approximately 3.5 acres)	
Riprap (6,100 sq yd) at $34/sq yd	207,400
Clay cap (3 ft deep) at $30/sq yd	510,000
Gravel layer (1 ft deep) at $5/sq yd	90,000
Soil cover (2 ft deep) at $6/sq yd	100,000
Soil/bentonite slurry wall (1,300 ft x 50 ft) at $8/sq/ft	460,000
	$1,367,400
Area D (approximately 10 acres)	
Site preparation, improvement, etc.	300,000
Soil cover (3 ft deep) at $9/sq yd	440,000
	$ 740,000
Equipment and Labor	
Equipment plus 100 working days at $10,000/day[1]	$ 850,000
Subtotal construction cost	$4,955,400
Engineering and construction management	$1,000,000
Contingency at 25% of construction cost	$1,239,000
Total	$7,194,400

[1]Cost of idle time allotted for site inspections, construction quality control, monitoring, and inclement weather.

REFERENCES

SECTION 9

DEVELOPMENT OF SELECTED ALTERNATIVES

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WESTON

SECTION 10

SURFACE RUNOFF AND DRAINAGE CONTROL

10.1 INTRODUCTION

Surface runoff and drainage control will prevent the transport of contaminated materials away from the site during the construction period and aid in preserving the final cover integrity in the post-construction years. The objectives of a stormwater control plan for the St. Louis site are:

1. Divert stormwater runoff around the site.

2. Retain and/or attenuate stormwater runoff from the site itself.

3. Minimize both disturbed area and time of exposure to erosion factors.

4. Stabilize disturbed areas immediately.

5. Retain sediment on-site.

10.2 STORMWATER AND SEDIMENTATION CONTROLS

10.2.1 Structural Controls

Stormwater runoff will be managed by means of a network of structural control measures (shown on Figure 10-1) such as:

1. Drainage ditches and conduits.
2. Diversions.
3. Sedimentation basins.

These controls will be designed to limit stormwater flows from the site to predevelopment levels. This is done to limit the impact of construction activities on the flow of Coldwater Creek, particularly at locations downstream of the site.

Stormwater runoff from off-site areas north of the site will be conveyed to Coldwater Creek by means of a drainage ditch to be constructed along the northern side of Brown Road. This ditch will serve to divert the flow from the site itself. The ditch will be sized to carry at least the runoff from a 25-year storm, and be stabilized by means of vegetation or riprap. All channel construction, improvements, and modifications will be designed for a stable channel which can be maintained easily.

Channels may be stabilized by using one or more of the following methods:

1. Rock Riprap Lining.

   Rock riprap will be designed to resist displacement when the channel is flowing at the bankfull discharge or 25-year frequency discharge, whichever is the lesser. Dumped and machine-placed riprap should not be installed on slopes steeper than 1 1/2 horizontal to 1 vertical. Where riprap is placed by hand, the slopes may be steeper. A filter blanket of sand and/or gravel will be placed between the riprap and base material. The filter blanket material will be at least 6 inches thick, with a gradation that is consistent with the base material and the riprap. Rock will be dense, resistant to the action of air and water, and suitable in all other respects for the purpose intended.

2. Concrete Lining.

   Concrete linings will be designed according to currently-accepted guidelines for structural and hydraulic adequacy. They must be designed to carry the required discharge and to withstand the loading imposed by site conditions.

Diversion dikes will be constructed around all active and/or disturbed construction areas. These diversions will serve to convey stormwater runoff to an on-site sedimentation basin, temporary in nature, and will be designed to carry the peak runoff of a two-year storm with 3 to 4 inches of freeboard. Velocities in the diversion should range from 2.5 to 5 ft/s.

The channel may be parabolic, V-shaped, or tapezoidal. The diversion must be designed to have stable side slopes. The side slopes will not be steeper than 2:1. The ridge will have a minimum width of 4 feet at the design water elevation, a minimum of 0.3-foot freeboard, and a reasonable settlement factor. The side slopes will be flat enough to ensure that the structure and its protective vegetative cover are easy to maintain.

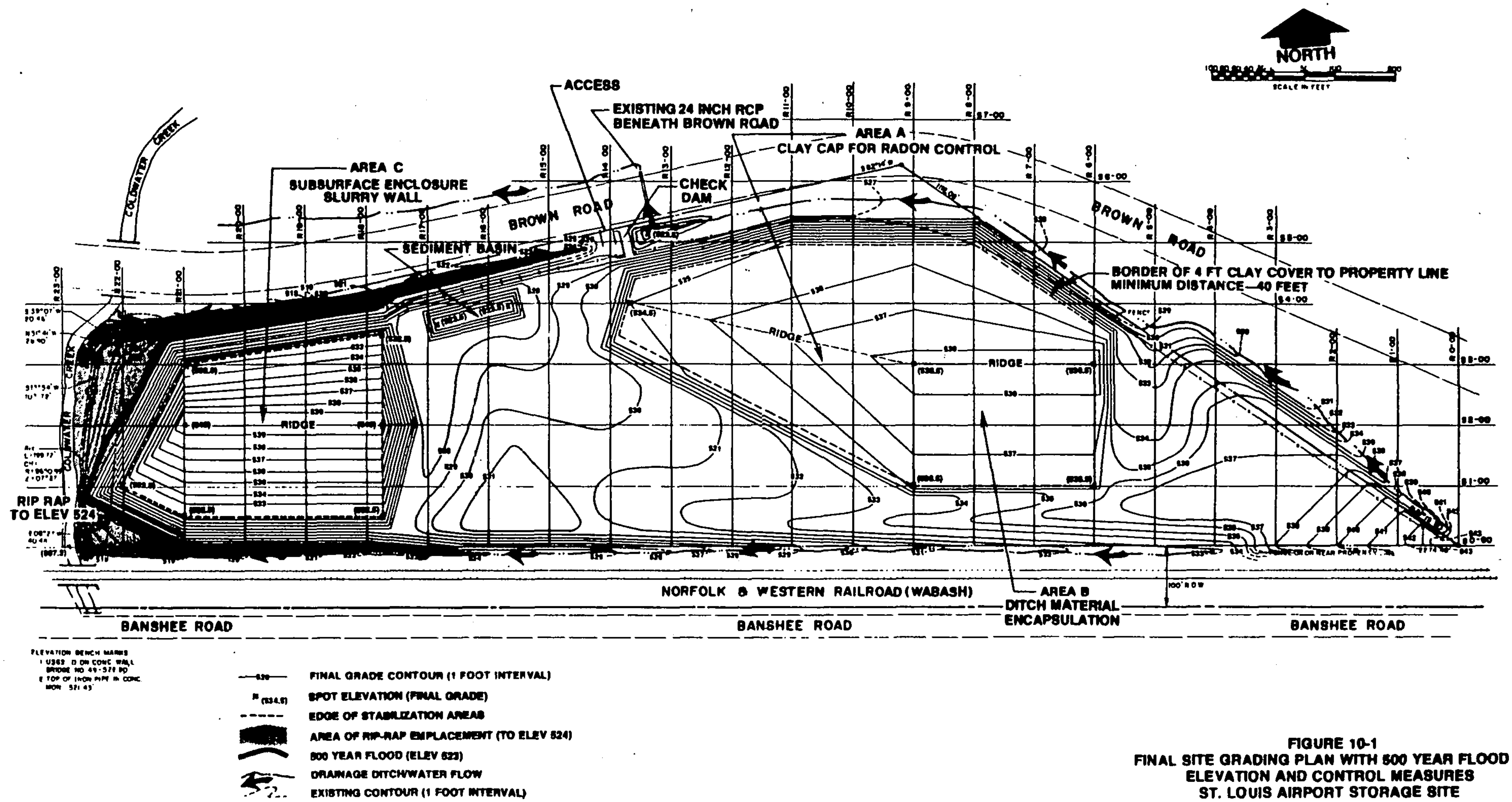

FIGURE 10-1
FINAL SITE GRADING PLAN WITH 500 YEAR FLOOD
ELEVATION AND CONTROL MEASURES
ST. LOUIS AIRPORT STORAGE SITE

Each diversion must have an adequate outlet. The outlet may be a constructed or natural waterway, a stabilized vegetated area, or a stabilized open channel. In all cases, the outlet must discharge in a manner that will not cause an erosion problem. Protected outlets will be constructed and stabilized prior to construction of the diversion.

Construction specifications for diversions include the following:

1. All trees, brush, stumps, obstructions, and other objectionable material will be removed and disposed of so that the proper functioning of the diversion is not impaired.

2. The diversion will be excavated or shaped to line, grade, and cross-section, and be free of irregularities which will impede normal flow.

3. Fills will be compacted as needed to prevent unequal settlement that would cause damage in the completed diversion.

4. All earth removed and not needed in construction will be spread or disposed of so that it will not interfere with the functioning of the diversion.

5. Stabilization.

   a. Vegetative protection.

      - Flow standards and specifications for disturbed area stabilization for time of seeding, sprigging, or sodding; liming and fertilizing; and site and seedbed preparation.

      - Mulching will be a requirement for all seeded or sprigged channels.

      - Temporary protection during construction will be provided when conditions permit the use of temporary diversions or other means to dispose of water.

b. Mechanical/vegetative protection -- Stone center diversions will be stabilized with riprap.

The final site grading will be performed to direct stormwater runoff to one of two drainage ditches which are to be constructed along the northern and southern boundaries of the site, or to a drainage ditch to be constructed between Areas A and C. These ditches will be constructed in accordance with the standards just described, and will convey runoff to one large or two small sedimentation basins located as shown on Figure 10-1.

Area B will be encircled by a small drainage ditch designed to convey "weepage" from the gravel layer of the cover complex to the sedimentation basin. Weepage from the waste areas will be conveyed to the basin by means of the drainage ditches discussed previously.

The purpose of the sedimentation basins is to detail runoff waters and trap sediment from erodible areas in order to protect properties and drainage ways below the installation from damage by excessive sedimentation and debris. The water will be stored temporarily, and the bulk of the sediment carried by the water will drop out and be retained in the basin while the water is automatically released.

The sedimentation basins will serve to collect any sediments which may be contaminated and will prevent them from being carried off-site by stormwater. In addition, the basins will function as stormwater detention basins, regulating the flow of stormwater into Coldwater Creek to predevelopment levels.

The sedimentation basins will be designed to accommodate excess runoff from a 100-year, 24-hour storm, and to release the stormwater at a rate less than or equal to the predevelopment peak discharge rate resulting from such a storm. The outlet structures will be designed to provide this peak discharge rate at the highest water-surface elevation reached before emergency overflow, allowing at least 1 foot of freeboard. The maximum water depth allowed will be 4 to 6 feet. The outlet structures will be two-stage in design, allowing effective control of storms less severe than the design storm. They will consist of a first-stage orifice and a second-stage weir such that the combined discharge at maximum design elevation will equal the desired peak discharge rate. The orifice will be designed as a perforated riser joined to a pipe which will extend through the embankment and outlet beyond the downstream toe of the fill.

The perforations will provide gradual drawdown in the basins. The risers will be located at the low points in the basins to ensure complete drainage. Each will have a base attached with a watertight connection and will have sufficient weight to prevent flotation of the riser. An anti-vortex device and trash rack will be securely installed on top of each riser and will be wrapped with filter cloth, such as Mirafi, to prevent clogging with sediment.

Protection against scour at the discharge ends of the pipe spillways will be provided in the form of impact basins, riprap, plunge pools, etc. The sedimentation basins will be vegetated to prevent erosion, with side slopes ranging from 4:1 to 2:1. Maintenance of stormwater management structures is discussed in Section 6.

10.2.2 Vegetative Controls

Temporary seeding (fast growing) is to be used to reduce erosion in areas which are disturbed for periods of up to one year or until a permanent vegetative cover is established. This seeding might be applicable in channels, permanent diversion, sedimentation basins, and other temporarily disturbed areas of the site.

Temporary mulching without seeding can be used for the protection of critical areas which have been graded or cleared and may be subject to erosion for six months or less (therefore seedings may not have a growing season in which to become established). Materials which can be used for temporary mulching are listed in Table 10-1.

Table 10-1

Temporary Mulching Materials

Material	Application Rate
Dry straw or hay	2 1/2 tons/acre
Wood waste, chips, sawdust, or bark	2 to 3 inches deep (6 to 9 tons/acre)
Erosion control matting or netting (e.g., excelsior, jute, textile, or plastic netting or matting)	In accordance with manufacturer's recommendations
Cutback asphalt, slurry curing	1,200 gals/acre
Polyethylene film	--

Permanent (long-term) seeding is used to stabilize areas after all land-disturbing activities are completed. It reduces erosion of slopes which have been graded to final contours, minimizing maintenance requirements. Specifications for permanent seeding are as follows:

10.3 FLOOD CONTROL

The 500-year flood elevation is depicted on Figure 10-1. All final grading on the site will be to levels above this elevation. In addition, the areas of the site which lie within this flood plain and the sides of the Coldwater Creek channel will be stabilized to prevent any large-scale erosion due to flooding. Such stabilization might include the use of large riprap or paving grids filled with vegetation. In addition to slope stabilization, the Coldwater Creek channel could be modified to convey a larger flow than is currently possible. This would limit the extent of the flood plain on the site.

10.4 TEMPORARY EROSION CONTROLS

An erosion control plan will be developed by the construction contractor and submitted to the project engineer before any site activitiy begins. The plan will provide erosion control measures for all disturbed areas of the site. Sediment barriers will be provided at storm drain inlets, across minor swales and ditches, along property lines, at discharge points to Coldwater Creek, etc. They will prevent sediment from leaving the site and entering natural drainageways by slowing stormwater runoff and causing deposition of sediment. Construction specifications for various types of sediment barriers are as follows:

1. Sandbags.

   Sandbags should be installed so that flow under or between bags is minimal. Anchoring with steel rods may be required if structure heights exceed two bags.

2. Hay or Straw Bales.

   Bales will be placed in a single row, lengthwise, on the contour, and embedded in the soil to a depth of 3 inches. Bales must be securely anchored in place by stakes or bars driven through the bales, or by other acceptable means to prevent displacement.

3. Brush.

Brush obtained from clearing operations may be piled in a row along the perimeter where the land is disturbed. Brush should be windrowed on the contour as nearly as possible. The brush may require compaction; construction equipment may be utilized to accomplish this purpose. Brush should be checked for radium uptake before it is used for erosion control.

If a greater filtering capacity is required, a commercially-available filtering fabric may be placed on the construction side of the brush barrier. The lower edge of the fabric must be buried in a trench 12 to 18-inches deep. The upper edge must be stapled, tied, or otherwise fastened to the brush barrier. If the barrier could be considered a "vision pollutant," consideration should be given to removing the brush barriers after the area is stabilized.

4. Log and Pole.

Log and pole structures will not be used in drainageways where normal discharges exceed 5 cu ft/sec.

5. Sediment Fences.

A sediment fence should be constructed of woven wire fencing with commercial filter fabric securely attached to the upper face. The bottom edge of the filter fabric should be installed in a trench 12 to 18-inches in depth. Fence posts of adequate strength and spacing will be installed to ensure stability under maximum loading conditions.

10.5 DECONTAMINATION OF CONSTRUCTION EQUIPMENT

10.5.1 On-Site Equipment and Vehicles

Vehicles and equipment which are only operating on-site may not have to be decontaminated until ready to leave the site. All on-site vehicles, however, will be monitored routinely to determine if the operator's cab or cab entry is contaminated. Decontamination of the vehicle operator's cab and cab entry point will be carried out as needed.

10.5.2 Equipment or Vehicles Leaving the Site

Vehicles or equipment preparing to leave the site will be monitored prior to leaving. If contamination is found, the equipment will be decontaminated. This may consist of dry removal, and washing as required on the decontamination pad as shown on Figure 10-2.

10.6 VEHICLE DECONTAMINATION AREA

10.6.1 Site Selection

The site selected should be close to the sole access gate to the site. The site should be situated so that the decontamination area is predominantly downwind from operating and personnel areas. The site should be situated or controlled so that all vehicles entering or leaving must cross the washrack. A source of water should be available nearby, and should be protected from backflow with a vacuum or suction break, with pressure supplied by a pump.

10.6.2 Water Supply

Water used for decontamination should be supplied from a pressure pump downstream of a vacuum or suction brake used to protect the water supply from possibility of backflow. The pump section should be from a tank used to hold make-up water and recycled water monitored and found to be below site background level.

10.6.3 Wastewater (Decontamination Water) Collection System: Design and Operation

The pad will be constructed of asphalt over a crushed stone bed, sloped and curbed to collect water at the center, and to protect area contamination from pad runoff. The pad will have a center drain connected by an open 6-inch wide channel covered with grating, running to a 3 foot x 3 foot x 3 foot concrete box sump. The sump will be used to hold wash water until the water is monitored. If the wash water contamination is found to be above the site background level, it will be pumped by a pump located at the sump box to an evaporation basin. The evaporation

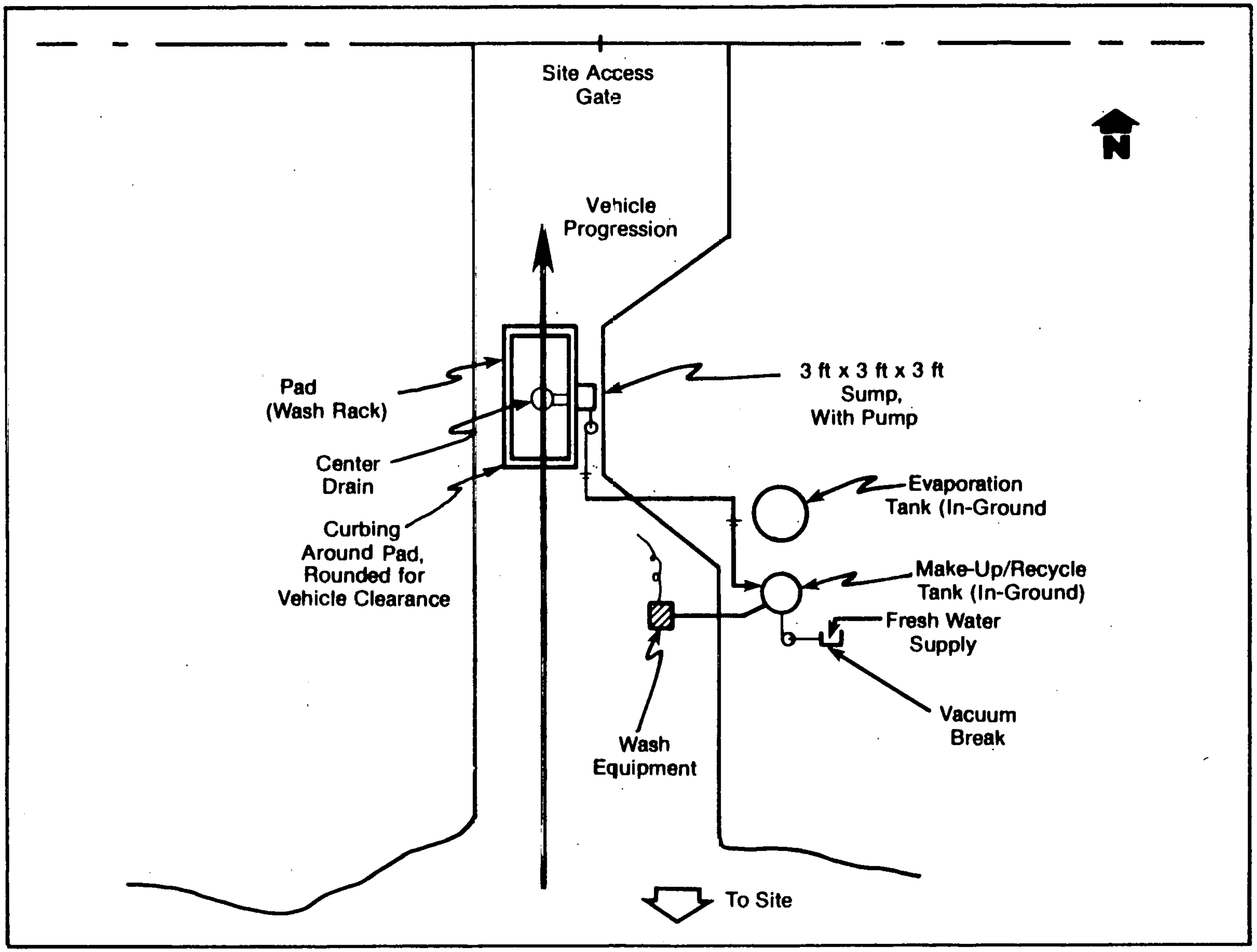

FIGURE 10-2 PROPOSED VEHICLE DECONTAMINATION AREA ST. LOUIS AIRPORT STORAGE SITE

basin will be constructed in-ground of gunnite, and curbed. It will have a capacity of 60 washes, or 15-foot diameter x 2.5-foot depth, based on 135 gals/wash, and 1-foot minimum freeboard to contain any precipitation falling directly into it. Connections between the sump and the basin will be above ground using 1 1/4-inch schedule 40 steel pipe, with the pump sized to deliver a nominal flow of 25 gals/min, to allow removal of the sump contents in 5 minutes. The sump pump discharge will be valved to the make-up water tank so that water contaminated to levels below site background may be recycled for use. The make-up storage tank will also be in-ground, of construction similar to the evaporation storage, and will be 10-foot diameter gunnite, and curbed. The wall thickness of both tanks will be no greater than necessary to provide structural integrity and watertight construction. This will facilitate breaking up the basin floors with air hammers following completion of site operations.

10.7 DUST CONTROL

Dust control during construction is essential to prevent surface and air movement of contaminated dust from exposed soil surfaces into streams, other land areas, or the atmosphere. The development of a comprehensive dust control program will be the construction contractor's responsibility. Construction activities will be performed in a manner which both minimizes the amount of dust generated and the potential for the dust to be carried off-site. No construction vehicles will be allowed to move on the site when wind velocities exceed 20 mph. Various methods of dust control are described as follows:

1. Mulches -- Synthetic resins may be used instead of asphalt to bind mulch material. Resins such as Curasol or Terratack should be used according to manufacturer's recommendations.

2. Vegetative cover -- See subsection 10.2.2.

3. Spray-on adhesives -- These are used on mineral soils; they are not effective on muck soils. Keep traffic off these areas. Refer to Table 10-2.

4. Tillage -- This practice is designed to roughen and bring clods to the surface. It is an emergency measure which should be used before wind erosion starts. Begin plowing on windward side of site. Chisel-type plows spaced about 12

inches apart, spring-tooth harrows, and similar plows are examples of equipment which may produce the desired effect.

5. Irrigation -- This is generally done as an emergency treatment. The site is sprinkled with water until the surface is wet; repeat as needed.

6. Barriers -- Solid board fences, snow fences, burlap fences, crate walls, bales of hay, and similar materials can be used to control air currents and soil blowing. Barriers placed at right angles to prevailing currents at intervals of about 15 times their height are effective in controlling wind erosion.

7. Calcium chloride -- Apply calcium chloride at a rate that will keep the surface moist; retreatment may be necessary.

The application of these methods will be left to the discretion of the construction contractor.

Table 10-2

Application of Spray-On Adhesives

Adhesive	Water Dilution	Type of Nozzle	Application Rate (Gallons/A.C.)
Anionic asphalt emulsion	7:1	Coarse spray	1,200
Latex emulsion	12 1/2:1	Fine spray	235
Resin-in-water emulsion	4:1	Fine spray	300

10.8 SITE SECURITY

10.8.1 Construction Phase

Security arrangements are required during the construction phase of the remedial action program to protect the public from coming into contact with the contaminated material and to protect the site and construction equipment from vandalism. The site currently has a fence around it, however, some portions of it are missing and other portions will have to be removed during the ditch decontamination process. The missing fence portions can be replaced; while the fence portions to be removed are not in place, it may be necessary to engage a 24-hour security guard for the site. This guard should be provided with an appropriate communication device to maintain continuous "open channel" radio contact with an outside emergency unit, such as the St. Louis Police Department, when making rounds. The use of the security guard should be continued until the first layer of the complex cover system is completely in place across the site so that no contaminated material is directly accessible to the public. The fence will be replaced at the end of the construction phase and appropriate warning signs will be posted. Portable lights may be installed around the site.

10.8.2 Post-Closure Phase

During the construction phase a 6-foot high chain link fence topped with three strands of barbed wire will be installed around the site. It will be equipped with two permanent gates with locks at vehicular access points. Keys to these gates will be issued to a controlled number of authorized personnel. Each key should be numbered and a list of all key holders maintained. Appropriate warning signs will be posted on the fence. Maintenance requirements for security facilities are described in Section 6.

10.9 POST-CLOSURE MAINTENANCE

10.9.1 Emergency Contact

During the post-closure period the following office should be contacted in the event of an emergency:

....

....

....

10.9.2 Inspections

During the post-closure period, the following structures and areas will be inspected throughout the first five years on a quarterly basis, and on an annual basis thereafter:

1. Final cover of the three waste areas and the remainder of the site.

2. Drainage and diversion systems.

3. Groundwater monitoring system.

4. Security facilities.

10.9.3 Maintenance Activities

Maintenance activities which will be provided include:

1. Soil replacement/sediment clean-out.
2. Vegetative maintenance.
3. Mechanical repairs.

10.9.4 Soil Replacement/Sediment Clean-Out

It is expected that some minor erosion will take place around the drainage ditches and swales during severe weather. During the annual inspection, the inspector will check for such minor damage, in addition to signs of cracking, stretching, excessive drying, etc. in the cover layers as well. Any damage should be repaired as soon as it is discovered to prevent more serious erosion which could lead to loss of containment. Eroded soils will be replaced and restabilized as needed. Severe storm erosion would require repair by outside contractors.

During the construction phase, the sediment basin(s) and drainage ditches will be cleaned on a regular basis. The sediment which is removed will be deposited along with any debris removed from the anti-vortex device in one of the waste areas and stabilized with the waste. When construction is completed the sediment basin(s) will be demolished and the remaining soils will be incorporated with the off-site material storage pile.

10.9.5 Vegetation Maintenance

During the final months of the construction period most of the site will be seeded to provide a stable vegetative cover. Maintenance of this vegetation will be required during the post-closure period. About six months following the seeding period, the entire site will be inspected to determine whether vegetation has been established. It is expected that additional seeding will be required in some problem areas.

The entire gross area will be mowed once a year (at the time of the annual inspection) in order to prevent the growth of woody/deep-rooted vegetation which could penetrate the cap.

Evidence of vegetation deterioration will be monitored during the annual inspection visits. If any deterioration is discovered, reseeding and mulching must be performed.

10.9.6 Mechanical Repairs

The chain link fence and gates surrounding the site should be carefully examined for broken or damaged sections during the annual inspection visit. Since this fence is the primary barrier to public access to the site, it must be maintained in good repair. It is estimated that the entire fence will need to be replaced as often as every 25 to 30 years.

The groundwater monitoring wells will be checked for damage during the inspection visit, when they are being sampled. Broken well caps will be replaced and any required repairs to well casings will be performed at this time.

10.10 WORKERS' HEALTH CONSIDERATIONS

The radiation levels present on the site are low and present no true hazard, however, in order to be conservative and to provide for public reassurance, a health and safety plan for the protection of employees, subcontractor personnel, and the general public has been and will be further developed. This health and safety plan will include policies and procedures to ensure compliance with NRC radiation protection criteria and the appropriate OSHA rules and regulations.

10.10.1 Employee Training

The health and safety plan initially requires all personnel to attend an orientation session. Here they will be instructed in:

1. Potential hazards associated with the job.
2. Measures that can and will be taken to ameliorate these hazards.
3. Purpose and types of radiation monitoring that will be performed.

4. Individual and collective responsibilities in worker and radiation safety and accident prevention.

5. Specific safety procedures that will be followed, including:

   a. Description of the entry and exit procedures.

   b. Dosimetry.

   c. Special clothing.

   d. Use of the employees' shelter.

The purpose is to instruct employees concerning potential hazards, to make them aware that safety procedures, although at times burdensome, have been put in place for their protection and that they should maximize the use of these procedures and minimize exposure. It will be impressed on all personnel that deviations from the health and safety plan are cause for dismissal.

10.10.2 Safety Equipment and Exposure Monitoring

In order to properly implement the health and safety plan, all personnel must submit pre- and post-job urine samples for radiological analysis, and wear radiation dosimeters at all times when on the job site. These steps are necessary in order to evaluate any potential radiation exposures, which by design, are to be kept as low as reasonably achievable. Personnel will also be required to adhere to all applicable OSHA requirements in order to minimize potential accidents.

Radiation exposure and accident potential of personnel on the job site will be minimized by having all employees report to the employee shelter where they will be issued and put on appropriate protective clothing, prior to entering the job site. They will then report to their specific job locations. Any time personnel leave the site, or at the end of the work day, they must report to the employee shelter and return all protective clothing and be monitored for radiation exposure. Members of the general public that have a need to enter the job site will follow the same procedures.

Radiation exposure of the off-site general public will be prevented by monitoring and cleaning all equipment prior to its leaving the job site. Exposure will also be prevented by conducting decontamination processes in a manner which mitigates the spread of contaminated materials off-site. This includes stopping all work under adverse environmental conditions.

The equipment to be used to accomplish these safety precautions consists of:

1. Thermoluminescent dosimeters.
2. G-M and gamma probes connected to ratemeters.
3. G-M field counting systems.
4. Air sampling apparatus.

10.11 RECORDKEEPING AND DOCUMENTATION

As-built drawings of all covers, drainage facilities, and other structures will be maintained as a basis for the annual inspections. A written record of each annual visit will be prepared including date, time, weather conditions, personnel, damage discovered, required repairs, and a general assessment of site integrity. When any repairs are made as a result of these visits, the date and nature of these repairs, along with the name of the contractor and the inspecting official, will be noted on the appropriate annual inspection report.

A record of all laboratory results received from monitoring activities will be maintained with the inspection results. These records will be examined annually for evidence of trends, contamination movement, etc. A list of all personnel holding keys to the site, along with the key numbers, will also be maintained.

SECTION 11

MONITORING PROGRAMS

11.1 INTRODUCTION

Activities at the St. Louis Airport storage site fall into four basic categories, as follows:

1. Radiological environmental monitoring.
2. Personnel and workplace monitoring.
3. General monitoring.
4. Modeling and simulation.

11.2 RADIOLOGICAL ENVIRONMENTAL MONITORING

Table 11-1 presents radiological criteria for the predominant pathways and isotopes at the airport site. These criteria are on the present knowledge of radiation levels and isotopes on the site. This information led to the development of a four-phase monitoring program, as follows:

- Phase I - During construction and closure activities.
- Phase II - Immediately post-closure.
- Phase III - First five years post-closure.
- Phase IV - Remainder of the post-closure period.

The proposed Phase I program is described in Table 11-2. This program will be in effect for the duration of the remedial action and is geared toward environmental protection and confirming the results of the personnel and workplace monitoring program.

The Phase II program will be conducted immediately after post-closure and has as its primary objective the determination of the remedial action's effectiveness. This will be accomplished by:

1. Measuring and evaluating the beta-gamma and gamma dose rates at 1-centimeter and 1-meter heights, respectively, over the entire site.

Table 11-1

Radiological Criteria for the Predominant Pathways/Isotopes

Media/ Pathway	Nuclide	Standard/ Guideline	Source	Criteria
External Radiation		Dose Limits To Public Individuals	NCRP, 1971	500 mrem/yr
		Decontamination Guidelines for Facilities and Equipment	USNRC, 1976	0.2 mrad/hr
		EPA Guidelines for Decontamination of Uranium Mill Tailings Sites	USEPA, 1978	10 μR/hr
		Clean-up Criteria for Uranium Mill Tailings Sites	USNRC, 1978	140 mrem/yr
Groundwater and Surface Water	U-238	10 CFR 20 -- Maximum Permissible Concentrations in Effluents to Unrestricted Areas	USNRC, 1960	40,000 pCi/L
	Ra-226			30 pCi/L
	Th-230			2,000 pCi/L
	Pb-210			100 pCi/L
	Ra-226	Primary Drinking Water Standards	USEPA, 1976	5 pCi/L
Particulates in Air (resuspension)	U-238	10 CFR 20 -- Maximum Permissible Concentration in Air, in Unrestricted Areas	USNRC, 1960	3 pCi/cu m
	Ra-226			3 pCi/cu m
	Pb-210			4 pCi/cu m
	Ac-227			0.08 pCi/cu m
	Th-230			0.08 pCi/cu m
Radon in Air	Rn-222 and daughters	10 CFR 712 -- Remedical Action Guide for Radon Daughter Concentrations	USDOE, 1976[1]	0.03 WL
		10 CFR 20 -- Maximum Permissible Concentration in Air in Restricted Areas	USNRC, 1960	3 pCi/L
		40 CFR 192 (proposed)	USEPA, 1978[2]	0.015 WL
	Rn-222 flux	40 CFR 192 (proposed)	USEPA, 1978	2 pCi/sq m/s
Soil	Uranium and thorium	10 CFR 40 -- Licensable Quantities	USNRC, 1961	0.05 by weight
	Ra-226	Definition of Radioactive	Dickson, 1978	5 pCi/g

[1]This limit is for structures other than dwellings and schoolrooms.
[2]This limit is for any occupied or unoccupied building.

Table 11-2

Proposed Phase I Construction Monitoring Program

Sample Type	Sampling Locations	Analyses	Frequency of Sampling and Analysis
External Radiation			
Thermoluminescent and dosimeters	16 -- On the fence in each ordinal direction	Gamma dose	Monthly
Groundwater	5 -- Monitoring wells if available (1 up-gradient, 1 mid-gradient, 3 down-gradient)	Gross alpha and beta Ra-226 U-238	Monthly
Surface Water	3 -- Coldwater Creek (1 each upstream, discharge area and downstream) 2 -- Sedimentation basins	Gross alpha and beta Ra-226	Monthly (continuous composite)
Particulates			
AP filters	6 -- On the fence -- north, northwest, north-northwest, east, east-southeast, and southern sectors.	Gross alpha and beta	Weekly
Radon in Air	Proposed on-site building. 2+25, 9+00, and in work area	Rn-222 and daughters	Continuous
Sediment and Surface Soils	2 -- Sedimentation basin(s) 6 -- Other on-site areas 3 -- Coldwater Creek (1 each upstream, discharge area, and downstream)	Ra-226, U-238	Monthly

2. Measuring and evaluating the radon flux rates from the site at approximately 20 locations.

3. Measuring and evaluating the alpha, beta, Ra-226, and U-238 levels in one upgradient, one midgradient, and three downgradient wells.

4. Measuring and evaluating the alpha, beta, Ra-226, and U-238 levels in Coldwater Creek water and sediment samples upstream of the site, in the site discharge area, and downstream.

5. Measuring and evaluating the alpha, beta, Ra-226, and U-238 levels in each drainage ditch's water and sediment just upstream of its discharge.

6. Measuring and evaluating the alpha, beta, Rn-222, and radon daughter product levels in the air environment on-site and immediately off-site in the downwind direction using high volume sampling techniques.

If the results of this phase show that the remedial action has been successful, Phase III, the third or short-term post-closure monitoring program will commence. This program is graded in that it is most intensive for the first five post-closure years and based on the program's results may then be appropriately lessened. The proposed program for the first five years is shown in Table 11-3.

The program outlined in Table 11-3 will be run for the first five years post-closure. At the end of each quarterly sampling period the results will be tabulated and reviewed, and if there is evidence of off-site migration of radioactivity or failure of some part of the remedial action, appropriate additional sampling and analysis may be performed. Also the causes of these results will be investigated and mitigation actions developed. Quarterly letter reports and an annual environmental monitoring report will be written at the end of each calendar year and a final five-year report will be written.

The annual report will list the results of all analyses and compare them to appropriate preclosure, background, and previous post-closure results. Any evidence of adverse environmental impact will be fully explored. The report will fully describe the

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Table 11-3

Proposed First Five Years Post-Closure Monitoring Program

Sample Type	Sampling Locations	Analyses	Frequency of Sampling and Analysis
Groundwater	1 -- Upgradient well 4 -- Midgradient wells 3 -- Downgradient wells	Gross alpha, gross beta, Ra-226, U-238	Quarterly
Surface Water (Coldwater Creek)	1 -- Upstream 1 -- Discharge area 1 -- Downstream	Gross alpha, gross beta, Ra-226, U-238	Quarterly
Sediment (Coldwater Creek)	1 -- Upstream 1 -- Discharge area 1 -- Downstream	Ra-226, U-238	Annually
Air Particulates	At the site fence -- north, northwest, north-northwest, east, east-southeast, and southern sectors.	Gross alpha, gross beta	Quarterly
Radon Flux	In areas of site disturbance or four locations	Rn-222	Annually
Surface Soil	In areas of site disturbance or four locations	Ra-226, U-238	Annually
Thermoluminescent dosimeters	On the site fence -- north, northwest, north-northwest, east, east-southeast, and southern sectors.	Gamma dose	Quarterly
Surface Water (drainage ditches)	1 from each ditch just upstream of discharge, if available	Gross alpha, gross beta, Ra-226, u-238	Quarterly
Sediment (drainage ditches)	1 from each ditch just upstream of discharge and at any erosion path entries.	Ra-226, U-238	Annually
Site Survey	Entire site and drainage ditches	Beta-gamma and gamma dose rates	Annually

monitoring programs, sampling procedures, radioanalytical procedures, and data analysis procedures. The five-year summary report will be similar in content but will also address the adequacy and sufficiency of reducing the monitoring program's scope.

If, as expected, the five-year summary report shows that there is no need to continue the initial program, the program will be reduced. This new and reduced program, to the extent warranted, will reduce all sampling and analysis frequencies to an annual basis, and the thermoluminescent dosimetry portion will be eliminated.

All other elements of the program will remain unchanged. An annual monitoring report will be prepared, as described previously. It should also be noted that the monitoring program can be reintensified at any time, should it be necessary.

11.3 PERSONNEL AND WORKPLACE MONITORING

The radiation hazards present on the site are low and present no true hazard. However, in order to protect and provide for employee and public health and safety, a personnel and workplace monitoring program has been developed. The proposed program is shown in Table 11-4, and will be effective for the duration of the construction period.

11.4 GENERAL MONITORING

The general monitoring programs at the St. Louis Airport site fall into five categories, as follows:

1. Erosion.
2. Groundwater.
3. Hydraulic barrier.
4. Settlement.
5. General visual.

These programs are described in the subsections that follow.

11.4.1 Erosion Monitoring

Erosion control methods will be assessed by measurements of staff gauges set within the sedimentation ponds, and measurements along the fixed grid survey network. Post-closure erosion of the stabilized site will be documented by a combination of:

Table 11-4

Proposed Personnel and Workplace Monitoring Program

Type of Monitoring	Sample or Monitoring Type	Analyses	Frequency
Personnel	Thermoluminescent dosimeter	Immersion dose	Monthly[1]
	Urinalysis	Gross alpha, gross beta, and Ra-226	Pre- and post-job or annually[1]
	Contamination check	Gross beta-gamma of individual with a G-M detector	Prior to leaving site
Equipment	Contamination check	Gross beta-gamma of equipment with a G-M detector	Prior to leaving site
Area and workplace	Exposure rate	Gross gamma exposure rate using a G-M detector.	Continuous
	Soil radioactivity	Gross beta-gamma of soils using a G-M detector.	Randomly throughout the workday
	Airborne radioactivity	Gross beta content of air particulates using a hi-vol sampler and G-M detector	Randomly throughout the workday
	Fill materials[2] and materials from other sites and areas	Gross beta-gamma of materials using a G-M detector and total weight or volume	As required

[1]Frequencies may be increased if radiation exposure is suspected.

[2]If fill materials contain radioactive contaminants, samples will be taken and analyzed in order to estimate the total radioactivity being buried.

1. Photographic records.

2. Level surveys.

3. Random walk surveys and quadrant measurements at the site during routine monitoring or maintenance visits.

4. Written site inspection reports.

If evidence of any disturbance is found during site maintenance visits, appropriate remedial actions will be determined and performed. A follow-up visit will be required to assure that these remedial actions have been completed properly, and are performing according to plan.

11.4.2 Groundwater Monitoring

In the event of failure of the remedial cover, liner, or slurry wall system, it is most likely that the contaminants would migrate as leachate into the subsurface water regime. In order to monitor the effectiveness of the various closure and capping methodologies to be employed at the site, the groundwater quality must be monitored. It will be necessary to monitor the vertical as well as horizontal migration of contaminants. As such, piezometer nests are recommended with individual screened piezometers located as follows:

1. Just below the seasonal low point of the zone of saturation.

2. Above geological unit 5 within the surface-water table regime.

3. Below geological unit 6 within the second identified water-bearing zone.

Deep borings already completed indicate that unit 6 narrows substantially to the east as the depth to bedrock decreases. As such, it will be necessary to determine the extent of unit 6 in the vicinity of fill Area 2 through exploratory drilling. Depending on the results of this study, the piezometer nests of Area 3 may be installed as a two-well set above unit 5.

Monitoring well construction specifications are as follows (see Figure 11-1):

1. Drilling Method -- Auger or air rotary; hole diameter - 12 inches.

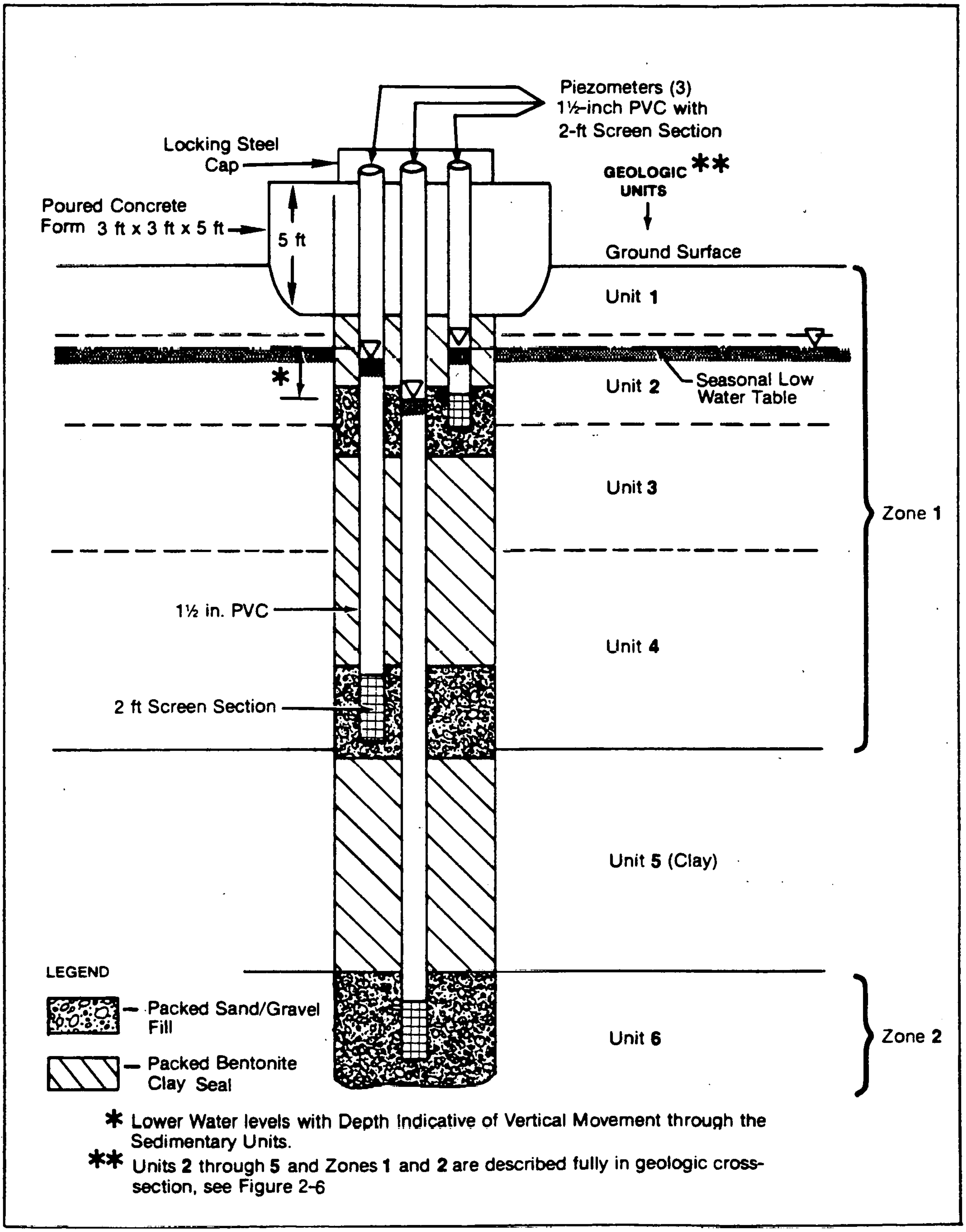


FIGURE 11-1 PIEZOMETER NEST MONITORING WELL CONSTRUCTION

2. Casing -- Screen sections of 2-inch commercially-available 2-foot sections of Schedule 80 PVC, slot size 0.020 or 0.030.

3. Blank Pipe.

   a. 2-inch PVC Schedule 80 with screw-type couplings to within 5 feet of the ground surface.

   b. 5 feet to the surface, plus stickup (3.5 feet). 8.5 feet should be of stainless steel connected with flush joints directly to the PVC blank well pipe.

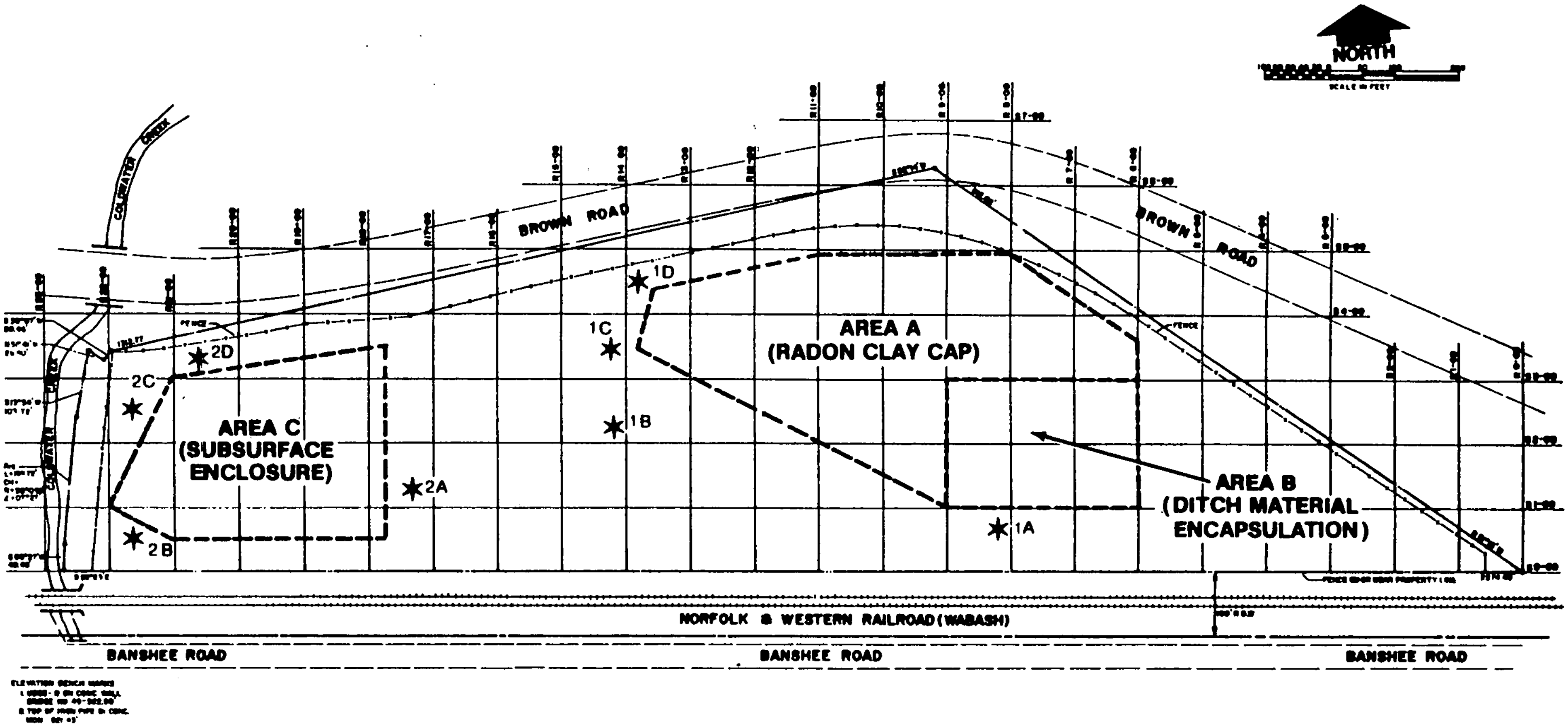
4. Bentonite Seal -- Between each piezometer, a bentonite seal consisting of packed commercially-available clay pellets will be placed. The pellets will be placed slowly above the sand/gravel filter pack, and then tamped down to ensure swelling to completely seal the void. This process will be continued to the desired seal thickness. The purpose is to ensure that vertical permeability and thus communication between the piezometer settings is not possible.

5. Gravel/Sand Filter Pack -- Graded sand or pea gravel larger than the screen openings will be placed around the 2-foot screen section to enhance sample collection and filtration.

6. Concrete Pad -- Above the final bentonite seal, a poured concrete pad 3 feet x 3 feet x 3 feet will be placed around the piezometers. A protective locking steel cap surrounding the two or three separate casings will be installed directly into the pad.

Well 1D will monitor groundwater flowing through and/or around Area 1 (waste encapsulation area) and serve as an upgradient background well, along with well 2A for Area 2 (waste encapsulation and slurry wall area). (Refer to Figure 11-2.) Wells 2B, 2C, and 2D will monitor the quality of groundwater which flows around Area 2. Groundwater quality parameters to be monitored on a quarterly basis during the first five years post-closure and annually thereafter include:

1. Gross alpha and beta radiation.
2. Uranium-238.



✶ PIEZOMETER NEST MONITORING LOCATIONS

FIGURE 11-2
PROPOSED PIEZOMETER NEST MONITORING LOCATIONS
ST. LOUIS AIRPORT STORAGE SITE

3. Radium-226.
4. Phosphate.
5. Fluorine.
6. Iron (soluble).
7. Total dissolved solids.
8. Conductivity.
9. pH.

In addition to these parameters, at least one set of samples collected during the initial year after closure should be analyzed for trace metals.

Data gathered during the characterization study identified a significant component of the total volume of groundwater flow through the site to be generated by upgradient recharge. As part of the evaluation of a partial or complete cover system, it will be necessary to separate this horizontal component of recharge from the total volume of recharge to the system, most notably through surface infiltration or vertical recharge. This may be accomplished by developing the Area 1 water budget based on readily-available meteorological data, the known physical characteristics of the subsurface geology, and measured water table fluctuations. A minimum of one year of monitoring after completion of site closure work should be established to incorporate seasonal fluctuations of both precipitation and rate of evapotranspiration. During this period, water level measurements of the existing shallow piezometer system will be collected on a monthly basis. An automatic 30-day water level recorder should be installed for the duration of the study period to provide a continuous record of the time-delay relationships between fluctuations in the saturated zone and climatic changes.

11.4.3 Hydraulic Barrier Monitoring

Any groundwater flow through the slurry wall will cause a change in the hydraulic head inside the wall relative to the head outside the wall. Such changes can be measured by a series of piezometers, placed inside and outside the wall.

A piezometer is a vertical tube or pipe placed in the ground to measure the hydrostatic head or pressure at a given location and depth. The tube must be sealed along its length, and be open to water flow at the bottom. When measurements are being made, it must be open to the atmosphere at the top. Between monitoring periods, a cap over the top prevents the tube from filling with debris.

The bottom or intake portion is usually a slotted pipe or commercial well point. It is designed to allow the inflow of water, but not sand grains or clay particles.

It is recommended that a minimum of three piezometers be placed inside the slurry wall. If these are placed at different depths, any vertical potential gradient can be measured.

As part of the quarterly radiological monitoring program site visits, the elevation of the water surface in each of the piezometers and the monitoring wells will be recorded. These data will be compared to previous records and an evaluation of any potential breach of the containment can be made.

11.4.4 Settlement Monitoring

In order to assure that hydraulic barriers remain effective, it will be necessary to monitor the proposed soil/bentonite wall by means of a settlement plate. The settlement plate provides a mechanism for measurement of differential settling of the soil/bentonite wall. A steel plate is placed at the top of the wall, and a steel extension arm continues up to the final ground surface. Any differential settlement of the slurry wall will be observed as a change in elevation of the extension, compared to a permanent monument to be installed on-site.

As part of the maintenance inspection, the elevation of the settling plate will be recorded. The data will be compared to previous records, and an evaluation of any potential breach of the containment can be made. In addition, elevation determinations will be made at six additional points across the site to monitor cover consolidation and differential setting.

11.4.5 General Visual Monitoring

The general visual monitoring program will take place during the routine site radiological monitoring program visits. The inspector will survey and record signs of surface erosion, burrowing animals, and other ground disturbances. Based on the results of these surveys appropriate remedial actions may be taken.

11.5 MODELING AND SIMULATION

As part of this study, WESTON was requested to evaluate modeling and simulation techniques for possible use as tools for predicting risks and monitoring subsurface migration of radionuclides. A detailed presentation of WESTON's evaluation can be found in Appendix D.

An assessment of various available surface pollutant transport models for possible application in the simulation of low-level radioactive waste transportation in subsurface water has been made. This assessment included flow and pollutant transport models which simulated unsaturated and saturated media. The finite element models developed by the Oak Ridge National Laboratory (FECWATER and FECWASTE) can be effectively used in simulating the radionuclide transport pnenomena from a low-level radioactive waste site.

In order to understand the potential pollution of groundwater in and around a low-level radioactive waste site, it is necessary either to monitor the site closely or to predict the potential for the spread of pollutant concentration in the future. Unfortunately, the movement of groundwater is slow (on the order of a few feet/year) that continuous monitoring of groundwater for as long as 10 years will not show significant radionuclide movement. Therefore, by monitoring only, it will not be possible to accurately identify the potential for radionuclide transport and concentration in groundwater in the distant future. By simulating the transport mechanism by mathematical modeling, however, it is possible to predict the potential transport of radioactivity over a long period of time in a cost-effective manner. It is also possible to conduct a risk assessment of radionuclide transport in a waste site that could result from pumping groundwater in the vicinity of the site. Therefore, it is preferable that mathematical modeling or simulation of the transport of low-level radioactive wastes from a waste site be undertaken to assess risk and future pollutant spread in the groundwater under various conditions.

In order to conduct a modeling study to assess potential pollution of groundwater from low-level radioactive wastes, the following study steps are recommended:

1. Data Collection.

   Assemble necessary hydrogeological and waste characterization data as required for simulation in the hydraulic flow model (FECWATER) and pollutant transport model (FEWASTE). The hydraulic flow model (FECWATER) will generate the net groundwater flow and velocity in both unsaturated and saturated media. The output from FECWATER will become input for FECWASTE to generate the radionuclide movement under various boundary conditions.

2. Model Simulation of Low-Level Radioactive Waste Site.

If historical data are available, it is always preferable that a site be simulated from the very beginning of the creation of the site, and to include all historical changes on the site since that time. These can be simulated in the model by incorporating various boundary conditions into the model. All available historical water quality data, including data collected in recent years, should be used in calibrating the model.

3. Evaluation of Decay Rates.

Laboratory column tests with the site soil should be performed to determine the leach rates of radionuclides. The radionuclide leach rates evaluated in the laboratory should be compared with the leach rates obtained from field observations. After proper evaluation, leach rates should be determined for use in the modeling runs.

4. Prediction of Pollutant Transport in the Future.

After proper simulation and calibration of the model, the model should be used to predict the behavior of radionuclide pollution transport in the site's groundwater. The model should be run to predict pollutant concentrations 100, 500, and 1,000 years in the future under existing site conditions (no action plan). The model should also be used to simulate and analyze alternative pollution containment plans. This simulation can be performed by simulating the proper boundary conditions that will result if the alternative containment plans are implemented.

5. Comparison of Transport of Pollutants Under Various Alternative Plans.

A comparison of the extent of pollution in the future under various alternative plans should be made. The times required for development of a steady-state condition, and the extent of dispersion of the pollutant at this condition should be determined under various options.

6. Risk Assessment.

   After calibration of the model with proper coefficients, and boundary values, various risk assessments from the spread of the pollutants as a result of a fracture in the lining, or pumping in nearby wells should be conducted.

SECTION 12

IMPLEMENTATION GUIDELINES

12.1 FINAL ENGINEERING DESIGN

The selected concepts were carefully evaluated for feasibility of design and construction. However, many items and details must be investigated further for the final design. The major items that will require in-depth analyses are:

1. The composition of the soil/bentonite backfill composition for the barrier must be determined by laboratory testing to optimize the mixtures of site soil and bentonite to bring about the desired permeability. In order to control groundwater movement through the barrier area, the permeability must in the range of 10^{-8} cm/s.

2. Refinements of the cover and liner composition to ensure the desired performance are needed. Detailed testing and evaluation of cover and liner materials are required to determine properties which control water movement into and out of the system.

Numerous design and construction details will have to be resolved when the results of these analyses are known.

12.2 FINAL SITE CONTOURS AND DRAINAGE PLAN

The final site configuration is shown on Figure 12-1. Except where the edges of clay caps require a 20 percent slope, gentle slopes are incorporated to carry drainage off-site with a minimum possibility for erosion. With the exception of one-half of the slurry trench area and the very southern boundary of the site, drainage will be directed to the Brown Road ditch. If it is deemed necessary, the sediment basin may be left in service and permanent check dams installed along Brown Road. This would trap sediment derived from approximately 90 percent of the area, however, both systems would require continued maintenance to be effective over the long-term.

12.3 CONSTRUCTION SEQUENCE

The physical size of the site (20 acres) will place some constraints on the construction sequence. The areas occupied by the major encapsulation and containment facilities cover a large portion of the site, as may be seen in the preliminary site preparation and grading plan, Figure 12-2. Simultaneous construction would result in mutual interference.

The recommended construction sequence is shown diagrammatically on Figure 12-3. In order to minimize the loss of eroded material during construction, the sediment control check dams along Brown Road should be built first. This may be followed immediately by grading the sedimentation basin area, with excess soil moved to the surplus fill area. The sedimentation basin may then be installed. At that time, work may then proceed simultaneously on the slurry trench area and the liner area. For the slurry trench area, the leveling berm may be built using imported soil and interior grading completed. During grading, some large chunks of concrete must be moved to area S1:R12 to await completion of the liner.

In the liner area, the site may be excavated and surplus soil placed under the radon cap and compacted in place. Any excess soil may be transferred to the surplus fill area for final compaction and grading. The liner may then be installed. Once the liner is in place and site grading accomplished, the equipment required to build the slurry trench may be staged in the surplus fill area and construction begun.

Once work on the slurry trench is underway, the ditch excavation and excavation at the east end of the site may proceed, with materials being transferred into the liner area and compacted in place. Further sequencing is not critical except high priority should be given to completing the cap over the liner to avoid collection of excess quantities of rainwater in the liner.

12.4 SOIL AVAILABILITY

12.4.1 General Materials Requirements

Imported soil will be required to provide caps, covers, linings, fill, and topsoil for closure of this site. Crushed stone and sand will be needed for caps, ditches, trenches, and for the vehicle decontamination area.

1. Clean Clay (Silt Loam).

   Imported soil in the form of clean clay will be used to provide fill, as well as material for the clay caps. The clean clay or silty loam must have a plastic limit of approximately 10, and a liquid limit of approximately 40.

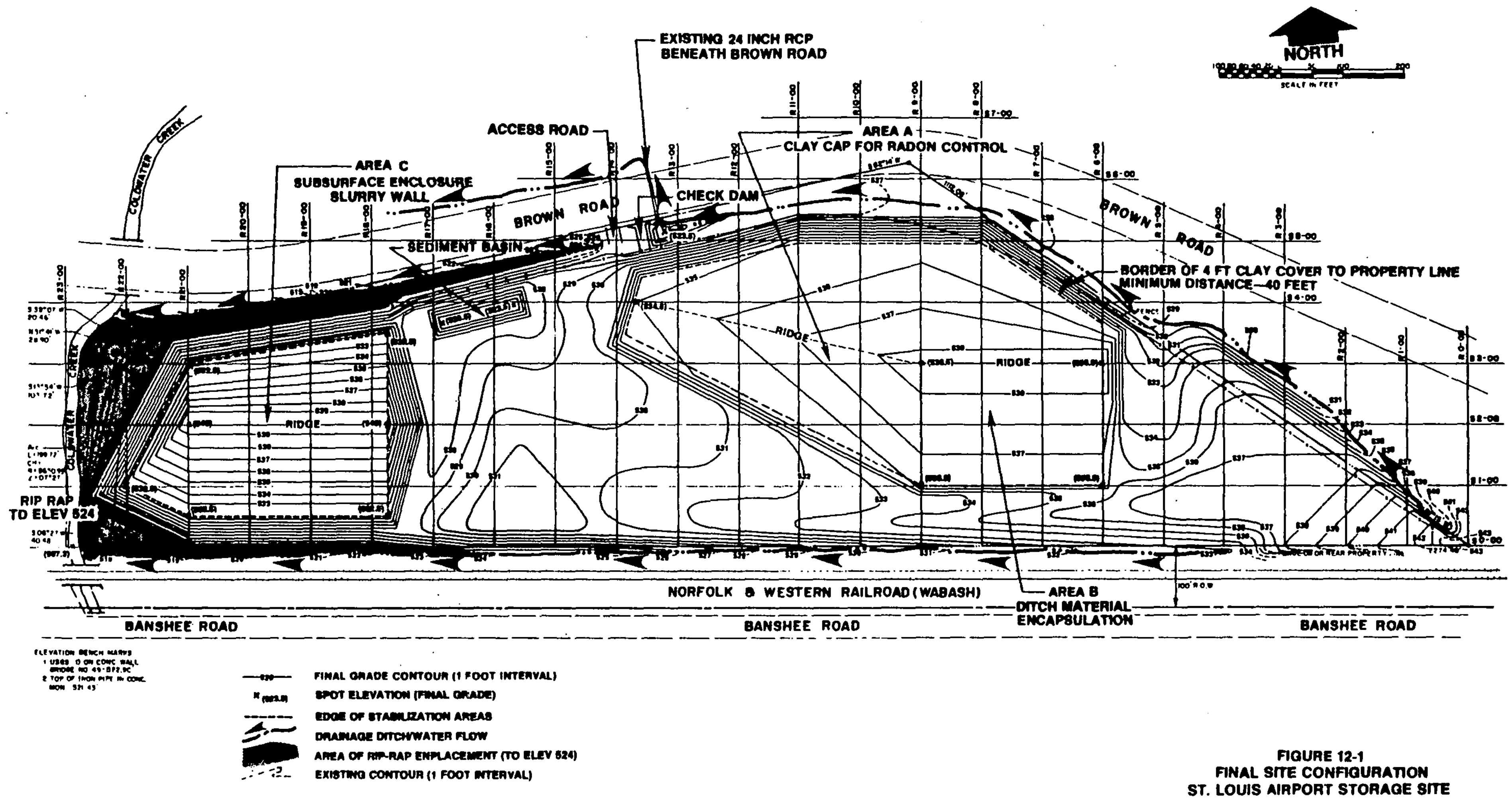


FIGURE 12-1
FINAL SITE CONFIGURATION
ST. LOUIS AIRPORT STORAGE SITE

This clay will be used as a fill in the following applications:

a. Leveling of berm.
b. Slurry trench cover.
c. Liner and cap cover.
d. Ditch replacement.
e. Remaining area cover.

The clean clay will be used in the following clay caps:

a. Slurry trench cap.
b. Ditch material cap.
c. Ditch material liner for radon cap.

Where silty loam is used in caps or liners, it will be compacted to the required density. After construction of the caps, including installation of bentonite and crushed stone layers, another layer of noncompacted silty clay will be added to within 6 inches of the final grade. All other areas will be covered with a noncompacted layer of this material to within 6 inches of the final grade.

It is estimated that approximately 160,000 cubic yards of lean clay (silty loam) will be needed to perform the work.

2. Topsoil.

A 6-inch layer of topsoil will be required over the entire site after all grading has been completed to within 6 inches of the final grade. This topsoil is to be:

a. Natural, fertile, and friable.
b. Neither excessively acid nor alkaline.
c. Free of substances harmful to grass growth.

It is estimated that about 43,000 cubic yards of topsoil will be needed for this purpose.

3. Sand and Gravel.

Sand and gravel (crushed stone) will be used to provide a filter medium for infiltration due to precipitation. Some crushed stone will be also used in the vehicle decontamination area, and for pipe bedding and erosion control. The gravel is a crushed dolomitic rock from a local quarry within five miles of the site.

Sizes of the crushed rock for the truck washing area and pipe bedding are as follows:

Mesh	Percent Passing
3 inch	100
2 inch	95
1 inch	40
No. 4	25

The No. 4 crushed stone will be used as part of the filter medium. Rock for erosion control will be riprap. It is estimated that about 7,000 tons of crushed stone of various sizes will be required.

Fine-grained alluvial sand is available from dredging operations, etc. in the area. A quantity of 5,000 tons will be required to provide enough material for application in the filter media.

12.4.2 Availability of Materials

Lean clay is apparently abundant in the St. Louis area. It is locally known as Menfro-Winfield soil. This is a deep, moderate- to well-drained soil, formed in loess on ridge tops and side slopes. It has a silty loam surface soil overlying a moderately permeable silty clay loam subsoil. Quantities of this material are presently being stripped from a local quarry and will be available for the next four to five years. The availability of this material has been discussed with local contractors who have verified that the quantities required can be made available when needed. The soils will have to be tested for suitability to the purpose intended before being delivered to the site, however.

According to local haulers and a local quarry owner, the topsoil will have to be imported from a distant source unless a local source becomes available. Local sources sometimes become available when an area is developed for a shopping center, housing complex, etc.

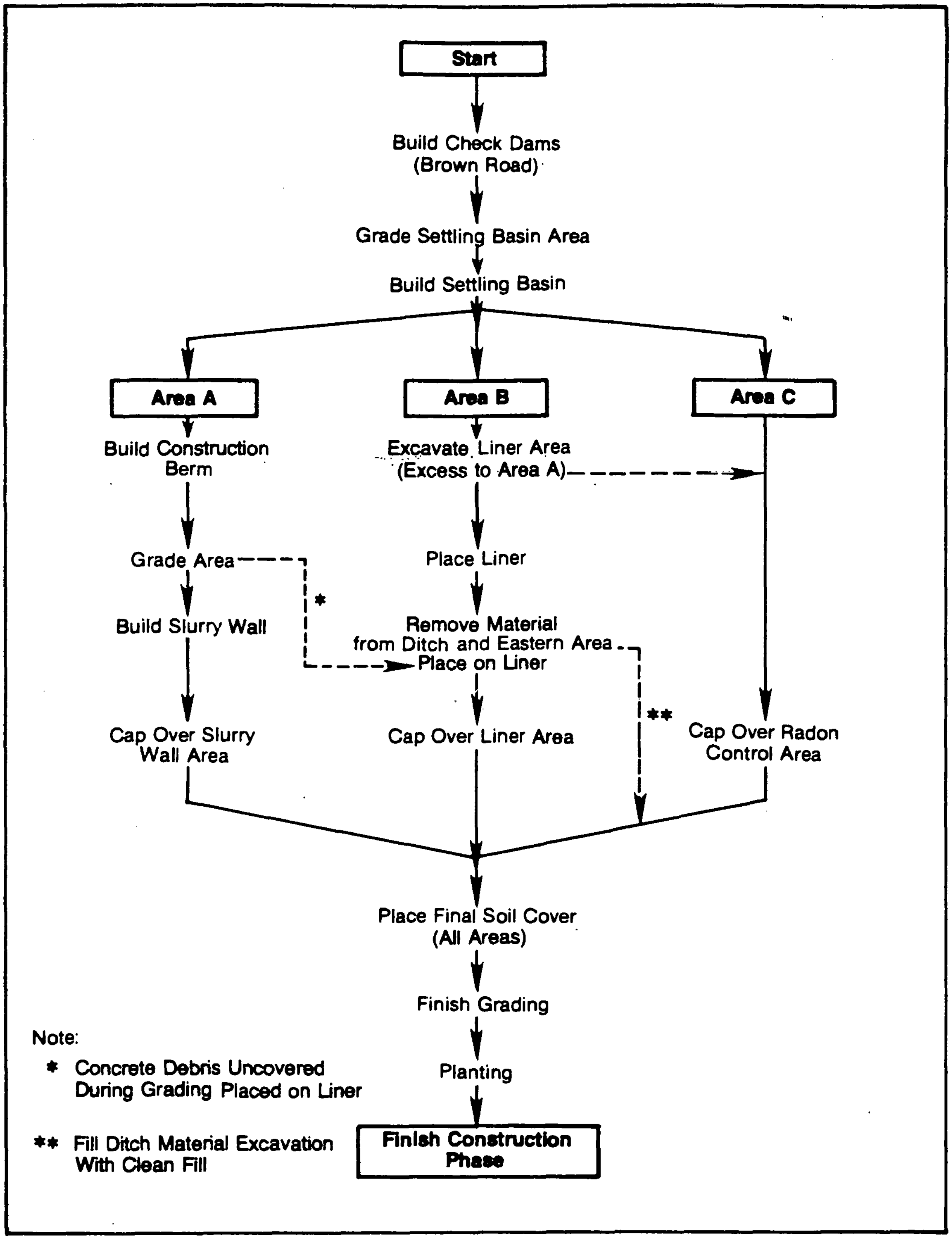


FIGURE 12-3 CONSTRUCTION SEQUENCE FOR IN SITU STABILIZATION OF RESIDUES ST. LOUIS AIRPORT STORAGE SITE

Good topsoil is available in the required quantities according to information obtained from a local hauler and local suppliers. Discussions with representatives of a local quarry have revealed that gravel will be available for the next five to six years from a quarry within 10 miles of the site. Crushed stone is available at this quarry from 1/4-inch diameter to riprap and shot rock sizes.

Alluvial sand from river beds, etc., is readily available in the fine gradation required.

12.5 FIELD SAMPLING OF SOILS

12.5.1 Soil Sampling Procedure

It is imperative that soils being considered for cover system materials be thoroughly documented as to their physical characteristics, volume, and the spatial distribution of each of the major, distinguishable soil types. These data will be collected from test pits or bore holes.

Soil type should be identified at regular depth intervals, even where the soil is obviously uniform to the depth of interest. Changes in soil type should be located. In the field, delineation of soil types is accomplished on the basis of characteristics observed and used in the field, e.g., color and feel when rubbed between the fingers. Brief descriptions of the field sampling methods will be included, i.e., whether by test pit, bore hole, or cleaning an existing bluff face.

The arrangement and spacing of samples must be adequate to delineate the vertical and lateral extent of the major soil types. Where the evaluation indicates that sampling intervals are too far apart, it may be necessary to obtain additional samples at intermediate positions. One effective technique is to sample at fairly close intervals along a single line across the borrow area. Elsewhere in the area only a few additional bore holes may be needed to confirm that the stratification (including thickness) along the cross-section also applies to other areas. A grid pattern may also be definitive.

12.5.2 Soil Testing Program

The major aspect of the testing program is the selection of tests. The minimum testing requirements for all diagnostic samples are given in Table 12-1.

Table 12-1

Index and Classification of Soil Tests

Name of Test	Standard or Preferred Method	Properties or Parameters Determined	Remarks/Special Equipment Requirements
Gradation analysis	ASTM D421 D422 D2217	Particle size distribution.	
Percent fines	ASTM D1140	Percent of weight of material finer than No. 200 sieve.	
Atterberg limits	ASTM D423 D424 D427	Plastic limit, liquid limit, plasticity index, shrinkage factors.	
Specific gravity	ASTM D854	Specific gravity or apparent specific gravity of soil solids.	Boiling should not be used for de-airing.
Soil description	ASTM D2488	Description of soil from visual/manual examination.	
Soil classification	ASTM D2487 ASTM D2216 D2974	Unified soil classification.	
Water content		Water content as percent of dry weight.	

Tests may be required in duplicate (or more) for better representation and checking. These tests are basically indexing tests, but are also useful in establishing the uniformity or variability within individual soil types. Other important tests are compaction and permeability. Only one of these additional tests or test series may be adequate to establish the characteristics of the unit as a whole, provided the limit is relatively uniform in its index properties. Additional testing is only required where special problems are anticipated, such as slope stability and consolidation.

12.5.3 Soil Volume Availability

In order to ensure that a sufficient volume of cover soil is available, accurate measurements of soil thickness and area are required. Additional sampling locations may be required for the sole purpose of obtaining a better calculation of soil volumes. If soil type uniformity has been demonstrated, additional soil testing is not required -- it may be necessary to check thicknesses, only.

An important factor in checking the volumes of available soils can be the bulking factor. Some natural soils, particularly those at depth, have a relatively high unit weight in situ. After excavation, working, and placement as cover over solid waste, these soils will have experienced a reduction in unit weight, i.e., a bulking effect, and available volumes tend to be underestimated. In contrast, other soils, particularly those near the surface, have a relatively low unit weight in situ so that available volumes are easily overestimated. The basis for any bulking factor must be checked, especially in cases where the soil is in short supply.

12.6 BARRIER CONSTRUCTION

Minimal site work, including excavation and grading, will be required initially. The broken concrete and debris will have to be excavated and stockpiled for future placement in selected locations. A construction berm (20-foot width) will be required to elevation 426 to accommodate the trench excavator. After the mixing plant and support facilities for this slurry construction are set up, the trench will be excavated from the surface to a point 5 feet into the gray-blue clay layers to ensure a proper seal. Backfill materials of a specified gradation will be placed in the excavated trench to form the wall. The wall will have an average depth of 48 feet and a total length of approximately 1,264 feet. The total wall surface will be approximately 61,000 square feet and have a total volume of 5,900 cubic yards in the 30-inch wall. Upon completion of the slurry trench, the equipment will be demobilized, and the area prepared to receive the cover and topsoil or blanket and topsoil.

12.7 COVER AND LINER PLACEMENT

As described in subsection 12.4, the soil to be placed in the cover liner will be a lean clay (CL) of medium plasticity having a liquid limit (LL) between 35 and 50 percent. To achieve the permeability needed for the liner and radon gas control for the cover, the fill must be placed in specified 6-inch thicknesses and compacted. The density required for proper performance should be at least 95% of the maximum density as determined by ASTM D1557-78. Water contact control will depend on the shape of compaction curves for the soil used in the fill. Based on the liquid limits, it is estimated that the range of placement will be within -1 percent to +2 percent of the optimum water content.

The water content should be as high as possible to achieve the required density and yet achieve the moisture control specified by the radon gas control testing. The fill will require processing including spreading, moisture addition (or drying by the use of a disk), leveling, and compaction. To ensure that a density that is as uniform as possible is developed throughout the list, a tapping ruler should be used.

12.8 QUALITY ASSURANCE

Since the performance of the treatment is dependent on proper construction, the techniques and results must be carefully monitored. Adequate inspection of all excavation and backfill operations during the barrier construction are needed to ensure that the performance of the wall is equal to the design intent. The depth of the barrier excavation will have to be monitored closely to ensure that the specified tie-in to the gray-blue clay is achieved. The backfill material for the barrier will require control to ensure that the specified gradients are obtained. Liner and cover materials will also require adequate quality assurance. These materials will require testing throughout the placement operation to ensure that they fill the specified liquid limits, and that the final fill has a specified density in water content.

12.9 CONTINUED MONITORING REQUIREMENTS

A two-phase continuing monitoring program for the post-construction period has been described completely in Section 10. It includes monitoring the following:

1. External radiation.
2. Groundwater.
3. Surface water.
4. Radon flux.
5. Sediments and surface soils.
6. Vegetation.
7. Settling.

Phase I specifies quarterly monitoring for five years into the post-construction period. At the conclusion of this period, test results will be evaluated and a decision made on future monitoring activities. Either the Phase I program will be continued, or the Phase II annual program will commence.

SECTION 13

CONCLUSIONS AND RECOMMENDATIONS

13.1 CONCLUSIONS

The study performed by WESTON of the St. Louis Airport site was initiated to ascertain the need for and subsequent development of stabilization plans for the buried radioactive residues. This study commenced with a complete site characterization from which the following conclusions were drawn:

1. The residues stored and buried on-site through 1966 consisted of uranium processing wastes, pitchblende raffinates, various radium-bearing residues, and a variety of other radiologically-contaminated materials.

2. In 1966 and 1967, the stored, but not the buried, residues were removed and sold for their mineral content. Then the site was covered with from 1 to 3 feet of fill.

3. Subsequent surveys of the site found contamination levels and radiation levels on the site and in the drainage ditches north of the site, as well as radon emanation rates from the site, above current and promulgated regulations, but no evidence of off-site migration of radioactivity in groundwater.

4. The site is in need of stabilization in order to meet various radiation guidelines and to provide for the public health and safety.

13.2 GOALS

The stabilization of the St. Louis Airport storage site has the following goals:

1. The application of best available, technologically-sound, cost-effective measures for stabilization of this site.

2. The prevention of groundwater and surface-water contamination.

3. The minimization of radon emanation from the site due to buried radioactivity.

4. The minimization of radiation exposure to persons working or living near, or using the site.

5. The application of feasible engineering techniques such that a 1,000-year life could be reasonably assured for the site after stabilization.

13.3 RECOMMENDATIONS

In order to meet these goals for the stabilization of the St. Louis Airport storage site, the following recommendations are made:

1. The site should be divided into four areas, A, B, C, and D. Area A is in the north-central section, Area B is in the south-central section, Area C is in the western section, and Area D is the remainder of the site.

2. A multilayer cover should be used in Areas A, B, and C for lowering the external direct dose, groundwater protection, and control of radon emanation. This cover is composed of an upper layer (2 feet of soil), a middle layer of coarse gravel or crushed rock (1 foot), and a bottom layer of a clay-soil mixture (4 feet in Area A and 3 feet in Areas B and C.

3. Area B which should be used for burial of the contaminated ditch material, in addition to the cover, should be fully lined and encapsulated using a clay-soil mixture (3 feet) for further groundwater protection.

4. Area C, in addition to the cover, should be surrounded by a bentonite-soil slurry wall (30-inches wide and approximately 50 feet deep) extending from the surface into the soil-clay layer for further groundwater protection.

5. Area D, the remainder of the site, should be covered with an average of 3 feet of soil to properly adjust drainage patterns and further ensure site integrity.

6. Waste conditioning is not necessary or recommended for the buried residuals.

7. All final grading on the site should be to levels above the 500-year flood elevation, in addition riprap will be required at the western edge of the property adjacent to Coldwater Creek.

8. An erosion control plan should be developed in detail and implemented by the construction contractor.

9. Security measures should be taken during the construction phase to protect the public health and safety.

10. The site and worker personnel should be routinely monitored during construction in order to protect worker and public health and safety.

11. The site should be rigorously monitored immediately post-construction to assure that the stabilization goals have been met.

12. The site should be routinely monitored post-construction in order to assess and ensure long-term stability.

The recommendations made above were carefully evaluated for feasibility and cost-effectiveness; however, there are two remaining technical uncertainties which should be addressed prior to implementation of the detailed stabilization plan. Therefore, it is recommended that the following items be analyzed in depth:

1. The composition of the soil/bentonite backfill composition for the barrier must be determined by laboratory testing to optimize the mixtures of site soil and bentonite to bring about the desired permeability. In order to control groundwater movement through the barrier area, the permeability must be in the range of 10^{-6} to 10^{-8} cm/s.

2. Refinements of the cover and liner composition to ensure the desired performance are needed. Detailed testing and evaluation of cover and

liner materials are required to determine properties which control water movement into and out of the system.

Of course, numerous other design and construction details will need to be resolved prior to implementing the final engineering design, such as:

1. Preconstruction monitoring to verify the final engineering design.

2. Analysis of the indigenous soils to be used as fill and cover materials for radon flux rates.

3. Final construction cost estimates.

APPENDIX [illegible]

EVALUATION OF COVER SYSTEM MATERIALS

APPENDIX A

EVALUATION OF COVER SYSTEM MATERIALS

A.1 ASPHALTS

A.1.1 Asphalt Emulsion (Spray Asphalt)

Historically, asphalt has had a productive life as a waterproofing agent, dating back more than 5,000 years. Early uses were simple, and included such things as caulking and cementing agents for baths and similar hydraulic structures. Past and present applications take advantage of the thermoplastic properties of asphalt. Although asphalt may be handled in a number of ways, pumping is generally used if large quantities are involved. Pumped asphalt can easily be applied to relatively horizontal surfaces by a spray application system.

Proper spray technique is important, but technical problems are always involved when spraying any material directly onto the ground. Since asphalt is sprayed in a unidirectional fashion, it is very difficult to ensure complete cover due to small protuberances which receive only partial cover. Naturally, this type of application is not watertight. As a final impediment to the use of asphalt sprayed directly onto the ground, there is the very serious problem of sun aging.

Most attempts to improve asphalt's aging properties have been accompanied by degradation of some other property. This phenomenon is not unique with asphalt. Every material known to man exhibits this tendency, which has been the subject of previous comments with respect to the compounding of rubber and plastic materials. Filters may be added to asphalt, and many different ones have been tried. Through their use, heat resistance was improved, although ductility and tensile strength both decreased. Eventually, all possibilities were exhausted, and it became apparent that asphalt sprayed directly onto the ground left much to be desired in the way of an efficient hydraulic lining. Catalytically-blown asphalt was also tried; it was an improvement in some respects because of its great ductility, but its resistant to sun aging was notoriously poor.

At about this time, asphalt emulsions made their appearance and interest was renewed. When certain clays were dispersed into the base emulsion, considerable resistance of the fresh coating to sag was experienced. Even after curing (removal of the water by evaporation), the coating showed little effect from sun aging.

Studies of asphalt emulsion sealants have been conducted by the Pacific Northwest Laboratory and have demonstrated that the sealants are effective in containing radon and other potentially hazardous materials within uranium mill tailings. The laboratory and field studies have further demonstrated that radon emanation from uranium tailings piles can be reduced by greater than 99% to near background levels.(1) Field tests at the tailings pile in Grand Junction, Colorado, confirmed that an 8-cm admix seal containing 22% asphalt by weight could be applied effectively with a cold-mix paver.(1) Other techniques were tested successfully, including a soil stabilizer and a hot, rubberized asphalt seal that was applied with a distributor truck. After the seals were applied and compacted, overburden was applied over the seal to protect the seal from ultraviolet degradation.

Pacific Northwest Laboratory has had considerable comment on its work with asphalt emulsion seals. It is generally felt that insufficient testing has been conducted to justify the use of asphalt emulsion seals for practical long-term low-level radioactive waste burial applications. For example, P.D. O'Brien of Sandia National Laboratories sent this comment to Pacific Northwest Laboratory, on 26 February 1981:

> "In summary, the asphalt emulsion radon seal system appears to be technically feasible and potentially acceptable. Much more development work is required, however, before the technology can be considered ready for practical application."(2)

Additionally, Ross A. Scarano of the Nuclear Regulatory Commission had these comments on 13 February 1981:

> "It seems that while the use of an asphalt emulsion seal system in tailings reclamation is promising, the technique has not been developed sufficiently for application in the near future."(3)

A.1.2 Asphalt Concrete (Hydraulic Asphalt)

Historically, an asphalt-based material (asphalt concrete) has been used as a seepage barrier for many thousands of years. As a caulk and a pure membrane it helped the early civilizations to waterproof first their canals and aqueducts, and later their baths and sewage conduits. Some of these facilities are still in use, attesting to the longevity of asphalt. Despite these fine credentials, asphalt concrete must be used properly in today's hydraulic structures if lasting results are to be obtained.

Some confusion has developed from data generated within the laboratory, where it is possible to produce asphalt concrete samples with zero porosity. The problem arises from the inability of contractors to duplicate the laboratory results over large areas in the field. Good initial performance from an asphalt cover demands rather careful attention to both mix design and installation details. The control of mix temperatures at the time of spreading, the time lag between this operation and compaction, and the compacting effectiveness itself are three important but difficult parameters to control. In essence, the contractors cannot ensure that these three factors will be successfully reproduced in the field. For example, obtaining good compaction requires different techniques and is more difficult to achieve on side slopes than on flatter areas.

To further complicate the problem, sun aging, creep tendencies, and normal subgrade movements all combine to reduce the effectiveness of the cover. Nevertheless, these factors are constantly interacting, thus hastening the total process of degradation. This interaction is illustrated by the increased aging deterioration as side slope steepness is increased. Additionally, asphalt concrete is subject to damage due to icing conditions, which can cause a spalling effect. Asphalt concrete cannot be used on vertical slope work; generally its use is restricted to slopes of 2:1.[4]

Because of their nature, asphalt concrete cover systems are prone to penetration by weeds, a problem that can plague all covers exhibiting any discontinuity. The black asphalt blanket absorbs heat readily and serves as an incubator for the weed seeds that lie below it. The problem is more or less eliminated if the structure is covered; otherwise, a soil sterilant is often used, particularly if the facility is built in a location where weed growth is suspect.

Asphalt concrete is expected to have equal or better capabilities for radon gas containment than asphalt emulsion. By more positive placement techniques, asphalt concrete is also less susceptible to voids and discontinuities during placement. Unfavorable material and placement costs tend to eliminate asphalt concrete as a viable cover option.

A.2 CONCRETE

Concrete is technically not an impervious material in the strictest sense of the word. In the laboratory it is possible to make a test sample that possesses rather good resistance to the passage of water, but in the field this does not seem to be an easily-attainable goal. Construction joints continue to present leakage problems, and field-applied concrete membranes have widely-varying degrees of permeability. Good-quality concrete also has the tendency, in time, to degrade with respect to its waterproof qualities.

The importance of subgrade conditions cannot be overemphasized in connection with unreinforced concrete covers. In the cover classification system, this material is a rigid, semi-impervious type. Although many of the flexible cover systems can tolerate some variance with respect to substrata stability, plain concrete cannot. Concrete covers without reinforcement are particularly vulnerable to the actions of frost, swelling, and shrinkage within the soils on which they rest. Undesirable surface soil conditions may be remedied by removing the portion of the subgrade in question and replacing it with a material of the desired properties. Nonexpansive materials are used, placed in layers not exceeding 6 inches, and compacted to at least 90% of standard maximum density.[4]

Concrete of good quality is resistant to many naturally-occurring chemicals. When properly proportioned, placed, and cured it is relatively impervious to most water, soil, and atmospheric conditions. There are some chemical environments under which the useful life of the best concrete will be shortened, and knowledge of these conditions permits measures to be taken to counteract or prevent deterioration.

Most corrosive chemicals must be in solution form and above some minimum concentration to produce a significant attack on concrete. Concrete is rarely, if ever, directly attacked by soil or dry chemicals. Concrete which is subjected to aggressive solutions under pressure is most vulnerable because the pressures tend to force the aggressive solution into the concrete. When free evaporation can also take place from an exposed face, dissolved salts may accumulate at that face, thus increasing their concentration and possibly resulting in mechanical damage from spalling in addition to chemical attack.

Properly mixed concrete can both control radon gas diffusion and water percolation through the cover. However, little work has been completed to date on mix design as it relates to gas diffusion. The long-term stability requirements of the cover would necessitate the use of reinforced concrete. Extremely high material and construction costs are most likely the controlling factor in the evaluation of concrete as a cover material. Due to these factors, concrete will not be considered further for application at the St. Louis Airport site.

A.3 SYNTHETIC MEMBRANES

Flexible synthetic membranes are assuming increased importance as cover materials because of their very low permeability to water and other fluids. These covers are products of the plastics and rubber industries. The polymeric materials used in the manufacture of these covers include vulcanizable and nonvulcanizable thermoplastics, plastics, and rubbers. They are all synthetic materials, varying from highly polar polymers, such as polyvinyl chloride (PVC), to nonpolar polymers, such as EPDM and butyl. They range from amorphous polymers, such as the rubbers, to crystalline polymers, such as polyethylene. Generally, polymeric materials are compounded with fillers, antidegradants, plasticizers, and curatives if vulcanization is needed. Compounds based on the same polymer can vary considerably in composition from manufacturer to manufacturer, depending on the grade and the price of the cover.

The membrane sheeting is usually made in a continuous process by plying together two thin sheets formed by passing the compound through the rolls of a calender. Plying two sheets together to make a membrane almost eliminates pinholes. Fabric reinforcement, usually a nylon or polyester scrim, can be sandwiched between these plies to give added strength to the cover. Sheets are typically 4 to 5 feet wide and 200 feet long. Several of these sheets are seamed by a fabricator in a factory to form a panel.

In general, synthetic covers are susceptible to the same types of long-term failure mechanisms as asphalts and concrete. First, synthetic covers are prone to punctures due to root penetration and damage during placement. Puncture damage will result in the escape of radon gas, and surface-water infiltration. Secondly, synthetic membranes are prone to microbial attack, which, in the context of a 1,000-year life, becomes quite significant. Finally, the impervious nature of these membranes does not allow controlled radon gas diffusion, but rather continuous build up.

Several synthetic covers have been selected for evaluation; however, in making the selection it was not possible to obtain liners from all liner producers. Representative liners of the respective types were selected. If several membranes of a given polymer were available, the membrane exhibiting the best physical properties was generally selected.

A.3.1 Chlorosulfonated Polyethylene (CSPE)

Chlorosulfonated polyethylene is a family of polymers prepared by reacting polyethylene in solution with chlorine and with sulfur dioxide. Presently available polymers contain from 25 to 43% chlorine and from 1.0 to 1.4% sulfur.(5) They can be used in both thermoplastic (uncrosslinked) and in vulcanized (crosslinked) compositions. Uncured CSPE is more thermoplastic than other commonly used elastomers. It is generally tougher at room temperature, but softens more rapidly as temperatures are increased.

Chlorosulfonated polyethylene is characterized by ozone resistance, ultraviolet stability, heat resistance, good weatherability, and resistance to deterioration by corrosive chemicals. It has good resistance to the growth of mold, mildew, fungus, and bacteria. Membranes of this material are available in both vulcanized and thermoplastic forms, but primarily in the latter. Usually they are reinforced with a polyester or nylon scrim and generally contain at least 45% CSPE polymer.(5) The fabric reinforcement gives needed tear strength to the sheeting for use on slopes, and reduces the distortion resulting from shrinkage when placed on the base, and when exposed to the heat of the sun.

Chlorosulfonated polyethylene can be seamed by heat sealing, dielectric heat sealing, solvent welding, or by using "bodied" solvent adhesive. Membranes of this polymer do not crack or fail from temperature extremes or weathering. Disadvantages of CSPE membranes include low tensile strength and a tendency to shrink from exposure to sunlight. Also, some CSPE's tend to harden with age due to crosslinking by moisture, ultraviolet radiation, and heat.

A.3.2 Polyvinyl Chloride (PVC)

Polyvinyl chloride (PVC) membranes are the most widely used of all polymeric membranes for waste impoundments. Polyvinyl chloride is produced by any of several polymerization processes from vinyl chloride monomer (VCM). It is a versatile thermoplastic polymer which is compounded with plasticizers and other modifiers to produce a wide range of physical properties.

Polyvinyl chloride membranes are produced in roll form in various widths and thicknesses. Most liners are used as unsupported sheeting, but fabric reinforcement can be incorporated. Polyvinyl chloride compounds contain 25% to 35% of one or more plasticizers to make the sheeting flexible and rubber-like.[5] They also contain 1% to 5% of a chemical stabilizer, and various amounts of other additives. The PVC compound should not contain any water-soluble ingredients. There is a wide choice of plasticizers that can be used in PVC sheeting, depending on the application and service conditions under which the PVC compound will be used. Plasticizer loss during service is a source of PVC degradation. There are three basic mechanisms for plasticizer loss: volatilization, extraction, and microbiological attack. Polyvinyl chloride polymer generally holds up well in burial tests, however, compounds of PVC films have deteriorated, presumably due to microbial attack.[6] The use of the proper plasticizers and an effective biocide can virtually eliminate microbiological attack and minimize volatility and extraction.[7] The PVC polymer itself is not affected by these conditions; however, it is affected by ultraviolet exposure.

The principal reason for loss of plasticizer is by volatilization in the heat of the sun rather than solution in the waste fluid. Carbon black prevents ultraviolet attack, but does cause the absorption of solar energy, thus raising the temperature to a high enough level to cause vaporization of the plasticizer. The soil or other suitable cover material used to bury the cover protects it from ultraviolet exposure and reduces the rate of plasticizer loss. Polyvinyl chloride sheeting is not recommended when it will be exposed to weathering and ultraviolet light conditions during its service life.

Plasticized PVC sheeting has good tensile, elongation, and puncture- and abrasion-resistance properties. It is readily seamed by solvent welding, adhesives, and heat and dielectric methods. Finally, PVC shows good chemical resistance to many inorganic chemicals.

A.3.3 Neoprene

Neoprene is the generic name of synthetic rubbers based on chloroprene. These rubbers are vulcanizable, usually with metal oxides, but also with sulfur. They closely parallel natural rubber in mechanical properties, e.g. flexibility and strength. However, neoprene is superior to natural rubber in its resistance to oils, weathering, ozone, and ultraviolet radiation; it is also resistant to puncture, abrasion, and mechanical damage.

Neoprene membranes have been used primarily for the containment of wastewater and other liquids containing traces of hydrocarbons. They also give satisfactory service with certain combinations of oils and acids for which other materials do not provide long-term service.

Neoprene sheeting for covers is vulcanized, thus vulcanizing cements and adhesives must be used for seaming.

A.3.4 Chlorinated Polyethylene (CPE)

Chlorinated polyethylene (CPE) is produced by a chemical reaction between chlorine and high-density polyethylene. Presently available polymers contain 25 to 45% chlorine and 0 to 25% crystallinity.(5) Chlorinated polyethylene is compounded and used in thermoplastic and crosslinked compositions.

Since CPE is a completely saturated polymer (no double bonds), it is not susceptible to ozone attack and weathers well. The polymer also has good tensile and elongation strength. Chlorinated polyethylene is characterized by resistance to deterioration by many corrosive and toxic chemicals. Because they contain little or no plasticizer, CPE covers have good resistance to the growth of mold, mildew, fungus, and bacteria. Membranes of CPE can also be formulated to withstand intermittent contact with aliphatic hydrocarbons and oils. Chlorinated polyethylene will swell in the presence of high concentrations of aromatic hydrocarbons and oils, but regains some of its original properties when removed from that environment.

Chlorinated polyethylene can be compounded with other polymers, making it a feasible base material for a broad spectrum of membranes. Chlorinated polyethylene can be alloyed with PVC, PE, and numerous synthetic rubbers. Usually, at least half the polymer content of CPE covers is CPE resin. This compound is widely used to improve the stress crack resistance and softness of ethylene polymers, and to improve the cold crack resistance of flexible polyvinyl chloride. Chlorinated polyethylene membranes are available in varied thicknesses in unreinforced or fabric-reinforced versions. Membranes of CPE are generally unvulcanized and thus can be seamed by bodied-solvent adhesives, solvent welding, or dielectric heat sealing. No synthetic liners will be considered for use at the St. Louis Airport site since they cannot be expected to last for 1,000 years.

A.3.5 Ethylene Propylene (EPDM)

EPDM is a thermoplastic grade of ethylene propylene rubber. The liners are constructed of multiple layers of EPDM sheeting laminated to one or two layers of nylon or polyester reinforcing fabric.

EPDM is immune to the effects of ozone and offers excellent resistance to temperature extremes, oxidation, ultraviolet light, and a wide range of acids, bases, salts, and corrosive chemicals. It can be fabricated in large factory-seamed panels to minimize on-site seaming; it is also free of pinholes, and will not delaminate.

Another feature of EPDM is that it can be heat-seamed at the job site with simple heat tools by relatively unskilled personnel. The heat seam sets within seconds to a strength exceeding that of the parent material. Disadvantages of EPDM liners include low resistance to some hydrocarbons and a relatively short expected lifetime.

EPDM was considered late in this evaluation, and therefore, detailed performance characteristics are not given. However, its performance should follow the same general trends of other synthetics.

A.4 SOILS

Historically, the cover and lining system with the longest record of successful performance is compacted earth. It enjoys this distinction partly because its origins go back several thousand years, when it was employed in the construction of dams and irrigation works in ancient civilizations. Its excellent record is also the result of some specific properties that, in combination with proper design and application techniques, makes this lining one of the best overall systems ever developed. Moreover, since installation is often done by earth-moving equipment from raw materials on the site, the economics of soil covers are favorable.

The compacted soil blanket is classified as a flexible membrane, although it is not a continuous one. Such a cover system permits the continual passage of a controlled amount of water through it. Properly placed, it serves as a uniform resistance in the path of water. Due to their permeable nature, compacted soils can also be engineered to properly control radon gas diffusion rates. Being flexible, the compacted soil blanket enjoys an excellent reputation with respect to normal subgrade settlement, which is of particular advantage in areas where seismic activity is prevalent.

Shrinkage can be a very serious problem in compacted earth covers, regardless of whether or not the facility has an auxiliary lining. It can serve as an important triggering mechanism for eventual failure. Low shrinkage depends on high density and minimal water loss from the cover.

Proper cover design must ensure that swelling is kept to a minimum. In general, clay-type soils are prone to losing strength when wet. This action also depends on the density and mineralogy of the soil; swelling tendencies increase with higher density. Swelling is best controlled by:

1. Proper soil selection.

2. Preventing water intrusion into the soil.

3. Making the lining so dense that adequate strength exists even in the weakened condition.

Soil covers must be controlled by the proper choice of ingredients, moisture content, and compaction. The water content of soils has a function almost parallel to that of the plasticizer in plastics. Without water, optimum properties cannot be developed in the soil. As water is added to dry soil during processing (compaction), the properties improve, but too much water causes a decrease in strength. At a compaction moisture content of 10 to 20% by weight (during installation), clays will absorb water principally by surface tension forces that greatly exceed gravitational forces.(5) As the moisture permeates the clay, gravitational forces will predominate and surface tension forces will be minimal. There is a ratio that will develop optimum properties of the compound for a particular use; all other concentrations will yield less than the best characteristics.

Another important problem with compacted earth facilities arises from the fact that water exerts an equal force in all directions. Upward movement in a cover structure can occur when the upward pressure exerted by the water beneath the cover exceeds the downward force due to its mass and external loading. This is the well-known reverse hydrostatic condition, whose forces have a devastating effect on linings of all types. The result of this action is rupture of the lining.

The reverse hydrostatic condition can occur within the soil structure. Here the result is called "heave." The soil expands with an accompanying decrease in void ratio, often trapping a blister of water within the soil mass. The roof in this miniature water-filled cavern then collapses to the floor. By this process the blister rises to the surface. As the bubble reaches the surface, the soil appears to be cooking, and the condition is termed "boil." Heave can occur in any soil, but boiling is limited to cohesionless (sandy type) materials. Boiling reduces the strength of the soil to zero.

After becoming aware of all the potential problems with compacted earth linings, the reader may logically ask why this lining was rated "one of the best" in the opening paragraph of this section. The answer has to do with proper design and control. Although the potential problems described do exist, most can be handled by means of proper engineering design, and the others may be effectively compromised.

A.5 SOIL ADMIXTURES

Several soil admixtures have been used for cover systems. This general category includes asphalt, concrete, bentonite clay, soil cement, and soil asphalts. Concrete and asphalts have been previously discussed, and therefore only the remaining three categories will be covered in this subsection.

A.5.1 Bentonite Clay

Bentonite clay is highly suitable for sealing structures by the blanket method due to its low permeability and high swelling characteristics. This method is most effective for sealing fine materials such as uranium mill tailings. Bentonite is particularly applicable in sealing when hard or salty waters are involved because its permeability decreases as its sodium percent increases.

To utilize the pure membrane method, the existing soil is over-excavated to a depth of 6 inches, a blanket of bentonite is laid down, and the 6-inch soil blanket is replaced. The quantity of clay to apply will depend on permeability test data on the original soil. In most soils, around 1 to 2 lbs/sq ft of bentonite will be required, although there have been instances where as much as 9 lbs/sq ft[4] was needed to effect a seal. In such cases, the thinner plastic membranes would no doubt have provided a more economical lining method.

Overexcavation may be avoided by applying the suitable clay blanket over the existing soil, and then adding the 6-inch protective blanket using additional soil. This method is best suited to heavier clay soils, where uniform mixing of bentonite into the soil is difficult or impossible. In any event, the top protective blanket should be of such a makeup that it will prevent erosion and subsequent destruction of the clay seal.

When the soil is granular (sandy to silty), the mixed layer membrane method is best. In this system the bentonite is first spread on the existing ground. A grain drill or fertilizer spreader is also effective in spreading the clay, but on very large jobs specially-equipped transport trucks are used. The latter equipment can effectively spread 2 lbs/sq ft of clay over an area of 6 to 8 acres per day.[4] The clay is then mixed with the top 3 or 4 inches of soil, using a spiketooth harrow, disk, rotary hoe, or similar equipment. The mixing operation is followed by the compaction step, using a sheep's-foot roller or other suitable equipment. In some cases, the sheep's-foot roller may be used for both mixing and compaction.

Of the factors working against the bentonite sealing process, erosion and undercutting are the most bothersome. Either action will destroy an effective seal. When this occurs, extensive earth preparation may be required before further clay treatment.

Other types of activity will also cause difficulties, such as those due to crayfish, earthworms, muskrats, prairie dogs, and plants of various kinds. Plants are even more destructive when they die, as the voids created by the decaying roots effectively funnel in the water.

Research was conducted at the Savannah River Laboratory (E.I. duPont de Nemours and Co.) on the applicability of bentonite as a protective cover for buried radioactive wastes in 1966.[8] The findings of this research are as follows:

1. Wyoming bentonite is highly effective in preventing rainwater infiltration into soil, and can be used to prevent leaching of buried waste.

2. Bentonite can be applied as a continuous layer on both horizontal and steeply-sloped surfaces.

3. A 2-foot thick soil cover is required to protect a subsurface bentonite layer from excessive drying and cracking.

4. A subsurface bentonite layer has little resistance to penetration by plant roots. When bentonite is used to protect buried radioactive wastes, the area must be kept free of all plant growth.

Additionally, bentonite and bentonite-enhanced soils can effectively limit radon gas diffusion. Radon gas diffusion rates can be engineered by selecting proper soil mixtures, porosities, and layer thickness. These diffusion rates can and have been computer modeled and field tested.

A.5.2 Soil Cement

Soil cement is a compacted mixture of portland cement, water, and selected soils. The result is a low-strength portland cement concrete with greater stability than natural soil. The permeability of this mixture varies with the type of soil; a more granular soil produces a more permeable soil cement. A fine-grained soil produces a soil cement with a permeability coefficient of about 10^{-6} cm/s.[9] To date, there have been few studies performed to design a soil cement with very low permeabilities (less than 10^{-8} cm/s), as opposed to mixes designed for high compressive strength.[10] To reduce the permeability of soil cement, coatings such as epoxy asphalt and epoxy coal-tar have been used.

Any soil, except high organic content soil, with less than 50% silt and clay, is suitable for soil cement. However, a well-graded soil with a maximum size of 0.75 inch and a maximum silt and clay content of 35% is preferable.[5] A high clay content impairs the ability to form a homogeneous cemented material, thus reducing the efficiency of producing an impermeable layer. Three criteria must be considered for soil cement covers: cement content, moisture content, and the degree of compaction. The optimum moisture and cement contents are determined by laboratory testing. The optimum moisture is that which results in maximum density of the compacted soil cement. Laboratory samples should be tested in wet/dry and freeze/thaw cycle tests to determine the optimum cement content.

The aging and weathering characteristics of soil cements are good, especially those associated with wet/dry, freeze/thaw cycles. Some degradation has been noted when this substance is exposed to highly acidic environments, but soil cements can resist moderate amounts of alkali, organic matter, and inorganic salts. One of the main deficiencies of soil cement as a liner material is its tendency to crack and shrink on drying.

A.5.3 Soil Asphalt

Soil asphalt is a mixture of selected soil (usually low plasticity) and liquid asphalt. A silty, gravelly soil with 10 to 25% silty fines is the perferred soil type. The permeability of soil asphalt after compaction varies with the percent compaction and the percent asphalt. A high void content (3 to 10%) soil asphalt has a measurable permeability.(5) Soil asphalts containing cutback asphalt are not recommended as lining materials. Soil asphalt made with asphalt emulsion is not sufficiently impermeable and requires a waterproof seal, such as a hydrocarbon-resistant or bituminous seal.

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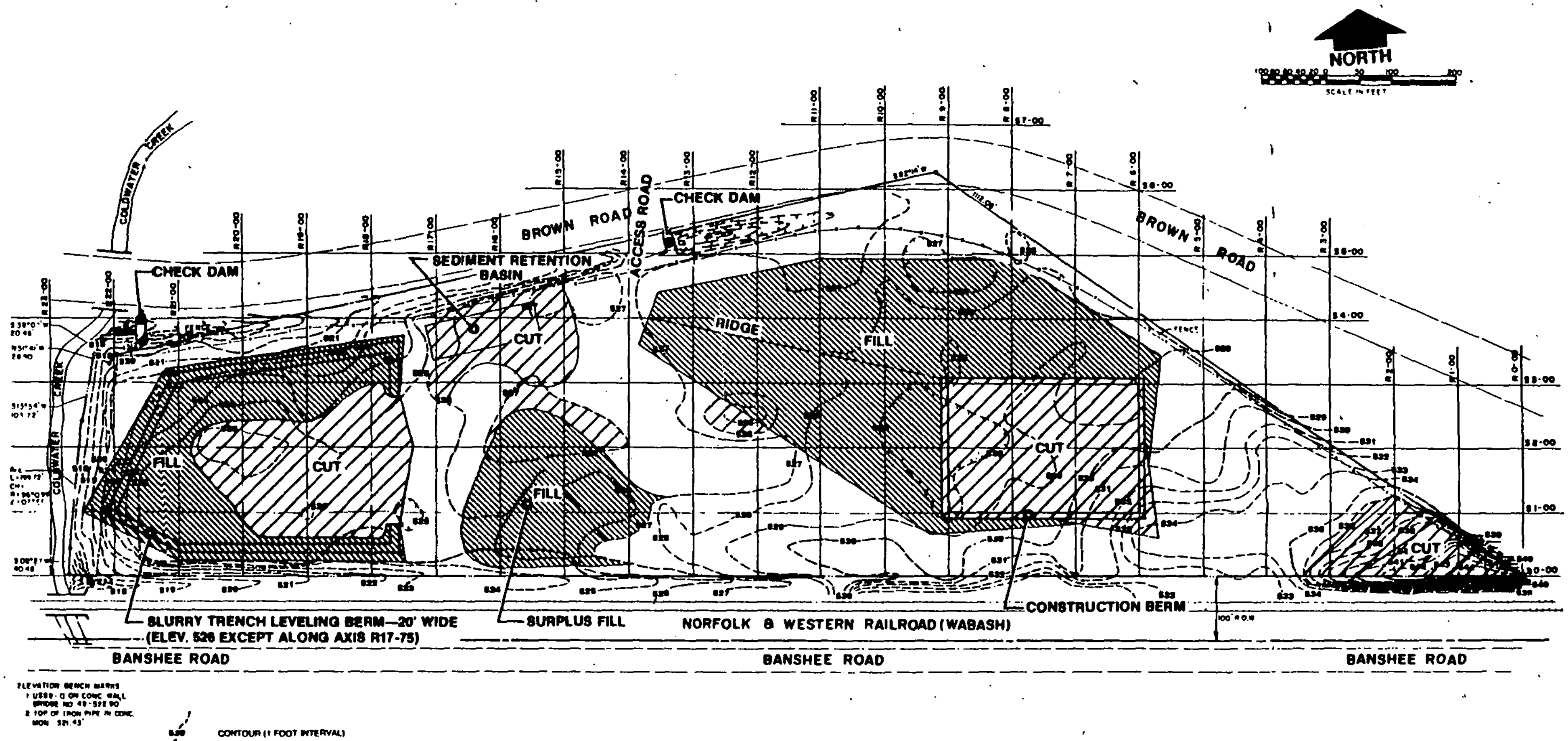

FIGURE 12-2
PRELIMINARY SITE PREPARATION AND GRADING PLAN
ST. LOUIS AIRPORT STORAGE SITE

APPENDIX [illegible]

COVER MATERIAL PERFORMANCE CRITERIA

APPENDIX B

COVER MATERIAL PERFORMANCE CRITERIA

B.1 ABILITY TO WITHSTAND CONSTRUCTION AND MAINTENANCE VEHICLE TRAFFIC

This criterion evaluates the ease by which construction and maintenance vehicles can maneuver on the material. High percent sand and gravel materials were given positive performance ratings, while high percent clay materials were given negative performance ratings. In this evaluation cement and asphaltic cover materials were given positive performance ratings due to their wide use in highway construction applications. Synthetic membranes were given negative performance evaluations because vehicle traffic is difficult without damage to the membrane.

B.2 ABILITY TO IMPEDE WATER PERCOLATION

The ability to impede water percolation is a major criterion in evaluating cover materials. Cover materials were evaluated on their respective permeabilities. Generally, materials with permeabilities less than 10^{-5} cm/s were given favorable performance ratings.[1] The only materials that were given negative performance ratings were on-site soils which had permeabilities of approximately $10^{(-4)}$ cm/s and high percent gravel and sand soils.[2]

B.3 RADON GAS CONTROL

Radon emissions from radium-bearing materials have long been recognized as a major potential health hazard. Since radon is an inert gas, it does not readily combine with other elements and can migrate considerable distances. Its migration is generally described by diffusion theory in which the dominant driving force is a radon gas concentration gradient. The controlling factors in radon gas diffusion are the diffusion coefficient, the depth of the cover material, and the total porosity of the material.[3] In general, the magnitude of the diffusion coefficient decreases rapidly with the increasing moisture content in the material. Thus, cover materials which show favorable performance in controlling radon gas diffusion are those that:

1. Retain sufficient moisture content.
2. Allow radon gas to diffuse at a controlled rate.
3. Are crack-resistant.
4. Can be applied to a sufficient thickness.

Synthetic cover materials were given poor performance ratings because of their susceptibility to failure by puncture. Punctures in a thin membrane will allow uncontrolled radon gas release, and thus cannot be tolerated. High porosity and permeability materials were also given poor performance ratings because they provide insufficient radon attenuation.

B.4 EROSION CONTROL

Rock and soil are eroded, transported, and deposited principally by water, ice, and wind. Depending on local conditions, these erosive agents can have major impacts on the integrity of waste containment systems, especially covers. Each cover material was evaluated based on direct contact with the environment. In actuality, many of these cover materials would not be exposed directly to the environment, however, for the purposes of the evaluation, it was assumed that each material would be directly exposed. Generally, any soil, except gravel and riprap, is highly susceptible to erosion when directly exposed to the environment. For this reason all cover materials were given positive performance ratings, except native soils, on-site soils, soil admixtures, bentonite, silty sand, and clay sand.

B.5 SURFACE CHARACTERISTICS THAT FAVOR SURFACE RUNOFF

The ability of a cover material to aid in surface runoff is critical in reducing the water flux through the cover. The criteria for this evaluation are identical to those for the ability to impede water percolation (as previously evaluated). Duplication of this evaluation was conducted because of the great importance of this performance criterion.

B.6 RESISTANCE TO DESICCATION

Desiccation is the ability of a material to dehydrate or lose water content. This criterion is important in evaluating eolian erosion. The erosive effect of wind is generally much less pronounced than that of either water or ice. Severe wind erosion problems develop only in regions where sufficiently thick, dry, unconsolidated, unvegetated, homogeneous deposits of silty or sandy material exist. In most areas of the arid western United States, surficial materials are mixtures of silt, sand, and gravel. As wind removes the finer-grained materials, the gravels eventually form an armored surface, or desert pavement, that prevents further erosion of the underlying silt and sand.

High silt and sand soils are ideal materials for eolian transport. If an entire unprotected overburdened or topsoil layer was removed, eolian erosion would probably cease at the gravel barrier because of the formation of armor by the gravel. Thus, in the performance evaluation all soils except well-graded gravel and riprap were given poor performance ratings in dessication criteria.

B.7 FREEZE/THAW STABILITY

In cold regions of the country, special attention may need to be directed to the effects of freezing. Freeze/thaw characteristics of all cover materials must be determined and cross-referenced with depth of frost penetration in the region of concern. Where more detail is needed, or in mountainous terrain where the dept of freezing can vary over short distances, frost penetration data must be obtained from local agricultural agencies. In general, inorganic silts and very fine sands with slight plasticity demonstrate large heave characteristics, and therefore, are greatly susceptible to freeze/thaw fractures. On the other hand, more sandy soils are susceptible to fast freeze conditions and therefore, deeper frost penetration.

In this performance evaluation only clayey sand soils, bentonite clay, gravel, riprap, and multilayered systems were given positive performance ratings. It should be noted that concrete is also susceptible to freeze/thaw fracturing, however, this problem can be remedied by proper mix design. Finally, all freezing problems can be remedied by a sufficiently thick topsoil cover.

B.8 SEISMIC STABILITY

For waste impoundments subjected to earthquakes but not located on an active fault, damage to such an impoundment from ground shaking may include the differential settlement of the foundation soils and wastes leading to strains in the liners and covers. If these strains are localized or large in magnitude, failure of the liner or cover may occur. Failure of a liner may lead to leakage in the transport of radionuclides. Failure of the cover may lead to escape of radon gas. Detecting the location and repairing the damaged liner section would be very difficult. Repairing a damaged cap would not be as difficult.

Ground motions also cause stress changes in the impoundment and natural slopes. Landslides in the natural slopes surrounding the impoundment may block access roads in diversion structures. Landslides into the impoundment may damage the cap and possibly displace the encapsulated radioactive waste. The potential magnitude of radioactive material released due to failure of any portion of the waste impoundment as a result of earthquakes will be influenced by:

1. The magnitude of the earthquake.

2. The distance from the waste impoundment to the active fault.

3. The soil conditions under the site.

4. The nature of the waste.

5. The disposal plan employed.

Cover materials were evaluated based on their ability to withstand minor seismic disturbances. Natural cover materials, except well-graded gravel and riprap, were given poor performance ratings because of their generally low tensile and shear strengths. It should be noted, however, that many of these natural soil materials could be designed to withstand minor seismic disturbances by proper selection of cover depth and compaction.

The cover materials that were given positive performance ratings were concrete and the multilayered covers. Concrete can and is often designed for earthquake stability. Many construction and design codes exist for earthquake design of concrete structures. Also, by the use of proper structural design criteria, a multilayered cover system could be designed to withstand minor seismic disturbances. Proper thickness and compaction of the cover materials, along with the layering effects of such covers, would provide sufficient stability for minor seismic disturbances.

B.9 CRACK RESISTANCE

This evaluation was based on each cover material's ability to resist cracking due to minor differential settlement of the subgrade. Other phenomena, such as water erosion and desiccation, could also cause the cover material to crack, however; these performance criteria were evaluated previously. Cracking due to differential settlement of the subgrade is a function of both the sheer and tensile strength of the cover material. In this analysis, it is felt that natural soils have insufficient tensile strength to withstand minor differential settlement of the subgrade. Again, these deficiencies could be remedied by proper structural design of thickness, percent moisture, and compaction of the soil layers. For this reason, the multilayered cover system was given a positive performance rating. Materials such as well-graded gravel and riprap which can easily reform after such a stress has been applied without significant damage, were also given positive performance ratings.

Synthetic membranes as a group were given poor performance ratings due to their inability to relieve the stress caused by differential settlement of the subbase. This continued stress in synthetic membranes after a differential displacement of the subbase is believed to be the ultimate cause of failure in such membranes. Construction-grade paving materials such as hydraulic asphalt and concrete were given positive performance ratings due to design capabilities to prevent cracking.

Where shear type differential settlements occur, the remaining effectiveness of the cover at the shear locations will depend on the thickness of the cover relative to the sheared displacement. Covers cannot tolerate any appreciable horizontal extension or cracking in the foundation strata as may be associated with considerable differential settlements. Large differential settlements would be associated with substantial depths of alluvium in valleys. Where steep-walled open pits are used, this differential settlement is accentuated by the pit geometry, and extremely large sheared displacements totalling as much as 10 feet may be applicable to a 100-foot depth of uncompacted backfill.[1] Thus, proper design of the cover thickness is critical in order to avoid potential problems with the cover cracking.

B.10 SIDE-SLOPE STABILITY

The side-slope stability of various cover materials was evaluated based on the angle of repose of that material. Materials with angles of repose greater than 1 on 2 (26°) were given positive performance ratings.[4] Additionally, synthetic liners were given negative performance ratings because they do not contribute to side-slope stability.

B.11 POTENTIAL FOR SIDE-SLOPE SEEPAGE

Side-slope seepage can only occur if the waste impoundment is saturated with water, thus creating a hydraulic force which pushes water through the side slope of the cover and out into the environment. Side-slope seepage can, therefore, be prevented by using low permeability materials. Only very high permeability materials were given poor performance ratings under this criterion, such as well-graded gravel, riprap, silty-sand soils.

Two basic philosophies may be adopted to limit the loss of fluid from the waste impoundment by seepage. The first involves containment of the fluid in the impounding area by the use of an impermeable barrier. This barrier may be provided by constructing liners of synthetic or natural materials, or by locating the impoundment on a naturally-impermeable stratum and including an impermeable cutoff in the dikes. The second strategy requires limitation of the water volume which can seep from the waste by placing the waste in an essentially dry state. In this case, since there is little or no water to lose by seepage, containment may not be necessary. However, since the waste still contains contaminants it is necessary to prevent the reentry of water which could then reach these contaminants and pollute other areas by seepage.

B.12 ABILITY TO DISCOURAGE RODENT BURROWING

Rigid covers, such as concrete, asphalt emulsion, and asphalt concrete, stand up well against animal traffic of all kinds; thinner membranes, however, do not perform as well. There are two types of hazards involved; large animals which do mechanical damage to thin linings because of their great weight and sharp hooves, and small animals which cause damage associated with their search for food and water.

Hoofed animals, such as cows, deer, or horses can easily damage synthetic membranes. Just how much damage they will do depends on the slope of the sidewalls and the firmness of the subgrade. Smaller animals such as gophers, beavers, rats, muskrats, prairie dogs, and mice will attack covers for two reasons:

1. They may be attracted to them because of the smell or attractive taste.

2. The cover may be blocking their natural path for food or water.

In the latter case, the behavior of the animal will depend on the accessibility of alternate food routes. If no alternate paths exist, most animals of this class will cut through any cover system for survival. For instance, rats trapped from their food source can cut through concrete, glass, or aluminum; of course, thin plastic or soil membranes offer absolutely no resistance to them. Damage from these causes is not common, but it does occur occasionally.

Animal intrusion studies have been conducted in the past by K. A. Gano at the Grand Junction, Colorado Uranium Mill Tailings Site. In 1980, ground squirrel intrusion tests were conducted near the time when these animals normally begin hibernation. Although test results were generally inconclusive, preliminary results showed the squirrels easily penetrated the overburdened cover, but were temporarily stopped by a crushed rock layer. In this evaluation of cover materials, hydraulic asphalt, asphalt concrete, well-graded gravel, riprap, soil asphalt, and soil cement were given positive performance ratings. Natural soil covers could be easily penetrated by burrowing rodents, and therefore were given negative performance ratings.

B.13 ABILITY TO SUPPORT VEGETATION

A cover material's ability to support vegetation is important for both aiding in evapotranspiration and in stabilization against wind and water erosion. Soil composed of a mixture of clay, silt, and sand such that none of these components dominates is called a loam. The stickiness of clay and the flowering nature of silt are balanced by the nonsticky and mealy or gritty characteristics contributed by sand. A loam is rated best overall for supporting vegetation as it is easily kept in good physical condition, and is conductive to good seed germination and easy penetration by roots.

Clay-rich soils may be productive when in good physical condition, but they require special management methods to prevent puddles or breaking down of the clay granules. Silt-rich soils lack the cohesive properties of clay and the grittiness of sand, are water retentive, and usually are easily kept in good condition. Soils made up largely of sand can be productive if sufficient organic matter is present internally or as a surface mulch to hold nutrients and moisture; sandy soils tend to dry out very rapidly and lose nutrients by leaching.

In the evaluation of cover materials, natural soils which contain a good mix of clay, silt, and sand were given positive performance ratings. All soils evaluated in this section, except bentonite, well-graded gravel, and riprap, were given positive performance ratings. Bentonite used as a soil admixture was also given a positive performance rating because it is anticipated that not more than 5 to 10 percent bentonite will be used. All other cementitious and synthetic cover materials were given poor performance ratings because of their obvious inability to support vegetation.

B.14 EASE OF CONSTRUCTION

All of the cover materials evaluated are practical materials in the construction of low-level radioactive waste impoundments. However, certain construction techniques are much simpler than others. In general, soil covers are more easily constructed because they require only grading and compaction. Soil materials, with the exception of bentonite as an admixture, were given positive performance ratings. Bentonite as a soil admixture is more difficult to utilize because of the layering and disking required to incorporate bentonite into native soils. Synthetic and cementitious cover materials were given negative performance ratings because of the difficulty of placement and/or paving of these materials.

B.15 ABILITY TO ENDURE A LOW-MAINTENANCE 1,000-YEAR LIFE

The ability of a cover material to endure a low maintenance 1,000-year life was evaluated in two ways. The first criteria were based on a material's historical use as a cover material. Historical applications are much more definitive criteria than accelerated short-term laboratory tests, and therefore were given more consideration. The second way in which probable 1,000-year life was estimated was by the material's resistance to biochemical degradation. Generally, synthetic membranes are subject to biochemical degradation over long periods of time. For these reasons synthetic cover materials were given poor performance ratings. Concrete, while susceptible to chemical attack, is quite stable against biological attack. It is belived that chemical attack in this application would be minimal, and concrete was therefore given a positive performance rating. All natural soil cover materials were given positive performance ratings because of their inherent resistance to biochemical degradation. It should also be noted that natural soils have been used for cover materials for thousands of years without significant biochemical degradation.

B.16 ABILITY TO IMPEDE PLANT ROOT PENETRATION

Root penetration is a major failure mechanism in the destruction of impermeable cover systems. Woody plants can have root systems that penetrate to depths of 1.5 meters. For this reason, the cover system will be stabilized with grasses only. Dormant seeds exist in many soils, and sterilization is required to eliminate the growth of woody plants from dormant seeds.

Damage to cover systems by root penetration is related directly to cover thickness and can be avoided by proper design. For the purposes of evaluation, however, the assumption was made that all natural soils are susceptible to root penetration, and therefore, were given poor performance ratings. Synthetic membranes, due to their thinness and known inability to resist root penetration, were also given poor performance ratings. Only concrete, asphalt emulsion, and hydraulic asphalt were given positive performance ratings due to their high structural and hydraulic stability.

B.17 ABILITY TO IMPEDE GAMMA WAVE RADIATION

Gamma wave penetration is a function of the particle density of a material. Ford, Bacon and Davis Utah, Inc. have shown that for uranium disposal sites a few feet of cover material are sufficient to reduce gamma wave radiation to acceptable levels. Two feet of compacted soil cover reduces the gamma levels by about two orders of magnitude. Therefore, an average cover of 2 feet should reduce gamma wave levels to less than 10 μR/hr above background.[5]

In the evaluation of cover material effectiveness to impede gamma wave radiation, only spray asphalt emulsions and synthetic membrane materials were given poor performance ratings. These materials are generally applied in relatively thin layers, and therefore, are insufficient to reduce gamma wave radiation to acceptable levels. All other materials evaluated can easily be applied to sufficient thickness to reduce gamma wave radiation well within acceptable limits.

REFERENCES

APPENDIX B

COVER MATERIAL PERFORMANCE CRITERIA

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APPENDIX C

RADON DIFFUSION MEASUREMENTS

APPENDIX C

RADON DIFFUSION MEASUREMENTS

Results of laboratory measurements performed by RAECO on soil gathered at the St. Louis Airport site and a representative clay material are given. These measurements of radon diffusion characteristics were used to develop the cover specifications given in Section 9.

C.1 METHODOLOGY

The tailings covers tested were compacted into PVC columns with 30-cm inner diameter and 1.1-cm walls. A 1.8-cm thick PVC plate was welded to the bottom of the pipe. Two 1.2-m sections were used to assemble each column. The coupling between them was carefully sealed to prevent escape of radon. Each column contained a 2-ft layer of uranium mill tailings as a radon source. The bare tailings were monitored for radon flux for 30 to 60 days after their initial compaction to achieve a reliable measure of the equilibrium radon flux released from the bare source. When a stable (reproducible) radon flux from a bare source was achieved, the cover materials were compacted on top of the tailings. Radon fluxes were again monitored from the top of the cover surface. Figure C-1 illustrates key elements of the diffusion columns. The radon measurements were continued until they showed no further trends with time.

The test columns were located in a laboratory enclosure which was kept at a slightly negative pressure with respect to the building atmosphere to continuously exhaust radon effluents from the columns and to avoid introduction of radon into the building ventilation system. Temperature, humidity, and barometric pressure were continuously monitored inside the laboratory enclosure.

Radon fluxes were sampled using charcoal canisters. The method for using the canisters was similar to those reported previously.[1,2] The canister sampling arrangement, illustrated on Figure C-2, consisted of an 8.3-cm diameter, 4.1-cm high can containing a Type AMA charcoal cartridge (Mine Safety Appliances Company, Pittsburgh, Pennsylvania), and a protective filter paper. The charcoal cartridges were heated to 125°C for 12 hours in a ventilated oven prior to use to expel any radon and moisture accumulated by previous usage or during storage. The cartridges were then sealed in polyethylene bags until use.

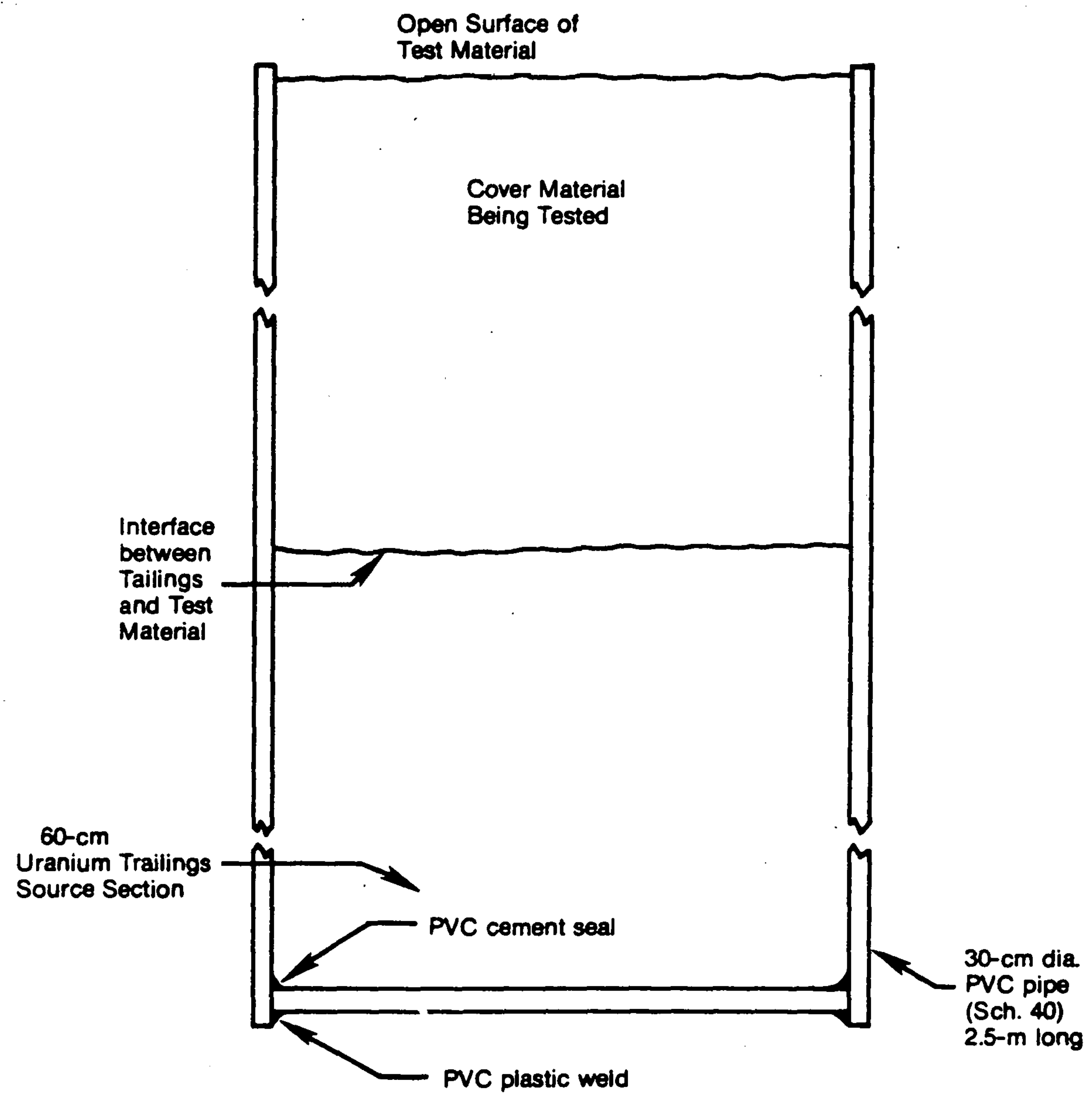

FIGURE C-1 DIFFUSION COLUMN CONSTRUCTION

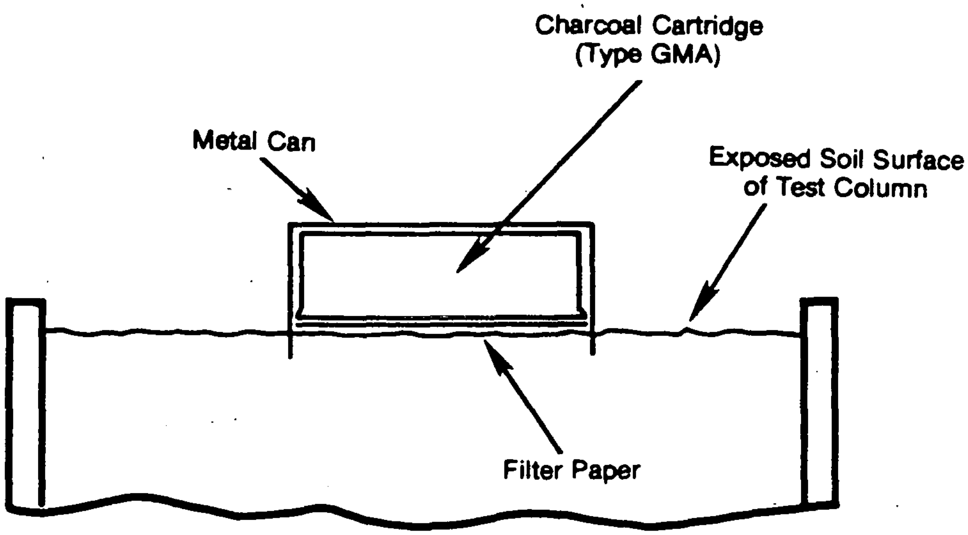

FIGURE C-2 RADON FLUX MEASUREMENT USING A CHARCOAL CANISTER.

Sample collection was initiated by inserting the canister and protective filter paper into the sampling can, and pressing the resulting assembly into the soil surface to be sampled. The filter paper prevented contamination of the cartridge by soil. After a typical sampling interval of 24 hours, the cartridge was removed from the can and sealed in a polyethylene bag for a 4-hour equilibration period prior to counting.

Radon adsorbed on the charcoal was analyzed by gamma-ray spectroscopy using the 609-keV peak from Bi-214. The cartridge was counted near the surface of a 13 x 13-cm NaI (Tl) scintillation crystal coupled to a multichannel pulse-height analyzer. The sample and detector were positioned in a shielded counting chamber having 10-cm lead walls. The counts in the 609-KeV peak were summed over 10- or 30-minute intervals, and were corrected for background using appropriate regions on each side of the energy spectrum peak. Calibration of the counting system was based on a pitchblende ore standard, as described in subsection C.3.

Radon fluxes sampled by charcoal canister were calculated using equation (C-1):

$$J = \frac{C_{nt}\,\lambda^{2}}{\epsilon\, A\,(1-e^{-\lambda t_s})\,(e^{-\lambda(t+t_c)})\,(0.037\ \text{dps/pCi})} \qquad \text{(C-1)}$$

Where:

C_{nt} = Net counts in 609-keV peak during counting interval t^c.

λ = Radon decay constant ($2.1 \times 10^{-6} sec^{-1}$).

ϵ = Detector efficiency (counts/disintegration).

A = Soil surface area sampled by canister (sq m).

t_s = Flux sampling time interval (sec).

t = Time from end of flux sampling to beginning of count (sec).

t_c = Counting time interval (sec).

This equation assumes that all radon exhaled from the soil surface beneath the canister was adsorbed onto the charcoal, and it or its daughters remained there until the canister was counted, and that the presence of the canister did not alter the radon flux inside the sampling area. These assumptions are validated in reference 3.

C.2 COVER MATERIAL CHARACTERIZATION

At the time of placement of the cover materials, measurements were made of the mass and volume of material compacted into the columns. From these measurements, the average cover material densities shown in Table C-1 were calculated. In addition, grab samples of the cover materials were taken at 1-foot intervals and processed to obtain moisture content. Average moistures are also shown in Table C-1.

Samples of the Berkeley soil were sent to American Testing Laboratories, Salt Lake City, Utah for determination of Atterburg limits. The following parameters were measured:

1. Liquid limit -- 37.1%
2. Plastic limit -- 22.9%
3. Plasticity index -- 14.2%

C.3 CALIBRATION

Calibration of the gamma-ray spectrometer was based on a 15.7-g aliquot of the standard pitchblende sample from the DOE Health Services Laboratory.[4] Two in-house standards (VT-1 and VT-2) were prepared and calibrated against the pitchblende standard for routine use in sample analysis and system standardization. All three samples were sealed in 8-cm diameter by 4-cm metal cans and were used after an initial 30-day equilibration period to assure equilibrium between the Bi-214 daughter of radon and the Ra-226 parent. The VT-1 and VT-2 standards consisted of 221.4-g and 238.4-g aliquots of dry uranium tailings, respectively. The sealed samples were leak-tested by sealing them inside a larger can, and were found to not leak a significant fraction of the gaseous radon activity.

The accuracy of the calibration was checked by comparing the three sealed standards with gamma-ray analysis by an independent method at a separate laboratory as indicated in Table C-2. The instrument used by Battelle, Pacific Northwest Laboratory was an anticoincidence shielded, multidimensional gamma-ray spectrometer

Table C-1

Densities and Moistures at the Time of Cover Placement in the Laboratory Columns

	Cover Material	
	Berkeley Soil 4 ft)	Clay (2 ft)
Density (g/cu cm)	1.84	1.80
Moisture content (g water/g dry soil)	0.25	0.53

which analyzed the 609-keV and 1,121-keV peaks from Bi-214 in coincidence.[5] Adjustments for the can geometry were reported to be the major source of uncertainty (estimated at approximately 5 percent for each of the counts). The bias of approximately 4 percent was on the order of the uncertainty of the measurements being compared, as indicated in Table C-2.

Because the intercomparison involved standards in different counting geometries and configurations, the agreement is considered excellent. In attempting to estimate the accuracy of the radium and radon-daughter gamma assays in this work, however, the bias discussed need not be considered. This is because the samples were counted in identical configurations to that of the pitchblende standard. Since the standard was characterized to a relative uncertainty of 0.7 percent and its mass was known to a similar degree of precision, the major source of uncertainty in the present measurements was in small variations in self-absorption and geometry which resulted from the sealed cans being partially filled. A variable efficiency curve was developed to account for these effects, which could cause variations on the order of 15 to 20 percent, but were probably corrected to an accuracy of approximately 5 percent.

C.4 MEASURED RADON FLUXES

Prior to placing the cover materials to be tested into the columns, the radon fluxes at the tops of the 60-cm of uranium mill tailings were measured. Three measurements were taken on each column, during three consecutive 24-hour periods. Table C-3 shows the bare tailings fluxes measured and their mean values.

Table C-2

Interlaboratory Comparison of Radium Determinations

Sample	Ra-226 Activity (dpm/g)	Ra-226 Activity (10^3 dpm)	Laboratory
Pitchblende	6060 ±40		DOE Health Services Laboratory, Idaho Falls, Idaho
Pitchblende	6060	956[1]	Rogers & Associates Engineering Corp.
VT-1		590 ±4[2]	Rogers & Associates Engineering Corp.
VT-2		722 ±10[2]	Rogers & Associates Engineering Corp.
Pitchblende	6060	989 ±49[3]	Battelle, Pacific Northwest Laboratory
VT-1		612 ±31[3]	Battelle, Pacific Northwest Laboratory
VT-2		758 ±38[3]	Battelle Pacific Northwest Laboratory

[1]System was calibrated by a 157.7-g aliquot of this standard.
[2]Uncertainty based on standard deviation of five replicate counts.
[3]Uncertainty based on counting statistics and, predominantly, uncertainty in geometry correction.

C.4 MEASURED RADON FLUXES

Prior to placing the cover materials to be tested into the columns, the radon fluxes at the tops of the 60-cm of uranium mill tailings were measured. Three measurements were taken on each column, during three consecutive 24-hour periods. Table C-3 shows the bare tailings fluxes measured and their mean values.

Table C-3

Bare Tailings Radon Fluxes (pCi/sq m/s)

	Column Used to Test:	
	Berkeley Soil	Clay
First measurement	297	289
Second measurement	309	283
Third measurement	327	315
Mean	311	297

The cover materials were then compacted on top of the uranium mill tailings, and the distribution of radon within the tailings and cover system was allowed to reach steady state. Precautions were taken to prevent the top of the cover materials from drying out. The time required to reach steady state (one month) was estimated from RAECO's prior experience with radon column tests, and verified by the nature of subsequent flux measurements taken at the tops of the columns.

After equilibration, the radon flux measurements shown in Table C-4 were obtained during three 24-hour intervals within a week's time.

While most of the radon flux at the top of each column comes from the tailings below the cover, it is possible that some of it comes from radon generated within the cover itself, from small amounts of radium in the cover material. The radium content of the clay was known to be less than 0.59 pCi/g from 11 prior assays of that material performed by RAECO. The radium concentration in the Berkeley soil measured was 0.84 pCi/g. The

Table C-4

Radon Fluxes on Top of the Cover Materials
(pCi/sq m/s)

	Column Used to Test:	
Flux	Berkeley Soil (4 ft)	Clay (2 ft)
First measurement	3.4	11.1
Second measurement	3.0	11.9
Tnird measurement	4.1	6.6
Mean	3.5	9.9

surface radon flux from the materials was estimated analytically and used to adjust the mean fluxes in Table 3-4 to 3.0 pCi/sq m/s and 9.4 pCi/sq m/s for the Berkeley soil and clay, respectively.

The key parameter used in determining the radon attenuation properties of a cover material for the St. Louis site is the bulk diffusion coefficient, D/p where D is the effective radon diffusion coefficient for the cover material, and p is the total porosity of that material at the emplaced moisture content. This parameter was calculated using the radon fluxes measured before and after placing the cover materials in the test columns using the following relationship[6]:

$$J_1 = J_o \exp(-a_1 x_1) \qquad \text{(C-2)}$$

Where:

J_1 = Radon flux at the top of the cover.

J_o = Radon flux at the top of the bare tailings.

x_1 = Thickness of the cover material (cm).

a_1 = $\sqrt{\lambda p/Dh}$

In equation (C-2) the dimensionless coefficient, h, is very close to unity because J_1 is much less than J_o [1] for the column test used in this work. Solving equation (C-2) for D/p:

$$D/p = \frac{\lambda x_1^2}{\left(\ln\left({}^{J_1}/J_o\right)\right)^2} \qquad \text{(C-3)}$$

Equation (C-3) was employed to calculate D/p for the two cover materials using the mean values of bare tailings fluxes from Table C-3, and the adjusted covered tailings fluxes just given. The following values were calculated:

1. Berkeley soil -- D/p = 1.5×10^{-3} sq cm/s.

2. Clay -- D/p = 6.6×10^{-4} sq cm/s.

The diffusion coefficient can be calculated separately by determining the porosity from the following relationship:

$$p = - \frac{\rho}{SG(1 + M)} \qquad \text{(C-4)}$$

Where:

ρ = Compacted cover material density from Table C-1.

SG = Specific gravity of soil material ≅ 2.7 g/cu cm.

M = Moisture content from Table C-1.

The following values were calculated for radon diffusion coefficients for the cover materials placed in the column:

1. Berkeley soil -- D = 6.6×10^{-4} sq cm/sec.

2. Clay -- D = 3.7×10^{-4} sq cm/sec.

It can be seen that the Berkeley soil is less effective than the clay in attenuating radon. However, the diffusion coefficient of the Berkeley soil is as low as some clays; hence, it is an effective radon attenuator. This is borne out by observation of the clay-like consistency of the Berkeley soil.

REFERENCES

APPENDIX C

RADON DIFFUSION MEASUREMENTS

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APPENDIX D

ASSESSMENT OF SUBSURFACE POLLUTANT TRANSPORT MODELS

APPENDIX D

ASSESSMENT OF SUBSURFACE POLLUTANT TRANSPORT MODELS

D.1 INTRODUCTION

This study is being conducted in order to assess the appropriateness of several available subsurface pollutant transport models for use to simulate past and predict future dispersion patterns where low-level radioactive constituents are entering groundwater. This analysis will result in a determination of the groundwater model considered most appropriate for utilization at low-level radioactive waste sites. In addition, an evaluation will be provided of the relative merits and cost-effectiveness of assessing future conditions through modeling, or alternatively, by an ongoing groundwater monitoring program both before and after any containment efforts are undertaken.

D.2 LITERATURE REVIEW

The first scientist to observe the phenomenon of dispersion in an aquifer was Slichter (1905).[1] In a paper on field measurements of the rate of movement of groundwater, he noted that a tracer at an observation well downstream appeared gradually, rather than abruptly, as would have been predicted by Darcy's law. In his analyses, Slichter treated the aquifer material as consisting of a series of flow tubes, or capillaries, and he related the lateral dispersion of a solute to the repeated branching of these capillaries.

Wentworth (1948)[2] was the first to postulate a "rinsing theory" based on the hypothesis that the pores of the medium act as mixing cells, and that the alternate filling of the pore by fresh water and the polluting fluid creates a partial mixing between the two fluids. Using the same hypothesis, Dankwerts (1953)[3] introduced a model which replaced a porous medium by a series of mixing cells.

Scheidegger (1953)[4] was the first to introduce a statistical model which he called "the completely disordered model." He hypothesized that the microscopic velocities of the fluid particles will follow approximately a normal probability distribution.

Taylor (1954)[5] used a mathematical approach to discuss the longitudinal dispersion in a tube for different cases of initial and boundary conditions (considering the velocity variations alone). He also introduced the effect of molecular diffusion on the longitudinal dispersion and solved the governing equation for some special boundary conditions.

Ogata (1958)[6] derived a mathematical solution for a radial dispersion equation in integral form. Because this type of integral is not solvable by operations methods, a numerical solution was carried out. In another paper, Ogata (1964)[7] gave a solution to a one-dimensional, convective-dispersion equation for a step-function input of soluble material. In addition, Ogata (1969)[8] solved a model for one-dimensional dispersion with linear adsorption isotherms.

Bachmat and Bearn (1964)[9] solved a convective-dispersion equation which assumed a linear relationship between the velocity and the dispersion coefficient. This equation was in general tensorial form and is applicable to uniform and nonuniform flow in any coordinate system.

Chin (1967)[10] derived a stochastic model of motion of small particles in a three-dimensional turbulent flow. In his model the distance and the duration of each step of the random walk of the particle were considered variables whose values depend on the flow properties and two randomly-generated numbers at the starting position of the step. This model can be used only for computer simulation of the particle motion in the Monte-Carlo method of estimating the concentration of particles, which is represented by the probability of the particle being at a certain position. This method can be used to solve unsteady state, three-dimensional problems which are not solvable by either analytical or numerical methods.

Green et al. (1970)[11] presented a mathematical model describing isothermal two-phase flow in porous media. They applied the model to the problem of vertical groundwater movement in unsaturated soils in the absence of evaporation and transpiration. The equations describing the flow are second order, nonlinear, partial differential equations. These equations were converted to finite difference form, and were solved with the aid of a digital computer.

Freeze (1972)[12] treated numerically a mathematical model for the subsurface water flow under a disposal site. He used his model to predict the motion of the pollutants generated by the site in the underlying aquifer using Darcy's law and the equation of continuity in three dimensions. Freeze based his analysis of sanitary landfill sites on studies in which he solved a three-dimensional flow model in a groundwater basin. Using this model he could include only the convective transport of the polluting substance. His model cannot incorporate the transport of pollutants due to molecular diffusion hydrochemical reactions between the pollutants and the porous materials of the aquifer.

Pinder and Gray, of Princeton University (1974),[13] conducted three sets of numerical experiments to evaluate the feasibility of approximating the equations of groundwater flow using a Galerkin finite element scheme for the time domain. The results suggest that the methods tried gave similar results and that a choice should be based on considerations of computational efficiency.

Surendra and Greenkorn, Purdue University (1974),[14] determined the dispersion and nonlinear adsorption parameters for flow in porous media.

Metry (1972, 1974, 1976) [15,16,17] developed several models for predicting dispersion and fate of pollutants and hazardous substances from a waste disposal site into unconfined aquifers. In a book on leachate control and treatment,[34] Metry introduced a two-dimensional model for predicting leachate migration in confined aquifers.

Davidson and his coworkers (1972, 1973, 1974)[18,19,20] developed several models for predicting the fate of polluting substances in soils. These models were applied for both the unsaturated and saturated transport of soluble matter in earth materials.

Choi (1972), cited in Fore, et al.,[21] developed a model to describe the rate process governing the transport and decay of a radioactive substance in a solidified waste and a surrounding fluid. The mathematical expressions utilized are useful in predicting concentrations in the system as well as in determining the effective diffusivity and the decay coefficient of the radioactive substance. Robertson (1973, 1974), cited in Pfuderer and Johnson (1979),[22] also developed models to predict groundwater transport of radioisotopes at the National Reactor Testing Site in Idaho.

Konikow and Bredehoeft (1978)[29] considered two-dimensional transport through the use of the method of characteristics to generate the velocity field from groundwater potential data in the U.S. Geological Survey (USGS) MC model. Another model developed by the USGS, PERCOL, will simulate groundwater flow in an artesian aquifer, a water-table aquifer, or a combined artesian and water-table aquifer.

The ability to simulate the transport and decay of radioactive wastes in subsurface media was considered in a number of recently-developed models. Arnett (1976)[23] examined this problem for the surface disposal site at Hanford Atomic Reservation. Grove (1976), cited in Fore, et al.,[21] developed the Solute Transport Model (STM) to predict radionuclide migration in a given subsurface environment. Ahlstrum (1976), cited in Miller (1978),[24] and Ahlstrum (1977), cited in Burkholder, et al. (1979),[25] developed three models, MMT, DPRWGW, and DPRWCR, to predict the movement of radionuclides and other contaminants in groundwater utilizing the discrete parcel random walk approach. Schwartz (1977), cited in Fore, et al.,[21] developed a model to describe the transport of low-level radioactive waste at proposed sites. Put (1977), cited in Pfuderer, et al.,[26] modeled radionuclide migration in homogeneous clay formations.

Other recent radionuclide transport models include the WHTM model by Patterson (1977), cited in Miller (1978)[24]; TRA-POND by Robertson (1977), cited in Pfuderer, et al.,[26]; MINUTE by Haeggblom (1977),[22]; GEOSPHERE by Grundfeldt (1977),[22]; and GARD by Rossinger (1979), all three cited in Pfuderer, et al.,[22]; two- and three-dimensional finite element models by Gureghian (1978), cited by Shriner and Peck[35]; by Lu (1978), cited by Pfuderer, et al.,[26] Codell (1979),[27], and Wight (1979), both cited in Carter, et al. (1979),[27] and Jansen (1979), cited in Burkholder, et al., (1979).[25]

Reeves and Duguid (1976, 1978), cited in Miller, (1978),[24] developed the OAK RIDGE FE and FET finite element flow and transport models which can be coupled to describe the combination of partially-saturated and saturated flow in two-dimensional transient situations. Pinder (1976), cited in Burkholder, et al.,[25] developed the ISOQUAD model for considering flow and conservative ion transport together utilizing a Galerkin-finite element simulation and applied it to a groundwater contamination site on Long Island, New York. Yeh (1980, 1981, 1981)[31,32,33] developed FEMWATER, FEMWASTE, and AT123D. The first two are finite element models to be paired to predict groundwater flow and waste transport in saturated and unsaturated subsurface conditions. AT123D is a generalized analytical transient, one-, two-, or three-dimensional model for estimating wastes in an aquifer system under widely-varying conditions.

D.3 EVALUATION OF MODELS

Predicting the potential for dispersion of groundwater contaminants associated with the land disposal of low-level radioactive wastes is a complex technological undertaking. The simultaneous interaction of numerous processes, including transport, decay, adsorption, and solubility, makes it difficult to predict a description of the relative concentrations of particular constituents for any individual hydrogeologic situation. To accomplish this task, investigators will frequently rely on the utilization of mathematical models to evaluate the performance of a specific land disposal site.

These models are concise mathematical expressions of the mechanisms or empirical relationships that describe physical occurrences. Unlike the fields of surface water or ambient air pollution, however, the study of subsurface water pollution has lagged behind, particularly because models to predict the distribution and concentration of contaminants have only recently been developed. Much of the development of groundwater models, as shown by the preceding literature survey, has occurred over the last decade. Thus, widespread knowledge of the capabilities and limitations of modeling is still being developed, and many excellent models are being underutilized.

D.3.1 Background

Numerical mathematical modeling is now an essential tool for prediction of the transport of pollutants in groundwater. Recent developments in numerical methods for groundwater hydrology, when coupled with field observations, provide powerful, inexpensive, and relatively reliable tools for prediction of groundwater flow quality and quantity.

Models available for geohydrological analysis are basically divided into two groups: hydraulic flow models and pollutant transport models. The hydraulic transport model generates the net groundwater flow in both unsaturated and saturated media. The pollutant transport model, when combined with input from the groundwater flow model, generates the concentrations of pollutants for any specified space and time. The following four processes are primarily responsible for changes in chemical concentration:

1. Convective transport of a pollutant in groundwater.

2. Hydrodynamic dispersion of a pollutant.

3. Adsorption or chemical reactions.

4. Decay or degeneration.

For simulation of conservative pollutants, the decay and adsorption terms are zero.

Since radionuclides decay by first-order kinetics to other radionuclides or stable isotopes, the description of their migration is very complex. Their complex behavior derives from the differences in adsorption properties and decay rates among chain members and their various release modes. In all the available models, this complexity in chain transformation of radionuclides has not been considered.

D.3.2 Groundwater Transport and Quality Models

Groundwater transport and quality models can be conveniently categorized into several distinct groups, depending on the method of analysis defined by the model and the approach used to solve a particular problem. These categories are discussed in the subsections that follow.

D.3.2.1 Empirical versus Conceptual Models.

Models can be classified as empirical or conceptual, depending on whether or not the assumed physical processes use input variables to produce output variables. Empirical models are based completely on data obtained either from observation or experimentation. Conceptual models are based on theoretical or proven physical and chemical relationships; however, the distinction between empirical and conceptual models is not always clear. Several models describing the adsorption of a particular chemical onto soil are empirical in nature (e.g., linear adsorption, Freundlich isotherm), while others are based on physiochemical theory (e.g., cation exchange equations). The use of column-leaching studies to measure the migration of contaminants through soil is an empirical approach, although it may yield certain parameters (dispersion coefficients and adsorption constants) required in conceptual models.

Differential equations used to describe the mass transport of a constituent through a porous medium constitute a conceptual model. These equations are generally based on conservation of mass, energy, and momentum. However, empirical relations are frequently used in their derivation (adsorption, zero- or first-order degradation effects, and Darcy's law for fluid flow). Certain writers have used the term "black box" to indicate the empirical nature of certain models, while the term "white box" or synthetic model has been used to describe conceptual models.

D.3.2.2 Stochastic versus Deterministic Models.

In a deterministic model, all input variables and system parameters are assumed to have fixed mathematical or logical relationships. As a consequence, these relationships completely define the system, and a single solution is obtained. Stochastic or probabilistic models, on the other hand, take into account the randomness or uncertainties that are associated with system parameters or input variables. Several stochastic models exist, depending on the basic assumptions made about the physical processes and the type of mathematics used in the model. Two groups of stochastic models of interest in simulating the water quality problem are:

1. Stochastic models where the system parameters and input variables are characterized by assumed probability distributions (normal, log-normal, etc.). Using the Monte-Carlo simulation technique, output variables are generated which are characterized by certain probability distributions. In this approach, the basic model is thought to be exact, but the complexity of the system under consideration is such that its parameters are more properly defined by probability (or frequency) distributions. The one-dimensional stochastic groundwater flow model discussed by Freeze (1975) is an example of such a model.

2. Another type of stochastic model results when the system parameters or input variables are uncertain, either because of a lack of reliable input data or due to measurement errors. Uncertainty may also result from the use of an over-simplified model where different mechanisms are sometimes lumped together, thus, leading to less well-defined parameters. The appropriate parameters are then characterized by a mean and variance, but no probability distributions are assumed. The model then generates a mean and variance for each output variable which can be used to construct a confidence interval, but no frequency distribution.

D.3.2.3 Static versus Dynamic Models.

This distinction depends on how the time dimension is viewed in the model. Static models are those which evaluate steady-state conditions, i.e., where the input variables do not change with time. When the input variables change with time, dynamic models result. Although static models, which are much simpler and require less computational effort than dynamic models, could be used to describe certain subsystems of the waste disposal/ groundwater system (e.g., description of fluid flow in the unsaturated zone under the disposal site), it appears that the whole system is dynamic and should be modeled accordingly.

D.3.2.4 Spatial Dimensionality of the Model.

Although a waste disposal site and the underlying groundwater constitute a three-dimensional system, useful and accurate results can often be obtained with models which consider only one or two spatial dimensions. For example, a one-dimensional model can be used successfully to describe the rate of contaminant migration through and below a landfill to the groundwater table. While considerable insight can be obtained with such a model, it stops short of providing accurate information regarding groundwater pollution under and immediately downgradient of the landfill because of the dilution of the landfill leachate by the flowing groundwater. This process cannot be evaluated with a one-dimensional model. An exception to this obviously occurs when the water table lies far below the soil surface and evaporation greatly exceeds the average yearly precipitation. In general, however, it seems that at a minimum, a two-dimensional model must be formulated. Two-dimensional models can also be applied on an areal basis. Here the system parameters and the input and output variables represent averaged quantities along the vertical dimension.

D.3.3 Mathematical Expression of Mass Transport Simulation

Common to all of these groundwater models, however, is the need to express mathematically the simulation of the mass transport of subsurface water and its soluble waste constituents. Two general expressions can be provided to describe this transport within a saturated/unsaturated three-dimensional medium. The expressions can then be modified to derive the vast majority of models used to simulate a land disposal site and the underlying groundwater system. These basic equations for the descriptions of the transport of waste constituents and groundwater flow are described as follows:

1. Constituent Transportation Equation.

$$\underset{(a)}{\frac{\rho\,\partial S_k}{\partial t}} + \underset{(b)}{\frac{\partial \Theta C_k}{\partial t}} = \frac{\partial}{\partial x_i}\underset{(c)}{\left(\Theta D_{ij}\,\frac{\partial C_k}{\partial x_i}\right)} - \underset{(d)}{\frac{\partial}{\partial x_i}\left(q_i C_k\right)} \qquad \text{(D-1)}$$

$$\underset{(e)}{\sum^{I_1}\left(a_m \Theta C_k{}^m\right)} \pm \underset{(f)}{\sum_{m=1}^{I_2} R_k} \pm \underset{(g)}{QC_k{}^*}$$

2. Water Flow Equation.

$$\left(\frac{\Theta}{n}\,S_s + C\right)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x_i}\left(K_{ij}\,\frac{\partial h}{\partial x_i} + K_{ij}\right) \pm Q \qquad \text{(D-2)}$$

$$i,\ j = 1,\ 2,\ 3$$

Table D-1 presents the definition of terms used in these equations. The terms are grouped within the constituent transport equation (D-1) to describe the different processes that will impact constituent concentrations. These processes are:

1. Changes in adsorbed constituent concentration.
2. Changes in solution constituent concentration.
3. Diffusion and dispersion effects.
4. Convective transport of the constituent by the fluid.
5. Production (+) or decay (-) reactions.
6. Additional chemical/soil or chemical/chemical interactions (i.e., precipitation, coprecipitation, chemical transformations, cation exchange reactions, volatilization, etc.).
7. Constituent concentration changes resulting from water sources (+) or sinks (-).

Mathematical solutions to the transport equations above, or to simplified versions of them, may be generated by several different techniques. These techniques fall into two basic approaches, however, either by analytical or by numerical methods.

Table D-1

Explanation of Symbols Used in the Mass Transport and Flow Equations

Symbol	Explanation
C_k	Solution concentration of chemical species k (mL^{-3})
C*	Constituent concentration of the source or sink term (mL^{-3})
C	Specific soil-water capacity, C = n (L^{-1})
D_{ij}	Dispersion coefficients (tensor) (L^2T^{-1})
h	Soil-water pressure head (L)
K_{ij}	Soil hydraulic conductivity (tensor) (LT^{-1})
n	Porosity (L^0)
q_i	Volumetric water velocity (LT^{-1})
Q	Soil-water source or sink term, $Q = Q_w(x_i - x_{wi})$ (T^{-1})
Q_w	Strength of source or sink term (L^3T^{-1})
R_k	Rate term expressing soil/chemical or chemical/ chemical interactions
S_k	Adsorbed constituent concentration of chemical species k (M^0)
S_s	Specific storage coefficient (L^{-1})
S_w	Degree of water saturation (L^0)
t	Time (T)
x_i	Distance in i-th coordinate direction (L)
x_{wi}	i-th coordinate of source or sink
m	m-th order rate constant for production or decay ($M^{1-n}L^{3n-3}T^{-1}$)
α	Dirac delta function
ρ	Soil (dry) bulk density (ML^{-3})
θ	Volumetric water content (L^0)

D.3.3.1 Analytical Methods.

In order to obtain an analytical solution one generally must assume a constant fluid velocity, dispersion coefficient, physical parameters, and input variables. Exact, explicit expressions for the constituent concentration can then be generated through the use of integral and differential calculus. Although the advantages of having analytical solutions are numerous (ease of use, and low cost of operation once derived), the necessity of having to make various simplifying assumptions in order to solve equation (D-1) severely restricts the applicability of analytical solutions to groundwater contamination problems arising from waste disposal.

In spite of these restrictions, it appears that some of the available two-and three-dimensional analytical solutions may be applied to well-defined hydrogeologic systems and should not be excluded from consideration.

D.3.3.2 Numerical Methods.

While some simple groundwater situations may lend themselves to analytical methods, most will involve such complex physical and chemical characteristics that the flexibility of a numerical approach is needed. When numerical techniques are used, the partial differential equations are generally reduced to a set of approximate algebraic equations, which subsequently are solved using methods of linear algebra. The most common numerical methods are finite differences, finite elements, or the method of characteristics.

When finite difference techniques are used, the derivatives in the governing partial differential equations are approximated with appropriate difference equations. This method has been used successfully in groundwater flow problems, but its application to groundwater quality studies is limited. This is partly a result of the procedure's inability to accurately reproduce the irregular boundaries of the system. Also, the possible introduction of numerical dispersion (the artificial smearing of a concentration front), or of the occurrence of undesirable oscillations in calculated concentration distributions, has limited its use to applications when dispersive transport was small compared to convective transport.

In general, finite difference techniques are numerically the simplest to use and the easiest to program. The method can yield accurate results when the area of interest is subdivided into a sufficiently fine grid of square or rectangular elements. The finite difference procedure has found frequent application in the simulation of one-dimensional unsaturated transport problems.

The dependent variables in the finite element method, pressure head and concentration, are generally approximated by a series of basic trial or shape functions and associated coefficients. The approximating series is then substituted into the governing equations, and the resulting errors or "residuals" are minimized through the use of weighted-residual theorems. In the Galerkin method, the locally-based shape functions are the same as the weighting functions. The approximate integral equations derived in this way are evaluated using the finite element method of discretion to minimize computational effort. Generally, a set of linear equations is obtained which can be solved by using appropriate matrix inversion subroutines or other methods. The domain of interest is again subdivided into elements which, unlike finite differences, can attain nearly any particular shape desired (triangular, rectangular, including elements having curved sides).

The finite element method has been successfully applied to field problems involving mass transport. In some cases, numerical dispersion remained a problem, but it is less than that observed using the finite difference method.[37] While the finite element method requires a somewhat more complex manipulation in generating solutions than the finite difference method, its solutions are generally more accurate, assuming the same net. Important advantages of the finite element method are its flexibility in describing irregular geometrical boundaries, its ease of introducing nonhomogeneous properties and anisotropy, and the possibility of using small elements in areas of relatively rapid change.

The method of characteristics, as generally used in groundwater quality simulation studies, employs a finite difference approach for the flow equation, while the constituent transport equation is solved with a set of characteristic equations. These characteristic equations are obtained from the main equations by deleting the convective transport terms and including them in separate equations. One must design for this purpose a standard finite difference network and insert "marker particles" or moving points into each finite difference cell. The marker particles are moved through the network as prescribed by local fluid velocities, thereby describing exactly the effects of the convective transport terms. The effects of the remaining terms in the transport equation are superimposed on the updated positions of the marker particles using the concentrations at these moving points, and an appropriate finite difference scheme. The method is fairly simple in concept and has been shown to produce acceptable results for a wide variety of field problems. An important drawback of this particular method is that it is not easy to program in two or three dimensions.

D.3.3.3 Summary

Each of the numerical schemes discussed appears to have specific advantages and disadvantages for application to field problems. These may be separated into factors affecting the accuracy, efficiency, and assessibility of the particular method. While important differences in accuracy and efficiency between the finite element and finite difference methods are known to exist (von Genuchten (1978)), it is not clear to what extent these differences become important when simulating large-scale field problems. The accuracy and efficiency in programming, as well as the general set up of the model and its assessibility, are also important factors which determine the usefulness of a particular solution scheme.

D.4 EXISTING MATHEMATICAL MODELS

D.4.1 Introduction

A compilation is given in this section of several models selected from those analyzed in the literature search which were regarded as appropriate for further evaluation with respect to this particular study. These models are differentiated into four distinct groups, depending on how they consider the subsurface media through which water flow and constituent transport occur. These groups are the following:

- Saturated-unsaturated transport models.
- Saturated-only transport models.
- Unsaturated-only transport models.
- Analytical transport models.

1. Saturated/Unsaturated Transport Models.

   The models in this group are probably the most generally appropriate because they consider both the unsaturated-flow conditions in a landfill and immediately under the waste disposal site, as well as the saturated zone of the underlying aquifer. These models can better account for dispersion of nonconservative materials, such as radioactive contaminants, and can better describe the dilution attenuation of leachate by flowing groundwater. Because they attempt to describe the entire contaminant dispersion and transport situation (see Figure D-1) they generally will need to be more complex than the other subsurface media model groups. The highly nonlinear character of the governing equations during saturated/unsaturated flow makes their solution more difficult, and, generally, small time steps in the numerical algorithm are necessary to ensure a correct solution.

   Several simplifications can be made to circumvent some of these problems. For example, either use monthly average rainfall and evaporation data rather than hourly or daily data, or assume steady-state flow conditions altogether. While steady-state flow conditions may be justified in some cases, it appears that predictions of the amount and quality of leachate reaching the groundwater may

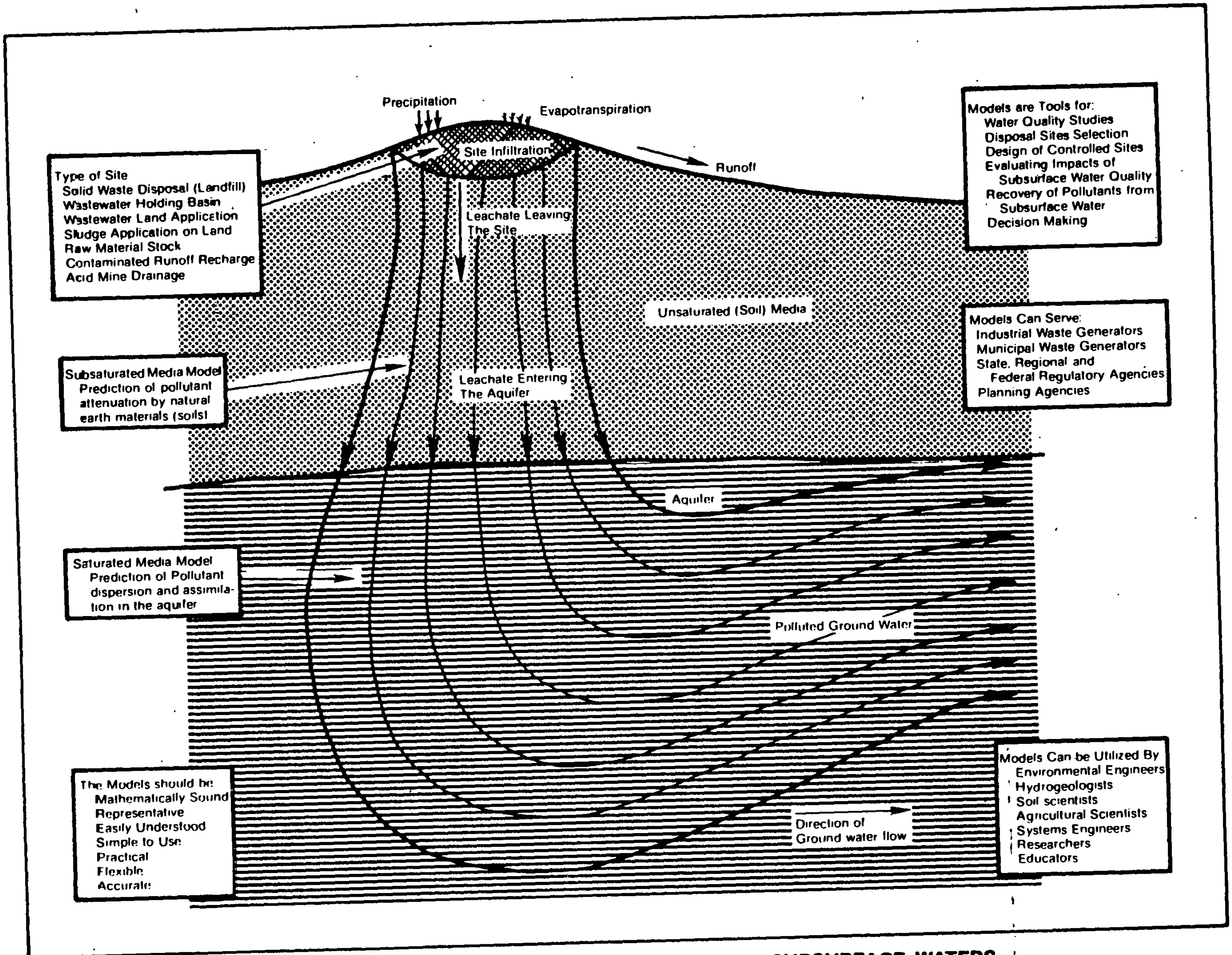

FIGURE D-1 MODELING OF POLLUTANT FATE IN SUBSURFACE WATERS be inaccurate when evaporation on a yearly basis is of equal magnitude or higher than precipitation. Also, seasonal water changes cannot be described with the steady-state model.

Another problem associated with the unsaturated zone is the need for additional input data. For example, the nonlinear relationships between moisture content, pressure head, and hydraulic conductivity have to be determined for each soil type present in the system. In addition, and of equal importance, the different soil/chemical interactions occurring in the unsaturated zone have to be quantified. Thus, it appears that the technology for modeling contaminant transport is far less advanced than that for modeling fluid flow, especially with respect to adsorption and exchange reactions in the unsaturated zone. Notwithstanding these problems, the saturated/unsaturated transport models appear to be the most promising tools for evaluating potential groundwater contamination from groundwater sites.

2. Saturated-Only Transport Models.

In these models, the dynamics of the unsaturated zone between the waste disposal site and the groundwater table are ignored. Hence, important mechanisms associated with unsaturated flow and contaminant transport are not taken into account unless they are represented in an approximate way through data adjustments. To use these models, it is necessary to have a method of quantifying the amount and quality of leachate reaching the groundwater table. Given that this can be done beforehand, i.e., in a predictive way, the models listed in this group appear to be useful tools for groundwater contamination simulations. The need for describing the unsaturated zone becomes much less when the waste disposal site is in direct contact with the saturated zone.

Models of this variety have found application in a wide variety of practical field problems, mostly in cases where groundwater pollution was observed and where calibration of the model to field data was possible. Figure D-2 is a typical pollutant profile of a constituent entering an aquifer as produced by a saturated-only transport model. Some additional work seems necessary to determine the accuracy of these models for use in a purely predictive context where calibration of the model is not possible.

3. Unsaturated-Only Transport Models.

Because these models consider only the unsaturated zone, they cannot be used alone to describe contaminant migration in groundwater systems. The models in this category (generally one dimensional) are useful when studying the mechanisms of pollutant transport in the unsaturated zone, especially the transient waste/soil interactions associated with column-leaching studies. Another important application of these models results when they are simultaneously paired with saturated-only transport models. These paired models can be utilized to predict the amount and type of leachate reaching a groundwater table, information which is used as input for the saturated-only transport model.

4. Analytical Models.

Analytical transport models, especially the two- and three-dimensional models, appear to have limited application to actual (field) groundwater contamination problems. Their application is restricted to those cases where the geohydrology of the area is very simple (flow in one direction, constant porosity, dispersivity, and conductivity). The different one-dimensional analytical models are again potentially useful as tools for identification and quantification of waste/soil interactions when used in conjunction with column-leaching experiments for quantification of adsorption constants, dispersion coefficients, etc.

D.4.2 Modeling of Nonconservative Substances.

The discussion of groundwater modeling techniques to this point has considered that the constituents undergoing analysis are

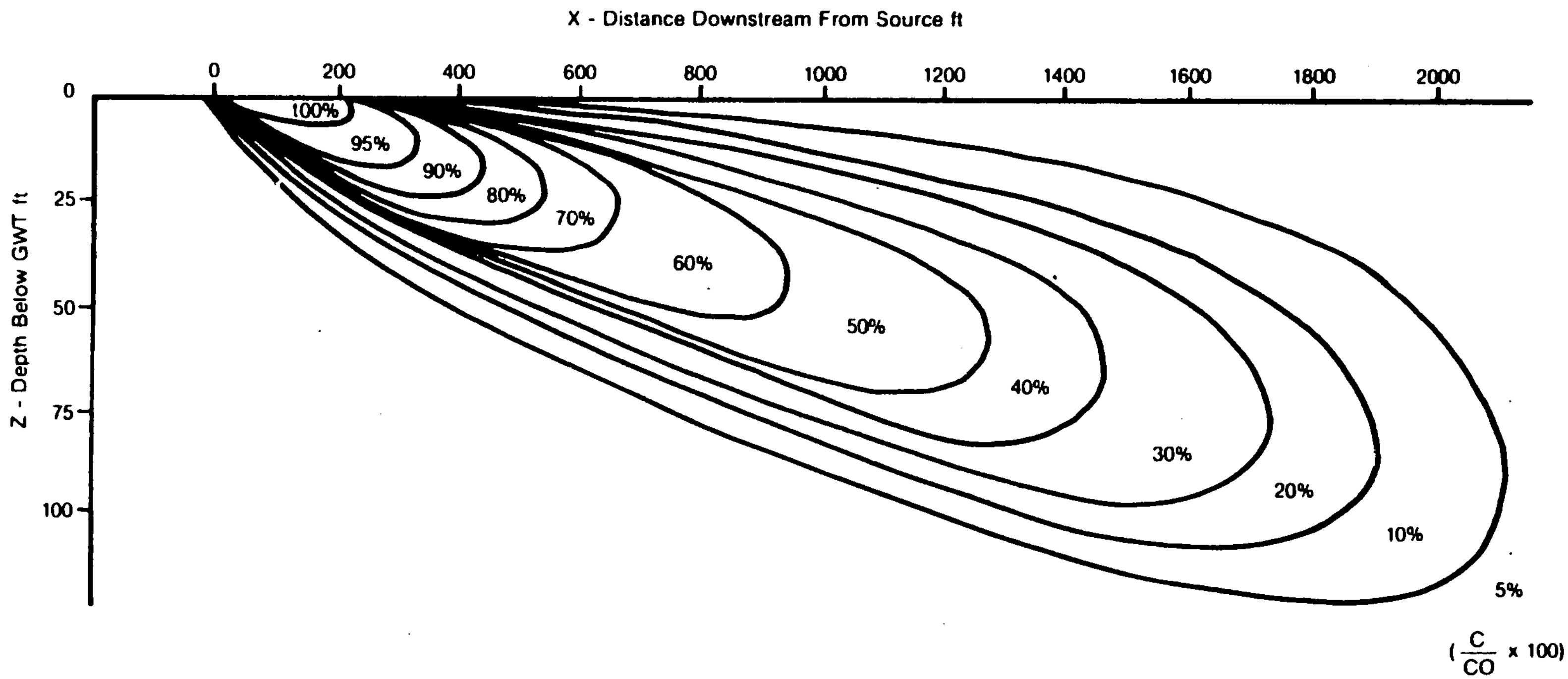

FIGURE D-2 POLLUTANT ISOPLETHS (RUN 1)

conservative, i.e., they are not removed from flow within the time frame under consideration. Many substances, however, may undergo physical, chemical, or nuclear activity which will result in changes in the quantities of material available for transport through the subsurface media. A substantial number of the groundwater models have included components that will allow consideration of these chemical and radioactive decay processes. These models will address uniform reduction of a particular chemical constituent from flow by utilizing decay coefficients. These decay coefficients are generally evaluated under laboratory conditions and are provided as input to the models.

D.4.3 Comparison of Specific Models.

This subsection provides a brief description of several models selected from those researched in the literature survey which were regarded as appropriate for further investigation in this study.

The following are widely-used geohydrological models and will be considered for detailed evaluation:

1. USGS Model -- Computer model of two-dimensional finite difference solute transport and dispersion in groundwater.

2. ISOQUADII (Princeton University Model) -- A two-dimensional finite element hydraulic and water quality model.

3. SEGOL-3 (University of Waterloo Model) -- A steady and nonsteady state three-dimensional finite element chemical transport model.

4. FEMWATER (Oak Ridge National Laboratory) -- A finite element model of water flow through saturated-unsaturated porous media.

   FEMWASTE (Oak Ridge National Laboratory) -- A finite element model of waste transport through saturated-unsaturated porous media.

5. FECWATER (Oak Ridge National Laboratory) -- Modified version of FEMWATER.

   FECWASTE (Oak Ridge National Laboratory) -- Modified version of FEMWASTE.

6. AT123D (Oak Ridge National Laboratory) -- Analytical transient one-, two-, and three-dimensional simulation of waste transport in an aquifer system.

7. LEACHATE I (Roy F. Weston, Inc.) -- A two-dimensional finite difference chemical transport model.

D.4.3.1 USGS Model.[29]

This is a finite difference model has been developed for calculating transient changes in the concentration of a nonreactive solute in saturated flowing groundwater. The methodology solves two simultaneous partial differential equations: a groundwater flow equation and a solute-transport equation. The groundwater flow equation describes the head distribution in the aquifer, and the solute-transport equation describes the chemical concentration in the system. These two equations have been coupled in the model to describe both steady and transient flow problems. The model computes the concentration of a dissolved chemical in an aquifer at any specific place and time. The following processes are considered in this model:

1. Convective transport.
2. Hydrodynamic dispersion.
3. Mixing.

Flow equation.

The equation describing the transient two-dimensional areal flow of a homogeneous compressible fluid through a nonhomogeneous anisotropic aquifer can be written as:

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_j}\right) = S\frac{\partial h}{\partial t} + W \qquad i,j = 1,2$$

Where:

T_{ij} = Transmissivity tensor, L^2/T.

h = Hydraulic head, L.

S = Storage coefficient (dimensionless).

t = Time, T.

W= W (x, y, t) = Volume flux per unit area (positive sign for outflow and negative for inflow), L/T.

x_i and x_j = Cartesian coordinates, L.

Considering fluxes of direct withdrawal or recharge, such as well pumpage, well injection, or evapotranspiration; and steady leakage into or out of the aquifer through a confining layer, streambed, or lakebed, then W(x,y,t) may be expressed as:

$$W\ (x,\ y,\ t) = Q\ (x,\ y,\ t) - \frac{K_z}{m}\ (H_s - h)$$

Where:

Q = Rate of withdrawal (positive sign) or recharge (negative sign), L/T.

K_z = Vertical hydraulic conductivity of the confining layer, streambed, or lakebed, L/T.

m = Thickness of the confining layer, streambed, or lakebed, L.

H_s = Hydraulic head in the source bed, stream, or lake, L.

An expression for the average seepage velocity of groundwater derived from Darcy's law can be written as:

$$V_i = -\frac{K_{ij}}{\epsilon} \frac{\partial h}{\partial x_j}$$

Where:

V_i = Seepage velocity in the direction of x_i, L/T.

K_{ij} = Hydraulic conductivity tensor, L/T.

ϵ = Effective porosity of the aquifer (dimensionless).

<u>Transport Equation</u>.

The equation used to describe two-dimensional areal transport and dispersion of a given nonreactive dissolved chemical species in flowing groundwater may be written as:

$$\frac{\partial (Cb)}{\partial t} = \frac{\partial}{\partial x_i} \left(bD_{ij} \frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i} (bCV_i) - \frac{C'W}{\epsilon}$$

$$i,j = 1,2$$

Where:

C = Concentration of the dissolved chemical species, M/L^2.

D_{ij} = Coefficient of hydrodynamic dispersion (a second order tensor), L^2/T.

b = Saturated thickness of the aquifer, L.

C' = Concentration of the dissolved chemical in a source or sink fluid, M/L^3.

The first term on the right side of this equation represents the change in concentration due to hydrodynamic dispersion. The second term describes the effects of convective transport, while the third term represents a fluid source or sink.

It should also be noted that adsorption and decay terms are not included in the transport equation, and therefore, this model cannot be used directly to simulate transport of a radionuclide solute through a porous medium.

Two general types of boundary conditions are incorporated in this model; these are constant-flux and constant-head conditions. Chemical concentrations in the source fluid must also be given as boundary conditions.

The model is programmed in FORTRAN IV, and the calculation procedures are shown on Figure D-3, which presents a simplified flow chart of the computation procedure.

The accuracy of the model evaluated using two idealized problems indicated the error will generally be less than 10 percent. The accuracy of the numerical solution is also sensitive to the initial concentrations of the chemical constituents, and to the size of the time increment.

Conclusions.

This model is suitable for simulating the two-dimensional transport and dispersion of a nonreactive solute in either steady-state or transient groundwater flow. The major drawback of the application of this model for simluation of radionuclide solute transport is that no decay term has been included in the transport partial differential equation. Therefore, the model, as it presently exists, is not suitable for consideration in low-level radioactive waste transport simulation in groundwater.

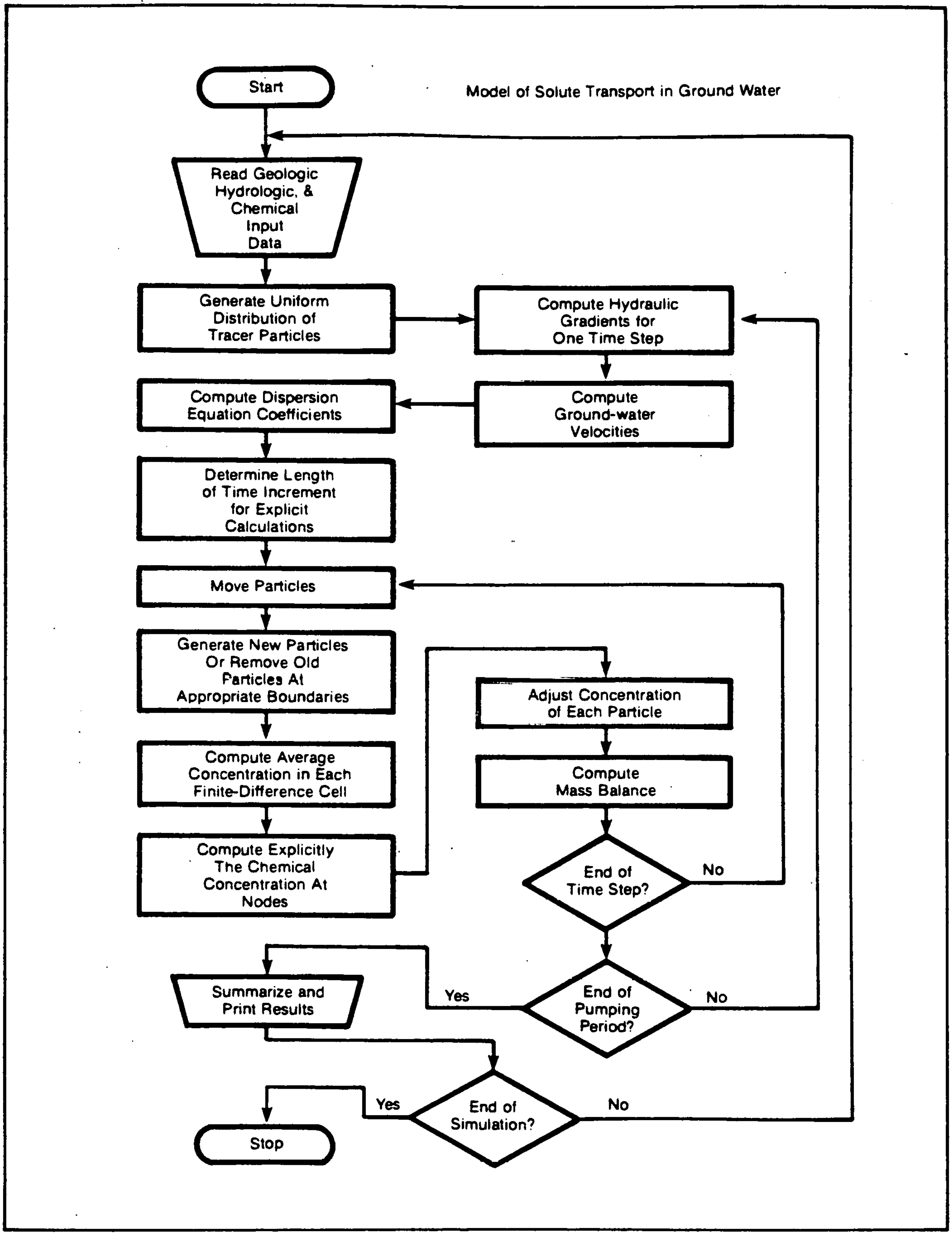

FIGURE D-3 SIMPLIFIED FLOW CHART ILLUSTRATING THE MAJOR STEPS IN THE CALCULATION PROCEDURE

D.4.3.2 ISOQUADII.

This model, developed at Princeton University by Pinder, has combined both the groundwater flow and solute transport equations. This model utilizes a Galerkin approximation with various basic functions, with a finite element integration scheme to solve the solute transport equation. Here also, the chemical solute has been assumed to be conservative, and therefore adsorption and radioactive decay terms are not included in the basic transport equation. The time integration is performed through a backward difference time scheme. It is also assumed that the contaminant does not significantly change the density of the fluid.

The two-dimensional partial differential equation for transporting a conservative solute through a saturated porous medium used in this model is given as:

$$L(c) = \frac{\delta}{\delta x}\left(D_{xx}\frac{\delta c}{\delta x}\right) + \frac{\delta}{\delta x}\left(D_{xy}\frac{\delta c}{\delta y}\right) + \frac{\delta c}{\delta y}\left(D_{yy}\frac{\delta c}{\delta y}\right) + \frac{\delta c}{\delta y}\left(D_{yx}\frac{\delta c}{\delta x}\right)$$

$$- \frac{\delta}{\delta x}(cq_x) - \frac{\delta}{\delta y}(cq_y) - \frac{\delta}{\delta t}(\theta bc) + Qc' + \frac{K'}{l'}(h-h_w)\ c''$$

where:

b = Saturated thickness of the aquifer (L).

c = Concentration (ML^{-3}).

c' = Concentration of the discharging (recharging) fluid (ML^{-3}).

c" = Concentration of the fluid discharging (recharging) the aquifer through leakage (ML^{-3}).

D = Dispersion coefficient ($L^3\ T^{-1}$).

K' = Hydraulic conductivity of the confining bed (LT^{-1}).

l' = Thickness of the confining bed (L).

q = Mass average flux vector (L^2T^{-1}).

Q = Rate of fluid withdrawal (LT^{-1}).

θ = Porosity.

The approximating integral equations required for the finite element formulation are obtained for the flow and transport equations using Galerkin's method.

Conclusions.

This is a two-dimensional steady- and transient-state simulation of conservative solute in groundwater using the finite element method. The use of this method has the advantage of approximating the geometry of the aquifer accurately.

Since this model does not incorporate a decay or adsorption term in the solute transport equation, it will not be possible to use this model to simulate the transport of radionuclide solute in the groundwater. This model also does not incorporate simulation of transport of solute in the unsaturated zone. Therefore, application of this model for radionuclide solute transport in saturated and unsaturated zones will be limited.

D.4.3.3 SEGOL-3.[30]

The flow and transport equations are coupled and solved using Galerkin's finite element approach. The model solves for both two- and three-dimensional combined partially-saturated and saturated flow. Since solution for both saturated and partially-saturated flow is possible, the free surface boundary condition is handled rationally. This model can also be used in the two-dimensional form, which is identical in all respects to the three-dimensional one except that the third dimension is discarded.

Flow Equation.

The equation governing the water movement in the saturated/unsaturated zone has been given in the form:

$$L_n = (k + \frac{\theta}{\epsilon} S_s) \frac{\delta h}{\delta t} - \frac{\delta}{\delta x_\alpha}(K_r K^s_{\alpha\beta} \frac{\delta h}{\delta x_\beta} + K_r K^s_{\alpha\beta}) - Q = 0$$

$$\alpha\beta = 1, 2, 3$$

Where:

$K = \frac{\delta \theta}{\delta h}$ = Moisture capacity (L^{-1}).

K_r = Relative hydraulic conductivity.

$K^s_{\alpha\beta}$ = Hydraulic conductivity at saturation (LT^{-1}).

$Q = Q_w\ (x_{w\alpha})\ \delta\ (x_\alpha - x_{w\alpha}\ )$ = Strength of source or or sink function (T^{-1}).

Q_w = Well discharge ($L^3\ T^{-1}$).

S_s = Specific storage (L^{-1}).

$x_{w\alpha}$ = Coordinate of discharge or recharge point (L).

ϵ = Porosity.

θ = Moisture content.

h = Pressure head (L).

In the unsaturated zone, this flow equation is nonlinear since moisture content and hydraulic conductivity are functions of the pressure head.

<u>Transport Equation</u>.

The equation describing the solute transport is taken in the form:

$$L_c = \frac{\delta \theta c}{\delta t} - \frac{\delta}{\delta x_\alpha} (\theta D_{\alpha\beta} \frac{\delta c}{\delta x_\beta}) - \frac{\delta q_\alpha c}{\delta x_\alpha} + Qc' = 0$$

Where:

c = Solute concentration (ML^{-3}).

c' = Concentration of the considered ion in the source or sink fluid (ML^{-3}).

$D_{\alpha\beta}$ = Dispersion tensor ($L^2\ T^{-1}$).

q_α = Volumetric flux of water (LT^{-1}).

This transport equation does not include an adsorption or decay term, and therefore, is applicable to conservative chemical solutes only. In this model, the nonlinear set of flow and transport equations are solved using the Galerkin finite element method. In the three-dimensional transport model, out-of-core equation solvers are used in order to decrease the storage requirements. In this approach, matrices are assembled by blocks. When a block has been processed, it is transferred to secondary storage so that only two blocks need to be in the memory at the same time. This procedure reduces the storage space, however, it also increases the solution time.

Functional simplified flow charts corresponding to saturated steady-state, transient-saturated, and unsaturated flow conditions are shown on Figures D-4, D-5, and D-6, respectively.

Conclusions.

This model is a three-dimensional finite element model which can simulate steady and transient transport of a conservative chemical solute in a saturated or unsaturated porous medium. SEGOL-3 does not incorporate a decay term in the transport equation, and as a result, this model cannot be used to simulate radionuclide transport.

D.4.3.4 FEMWATER and FEMWASTE.

These two models are modified and expanded versions of previously developed models at the Oak Ridge National Laboratory. FEMWATER(31) is a revised finite element model of water flow through porous media to simulate the groundwater dynamics in a saturated/unsaturated subsurface system. The response of the groundwater basin to rainfall, artificial withdrawal, and other recharge or discharge sources (such as lakes, reservoirs, and streams) may be included in the simulation.

FEMWASTE model(32) is a finite element model of waste transport through porous media simulating the spatial and temporal distribution of waste concentration under dynamic groundwater conditions. The transport mechanisms include advection; convective flow, hydrodynamic dispersion, chemical adsorption, and first-order decay. The new model differs from the previous one in the following aspects:

1. Reformulation of the distribution coefficient and retardation factor.

2. Computation of the waste flux field.

3. Method of evaluating mass balance over the whole region.

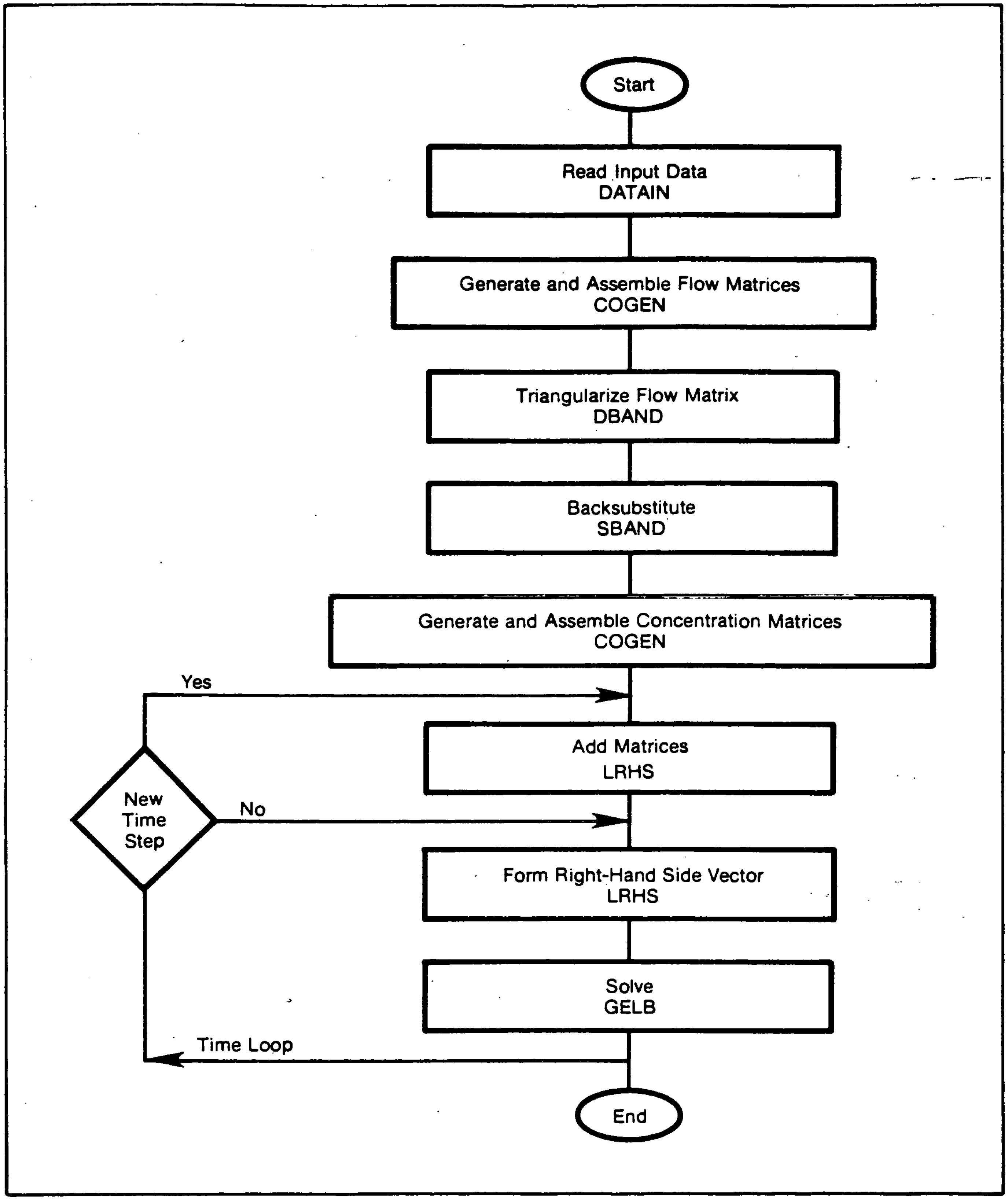

FIGURE D-4 FLOW CHART FOR STEADY-STATE, SATURATED ANALYSIS

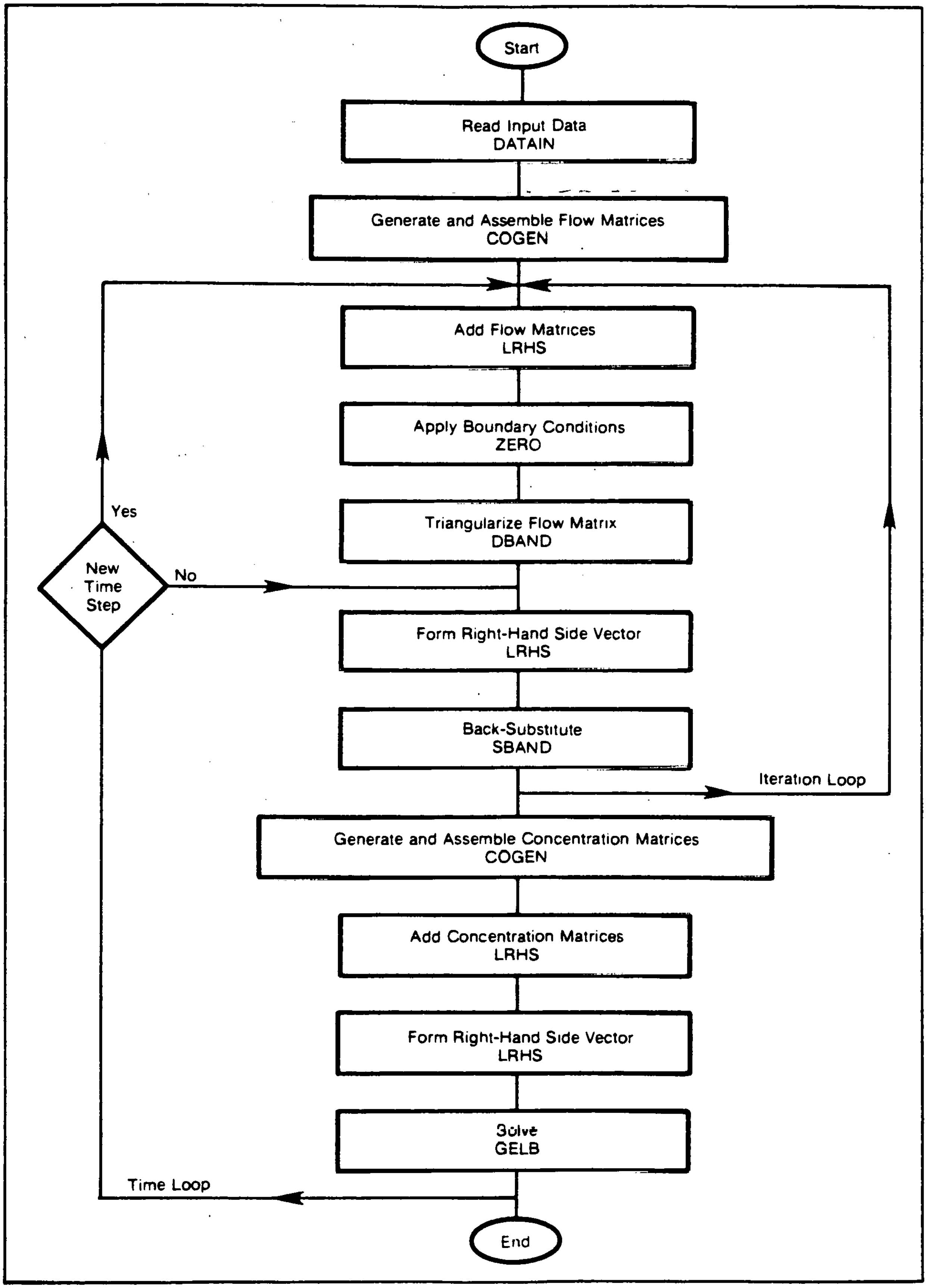

FIGURE D-5 FLOW CHART FOR TRANSIENT, SATURATED ANALYSIS

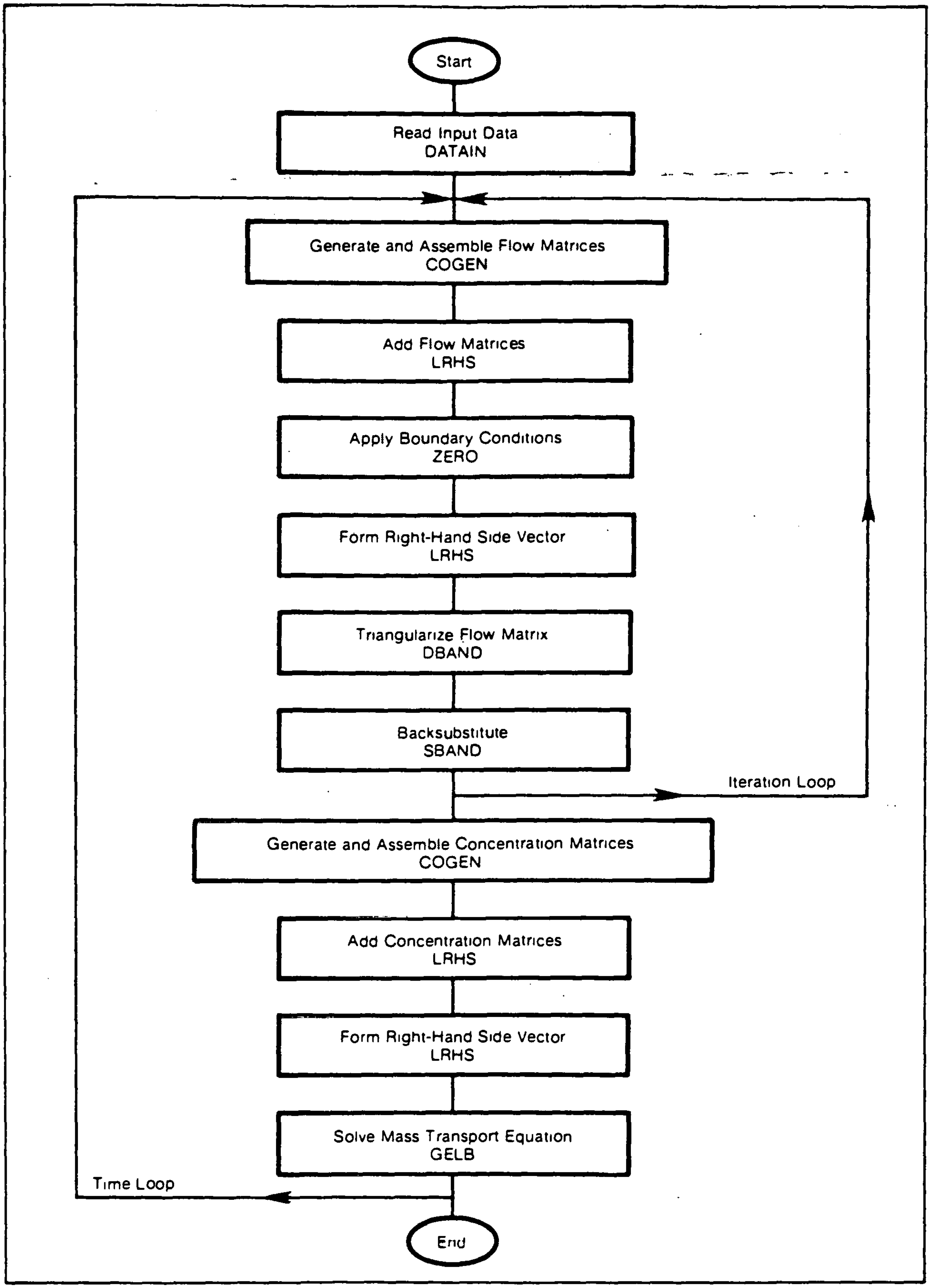

FIGURE D-6 FLOW CHART FOR TRANSIENT, UNSATURATED ANALYSIS

4. Implementation of upstream weighting functions.

5. Application of boundary conditions.

To study the transport of dissolved constituents in a subsurface flow system, the velocity field must be determined first. In this model, the Darcian velocity field is continuous everywhere in the flow regime, including element boundaries and nodal points, and overall mass balance is preserved. The velocity field for both saturated and unsaturated zones obtained by using this model can be coupled with the FEMWASTE model to generate the waste concentrations at various space locations and times in both saturated and unsaturated zones.

Flow Equations.

The governing equations for describing the pressure field and the velocity field in a two-dimensional subsurface system are obtained from the principle of conservation of mass and Darcy's law. This can be written in the form:

$$L(h) = F\frac{\partial h}{\partial t} - \left[\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial H}{\partial x} + K_{xz}\frac{\partial H}{\partial z}\right) + \frac{\partial}{\partial z}\left(K_{zx}\frac{\partial H}{\partial x} + K_{zz}\frac{\partial H}{\partial z}\right)\right] - Q = 0$$

Where:

$$F = \frac{\theta}{n}\ \alpha' + \beta'\ \theta + \frac{d\theta}{dh}$$

and

$$H = h + z$$

in which:

h = Pressure head.

θ = Moisture content.

n = Effective porosity.

α' and β' = Modified coefficients of compressibility of the medium and water, respectively.

K_{xx}, K_{xz}, K_{zx}, and K_{zz} = Hydraulic conductivity tensor components.

x and z = Horizontal and vertical coordinates, respectively.

t = Time.

Q = Artificial recharge or withdrawal.

L = An operator.

The initial condition of pressure head, $h = h_o\ (n,z)$, should be known. In this model three types of boundary conditions are available for use. In the first boundary type (Dirichlet), the pressure head is prescribed. In the second type (Neumann), the flux is prescribed, and in the third type either the Dirichlet or the Neumann conditions can be prescribed.

After the pressure equation is solved for the pressure head, h (subject to initial and boundary conditions), the velocity components are then obtained by using Darcy's equation as:

$$V_x = -\left(K_{xx} \frac{\partial h}{\partial x} + K_{xz} \frac{\partial h}{\partial z} + K_{xz} \right)$$

and

$$V_z = -\left(K_{zx} \frac{\partial h}{\partial x} + K_{zz} \frac{\partial h}{\partial z} + K_{zz} \right)$$

Transport Equation.

The equation describing the transport of a pollutant constituent in a two-dimensional subsurface porous system is obtained from the law of mass balance. This can be written in the form:

$$L(c) = \frac{\partial}{\partial t}\ (\theta c + \rho s) + (\theta c + \rho s)\ \alpha' \frac{\partial h}{\partial t} + \left(\frac{\partial V_x c}{\partial x} + \frac{\partial V_z c}{\partial z} \right)$$

$$-\left[\frac{\partial}{\partial x}\ (\theta D_{xx} \frac{\partial c}{\partial x} + \theta D_{xz} \frac{\partial c}{\partial z}) + \frac{\partial}{\partial z} (\theta D_{zx} \frac{\partial c}{\partial x} + \theta D_{zz} \frac{\partial c}{\partial z}) \right]$$

$$+ \lambda(\theta c + \rho s) - M$$

Where:

θ	= Moisture content.
c	= Concentration of dissolved constituent in water.
ρ	= Bulk density of the solid.
s	= Concentration of the constituent adsorbed on the solid.
α'	= Modified coefficient of compressibility of the medium.
h	= Pressure head of the water.
D_{xx}, D_{xz}, D_{zx}, and D_{zz}	= Dispersion coefficient tensor components.
V_x and V_z	= Darcian velocity components in the x- and z- directions, respectively.
λ	= Decay constant.
M	= Artificial source.
x and z	= Horizontal and vertical coordinates, respectively.
t	= Time.
L	= An operator.

The pollutant transport equation expresses the mass balance in an initially small bulk volume. The first term represents the rate of change of total mass (including dissolved and adsorbed) in the element volume. The second term is the mass change due to the bulk volume under pressure. The third and fourth terms represent the mass fluxes out of and into the volume by advection and dispersion, respectively. The fifth term is the mass change due to decay, while the last term is the artificial input or withdrawal. Variables θ , h, V_x, and V_z, can be obtained from the output of the FEMWATER model. The dispersion coefficient tensors are related to flow field and media properties as:

$$\theta D_{xx} = a_T V + (a_L - a_T) V_x{}^2/V + D_m T,$$

$$\theta D_{xz} = \theta D_{zx} = (a_L - a_T) V_x V_z / V$$

and

$$\theta D_{zz} = a_T V + (a_L = a_T) V_z{}^2/V + D_m T$$

where:

V	=	$\sqrt{V_x{}^2 + V_z{}^2}$
a_T and a_L	=	Transverse and longitudinal dispersivities, respectively.
T	=	Tortuosity.
D_m	=	Molecular diffusion coefficient.

The decay constant, λ , is a property of the constituent, and ρ and α' are the properties of the porous media under consideration. The independent variables include x, z, and t. Thus, there are two dependent unknowns, c and s, in the transport equation. It is assumed that the adsorption of the solute pollutant by the porous medium is to occur at a rapid rate, and the concentration of the solute is in equilibrium with the material adsorbed by the solid. This can be expressed as:

$$\rho = K_d c$$

where K is the distribution coefficient. Again, K can be related with the moisture content θ as:

$$R_d = 1 + \frac{P_{kd}}{\theta}$$

where R_d is the retardation factor.

In order to solve the transport equation, some type of initial and boundary conditions, as used in the solution of the flow equation, are assumed. Both the flow and transport equations are solved using a finite element scheme, and velocities, and concentrations of solutes at various spaces and times are calculated.

Conclusions.

The model FEMWATER, coupled with the model FEMWASTE, generates the flow field and concentration of a pollutant in both saturated and unsaturated porous media. The transport equation used in this model incorporates all transport mechanisms, such as chemical sorption, first-order decay, advection, and hydrodynamic dispersion. The attenuation of a dissolved pollutant in the water is accomplished through chemical sorption and first-order decay. Thus, the proper formulation of chemical sorption by the soil matrix, which is very important to the study of attenuation of low-level radioactive waste in groundwater, is properly characterized in this model, by the distribution coefficient, K_d, and retardation factor, R_d.

The model FEMWATER, coupled with the model FEMWASTE, offers several advantages in simulating the transport of low-level radioactive waste in groundwater. These advantages are as follows:

1. The model incorporates a proper formulation of chemical adsorption and first-order decay.

2. The finite element approximation used in these models has the inherent ability to handle complex boundaries.

3. These models simulate both unsaturated and saturated porous media, producing a continuous simulation of velocity and concentration in space and time.

4. More than 20 organizations, including the Nuclear Regulatory Commission, have been using these models.

D.4.3.5 FECWATER and FECWASTE.

The Oak Ridge National Laboratory is now making modifications of FEMWATER and FEMWASTE, and the corresponding modified models will be available very soon. The FECWATER and FECWASTE models will have the following additional special features:

1. The time step size can be changed within a particular simulation period.

2. The boundary conditions are flexible and historical changes in geometry and concentration of waste sources can be simulated in one simulation run. These features will be particularly helpful in simulating the historical changes of site characteristics of low-level radioactive waste sites.

Conclusions.

These two models (FECWATER and FECWASTE) coupled together will give a versatile, flexible model system for evaluating the potential contamination of groundwater by low-level radioactive waste. These models will simulate two-dimensional flow and concentration of nonconservative wastes in heterogeneous saturated and unsaturated porous media. Boundary conditions and time steps are flexible, and, as a result, any complex site with all historical and future changes in characteristics, can be simulated using these models.

D.4.3.6 AT123D.

This one-, two-, or three-dimensional model was developed for estimating the concentration of nonconservative wastes in a groundwater aquifer system. This model is an analytical solution of a generalized three-dimensional transport equation. Mechanisms included in the formulation of the transport equation are:

1. Advection.

2. Hydrodynamic dispersion.

3. Adsorption.

4. Decay and degeneration.

5. Waste losses to the atmosphere.

Three types of boundary conditions (Dirichlet, Neumann, and mixed) can be used in this model in developing analytical solutions to the transport equation.

The following simplified assumptions are made in order to solve the complex transport equation:

1. Aquifer has been assumed to be uniform and homogeneous, i.e., seepage velocity, porosity, permeability, and dispersivity are uniform.

2. Sorption of the waste constituent by the solid soil matrix has been assumed to occur at a rapid rate such that the dissolved material is adsorbed by the solids under isothermal conditions.

Due to the assumption of a uniform aquifer, applications of this analytical model are limited. Therefore, under heterogeneous aquifer conditions, numerical simulations of groundwater dynamics and mass transport are necessary. However, this model is particularly useful for the "first-pass" estimation of screening waste disposal sites, and the design of a monitoring system.

Conclusions.

This model (AT123D) is applicable under saturated aquifer conditions only, and can accept only a regular geometry of source and/or sink. Therefore, this model will be useful for preliminary design of groundwater monitoring systems, but will not be applicable for simulating complex transport of low-level radioactive waste in a heterogeneous aquifer.

D.4.3.7 LEACHATE I.

LEACHATE I is essentially a combination of two models:

1. A one-dimensional model that predicts the attenuation of pollutants in unsaturated media (soils).

2. A two-dimensional model that predicts pollutant dispersion and assimilation in saturated media (aquifers).

This model can simulate the transport of conservative and nonconservative pollutants in a porous media. Flow and velocity distributions in the aquifer are required as input to this model. LEACHATE I in its present form can only simulate a homogeneous aquifer.

Transport Equations.

Unsaturated Media (Soils) Model.

A one-dimensional mathematical model was developed to describe diffusion and chemical reactions in unsaturated media. The model is based on the following second-order partial differential equation:

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} - v \frac{\partial c}{\partial x} - \frac{\rho}{\theta} \frac{\partial s}{\partial t} - kc$$

Where:

c = Consistent concentration in soil solution.

S = Absorbed constituent concentration.

t = Time.

D_x = Hydrodynamic dispersion coefficient.

x = Distance

v = Average pore-water velocity.

ρ = Bulk density of dry soil.

θ = Soil/water content fraction.

k = Transformation rate constant.

$\frac{\partial s}{\partial t} = K_d\, c$ ·

k_d = Pollutant distribution factor.

This one-dimensional equation has been solved analytically to generate the concentrations of pollutants at various depths and times.

Saturated Media (Aquifer) Models.

A two-dimensional mathematical model was developed to describe the dispersion and adsorption of pollutants in saturated media (aquifers). The model is based on this partial differential equation:

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} + D_z \frac{\partial^2 c}{\partial z^2} - u \frac{\partial c}{\partial x} - w \frac{\partial c}{\partial z} - Kc$$

Where:

u, w = Groundwater velocity vector components.

c = Concentration of pollutants.

D_x, D_z = Coefficients of effective dispersion.

$f(c)$ = Chemical reaction term.

Finite difference numerical analysis is utilized to solve the mathematical model for various boundary and initial conditions. The computer simulation is expressed as two-dimensional concentration profiles which can be oriented in either the vertical or the horizontal domain, under transient or steady-state conditions. Inputs to the model represent different variables regarding aquifer geophysical and geochemical characteristics, hydrology of the disposal site, and chemical and physical characteristics of polluting substances.

Conclusions.

This model can simulate conservative and nonconservative pollutant transport in one-dimensional unsaturated and two-dimensional saturated media. The output from the unsaturated model is given as input to the saturated model, along with the characteristics of groundwater systems and chemical and physical characteristics of polluting substances. The limitations of this model are:

1. Assumption of homogeneous aquifer.

2. Fixed boundary conditions.

3. Requirements for flow and pressure head distribution as input.

D.5 SELECTION OF MODEL

Each of the models described previously, has been developed under specific circumstances and will have varying advantages and limitations when considered for any particular disposal site. Table D-2 provides a direct comparison of their appropriateness for simulating radioactive contaminant transport and dispersal in subsurface media. This table presents the important characteristics available for each model. It shows the capabilities of various models in terms of dimension of model, mechanisms of transport considered, method of solution, nonhomogeneity of aquifer conditions, boundary conditions, assumptions, etc. The suitability of a computer model for proper simulation of the transport of low-level radioactive wastes in groundwater under various surface boundary and groundwater system conditions depends on its generality and flexibility. A generalized, minimum two-dimensional model, capable of simulating flow and pollutant transport mechanisms, including decay in saturated and unsaturated porous media under variable boundary conditions is required. The following nine specific criteria have been developed for the evaluation of models suitable for simulation of low-level radioactive groundwater systems:

1. Should be two-dimensional as a minimum.
2. Should be able to simulate both saturated and subsaturated porous media.
3. Should be able to generate pressure and velocity fields.
4. Should be able to simulate steady and transient conditions.
5. Should be able to simulate nonconservative pollutants with decay.
6. Should be able to handle various boundary conditions during the period of simulation.
7. Should be able to incorporate variable time steps during the period of simulation.
8. Should be able to simulate spatially-variable aquifer conditions.
9. Should be able to simulate heterogeneous and anisotropic aquifers.

Table D-2

Evaluation of Various Models

Name of Model/ Originating Organization	Model Type Based on Equations Used	Model Dimension	Method of Solution	Applicability Conditions	Flow Condition State	Transport Mechanism Considered	Source Terms Applicable	Parameters Modeled	Aquifer Characteristics
1. Solute Transport and Dispersion in a Porous Medium (USGS)	Combined flow and solute transport equations	2-dimensions	Finite difference method and method of characteristics	Saturated zone only	Steady and nonsteady state	Advection, dispersion and mixing; no decay term	Well discharge, recharge, leakage	Nonreactive chemicals	Heterogeneous and anisotropic
2. ISOQUAD (Princeton University)	Combined flow and solute transport equations	2-dimensions	Finite element method using Galerkin's approach	Saturated zone only	Steady and transient state	Advection, dispersion, and mixing; no decay term	Well discharge, recharge, leakage	Conservative chemicals	Heterogeneous
3. SUCOL-1 (University of Waterloo)	Combined flow and solute transport equations	2-3 dimensions	Finite element method using Galerkin's approach	Saturated and unsaturated zones	Steady and transient state	Advection, dispersion, mixing; no decay term	Well discharge, recharge, leakage	Conservative chemicals	Heterogeneous
4. FEMWATER FEMWASTE (Oak Ridge National Laboratory)	Combined flow and solute transport equations	2-dimensions	Finite element method	Saturated and unsaturated	Steady and transient	Advection, dispersion, mixing, and decay	Well discharge, recharge, leakage	Conservative and nonconservative chemicals	Heterogeneous and anisotropic
5. FECWATER FECWASTE (Oak Ridge National Laboratory)	Same as FEMWATER AND FEMWASTE							Nonconservative chemical sorption and decay	Heterogeneous and anisotropic
6. AT123D (Oak Ridge National Laboratory)	Solute transport only	1-2-3 dimensions	Analytical solution	Saturated only	Steady and transient	Advection, dispersion, mixing, sorption, and decay	Only source and sink	Conservative and nonconservative chemicals	Homogeneous
7. LEACHATE I (Roy F. Weston Inc.)	Solute transport only	1-dimensions	Finite difference	Unsaturated and saturated	Steady and transient	Advection, dispersion, mixing, sorption, and decay	Only source and sink	Conservative and nonconservative chemicals	Homogeneous

Name of Model/ Originating Organization	Assumptions	Boundary Conditions	Time Step	Solution Problems	Variability of Aquifer Conditions	Simplicity of Data Inputs	Flexibility	Program Language Used	Remarks
1. Solute Transport and Dispersion in a Porous Medium (USGS)	No change in fluid density, temperature, and viscosity	Fixed	Variable	Has several stability criteria	Spatially variable	Simple	Flexible	FORTRAN IV	Suitable for nonreactive solute transport under steady and transient conditions.
2. ISOQUAD (Princeton University)	No change in fluid density, temperature, and viscosity	Fixed	Variable			Simple		FORTRAN IV	Applicable for simulation of conservative solute transport only.
3. SUCOL-1 (University of Waterloo)	No change in fluid density, temperature, and viscosity	Variable	Variable		Spatially variable			FORTRAN	Applicable for simulation of conservative solute transport only.
4. FEMWATER FEMWASTE (Oak Ridge National Laboratory)	No change in fluid density, temperature, and viscosity	Fixed	Fixed		Spatially variable		Flexible	FORTRAN	Applicable for conservative and nonconservative solute in saturated and unsaturated porous media.
5. FECWATER FECWASTE (Oak Ridge National Laboratory)	No change in fluid density, temperature, and viscosity	Variable	Variable		Same as FEMWATER AND FEMWASTE				Very flexible. Variable boundary and time step. Nonconservative solute. Saturated and unsaturated. Will be available in five months.
6. AT123D (Oak Ridge National Laboratory)	No change in fluid density, temperature, and viscosity	Fixed			Uniform	Simple	Not flexible; can be used under specific conditions	FORTRAN IV	Not suitable for complex heterogeneous aquifer simulation.
7. LEACHATE I (Roy F. Weston Inc.)	No change in fluid density, temperature, and viscosity	Fixed	Fixed	Stability criteria to be satisfied	Uniform	Simple	Not flexible; can be used only under homogeneous aquifer conditions	FORTRAN IV	Not suitable for complex heterogeneous aquifer simulation.

An evaluation of all the models with respect to these criteria has been made and is shown in Table D-3. This table indicates that only the system developed from the FECWATER and FECWASTE models, developed by the Oak Ridge National Laboratory, satisfies all of the nine test criteria, and, therefore, this model system is the most suitable for simulating the transport of low-level radioactive wastes in a groundwater system.

D.6 LIMITATIONS IN THE APPLICATION OF GROUNDWATER MODELS

D.6.1 Input Parameters

A successful simulation is dependent on the availability and accuracy of the different system parameters and input variables. Some of the difficulties in quantifying such parameters are the following:

1. Lack of understanding of certain soil/waste interactions. Although much has been learned in recent years about the physical and chemical interactions between soils and certain chemicals, much remains to be done to quantify these relationships into formulas for use in simulation models. This is especially true for those systems containing adsorption, exchange reactions, chemical chain reactions, and decay.

2. Lack of standard procedures for quantifying major input variables (e.g., adsorption, exchange constants, decay constants, and dispersion coefficients).

3. General lack of field data on hydrogeologic parameters and behavior of contaminants (especially nonconservative ones) in subsurface environments. There is uncertainty concerning the precision and accuracy of major hydrologic and geochemical parameters.

4. Difficulty and cost of conducting laboratory and field experiments for the quantification of input data. Because of the complex nature of most waste leachates and the number of processes

Table D-3

Testing of Evaluation Criteria

Required Criteria	USGS Model	ISOQUADII	SEGOL-3	FEMWATER FEMWASTE	FECWATER FECWASTE	AT123D	LEACHATE I
Minimum two dimensions	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Can simulate both saturated and subsaturated media	No	No	Yes	Yes	Yes	No	Yes
Can generate pressure and velocity field	Yes	Yes	Yes	Yes	Yes	No	No
Steady and transient modeling	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sorption and decay term included	No	No	No	Yes	Yes	Yes	Yes
Variable boundary condition	No	No	Yes	No	Yes	No	No
Variable time step	Yes	Yes	Yes		Yes	No	No
Spatially-variable aquifer	Yes	No	Yes	Yes	Yes	No	No
Heterogeneous aquifer simulation	Yes	Yes	Yes	Yes	Yes	No	No

that may occur within the saturated or unsaturated soil to influence the behavior of a waste constituent, soil column studies are generally used to simulate natural field conditions. These experiments are used to quantify the potential for a given soil to attenuate specific constituents commonly present in disposal sites. Column studies are also useful in determining hydraulic properties and dispersion coefficients of specific soil or clay materials.

D.6.2 Complexity of Models

Computer simulation models are generally not easily understood by the "average" technical staff that would be associated with site selection or approval. The use of simulation models requires a degree of expertise for analyzing the system, quantifying the model input parameters, executing the model, and interpreting its results. While simplification of such models would overcome some of these limitations it would also impair the accuracy of the model and its capability to describe the true processes in the system. Furthermore, using models without an understanding of their logic, capabilities, and limitations may result in misrepresentations of the physical system and lead to unrealistic results. Some of the required expertise includes:

1. Mathematics (computer science, programming, and systems analysis).

2. Engineering.

3. Earth sciences (soil physics, soil chemistry, and hydrogeology).

4. Laboratory and field experimentation.

D.6.3 Equipment and Facilities

The use of simulation models requires that sophisticated equipment and certain facilities be available. These include:

1. A computer, and possibly plotters and other data-processing facilities for execution of the model.

2. Laboratory and field equipment for quantification of waste/soil characteristics and major

input parameters (adsorption and cation exchange properties, aquifer characteristics, dispersion coefficients, soil hydraulic properties, etc.).

D.6.4 Accuracy and Precision

The accuracy and precision of most existing models are still uncertain. Factors which contribute to this situation include the following:

1. Unknown accuracy of the main parameters entering the model (as discussed previously).

2. Many of the transport phenomena simulated in currently available models are limited to those which can be expressed in an explicit manner. The successful use of a simulation model requires that the different mechanisms present in the system can be quantified. Because many of the complex soil physical, chemical, and biological processes are still under examination, their quantification into reliable mathematical expressions remains incomplete. For example, it is known that extreme variations in quantity and quality of leachate occur over time, probably as an interplay between variables such as rainfall, evaporation, temperature, pH, and the age of the waste. Reliable predictions of leachate generation cannot be obtained before these interrelationships have been studied in detail, and certain quantitative relationships have been established.

3. Oversimplification of the actual physical processes occurring at the site and/or the receiving aquifer in order to complete the simulation. For example, heterogeneity of the site and the receiving aquifer are generally only included in a very approximate manner (e.g., channeling processes in a waste dump site, fractured flow in an aquifer, etc.).

D.7 MODELING VS. MONITORING OF SUBSURFACE CONTAMINANT DISPERSION

In determining how to develop predictions for assessing the future conditions of a subsurface waste disposal site subject to contaminant transport and dispersion, two basic techniques exist for consideration. The first would consist of initial field monitoring and laboratory studies of the disposal site and soils, followed by mathematical modeling of the designated constituents over the time period under consideration to develop anticipated concentration profiles. The second would involve substantial field monitoring of the disposal site for a long enough period to allow direct extrapolation of observed data to the end of the time horizon being considered.

The primary advantage of a modeling approach to the future assessment of a subsurface disposal site is its ability to make quantitative predictions of constituent concentration profiles under varying conditions. This feature alone gives a computer simulation model a unique advantage over other procedures. Types and levels of contaminants at various points and at different time intervals can be quantified relatively easily. In addition, the shape of a concentration plume can be described by such a model. The simulations can be useful tools in analyzing alternative containment techniques, and rapidly determining the impact of such practices. The computer model can also simulate and predict long-term effects, an important consideration when evaluating transport phenomena where movement may only be on the order of a few feet per year.

Site monitoring, on the other hand, provides extremely accurate point-specific data on conditions over the monitoring time period. By monitoring at enough locations a very descriptive map of the present situation can be determined. In order to develop a predictive capability, however, it would be necessary to continue a monitoring program for a sufficient period in order to reasonably extrapolate the results of the monitoring to future conditions. Because of the long time periods involved in subsurface low-level radioactive waste transport, where predictions in the range of a thousand years may be desired, extremely long monitoring periods may be necessary. This type of program would become very costly, and would not allow evaluation of alternative management policies in controlling the disposal site.

For these reasons, computer model simulations provide a substantial advantage over monitoring for developing predictions of future subsurface conditions at waste disposal sites. They also offer the substantial added capability of allowing rapid evaluation of alternative practices and estimates of the expected impacts of such actions. They allow the investigation of the long-term results of various contaminant options that could not be investigated by monitoring.

D.8 SUMMARY AND RECOMMENDATIONS

An assessment of various available subsurface pollutant transport models for possible application in the simulation of low-level radioactive waste transportation in subsurface water has been made. This assessment included flow and pollutant transport models which simulate unsaturated and saturated media. The finite element models developed by the Oak Ridge National Laboratory (FECWATER and FECWASTE) can be effectively used in simulating the radionuclide transport phenomena from a low-level radioactive waste site.

In order to understand the potential pollution of groundwater in and around a low-level radioactive waste site, it is necessary either to monitor the site closely or to predict the potential for the spread of pollutant concentration in the future. Unfortunately, the movement of groundwater is so slow (on the order of a few feet/year) that continuous monitoring of groundwater for as long as 10 years will not show significant movement of pollution transport. Therefore, by monitoring only, it will not be possible to accurately identify the potential for pollutant transport and concentration in groundwater in the distant future. On the other hand, by simulating the pollutant transport mechanism by mathematical modeling, it is possible to predict the potential transport of pollutants over a long period of time in a cost-effective manner. It is also possible to conduct a risk assessment of pollutant transport in a waste site that would result from pumping groundwater in the vicinity of the site. Therefore, it is preferable that mathematical modeling simulation of the transport of low-level radioactive wastes from a waste site be undertaken to predict risk assessment and future pollutant spread in the groundwater under various action plan conditions.

In order to conduct a modeling study to assess potential pollution of groundwater from low-level radioactive wastes, the following study steps are recommended:

1. Data Collection.

   Assemble necessary hydrogeological and waste characterization data as required for simulation in the hydraulic flow model (FECWATER) and pollutant transport model (FECWASTE). The hydraulic flow model (FECWATER) will generate the net groundwater flow and velocity in both unsaturated and saturated media. The output from FECWATER will become input for FECWASTE to generate the radionuclide movement under various boundary conditions.

2. Model Simulation of a Low-Level Radioactive Waste Site.

If historical data are available, it is always preferable that a site be simulated from the very beginning of the creation of the site, and to include all historical changes on the site since that time. These can be simulated in the model by incorporating various boundary conditions into the model. All available historical water quality data, including data collected in recent years, should be used in calibrating the model.

3. Evaluation of Decay Rates.

Laboratory column tests with the site soil should be performed to determine the leaching rate of radionuclides. These rates are evaluated in the laboratory and should be compared with the leaching rates obtained from field observations. After proper evaluation, leaching rates should be determined for use in tne modeling runs.

4. Prediction of Pollutant Transport in the Future.

After proper simulation and calibration of the model, the model should be used to predict the behavior of radionuclide pollution transport in the site groundwater. The model should be run to predict pollutant concentrations 100, 500, and 1,000 years in the future under existing site conditions (no action plan). The model should also be used to simulate and analyze alternative pollution containment plans. These simulations can be performed by simulating the proper boundary conditions that will result if the alternative containment plans are implemented.

5. Time for Development of a Steady State.

The model should also be used to find the future time at which a steady-state distribution of pollutants would be achieved under various alternative plans.

6. <u>Comparison of Transport of Pollutants Under Various Alternative Plans</u>.

A comparison of the extent of pollution in the future under various alternative plans should be made. The times required for development of a steady-state condition, and the extent of dispersion of the pollutant at this condition should be determined under various options.

7. <u>Risk Assessment</u>.

After calibration of the model with a proper decay coefficient, various risk assessments from the spread of the pollutant as a result of a fracture in the lining, or pumping in nearby wells should be conducted.

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APPENDIX [illegible]

GLOSSARY

APPENDIX E

GLOSSARY

AEC - Atomic Energy Commission

AEC-ORO - Atomic Energy Commission - Oak Ridge Operations

AJ-4 - Barium sulfate cake residue

AM-7 - Pitchblende raffinate

AM-10 - Colorado raffinate residue

anticline - A fold in the rock structure which is convex upward.

aquifer - A body of rock that contains sufficient saturated permeable material to conduct groundwater.

aquitard - A confining bed that retards but does not prevent the flow of water to or from an aquifer.

confined aquifer - An aquifer bounded above and below by impermeable beds or beds of lower hydraulic conductivity than the aquifer.

EPA - Environmental Protection Agency

external gamma radiation - Gamma radiation emitted from a source(s) external to the body, as opposed to internal gamma radiation emitted from ingested or inhaled sources.

fault - A surface or zone of rock fracture in which there has been movement on the fault plane.

GPR - Ground-penetrating radar

K-65 - Radium-bearing residues

lineament - Any line, on an aerial photograph, that is structurally controlled.

liquid limit - The highest water content at which a soil has a small but definite shear resistance.

loess - Homogeneous blanket of fine-grained sediments

μR - MicroRoentgen; a unit of radiation dose in air.

MED - Manhattan Engineer District

NRC - Nuclear Regulatory Commission

mrad - Millirad; a unit of absorbed radiation dose equivalent to the absorption of 0.1 erg of energy per gram of material of interest.

mrem - Millirem; the mrad dose multiplied by a modifying factor specific to the type and energy of the incident radiation.

ORNL - Oak Ridge National Laboratory

pCi - PicoCurie; a unit of radioactivity equivalent to 2.22 nuclear disintegrations per minute. A Curie is 2.22 x 10^{12} nuclear disintegrations per minute.

pCi/g - PicoCuries per gram (= 10^{-12} Curie per gram)

physiography - The description and origin of land forms in a geological sense.

piezometer - A nonpumping well, generally of small diameter, containing a small well screen which is used to measure the elevation of the water surface.

piezometric surface (potentiometric) - A surface that represents the level to which water will rise in tightly-cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one piezometric surface. The water table is a piezometric surface in an unconfined aquifer.

plasticity index - The difference between the liquid limit and the plastic limit.

plastic limit - The lowest water content at which a soil remains plastic, i.e., capable of deformation without crumbling.

radioactivity - The spontaneous decay or disintegration of an unstable atomic nucleus, usually accompanied by the emission of ionizing radiation.

radionuclide - Any element which is radioactive.

radium - A radioactive element, chemically similar to barium, formed as a daughter product of uranium (U-238). The most common isotope of radium, Ra-226 has a half-life of 1,620 years. Radium is present in all uranium-bearing ores. Trace quantities of both uranium and radium are found in all areas.

radon - A radioactive, chemically inert gas, having a half-life of 3.8 days (Rn-222); formed as a daughter product of radium (Ra-226).

radon daughter - Usually refers to one of the several short-lived alpha-emitting radioactive daughter products of radon.

raffinate - The part of a liquid (especially an oil) remaining after its more soluble components have been extracted by a solvent.

SLAPSS - St. Louis Airport Storage Site

stratigraphy - The study of the form, depositional history, geographic distribution, chronological succession, classification, and correlation and mutual relationships of rock strata.

syncline - A fold in the rock structure which is concave upward.

unconfined aquifer - An aquifer that is not bounded by impermeable beds or beds of lower permeability than the aquifer. An unconfined aquifer has a water table.