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THE EFFECT OF SOIL EROSION ON THE LONG-TERM STABILITY
OF FUSRAP NEAR-SURFACE WASTE-BURIAL SITES

by

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ABSTRACT

Decontamination of FUSRAP sites could result in the generation of large volumes (in excess of 400,000 m³) of low-activity radioactive wastes (primarily contaminated soil and building materials) requiring subsequent disposal. It is likely that near-surface burial will be seriously considered as an option for disposal of these materials. A number of factors--including soil erosion--could adversely affect the long-term stability of a near-surface waste-burial site. The majority of FUSRAP sites are located in the humid eastern United States, where the principal cause of erosion is the action of water. This report examines the effect of soil erosion by water on burial-site stability based on analysis of four hypothetical near-surface burial sites. The Universal Soil Loss Equation was employed to estimate average annual soil loss from burial sites and the 1000-year effects of soil loss on the soil barrier (burial trench cap) placed over low-activity wastes. Results suggest that the land use of the burial site and the slope gradient of the burial trench cap significantly affect the rate of soil erosion. The development of measures limiting the potential land use of a burial site (e.g., mixing large rocks into the burial trench cap) may be required to preserve the integrity of a burial trench for long periods of time.

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1. INTRODUCTION

During the 1940s and 1950s, the U.S. Army Corps of Engineers Manhattan Engineer District (MED) and the U.S. Atomic Energy Commission (AEC) conducted programs that resulted in a number of sites throughout the continental United States becoming radioactively contaminated. When MED/AEC activities were terminated, many of these sites were decontaminated in accordance with health and safety criteria and guidelines then in use. Recent radiological surveys of these formerly utilized sites have indicated that residual radioactive contamination exists at levels that may require remedial action at a number of the sites. The U.S. Department of Energy's (DOE) Formerly Utilized Sites Remedial Action Program (FUSRAP) was initiated for the purpose of decontaminating these sites to permit their unrestricted use or to stabilize and/or otherwise control residual radioactivity at the sites to meet current criteria for the protection of public health and safety.

Large volumes of soil and rubble containing trace amounts of radionuclides could be generated by the decontamination activities and require subsequent disposal. The manner in which these wastes are disposed is of considerable concern because these materials may require isolation from the public and the environment for extended periods of time. A number of options exist for the disposal of low-activity wastes, such as ocean disposal and placement in mine cavities. Options that have received much attention are in-situ stabilization, which would stabilize the radionuclides in place without removal; and near-surface disposal, which is defined in 10 CFR Part 61 as disposal within the uppermost 30 m (100 ft) of the earth's surface.

In-situ stabilization and near-surface disposal by burial, both of which may be characterized as near-surface burial, are among the most likely options for disposal of the FUSRAP wastes. At present, there are no specific regulations governing the near-surface burial of FUSRAP wastes. Most of the radionuclides at FUSRAP sites are currently distributed within 0.1 to 3 m of the earth's surface; for in-situ stabilization they would remain in place, but cover material might be added. If the near-surface disposal option were adopted, the wastes would probably be placed in trenches 6-10 m (20-33 ft) deep and buried beneath a 2-3 m (7-10 ft) cap and cover layer of soil.

A number of factors have the potential to adversely affect long-term burial-site stability, including: seismic activity, flooding, groundwater intrusion, soil erosion, biotic activity (e.g., disruption of the burial trench cap by burrowing animals), and human intrusion. Although most of these factors can be dealt with through proper site selection or burial-site design (e.g., through the use of biobarriers and intruder barriers), soil erosion will occur at all burial sites. Soil erosion, i.e., the physical removal of soil material from the surface of a burial site by the action of wind or water, could prove to be a major problem because this process not only

degrades the stability of the burial site, but also provides a mechanism for the transport of waste constituents into the surrounding environment. Erosion may also serve to enhance the probability of biological intrusion of buried wastes. The gradual loss of material from the soil barrier placed over the buried wastes would eventually allow penetration of the wastes by plant roots. The subsequent uptake, translocation, and accumulation of waste constituents by plants could serve to transport these materials into food chains and the surrounding environment.

It is clear that near-surface burial facilities for FUSRAP wastes should be designed and constructed to preserve the integrity of the sites over long periods of time. Unfortunately, the period of time that must be taken into account in assessing the environmental impacts caused by near-surface burial (in particular, the definition of "long term") has not yet been established. Most assessments of this type do not attempt analyses that extend beyond 1000 years, due in part to the limitations of models employed to predict the influence of factors such as soil erosion and groundwater intrusion on burial trench stability. As a result, the analysis of the effect of soil erosion on burial trench stability presented in this report will be limited to a "long-term" period of 1000 years, although it is recognized that much longer periods of time may be appropriate for determining whether near-surface burial is an appropriate disposal technique for FUSRAP wastes.

The length of time that FUSRAP wastes placed in near-surface burial sites will be isolated from the surrounding environment is, in part, dependent upon the amount of soil material placed over the wastes. As the thickness of the trench cap is increased, the length of time required for soil erosion to expose the buried wastes also increases. In the licensing requirements for land disposal of low-level radioactive wastes recently issued by the U.S. Nuclear Regulatory Commission in 10 CFR Part 61, the burial trenches for Class C intruder protected wastes* must remain stable for a period of 500 years--a time period sufficient to allow the shorter-lived radionuclides present in the wastes to decay to acceptable levels (U.S. Nucl. Reg. Comm. 1982). The radionuclides of concern in FUSRAP wastes have very long half-lives (e.g., uranium-238 has a half-life of 4.5×10^9 years and thorium-232 has a half-life of 1.4×10^{10} years). Obviously, it will not be possible to design a burial site such that its integrity will be retained for a period sufficient for these long-lived radionuclides to decay an appreciable amount. However, if near-surface burial of FUSRAP materials is implemented, the site should be designed to prolong the isolation of waste materials for as long as reasonably possible based on current engineering techniques.

The purpose of this report is to (1) estimate the rates of erosional soil loss likely to occur at hypothetical (model) FUSRAP near-surface burial sites, (2) assess how these erosion rates will affect soil cover layers, (3) determine

*The NRC regulations governing land disposal of low-level radioactive wastes (10 CFR Part 61) define three classes of wastes (A, B, and C) that would be accepted at NRC-licensed disposal sites; Class C intruder protected wastes are those with the highest allowed radioactivity content.

appropriate slope gradients and slope lengths for long-term burial sites, (4) evaluate the effect of various burial-site land uses on soil erosion rates, and (5) determine whether soil erosion will allow subsequent plant root intrusion of buried FUSRAP waste materials. Discussion will begin by introducing the reader to the history of the FUSRAP program and the assessment approach employed in this document.

1.1 DESCRIPTION OF THE FUSRAP PROGRAM

The MED and its successor, the AEC, conducted programs during the 1940s and 1950s involving research, development, processing, and production of uranium and thorium, and the storage of radioactive ores and their processing residues. These programs were conducted pursuant to the First War Powers Act of 1941 and the Atomic Energy Acts of 1946 and 1954, as amended. Virtually all of this work was performed for the government by private contractors at sites that were either federally, privately, or institutionally owned (U.S. Dep. Energy 1981). Many of these sites became contaminated as a result of work done for the government. When the contracts for MED/AEC activities were terminated, the sites involved were decontaminated according to health and safety criteria and guidelines then in use and applied on a site-specific basis. Radiological criteria, guidelines, and proposed guidelines for returning sites to unrestricted use, however, have become more stringent as research on the effects of low-level radiation has progressed and instrumentation for detecting and measuring low-level radiation has become more sophisticated.

A program was initiated by the AEC in 1974 to identify these formerly utilized MED/AEC sites, based on a review of historical records, to determine their radiological status. These activities were continued by the U.S. Energy Research and Development Administration (ERDA), successor to the AEC, and were extended to include contacts with current and former site owners, site visits, radiological surveys, and analyses of potential risks to public health. Under the U.S. Department of Energy Organization Act of 1977, the functions and authority of ERDA were transferred to DOE, including responsibility for the site survey program.

The results of several site surveys indicated that some remedial action was required at several of these sites as well as on adjacent or remote properties that had become contaminated by materials removed from the original processing sites. DOE subsequently initiated the Formerly Utilized Sites Remedial Action Program (FUSRAP). Through its various staff and program units, DOE is identifying the sites, characterizing their radiological condition, determining the need for remedial action at the sites, implementing the required remedial actions (including suitable disposal or stabilization of residual materials), and ultimately certifying the radiological condition of FUSRAP sites after remedial action has been completed.

To date, 35 formerly utilized MED/AEC sites have been identified (Figure 1.1). The need for remedial action has been established for 21 of these sites, and a probable need has been established for the remaining 14 sites (Ramsey 1981). The DOE Office of General Counsel has determined that DOE has the responsibility and authority to conduct remedial action at 10 of the 21 sites that need remedial action and at 4 of the sites that have a probable need.

Figure 1.1. Location of FUSRAP Sites as of September 1981.
Source: Argonne National Laboratory (1982).

1.2 SOIL EROSION ASSESSMENT APPROACH

Currently available techniques for estimating long-term erosional soil loss require fairly detailed information describing the soils involved (e.g., textural classification, permeability). Because no sites for the near-surface burial of FUSRAP wastes have yet been identified, it is not possible to obtain appropriate site-specific data. However, the objectives of this assessment can be met by developing information relative to hypothetical (model) near-surface burial sites. Due to the geographic distribution of FUSRAP sites (Figure 1.1), regions where waste-burial facilities may be needed can be identified. When this information is coupled with simple site-selection criteria that would be employed in siting any disposal facility [i.e., locations within 800 km (500 mi) of FUSRAP sites in seismically stable (Class I) regions], potential locations for near-surface burial sites can be identified.

This simple approach suggests that western New York, south-central New Jersey, north-central Ohio, and eastern Missouri are potential locations for waste-burial sites in the eastern United States. The availability of current (i.e., less than 15-year-old) soil surveys for counties in each of these regions was then determined through consultation with state offices of the U.S. Soil Conservation Service. Modern soil surveys should contain the information that is required to estimate soil erosion rates--i.e., the local climate conditions, agricultural practices, and soil characteristics. Appropriate county soil surveys were obtained, and specific soil types were identified for use as cover material for burial trenches at the model sites based on the following selection criteria: (1) the soil type represented approximately 10% or more of the county's soil, (2) the soil type had a soil capability ranking of Class I or II (i.e., no restrictions on the soil's use), and (3) the soil type was located on moderate slopes (0-15%). These criteria are intended to prevent the selection of a soil type with unique or unusual characteristics that might limit the usefulness of the erosion assessment.

2. ASSESSMENT METHODOLOGY

2.1 CHARACTERISTICS OF THE SOIL LOSS PROCESS

Physical removal of particles from a soil surface occurs through the action of both wind and water. In the humid eastern United States, where the majority of FUSRAP sites are located, the principal cause of soil loss is the action of water (i.e., the overland flow of water, raindrop impact, and freezing and thawing). This report focuses on the effects of water erosion on near-surface waste-burial sites.

In the water erosion process, soil particles are detached from the soil mass, transported downslope, and eventually deposited (Meyer et al. 1975). Impacting raindrops and flowing water are the erosive agents that work against the resisting forces of gravity and particle cohesion to detach and move soil material. When raindrops strike the soil surface, the erosion process normally begins. The explosive character of impacting raindrops disengages soil particles from the soil mass, and these particles are splashed in all directions from the impact point (Meyer et al. 1975). Under certain circumstances, raindrop splash can transport an appreciable amount of soil downslope (Brady 1974; Meyer et al. 1975). In addition, the beating of raindrops against the soil surface tends to destroy soil granulation. Water may also erode a soil surface by dissolution of soluble constituents. Runoff is the principal transport mechanism of the erosion-sedimentation processes induced by water.

The type of erosion affecting a specific burial site will be determined by a variety of factors including the intensity, frequency, and duration of rainfall; the cohesiveness of the soil particles; topographic factors such as length, roughness, and grade of slope; type of vegetative cover; and, in some areas, the magnitude of the snowmelt phenomenon. However, the principal surface-material characteristics influencing runoff and erosion are the type and density of vegetation occurring on the surface, the soil infiltration capacity (maximum rate at which water enters soil), and the structural stability of the burial-site soils and buried waste materials (Brady 1974). Runoff will not occur unless the rainfall rate exceeds the infiltration capacity of the soil (Meyer et al. 1975). Because attempts to reduce infiltration into the buried wastes may be made during burial-site construction (e.g., through soil compaction), the potential amount and intensity of runoff could be increased.

Once the rate of infiltration is exceeded by the rainfall rate, excess water begins ponding on the soil surface because of land microrelief (Meyer et al. 1975). If the excess rainfall rate continues for a sufficient period of time, the overland flow of water (surface runoff) begins. Surface runoff normally flows at a shallow (thin-film) depth for a short distance. This type of runoff is termed sheet or interrill flow. As surface runoff flows downslope, the flow is concentrated due to the influence of tillage marks, natural

microtopography, construction disturbances, or previous erosion (Meyer et al. 1975). The areas of concentrated flow are called rills, and the surface runoff occurring in them is termed rill flow.

The three principal types of water erosion generally recognized--sheet (or interrill), rill, and gully erosion--are related to the type of runoff flow. Sheet erosion results from the relatively uniform removal of particles from the exposed surface by runoff and may be responsible for large soil losses over long periods of time. Evidence of sheet erosion is apparent by the presence of perched pebbles and stones; in general, the higher the pedestal, the greater the intensity of active erosion. Sorting of surface materials may also be apparent because larger particles are less readily dislodged than smaller particles through sheet erosion. Rill erosion results from channelized flow of runoff, and development of rills occurs due to the continued abrasion of water and entrained sediment as well as soil sloughing from the sides of the rill. As runoff flow continues, erosion by rilling increases and rill patterns develop on sloping land (Meyer et al. 1975). The closer the spacing and the greater the depth of the rills, the greater is the intensity of active erosion. Gullies are essentially large rills formed by the coalescence of smaller rills. Gully erosion can develop quickly, resulting in large soil losses; but unlike sheet erosion, which affects large areas, gully erosion tends to be localized.

2.2 UNIVERSAL SOIL LOSS EQUATION

Assessment of water erosional losses requires a knowledge of the relationship between the factors that cause a loss of soil or waste material and those that help reduce such losses. Numerous controlled field plot and small watershed studies have been conducted to supply information regarding these complex interactions, and these studies have been incorporated into many forms of empirical soil loss equations. The purpose of these equations is to provide insight into the soil erosion process that will enable conservation planners to project limited erosion data to the many localities and conditions that are not directly represented in the research.

The best known and most widely applied of these empirical equations is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). Although the USLE was designed to predict losses from agricultural fields where water erosion was the predominant erosion force, the equation has been modified to facilitate characterizing the water-erosion potential of many areas. In recent years, the USLE has been modified to predict potential soil erosion from construction sites, areas strip-mined for coal, and storage sites for coal-combustion wastes. The USLE estimates average annual or long-term average seasonal erosion. The equation is simple, easy to use, and widely accepted as an appropriate tool for analyzing water erosion (Foster 1979). A major strength of the equation is its extensive parameter data set that can be used to select input parameters generally appropriate for the geographic location, soil, topography, and vegetation management practices of a given site.

However, use of the USLE does have several limitations; the advantages and disadvantages are summarized in Table 2.1. Among the more important limitations of the USLE is the fact that it does not include soil loss due to gully erosion. Gullying can result in significant amounts of erosion in very

Table 2.1. Advantages and Disadvantages Associated With Using the Universal Soil Loss Equation†¹

Advantages	Disadvantages
Widely accepted tool to predict water erosion soil losses	Originally developed to predict erosion from agricultural lands
Yields good estimates of long-term average erosion rates	Does not accurately estimate erosion for a specific season or year
Applies best to uniform slopes (as would be expected at a FUSRAP burial site)	Only predicts soil loss due to sheet and rill erosion; does not predict erosion from concentrated water flow (gullying)
Well adapted to predict soil loss over long periods of time	Does not estimate onsite deposition† ² Does not account for the influx of soil material from offsite

†¹ Data from Foster (1979).

†² An assumption of the USLE is that all soil particles dislodged from the soil surface of concern are transported and deposited downslope of that surface. No dislodged soil particles come to rest on the soil surface being considered.

short periods of time. This could result in the rapid exposure of buried FUSRAP wastes and their transport into the surrounding environment. There is no accepted method available today for quantifying the probability of gully occurrence or rate of growth. However, if a waste-burial trench is designed and constructed to prevent the channelized flow of water, the potential for gully formation can be minimized. It is assumed that this will be the case for the model burial sites considered in this report. Despite the limitations of the USLE, it is currently the only practical equation available for estimating average annual or seasonal water erosion from farm fields and other soil surfaces (Foster 1979).

The USLE is an erosion model that can be used to estimate the sediment generated and displaced from a given area by sheet and rill erosion over time. For a given site, the soil erosion loss is computed to be the product of five major factors:

$$\text{Erosion Loss} = R \times K \times LS \times C \times P$$

where erosion loss is the computed soil loss per unit area per year. Each of these five factors is discussed below.

Rainfall and Runoff Factors (R). Rainfall and runoff factors, or R values, represent the integration of raindrop effect and the amount of runoff, and they are represented by the rainfall erosion index. The relation of soil loss to this parameter is assumed to be linear. The rainfall erosion index for each locality represents the average annual total of storm energies as a function of the amount of rain and the intensity for each storm multiplied by the maximum 30-minute rainfall intensity recorded for the area. Adjustments in R values are required for areas where significant runoff results from ice or snowmelt. Rainfall and runoff factors have been calculated for numerous areas throughout the contiguous United States and are graphically displayed in Figure 2.1 (Wischmeier and Smith 1978). In general, the greater the R value, the greater the potential for erosion due to precipitation.

Erodibility Factors (K). Soil erodibility factors (K) are quantitative values that are experimentally determined. For a particular soil, the K factor is the rate of soil loss per erosion index unit as measured on a "unit" plot. A unit plot has been defined as 22-m (73-ft) long, with a uniform lengthwise slope of 9% on continuously fallow land (i.e., tilled and kept free of vegetation for more than two years), tilled up and down the slope. Tables of experimentally determined soil erodibility factors, or K values, are available from state Soil Conservation Service offices for many specific soils. It is also possible to estimate the K factor of a particular soil using a procedure developed by Wischmeier and Smith (1978).

Topographic Factors (LS). Topographic factors (LS) are a combination of the effect of a slope length factor (L) and a slope gradient factor (S). Slope length is defined as the distance from the point of origin of overland flow to the point where either the slope gradient decreases enough that deposition of entrained soil particles begins or the runoff water enters a well-defined channel within a drainage network. The L factor is the ratio of soil loss from the field slope length of the area in question to that from a 22-m (73-ft) slope length under identical conditions. The S factor is the ratio of soil loss from a field slope gradient to that from a 9% slope under otherwise identical conditions.

Cover Factors (C). Cover factors (C) represent the effects of vegetative cover and land management practices. The C factor is the ratio of soil loss from land cropped or maintained under specified conditions to the corresponding loss from a clean-tilled, continuously fallow field. In a case in which all aboveground vegetation and plant roots are removed, the C value for the denuded area will be equal to one. In a case in which a regional waste-burial site would be allowed to return to the natural plant community successional process of that region, the C value would change with each successional sere.

Support Practice Factors (P). The support practice factor (P) is the ratio of soil loss with a support practice (e.g., contouring, stripcropping, or terracing) to that with straight-row farming up and down the slope. The P factors at unrevegetated, unprotected sites may be equal to one; P factors for managed burial sites could be less than one. Contour terracing could be used to alter slope characteristics, but the erosion-reducing effects due to terracing would be accounted for in the determination of LS values.

Figure 2.1. Average Annual Values of the Rainfall Erosion Index. From Wischmeier and Smith (1978).

3. DESCRIPTION OF FOUR MODEL NEAR-SURFACE WASTE-BURIAL SITES

Information describing four model near-surface waste-burial sites is presented to illustrate the effects of varying soil characteristics, climatic conditions, and vegetation management practices on the rate of soil erosion from the cap of a burial trench. All model waste-burial sites are composed of shallow-land burial trenches having average dimensions of 180-m (590-ft) long, by 60-m (200-ft) wide, by 8-m (26-ft) deep. The length and width of disposal trenches may vary somewhat due to local conditions. Wastes from FUSRAP sites are placed to within 1 m of the top of the trench. Earthen fill is then backfilled into the trench. A cap (1 to 2 m in thickness) composed of soil and subsoil is then placed onto the backfill and mounded to promote runoff away from the disposal trench. These trench design details are in general agreement with those presented by the U.S. Nuclear Regulatory Commission (1982) in its environmental impact statement on licensing requirements for land disposal of low-level radioactive wastes (10 CFR Part 61). Although various support facilities and buildings will be built on the burial site during construction and filling of the burial trenches, it is assumed that these structures will be removed prior to site closure.

It is likely that the soil and subsoil of the burial trench will be compacted to reduce the rate of water infiltration into the underlying wastes. The compaction of soil drastically alters some of its physical characteristics (e.g., soil bulk density). The soil erodibility factor (K) of the USLE is based upon the physical characteristics of soil; therefore, to apply the USLE, the physical characteristics of the compacted soil of the trench cap must be known. Because these characteristics cannot be known without site-specific measurement, it has been assumed for this report that no special compaction is performed on the backfill or cap other than that provided by trucks and heavy earth-moving equipment used to place the soil material over the wastes. This will allow application of the USLE using information contained in county soil surveys. It should be noted that this assumption will not significantly affect the accuracy of the 1000-year erosion assessment. Within 5-10 years following soil compaction, the action of (1) plant roots penetrating the trench cap, and (2) frost heave will return the physical character of the soil to a state similar to that of undisturbed soil of the same classification.

After the wastes are placed in the trench, the cap will be covered with sufficient topsoil or other soil to promote good drainage characteristics and provide an appropriate medium for plant growth. Topsoil will be spread according to the final contours planned for the site surface. Depending upon the slope gradient employed, between 2 and 3 m of soil material will lie between the buried wastes and the earth's surface. To determine the effect of slope gradient on soil loss from the trench cap, four slopes of 2, 5, 10, and 15% will be evaluated. The length of slope will be held constant at 30 m (100 ft). These slope-gradient and slope-length conditions correspond to LS factors of 0.2, 0.5, 1.4, and 2.6 for slope gradients of 2, 5, 10 and 15%, respectively (Wischmeier and Smith 1978).

3.1 NEW YORK MODEL WASTE-BURIAL SITE

The New York model waste-burial site is assumed to be located in Wyoming County, in the western part of the state. The county is about 32 km (20 mi) east of Lake Erie, 56 km (35 mi) south of Lake Ontario, and about 56 km (35 mi) north of the Pennsylvania state line (U.S. Soil Conserv. Serv. 1974). Wyoming County has an area of about 155,000 ha (383,000 acres) or about 1550 km² (600 mi²). The rainfall factor (R) of this area is estimated to be 88 (Figure 2.1).

The principal land use of the county is farming, with about two-thirds of the land area used to grow crops (U.S. Soil Conserv. Serv. 1974). Important crops include white potatoes, dry beans, wheat, maple products, and crops grown for use in dairy farming (e.g., field corn). Dairy farming is the dominant type of farming.

The remaining one-third of the county is forested. Most of the forested areas are scattered throughout the county, principally on steeper slopes. The dominant native plant community in the county is the beech-maple forest association. This association occurs only on glaciated land and is best developed on mesic, fairly well-drained sites (VanKat 1979). The dominant plant species are American beech (Fagus grandifolia) and sugar maple (Acer saccharum); the beech is usually somewhat more important in the canopy, with the maple dominant in the understory.

The model burial site is assumed to be located in soils of the Bath-Mardin soil association, which comprises about 9.5% of the soils of the county. Specifically, the model site is assumed to be located in an area of Bath-Channery silt loam soil, with 0 to 3% slopes. This soil type is deep and well-drained, and was formed in acid, loamy, glacial till derived mainly from sandstone and shale. This soil is nearly level and generally located on higher plateaus; it receives little or no runoff from adjacent slopes. Individual areas of this soil range from 2 to 20 ha (5 to 50 acres) in size. Bath-Channery silt loam has an average bulk density of 1908 kg/m³ (119 lb/ft³) and a plant rooting zone of 46 to 86 cm (18 to 34 in.). The soil erodibility factor (K) for Bath-Channery silt loam has been calculated by the U.S. Soil Conservation Service as being 0.24.

3.2 NEW JERSEY MODEL WASTE-BURIAL SITE

The New Jersey model waste-burial site is assumed to be located in Burlington County, in the central part of the state. The county is 24 km (15 mi) south of Trenton and 32 km (20 mi) east of Camden, lying southeast of the Delaware River (U.S. Soil Conserv. Serv. 1971). Burlington County has an area of about 212,000 ha (524,000 acres), or 2120 km² (820 mi²). The rainfall factor (R) of this area is estimated to be 200 (Figure 2.1).

Land use in the county is divided between forest (54%), farmland (30%), residential communities (12%), and federally owned land (4%). Most of the productive farmland is located in the approximately one-third of the county that parallels the Delaware River. Important crops include sweet corn and peaches, as well as other general crops (e.g., field corn, soybeans, small grains) and vegetables. In some of the eastern portions of the county, blueberries and cranberries are grown extensively.

The principal native plant community in Burlington County is the oak-hickory forest association. Mature stands are dominated by oaks, with hickories secondary in importance (VanKat 1979). Some of the more widespread oaks include white oak (*Quercus alba*), red oak (*Q. rubra*), and black oak (*Q. velutina*). Common hickories include bitternut hickory (*Carya cordiformis*), mockernut hickory (*C. tomentosa*), red hickory (*C. ovalis*), and shagbark hickory (*C. ovata*). In addition, large tracts of the county are covered by pine forests that are dominated by pitch pine (*Pinus rigida*) and Virginia pine (*P. virginiana*).

The model burial site is assumed to be located in soils of the Freehold-Holmdel-Adelphia soil association, which comprises about 18% of the soils of the county. Specifically, the model site is located in an area of Freehold fine sandy loam soil, with 0 to 2% slopes. This soil type is a well-drained soil that has a moderately high available-water capacity. Freehold soils, which were generally formed in glauconitic marine deposits, contain small amounts of glauconite. These soils are well suited to crops and are the most extensively farmed soils in the county. This soil has an average bulk density of 1844 kg/m³ (115 lb/ft³) and a soil erodibility factor (K) of 0.33 (U.S. Soil Conserv. Serv. 1971).

3.3 OHIO MODEL WASTE-BURIAL SITE

The Ohio model waste-burial site is assumed to be located in Ashland County, in the north-central part of the state. The county is about 72 km (45 mi) southwest of Cleveland, 137 km (85 mi) southeast of Toledo, and 121 km (75 mi) northeast of Columbus (U.S. Soil Conserv. Serv. 1980). Ashland County has an area of about 109,700 ha (271,100 acres). The rainfall factor (R) of Ashland County is estimated to be 125 (Figure 2.1).

About 83,000 ha (205,000 acres) of the county is devoted to farming (U.S. Soil Conserv. Serv. 1980). Dairy farming makes up 52% of all farming and is especially predominant in central and southern Ashland County. Soybeans and corn are the main cash crops. Corn, oats, and wheat are grown for use as feed for beef, cattle, and hogs.

The predominant native plant community in Ashland County is the beech-maple forest association (VanKat 1979) (see Section 3.1).

The model burial site is assumed to be located in soils of the Canfield-Wooster-Ravenna soil association, which makes up about 14% of the soil of Ashland County. Specifically, the model site is located in an area of Canfield silt loam soil, with 2 to 6% slopes. This soil type is a gently sloping, deep, moderately well-drained soil on till plains and moraines. It occurs in convex areas having long, uniform slopes. Such areas range between 8 and 81 ha (20 to 200 acres) in size. This is the most extensive soil of the county. Canfield silt loam has an average bulk density of 1924 kg/m³ (120 lb/ft³) and a soil erodibility factor (K) of 0.37 (U.S. Soil Conserv. Serv. 1980).

3.4 MISSOURI MODEL WASTE-BURIAL SITE

The Missouri model waste-burial site is assumed to be located in Warren County, in the east-central part of the state. The county is about 72 km (45 mi) northwest of St. Louis, 97 km (60 mi) northeast of Jefferson City, and 72 km (45 mi) east of Columbia. Warren County has an area of about 111,000 ha (274,000 acres) or about 1110 km² (430 mi²) (U.S. Soil Conserv. Serv. 1978). The rainfall factor (R) of this area is estimated to be 210 (Figure 2.1).

About 65% of the acreage of Warren County is used for farming (U.S. Soil Conserv. Serv. 1978). Cropland makes up about 55% of Warren County, with 33% woodland and the remainder open pasture. Although corn, soybeans, and wheat are the principal crops, livestock (mostly beef cattle and hogs) is the biggest income product of the area.

The principal native plant communities in Warren County include the oak-hickory forest association and the bluestem prairie parkland (Bailey 1978; VanKat 1979). The oak-hickory forest was described in Section 3.2. The bluestem prairie parkland vegetation is forest-steppe, characterized by the intermingling of prairie and groves or strips of deciduous trees (Bailey 1978). Dominant prairie species include big bluestem (Andropogon gerardi), little bluestem (A. scoparius), Indian grass (Sorghastrum nutans), switchgrass (Panicum virgatum), Canada wild-rye (Elymus canadensis), needlegrass (Stipa spartea), prairie dropseed (Sporobolus heterolepis), side-oats grama (Bouteloua curtipendula), and Junegrass (Koeleria cristata). The deciduous trees of the bluestem prairie parkland are those of the oak-hickory association.

The model burial site is assumed to be located in soils of the Mexico-Armster-Putnam soil association, which comprises 35% of the soils of the county. Specifically, the model site is located in an area of Mexico silt loam soil, with 1 to 5% slopes. This soil type consists of deep, somewhat poorly drained, gently sloping soil on uplands. Mexico silt loams were formed in loess under tall grass prairie. This soil occurs on areas of 32 to 162 ha (80 to 400 acres) in size that are used mainly for corn, soybeans, wheat, and rotation meadow. The soil is well suited for these uses, as well as for permanent pasture. The average bulk density of Mexico silt loam is 1332 kg/m³ (83.1 lb/ft³); the soil erodibility factor (K) is 0.43 (U.S. Soil Conserv. Serv. 1978).

4. DESCRIPTION OF VEGETATION MANAGEMENT PRACTICES AT THE FOUR MODEL WASTE-BURIAL SITES

4.1 INTRODUCTION

One of the more important factors in determining the rate of erosion from a FUSRAP near-surface waste-burial site will be the manner in which vegetation established on the site is managed following site closure. Although it is likely that backfilled burial trenches will be initially seeded with mixtures of grasses and legumes, the type of plant community that will develop on the site in subsequent years is unclear. Plant community development will in large part be determined by the land use chosen for the burial site and the management practices associated with that use.

It should be noted that for purposes of this assessment, it is assumed that the land use chosen for the burial site will not result in extensive disruption of the trench cap. The abrupt soil loss and potential for waste transport into the surrounding environment resulting from such disruption cannot be readily accounted for by the approach employed in this assessment. Use of a near-surface burial site for commercial or industrial development is also precluded due to the likelihood that construction activities would disturb the buried waste materials.

Potential land uses of FUSRAP near-surface burial sites that will not cause extensive disruption of the burial trench cap, and the requirements of each land use are presented in Table 4.1. Although currently proposed criteria for the disposal of low-level radioactive wastes will restrict burial-site land use during a 100-year period of institutional control following site closure, it is not clear whether land use will be restricted during ensuing years. It is assumed in this report that the burial site will be released for unrestricted use following the lapse of institutional control. To determine the effect of various land uses on soil erosion, three different burial-site land uses will be considered in the assessment: (1) the development of wildlife habitat through natural succession to the local climax vegetation, (2) use of the site as permanent pasture (i.e., sustained as pasture through active maintenance and grazing pressure), and (3) use of the site for row-crop agricultural culture.

4.2 VEGETATION MANAGEMENT PRACTICES

Natural successional patterns will vary with burial-site location. It is assumed that natural succession will begin at the end of the period of institutional control. At the New York and Ohio burial sites, natural succession could lead to the establishment of a mature beech-maple forest after about 250 years. In New Jersey, about 200 years would be required for the development of a mature oak-hickory forest (Whittaker 1975). Mature tall grass

Table 4.1. Potential Land Uses and Requirements of Revegetated FUSRAP Near-Surface Waste-Burial Sites†¹

Potential Land Use	Land-Use Requirements
Wildlife habitat	Development of adequate plant cover and vegetation through natural succession.
Livestock grazing or limited agriculture	Development of adequate plant cover and vegetation in permanent pasture communities; added protection of fill slopes to prevent erosion resulting from animal or vehicle traffic; maintenance of vegetation.
Row-crop agriculture	Management and maintenance of vegetation and soil fertility; stable underlying wastes; possible increased erosion control to prevent exposure of buried wastes.

†¹ Adapted from GAI Consultants (1979).

prairie could be established at the Missouri burial site in about 100 years. The various successional seres involved will influence the value of the vegetative cover factor (C) of the USLE. Using information presented in Wischmeier and Smith (1978), appropriate C factors have been determined for each successional sere (see Table 4.2).

The assumptions for permanent pasture at all burial sites are as follows. Permanent pasture will be composed of grass and grasslike plants. The average plant canopy height will be 51 cm (20 in.), the average plant canopy cover 75%, and the average ground cover 80%. Decaying compacted plant litter (5-cm [2-in.] deep) will cover much of the soil surface. These characteristics result in a C factor of 0.038 for this land use (Wischmeier and Smith 1978).

The crops grown on burial sites employed for row-crop agriculture will vary between model sites. However, it is difficult to determine C factors for row-crop agriculture without knowledge of local planting times, the amount of crop residues left in the field, and the type, frequency, and timing of tillage (Wischmeier and Smith 1978). Therefore, the C factor for row-crop agriculture at all four model burial sites is assumed to be 0.35 (Wischmeier and Smith 1978). This value corresponds to that of a midwestern 4-year crop rotation of wheat, meadow, and corn (grown in two successive years) using good soil management practices (e.g., contour plantings) on moderately sloping land.

The final variable of the USLE is the support practice factor (P). In this assessment, the P factors for burial sites used for row-crop agriculture and permanent pasture are 0.60, 0.50, 0.60, and 0.70 for areas with slopes of 2, 5, 10, and 15%, respectively (Wischmeier and Smith 1978). The P factor for burial sites allowed to return to natural succession is assumed to be 1.0, i.e., no support practice employed.

Table 4.2. The Influence of Stage of Succession on the Vegetative Cover Factor of the Universal Soil Loss Equation at Four Model Near-Surface Waste-Burial Sites

Stage of Natural Succession† ¹	Length of Stage (years)	Vegetative Cover Factor (C)‡ ²
<u>New York Model Site</u>		
Old field/meadow	25	0.011
Shrub/young trees	25	0.012
Early forest development	200	0.011
Mature beech-maple forest	650	0.0001
<u>New Jersey Model Site</u>		
Old field/meadow	20	0.011
Shrub	15	0.040
Young pine/oak forest	165	0.011
Mature oak-hickory forest	700	0.001
<u>Ohio Model Site</u>		
Old field/meadow	25	0.011
Shrub/young trees	25	0.012
Early forest development	200	0.011
Mature beech-maple forest	650	0.0001
<u>Missouri Model Site</u>		
Old field/meadow	25	0.011
Prairie development	75	0.011
Tall grass prairie	800	0.003

†¹ General successional patterns developed from information in Daubenmire (1968), Whittaker (1975), and VanKat (1979).

‡² Data from Wischmeier and Smith (1978).

5. ASSESSMENT OF LONG-TERM SOIL LOSS FROM THE FOUR MODEL WASTE-BURIAL SITES

Long-term soil losses from the four model waste-burial sites were assessed by applying the USLE to the sites using the parameters described in Sections 3 and 4. The average annual soil loss from each site was calculated using three vegetation management practices and four slope gradients; these data are presented in Table 5.1. As would be expected, soil loss at all four model sites increases with increasing slope gradient. Erosional loss also increases with the intensity of land use, i.e., natural succession < permanent pasture < row-crop agriculture.

Using the soil-loss data, the average annual and long-term (1000-year) losses of soil material from the burial trench cap were calculated in the following manner. Initially, the bulk density of the soil at each model burial site (see Section 3) was used to determine the weight of a 2.54-cm (1-in.) layer of soil 1 ha (2.5 acres) in extent. These weight values, along with estimates of soil erosion (t/ha/yr) for each site, were then used to estimate the amount of trench cap lost annually (mm/yr) or over the long-term period (cm/1000 yr). For natural succession, the individual seres were evaluated separately over the appropriate lengths of time (see Table 4.2) to give the long-term losses over the assessment period, and these values were averaged to give the annual average soil losses. It was assumed that there would be no net loss of soil during the 100-year period of institutional control or, if significant erosion did occur, site maintenance actions would include the addition of soil material to the trench cap. Therefore, erosion was estimated for the subsequent 900 years of the 1000-year assessment period. Estimates of the average annual and long-term loss of soil material from the trench cap at each of the four model waste-burial sites are presented in Tables 5.2 and 5.3. It should be emphasized that these estimates are derived by extrapolation of the average annual soil loss estimates made with the USLE. The USLE does not take into account changes in environmental factors, such as climate or topographic relief, that will undoubtedly occur during this period. Changes in these factors will subsequently alter the composition and structure of plant communities on the burial trench. Changes in these factors will, in turn, alter the rate of soil erosion.

Table 5.1. Average Annual Loss of Soil at the Four Model Waste-Burial Sites Under Three Vegetation Management Practices and Four Slope Gradients

Vegetation Management Practice	Soil Loss (t/ha/yr) per Slope Gradient			
	2%	5%	10%	15%
<u>NEW YORK MODEL SITE</u>				
Natural succession:				
Old field stage	0.06	0.14	0.43	0.94
Shrub/young tree stage	0.07	0.15	0.47	1.0
Early forest stage	0.06	0.14	0.43	0.94
Mature beech-maple forest	0.001	0.001	0.004	0.009
Permanent pasture	0.22	0.5	1.5	3.2
Row-crop agriculture	1.9	4.3	13	29

<u>NEW JERSEY MODEL SITE</u>				
Natural succession:				
Old field stage	0.34	0.87	2.2	4.2
Shrub stage	1.2	3.2	8.1	15
Young pine/oak forest stage	0.34	0.87	2.2	4.2
Mature oak-hickory forest	0.03	0.09	0.20	0.38
Permanent pasture	0.67	1.5	4.6	10
Row-crop agriculture	6.0	13	41	90

<u>OHIO MODEL SITE</u>				
Natural succession:				
Old field stage	0.22	0.61	1.6	2.9
Shrub/young tree stage	0.27	0.67	1.7	3.2
Early forest stage	0.22	0.61	1.6	2.9
Mature beech-maple forest	0.002	0.007	0.01	0.02
Permanent pasture	0.47	1.1	3.3	7.1
Row-crop agriculture	4.3	9.5	29	63

<u>MISSOURI MODEL SITE</u>				
Natural succession:				
Old field stage	0.27	0.61	1.8	4.0
Prairie development stage	0.27	0.61	1.8	4.0
Tall grass prairie	0.07	0.16	0.49	1.1
Permanent pasture	0.92	2.1	6.3	14
Row-crop agriculture	8.3	18	57	120

Table 5.2. Average Annual Loss of the Burial Trench Cap at the Four Model Waste-Burial Sites Under Three Vegetation Management Practices and Four Slope Gradients

Vegetation Management Practice	Burial Trench Cap Loss (mm/yr) per Slope Gradient† ¹			
	2%	5%	10%	15%
<u>NEW YORK MODEL SITE</u>				
Natural succession† ²	0.0008	0.002	0.006	0.01
Permanent pasture	0.01	0.02	0.07	0.2
Row-crop agriculture	0.09	0.2	0.6	1

<u>NEW JERSEY MODEL SITE</u>				
Natural succession† ³	0.006	0.01	0.04	0.07
Permanent pasture	0.03	0.07	0.2	0.5
Row-crop agriculture	0.3	0.6	2	4

<u>OHIO MODEL SITE</u>				
Natural succession† ⁴	0.003	0.008	0.02	0.04
Permanent pasture	0.02	0.05	0.2	0.3
Row-crop agriculture	0.2	0.4	1	3

<u>MISSOURI MODEL SITE</u>				
Natural succession† ⁵	0.006	0.01	0.04	0.1
Permanent pasture	0.06	0.1	0.4	1
Row-crop agriculture	0.6	1	4	8

†¹ All data have been rounded to one significant figure. No losses are assumed to occur during the 100 years of institutional controls.

†² Natural succession to beech-maple forest.

†³ Natural succession to oak-hickory forest.

†⁴ Natural succession to beech-maple forest.

†⁵ Natural succession to tall grass prairie.

Table 5.3. Long-Term Loss of the Burial Trench Cap at the Four Model Waste-Burial Sites Under Three Vegetation Management Practices and Four Slope Gradients

Vegetation Management Practice	Burial Trench Cap Loss (cm/1000 yr) per Slope Gradient† ¹			
	2%	5%	10%	15%
<u>NEW YORK MODEL SITE</u>				
Natural succession† ²	0.08	0.2	0.5	1
Permanent pasture	0.9	2	6	10
Row-crop agriculture	8	20	60	100

<u>NEW JERSEY MODEL SITE</u>				
Natural succession† ³	0.5	1	3	6
Permanent pasture	3	7	20	40
Row-crop agriculture	30	60	200	400

<u>OHIO MODEL SITE</u>				
Natural succession† ⁴	0.3	0.7	2	4
Permanent pasture	2	5	10	30
Row-crop agriculture	20	40	100	300

<u>MISSOURI MODEL SITE</u>				
Natural succession† ⁵	0.6	1	4	9
Permanent pasture	6	10	40	90
Row-crop agriculture	50	100	300	700

†¹ All data have been rounded to one significant figure. No losses are assumed to occur during the 100 years of institutional controls.

†² Natural succession to beech-maple forest.

†³ Natural succession to oak-hickory forest.

†⁴ Natural succession to beech-maple forest.

†⁵ Natural succession to tall grass prairie.

6. LONG-TERM STABILITY OF THE FOUR MODEL WASTE-BURIAL SITES

Although the constraints of the USLE limit the accuracy of soil erosion loss estimates for the model waste-burial sites, the data developed in this assessment allow a number of general conclusions to be made. As one would expect, the slope of the burial trench cap has a large effect on soil erosion. Regardless of the vegetation management practices employed, the loss of soil material from the trench cap will more than double when the slope of the cap is increased from 5 to 10%. The use of slopes of 5% or less reduces the velocity of runoff, allows for a greater amount of infiltration, and therefore reduces the amount of soil erosion.

The vegetation management practices, or land uses, employed at the model sites also have a significant effect on erosion. As the intensity of land use increases from wildlife habitat (developed through natural succession) to row-crop agriculture, soil material loss from the trench cap also increases. By the end of the 1000-year assessment period, use of the four model sites with 10 or 15% slopes for row-crop agriculture could result in erosional loss of significant portions or potentially all of the soil cap placed over the buried wastes. It would appear that use of a burial trench for row-crop agriculture could lead to disruption of burial-trench integrity and allow for FUSRAP waste constituents to be dispersed into the environment far more rapidly than for the other land uses considered in this analysis. This conclusion suggests that measures may be needed to limit the potential land use of a burial site following the 100-year period of institutional control. These measures might include the development of "land-use barriers" such as mixing large rocks with the soil materials of the trench cap to discourage plowing or disking of the burial site.

With the exception of the Missouri model burial trench with 15% slopes, use of the model facilities for permanent pasture would not result in significant erosion (i.e., 30 to 50% loss of the soil cap) of the trench cap over the 1000-year assessment period. This land use does not appear to jeopardize the long-term stability of the model burial sites. Permanent pasture may also be a land use compatible with the land-use barrier discussed above.

The principal effect of erosional losses would be a reduction in thickness of the soil barrier placed over the buried FUSRAP wastes. This would increase the potential for plant root intrusion of the buried wastes and allow the subsequent uptake and translocation of radionuclides by plants. For example, the effective rooting depth for crop plants at the New York model site is between 46 and 87 cm. Once a burial trench is backfilled, approximately 2.5 m of soil will overlie the buried wastes. Thus, if the site were used for row-crop agriculture and plants became established on the trench cap, a "buffer zone" of about 163 cm of soil would exist between the maximum plant rooting zone and the FUSRAP wastes. If the trench cap had 15% slopes,

sufficient erosion might occur during the assessment period to remove a significant portion of the buffer zone and potentially allow root penetration of the waste materials.

The lowest rate of long-term soil barrier loss would be achieved by allowing the burial trenches to revert to wildlife habitat through natural succession. This is due primarily to (1) the dense plant canopy of forest and prairie plant communities, which reduces the energy of raindrop impact onto the soil surface, and (2) the thick layer of detritus that develops over the soil surface in these ecosystems, which further shields the underlying soil from raindrop impact. Vegetation and detritus also obstruct the flow and reduce the velocity of surface runoff, thus reducing the erosive force of the runoff.

However, although the estimated rate of soil barrier loss is lowest when native climax plant communities are allowed to develop, the potential for root penetration of the buried wastes is increased. A mature tree, 30-m (100-ft) tall, will have a root system penetrating up to 3 m (10 ft) into the soil (Edlin 1976), whereas the root systems of mature prairie species will penetrate the uppermost 0.6 to 6 m (2 to 20 ft) of the soil (Weaver 1968). Thus, the development of climax native plant communities on the trench cap will likely result in root intrusion of the buried wastes. The use of biobarriers--physical (e.g., coarse rock layers placed between the wastes and soil cap) or chemical (e.g., controlled-release herbicides placed at the waste/soil cap interface as a barrier to plant roots)--will initially prevent root penetration of FUSRAP wastes. These barriers will eventually be breached, perhaps within 100 to 300 years--roughly corresponding to the length of time thought to be required to develop climax vegetation on a disturbed site.

In other words, biobarrier systems appear to be ineffective in preventing the eventual intrusion of FUSRAP wastes by the deep roots of climax vegetation. The only method of preventing root intrusion by natural vegetation would seem to be burial of waste materials beneath a far deeper soil cap, the thickness of which would far exceed the maximum rooting depth of the climax vegetation expected to occur at the burial site. This alternative could drastically increase the cost of waste disposal.

It should be noted that in a recent review of the literature describing the uptake and accumulation of radionuclides in FUSRAP wastes (Knight 1983), it was reported that the principal radionuclides present--i.e., uranium, thorium, and radium--have a low propensity for plant uptake. Although some plant uptake and accumulation of these radionuclides does occur, the amount transferred from the plant growth medium to shoot or root tissue is probably small. It appears that the small amounts of radionuclides taken up by plants may be accumulated in root tissue. Thus, root intrusion of FUSRAP near-surface burial trenches, and the subsequent death and decay of root tissue, might result in the movement of these radionuclides from the waste materials into the uncontaminated trench cap overlying the wastes. During extended periods of time, this increase in trench cap radionuclide levels could become significant. Information describing the uptake and accumulation of these radionuclides by plant root tissue is needed to determine whether or not this phenomenon would occur.

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