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OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

ORNL/TM-9877

Characterization Plan for Solid Waste Storage Area 6

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ENVIRONMENTAL SCIENCES DIVISION

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ENVIRONMENTAL SCIENCES DIVISON

CHARACTERIZATION PLAN FOR SOLID WASTE STORAGE AREA 6

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) has issued Orders 5820.2 and 5480.14, which provide policy and guidelines for the management of radioactive wastes and the implementation of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) program, for inactive waste disposal facilities. Existing DOE waste management facilities are required to comply with both of these orders. Solid Waste Storage Area 6 (SWSA-6) is the only currently operating low-level radioactive waste (LLW) disposal facility at the Oak Ridge National Laboratory (ORNL). To maintain operations in SWSA-6 and to comply with the closure requirements, it is necessary to obtain site characterization information sufficient to verify that the site will not represent a significant radiological hazard to future generations and that minimum maintenance and surveilance will be required to maintain this condition. CERCLA compliance will require essentially the same type of analysis. Although SWSA-6 is a LLW burial facility, it is possible that some potentially hazardous chemical wastes were also buried prior to enactment of the Resource Conservation and Recovery Act of 1976. At this time, the extent of nonradioactive contamination in SWSA 6 is not known.

Operation's of SWSA-6 began in 1973, prior to the requirement for detailed preoperational site evaluation techniques (such as those currently imposed on new shallow land burial sites by DOE or the Nuclear Regulatory Commission). As a result, much of the site information now required to assure compliance was not collected prior to waste burials. Most of the existing SWSA-6 site data were obtained after operations were initiated and relate mainly to actions performed to prevent entrance of water through the trench cap, to lower the water table in the vicinity of trenches known to contain water, and to isolate the LLW by grout injection or liner systems. As a result of these studies, considerable information has been gathered on portions of the SWSA-6 site. The purpose of this plan is to review the existing

information on SWSA-6 and develop cost estimates and schedules for obtaining additional information necessary to characterize the site.

The ultimate goal of the site characterization effort is to provide information sufficient to conducting a pathways analysis, to establish that contaminant migration from SWSA-6 will not represent a health problem to present or future populations. Because modeling activities (both transport and exposure) represent the major effort in the pathways analysis, it is essential that data collection be tailored to meet the needs of the models selected. Otherwise, considerable time and effort could be devoted to collecting unncessary data.

The following approach has been used in developing this plan: (1) identification of existing information regarding the characteristics of the site, (2) development of preliminary conceptual models describing our current understanding of the site, and (3) development of a plan for obtaining whatever additional site information is required to validate the preliminary conceptual models and allow future pathways analysis and performance assessment of the site.

The format of this report follows the approach outlined above. Sections (1 through 5) present background information on the site, the approach to the plan, a summary of the pathways analysis, and the development of source terms for the analysis. Also included is a description of the current status of information regarding SWSA-6 used in defining additional data needs. Section 6 includes a description of the additional studies required to characterize the site, and Sect. 7 presents costs, manpower requirements, and schedules for accomplishing the additional work.

PATHWAYS ANALYSIS AND PERFORMANCE ASSESSMENT

The pathways analysis to support the SWSA-6 performance assessment will include three major phases: development of conceptual models to define the potential pathways to man; selection of appropriate numerical codes for quantifying the contaminant migration along the pathways of interest and calibration of these numerical models; and

simulation of possible releases of contamination from the site, using parameters and/or scenarios describing future events. As currently envisioned, most of the Phase 3 efforts will be undertaken when site characterization has been completed.

SOURCE TERM

Characterization of the source term is probably the most important task in the site characterization activity. The most common approach reported for determining the source term is to determine the inventory of contaminants present and assume that some fraction of each contaminant is released at a specified rate. This approach requires an accurate determination of the total amount of each contaminant present, some estimate of release rate, and assumptions relative to the physical and chemical form of the wastes. The presence and type of packaging material is also a major consideration.

A wide variety of wastes, waste forms, and radionuclides have been buried at SWSA-6. Essentially no information on waste form or the chemical and physical characteristics of the waste is currently available. Additionally, no information has been maintained regarding the possible content of hazardous materials, chelating agents, or solvents in the waste. For radionuclides, information exists only for the period starting in 1976. Much of this radionuclide inventory is based on "less than" type numbers or descriptions such as "mixed fission products". Thus it appears that some methodology other than inventory and release factor approach will be required to quantify the source term for SWSA-6.

The approach selected for estimating the groundwater source term for the trenches is to measure contaminant concentrations in the trench leachates and combine this information with the groundwater flux to yield a source term. This approach has the advantage of automatically focusing the performance modeling directly on soluble contaminants (i.e., those found in the leachates) and avoids the requirement for detailed knowledge of the total contaminant inventory.

Unfortunately, this approach may not be satisfactory for the auger holes, since the methodology used in constructing and operating the auger holes, as well as safety and health physics considerations, appear to preclude drilling holes for sampling into the disposal units. The source term for wastes in the auger holes (a much smaller volume than in the trenches, but the location of 91% of the total radioactivity) will have to be estimated based on existing inventory data. Monitoring wells will be drilled near the auger holes to detect the presence or absence of contaminants that may have moved from the holes. It should be pointed out, however, that although the auger holes contain most of the activity, the locations of these holes (in the upper reaches of the facility where the water table is deep), and the nature of the waste (sealed sources, metal parts containing induced activity, etc.) may limit the potential for the release of radionuclides from these types of disposal units.

The source term for the air and surface water transport pathways will be based on inventory data and release rates. Typical unit waste masses (TUWM), representing the average content of radionuclides in the waste disposed of in the trenches and auger holes, will be constructed based on available records. These TUWM and the results of erosion studies, water budgets, and meteorological observations will be the basis for constructing the source terms for the air and surface water transport pathways.

GEOLOGY AND SOILS

Previous waste disposal research and development activities conducted near SWSA-6 have produced a considerable amount of information regarding the local geology. However, on a site-specific basis, additional investigations are required to provide information on overall geologic characteristics and specific information on fracture networks. Geologic characterization can be divided into five tasks: installing core wells, geophysical studies; shallow trench characterizations; laboratory analyses; and data interpretation. The results of these investigations will increase the basic understanding

of geologic processes that were or are active in SWSA-6 and provide physical boundaries for and constrain numerical models of SWSA-6. Specifically, processes that were involved in the transformation from bedrock to saprolite to soil will be better understood and structural fabrics, which appear to control groundwater movement, will be characterized.

Soil properties must be investigated to facilitate understanding of the ability of the site to isolate of the waste, as well as the site's long-term stability. Although much general information on local soils (including a newly prepared soils map) exists, site-specific studies that support the hydrologic and geochemical investigations required as a part of the performance assessment are still needed. Measurements of soil physical properties provide the information needed to evaluate hydrologic and site stability, whereas soil chemical and mineralogical investigations provide the information needed to predict contaminant transport (both chemical and radionuclide).

HYDROLOGY

Observations at LLW disposal facilities sited over Conasauga Group bedrock on the Oak Ridge Reservation (ORR) suggest that the dominant pathway for transport of waste constituents in SWSA-6 is subsurface flow to surface streams carry the waste constituents offsite. Thus, characterization of the SWSA-6 groundwater flow system is critical to evaluations of the potential for offsite exposures and should be directed toward determinations of the direction of contaminant movement and estimations of flow rates and velocities along transport pathways. Some shallow groundwater may penetrate to greater depths, particularly along tear faults or other geologic structures that cut across stratigraphic boundaries; however, very little is known about the extent of vertical water movement on the ORR.

Another important hydrologic requirement is estimating the flow of water into the trenches, its residence time, and the rate of seepage of leachate from the trenches. This information, coupled with trench water analyses, will be used to estimate the groundwater source term

for use in transport modeling. Also needed will be additional investigations aimed at determining the site-specific hydrology of SWSA-6 and the measurement of hydrologic parameters required for groundwater transport modeling. Much of this information will be obtained from a number of new wells installed to provide additional water-level observations and groundwater samples. Geophysical logging of these wells will be conducted as a part of the geologic characterization.

The existing stream gauging stations in SWSA-6 will be upgraded to a more permanent status, and the current measurement and sampling program will be continued. Existing meteorological stations on SWSA-6 will continue to be operated and maintained.

GEOCHEMISTRY

Most of the geochemical investigations required in the characterization plan will be directed at determining the source term for use in the pathways analysis. It will also be necessary to determine the retardation properties of the site soils, for use in modeling contaminant transport (both radionuclide and chemical). A limited leaching program will also be established in an attempt to correlate observed leachate concentration with waste composition. In addition, groundwater samples will be used to provide background geochemical information on the site and to establish the extent of existing contaminant migration.

COSTS AND SCHEDULES

The characterization plan outlined in this report has been developed on the basis that a two-year period is available in which to install additional facilities, collect data, analyze the information obtained, and conduct a preliminary pathways analysis. Section 7 details the estimated costs and schedules required to complete the site characterization effort and provide the information needed to conduct the pathways analysis and performance assessment.

ABSTRACT

BOEGLY, W. J., Jr., R. B. DREIER, D. D. HUFF, A. D. KELMERS, D. C. KOCHER, S. Y. LEE, F. R. O'DONNELL, F. G. PIN, and E. D. SMITH. 1985. Characterization plan for solid waste storage area 6. ORNL/TM-9877. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 168 pp.

Solid Waste Storage Area 6 (SWSA-6) is the only currently operating low-level radioactive waste (LLW) shallow land burial facility at the Oak Ridge National Laboratory. The U.S. Department of Energy (DOE) recently issued DOE Order 5820.2, which provides new policy and guidelines for the management of radioactive wastes. To ensure that SWSA-6 complies with this Order it will be necessary to establish whether sufficient data on the geology, hydrology, soils, and climatology of SWSA-6 exist, and to develop plans to obtain any additional information required. It will also be necessary to establish a source term from the buried waste and provide geochemical information for hydrologic and dosimetric calculations. Where data gaps exist, methodology for obtaining this information must be developed. The purpose of this Plan is to review existing information on SWSA-6 and develop cost estimates and schedules for obtaining any required additional information.

Routine operation of SWSA-6 was initiated in 1973, and it is estimated that about 29,100 m^3 (1,000,000 ft^3) of LLW containing about 250,000 Ci of radioactivity have been buried through 1984. Both low-activity- and high-activity-level wastes were buried in trenches and auger holes at the site. It is possible that before 1980, wastes were buried that would be considered hazardous wastes under the Resource Conservation and Recovery Act. Since SWSA-6 was sited prior to enactment of current disposal regulations, a detailed site survey of the geologic and hydrologic properties of the site was not performed before wastes were buried. However, during the operation of SWSA-6 some information on site characteristics has been collected as a result of various research and development programs aimed at improving disposal practices and of attempts to investigate corrective actions.

This information is useful in understanding the existing problems at the site; however, in many cases, the information is not complete enough to allow a detailed analysis of the long-term performance of the site for compliance purposes.

Plan and cost estimates have been developed to provide the information necessary to conduct a performance assessment of the site. The plan is based on a two-year data collection period, at an estimated cost of $1,650,000.

1. INTRODUCTION

U.S. Department of Energy (DOE) Order 5820.2 provides policy and guidelines for the management of radioactive wastes (DOE 1984). Both new and existing DOE waste management facilities are required to comply with this order. New waste management facilities are required to be sited, designed, operated, and closed using criteria specified in the order; however, existing facilities, as a minimum must comply with the operating and closure portions of the order. The purpose of this plan is to review existing information on Solid Waste Storage Area 6 (SWSA-6) and develop cost estimates and schedules for obtaining the site information necessary to characterize the site for later use in developing plans for its closure.

Solid Waste Storage Area 6 is the only currently operating low-level radioactive waste (LLW) shallow land burial (SLB) facility at the Oak Ridge National Laboratory (ORNL). Examination of the operational requirements of 5820.2 indicates that there are only a few areas in which the current operation of SWSA-6 is not in compliance. However, for closure of SWSA-6, the compliance requirements may be more difficult to achieve. The major obstacle to meeting the closure requirements of 5820.2 is the lack of detailed site characterization information, such as that specified for new burial facilities, but also that required for closure of existing sites.

The identification, investigation, and cleanup of existing or abandoned waste management facilities have been mandated by the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), which establishes a federal program to identify, assess, and abate uncontrolled and nonpermitted sources of the release of hazardous substances into the environment. DOE has issued an order (DOE Order 5480.14) establishing a CERCLA-like program to identify and evaluate abandoned DOE waste sites and other potential sources of hazardous substance releases and to plan for their cleanup. The requirements of this order are consistent with the technical requirements of CERCLA.

Characterization of SWSA-6 is an essential step toward compliance with DOE Orders 5480.14 and 5820.2. To ensure that SWSA-6 complies with DOE 5820.2 and 5480.14, it will be necessary to establish whether sufficient data exist to characterize the geology, hydrology, soils, and climatology, and if they do not, to develop plans to obtain any additional information required. It will also be necessary to determine if sufficient data exist to establish a source term and provide the required geochemical information for hydrologic and dosimetric calculations. Where data gaps exist, methodology for obtaining this information must be developed.

1.1 BRIEF HISTORY OF ORNL LLW DISPOSAL

Solid LLW has been buried at ORNL since the Laboratory's inception; to date, six burial grounds (called solid waste storage areas or SWSA) have been used for this purpose (Sease et al. 1982; Evaluation Research Corporation 1982). Figure 1 illustrates the locations of the six SWSAs relative to ORNL. The first three locations were chosen mainly for their proximity to the waste sources, whereas the last three were located based on the recommendations made in geologic and hydrologic studies (Boyle et al. 1982; Webster 1976). It is estimated that at least 170,000 m^3 (6×10^6 ft^3) of LLW had been buried at ORNL through 1980 (Gilbert/Commonwealth 1980).

As Fig. 1 shows, the first three ORNL burial grounds were located in Bethel Valley and were relatively small [less than 4 ha (10 acres)]. In 1949, concern was expressed regarding the continued use of SWSA-3 as LLW disposal area because of the lack of knowledge about radionuclide transport through fractures in the underlying Chickamauga limestone formation (Western 1949). According to Western (1949), Stockdale recommended that the best burial ground site, readily accessible from ORNL, was north of White Oak Lake in the Conasauga Shale. All of the subsequent LLW facilities (SWSAs-4, 5, and 6) were located in the Conasauga Group of Melton Valley, rather than in the Chickamauga Limestone of Bethel Valley.

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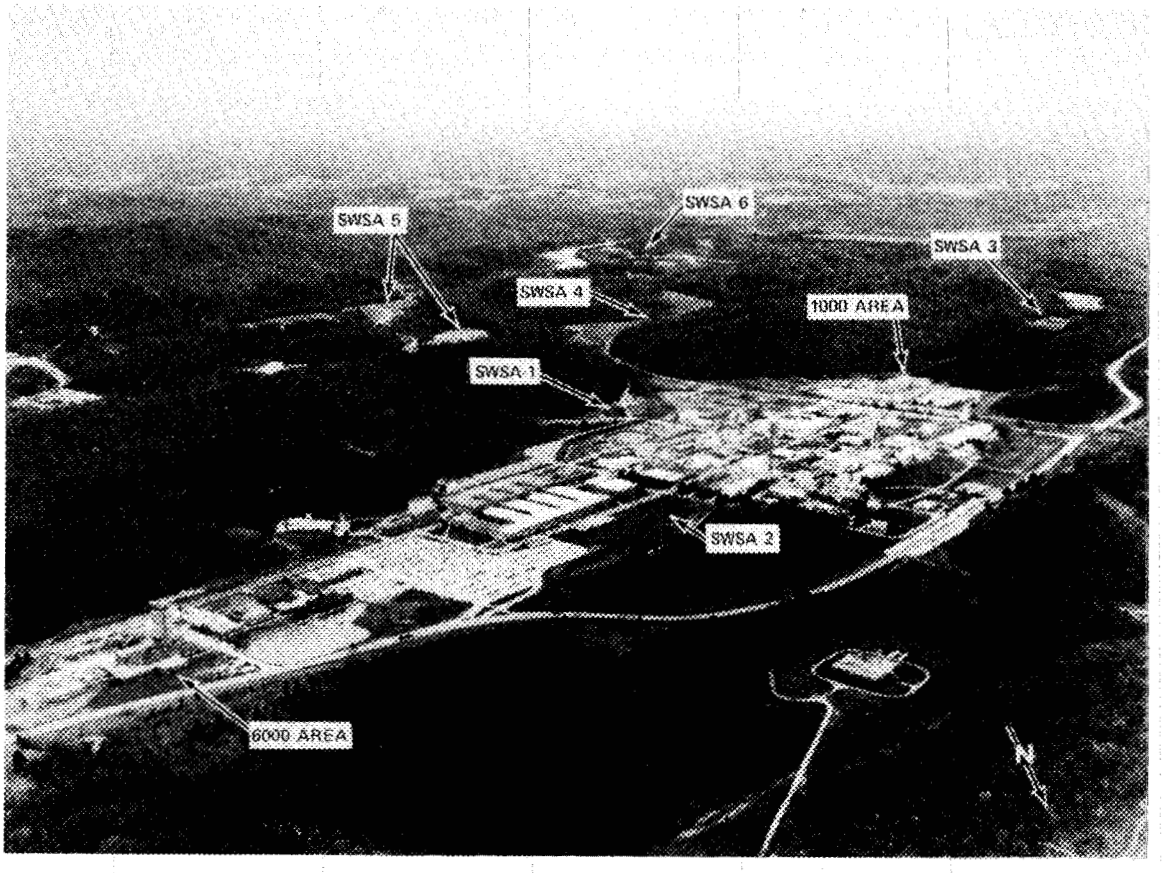

Fig. 1. Aerial view of Oak Ridge National Laboratory showing approximate locations of solid waste storage areas.

The area selected for SWSA-6 (see Fig. 2) was located in Melton Valley, northwest of White Oak Lake and southeast of Lagoon Road and Haw Ridge (Webster 1976). The site included 28 ha (68 acres), of which about one-third was reported to be suitable for waste burial. The balance of the site consisted of steep slopes and areas having shallow groundwater, which might not be satisfactory for burial operations (Lomenick and Wyrick 1965).

Although some LLW was buried in SWSA-6 as early as 1969, major burials at the site did not begin until SWSA-5 was closed in 1973 (Webster 1976). Both trenches and auger holes have been used for burials in SWSA-6. Appendix A contains a list of the trenches and auger holes in SWSA-6 as of June 1985. Wastes classified as transuranic wastes (TRU) are currently stored in SWSA-5; none of these wastes are stored in SWSA-6. Figure 3 shows the general areas of SWSA-6 in which the trenches and auger holes are located. Although these are not shown in Fig. 3, ORNL maintains detailed drawings of the location of each trench and auger hole (ORNL-DWG Nos. C-21205-EA-010F and C-21205-EA-011F) and log-book records of the type of waste (low- or high-activity-level, biological, asbestos, compacted bales, or chemical) placed in each trench or auger hole (high-level or fissile). In general, high-activity-level wastes are buried in trenches or auger holes in the northern or higher portions of the burial ground, where the water table is farthest below the surface. Boegly (1984) reports that 29,100 m^3 (1×10^6 ft^3) of LLW had been placed in SWSA-6 by the end of September 1984 (Boegly 1984).

1.2. CURRENT DISPOSAL PRACTICES

ORNL disposes of or stores all radioactive solid waste generated at the Laboratory, as well as solid waste for which the DOE-Oak Ridge Operations Office (ORO) authorizes acceptance from other DOE contractors, licensees, or other government agencies. For disposal/storage purposes, ORNL classifies solid radioactive wastes as being in one of five categories: ^{233}U/transuranium waste, ^{235}U water,

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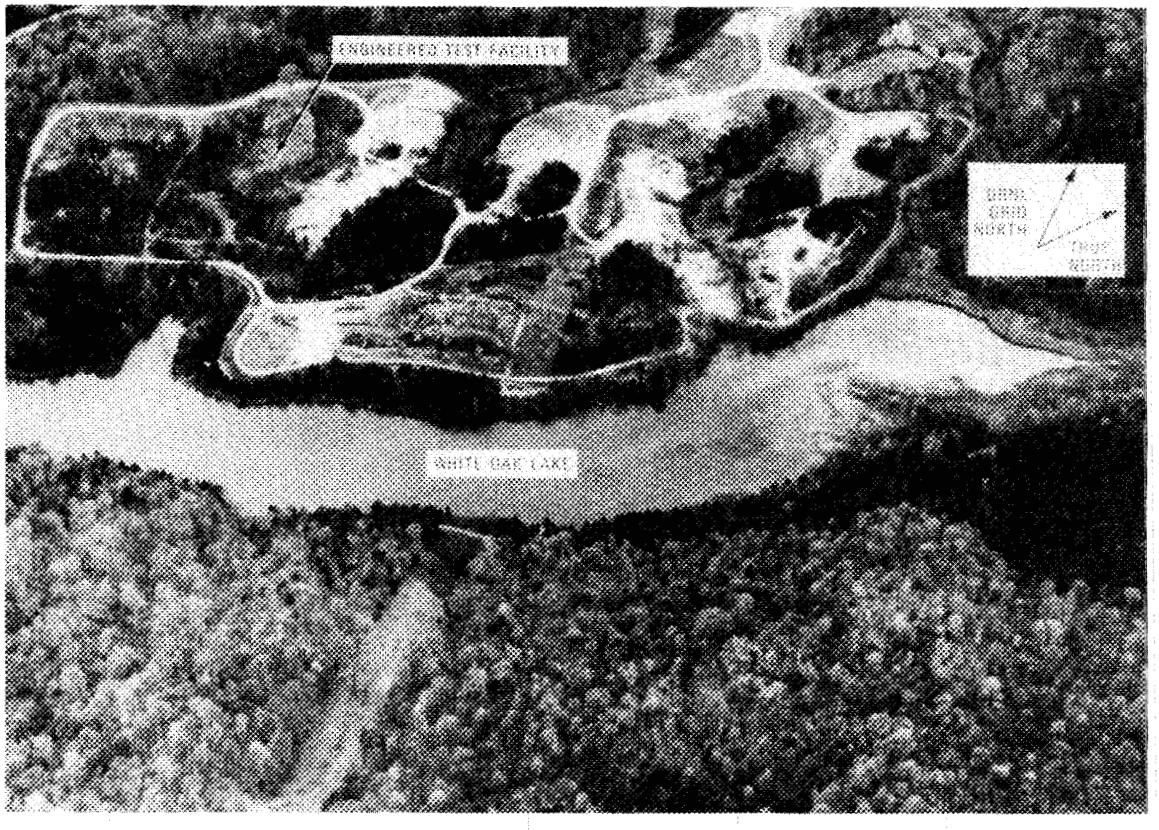

Fig. 2. Aerial view of SWSA-6, looking northwest over White Oak Lake.

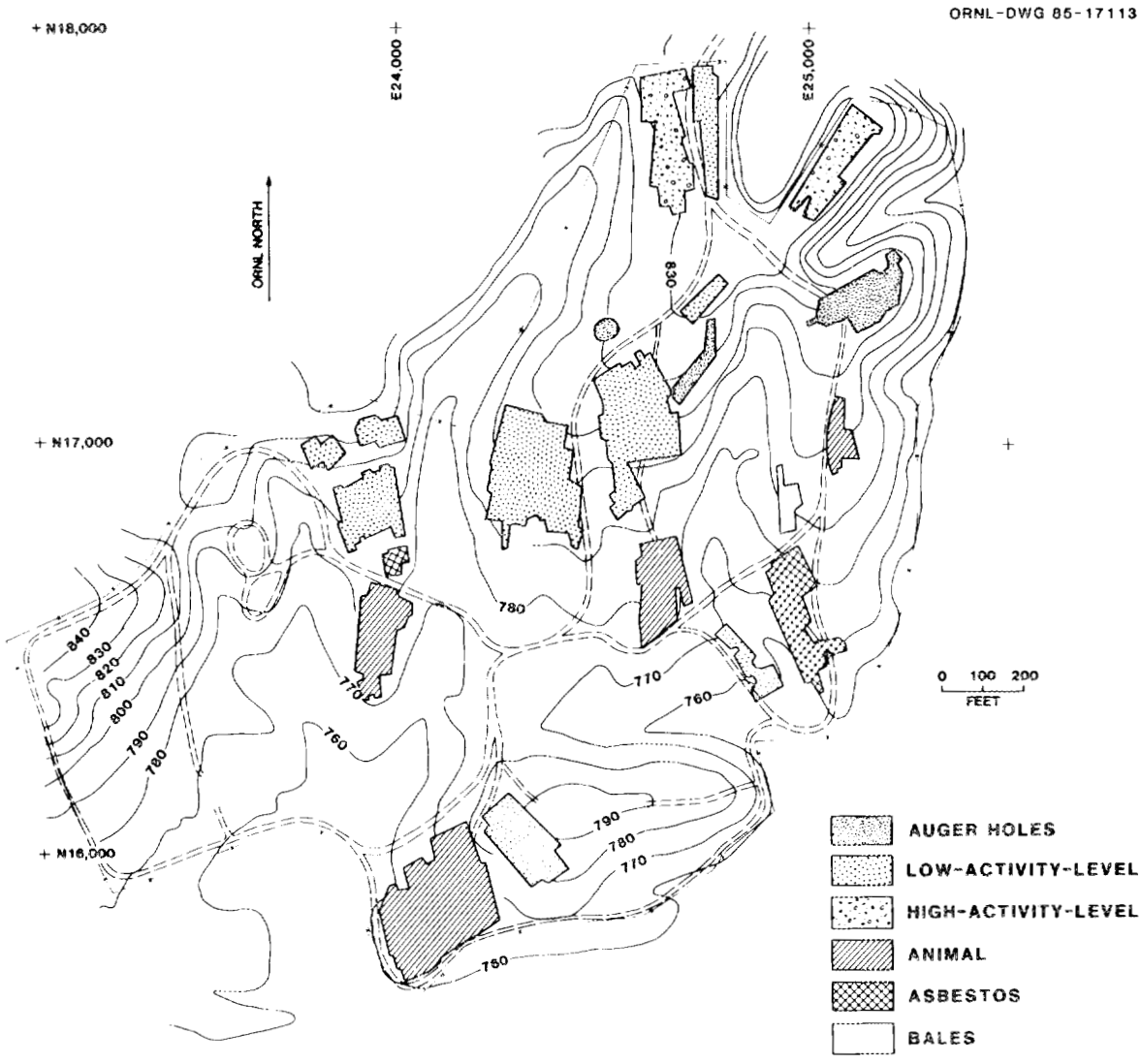

Fig. 3. Map of SWSA-6 showing generalized locations of trenches and auger holes.

general radioactive waste (radwaste), mixed wastes, and low-hazard contaminated waste. Essentially all of the waste buried in SWSA-6 falls into the last three categories. Transuranium wastes must be retrievably stored for a minimum of 20 years (DOE Order 5820.2); ^{235}U wastes are no longer generated in significant quantities at ORNL. General radioactive wastes are divided into two subclasses, depending on the radiation level. High-activity radwaste has a radiation level of greater than 2 mSv/h (200 mrem/h) at the surface of the container, and low-level radwaste is 2 mSv/h (200 mrem/h) or less. Low-level radwaste is further subdivided into compactible and noncompactible fractions so that the compactible material can be reduced to minimum volume prior to burial. General radwastes are disposed of in trenches or unlined auger holes, with auger holes being used for the high-activity fraction when required. It should be noted that the term "mixed" waste does not imply a mixture of chemically hazardous and radioactive wastes; rather, ORNL mixed wastes contain a combination of two of the first three categories of wastes. The final category (low-hazard contaminated waste) has no measurable contamination; however, it has been judged by the generator to be radioactively contaminated above ORNL "Health Physics Material Transfer Clearance Tag" (free of radiation or contamination hazard) limits. This waste is also described as "suspect" waste and is segregated from LLW and disposed of in separate areas. In addition to the burial areas for the waste types described above, separate areas are provided in SWSA-6 for the disposal of animal carcasses and biological wastes and for asbestos-containing wastes.

Currently, LLW from ORNL is segregated at the source by the waste generator into compactible (paper, plastics, cloth, etc.) and noncompactible waste (metals, glass, concrete, etc.) prior to collection and disposal. Current disposal procedures do not allow the presence of free liquids in the solid waste. Handling procedures for radwastes generated at ORNL are described in Sect. 5.1 of the "Health Physics Procedure Manual."

1.2.1 Trenches

Trenches are usually 15 m (50 ft) long and 3 m (10 ft) wide, depending on specific site topography. Their depth ranges from 4.25 to 5.5 m (14 to 18 ft), with the depth of a specific trench being determined by the depth of the water table. The bottom of each trench must be at least 0.6 m (2 ft) above the water table. When a trench is excavated and water is found, the trench is backfilled using Conasauga shale to a depth at least 0.6 m (2 ft) above the observed water depth. Minimum spacing between trenches is limited to 1.5 m (5 ft). Details of a typical trench are shown in Fig. 4. When the level of waste is 0.9 m (3 ft) below the top of the trench, the trench is backfilled with soil and packed by running heavy equipment over the trench. Once the trench is backfilled, the area is seeded to minimize erosion.

The monitoring pipe shown in Fig. 4, is no longer installed prior to the addition of waste; instead, it is installed after the trench is filled and covered. The monitoring pipe is located on the centerline of the trench, about 1.2 m (4 ft) from the lower end of the trench. Prior to trench closure the area is surveyed and the location of the corners of the trench identified. At present, markers are not placed at the corners of the trench; the location of the monitoring pipe is used to designate the general location of the trench.

1.2.2 Auger Holes or Wells

Auger holes are basically a specialized form of trench burial that allows greater control of radiation exposures during disposal operations. Detailed practices and procedures have been developed over many years of experience. Auger hole diameters are not standardized but vary depending on the function and the material being emplaced (see Table A.1). Most of the holes are approximately 1 m (40 in.) in diameter, and the depth is such that at least 0.6 m (2 ft) of earth separates the bottom of the hole and the highest known water table. In the case of SWSA-6, the auger holes are 18 ft or less in depth; existing equipment does not allow excavation below 18 ft. Auger holes are spaced a minimum of 0.9 m (3 ft) apart, edge to edge. No liner is

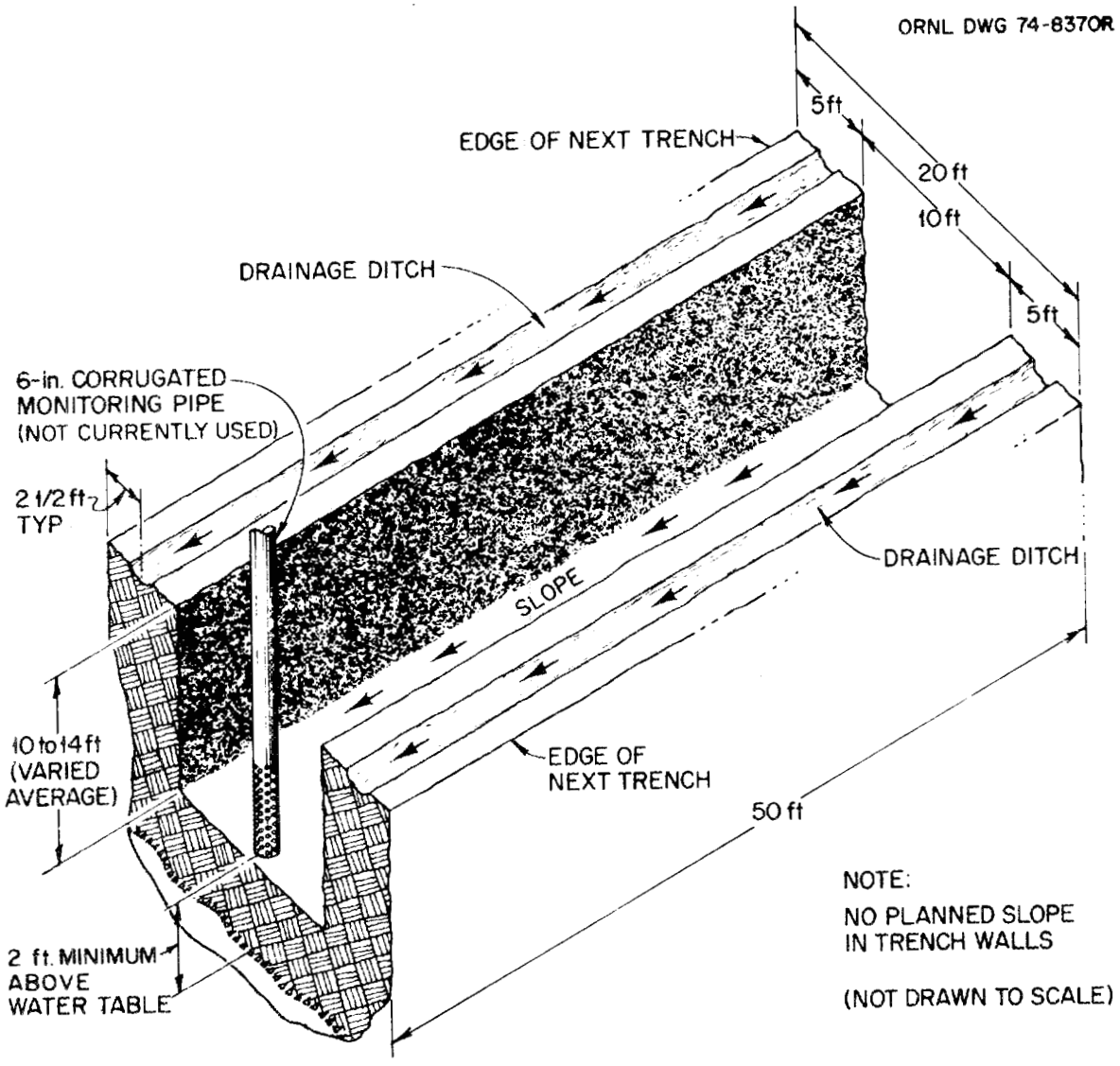

Fig. 4. Cross section of a typical ORNL disposal trench (1 ft = 0.3 m).

used and soil is added to the hole when necessary to limit radiation levels to less than 1 mSv/h (100 mrem/h) at the surface of the hole. The auger hole is sealed when either the waste is within 0.9 m (3 ft) of the surface or, in the case of fissile material, when 300 g of fissile isotopes are disposed of. Auger holes are normally sealed by adding concrete to the hole, followed by the addition of 1 to 2 ft of soil.

Auger holes are located in the higher elevations of SWSA-6, where the water table is deepest. Figure 3 shows the general locations of auger holes, and Appendix A lists the number and sizes of each used to date.

2. RATIONALE FOR THE SOLID WASTE STORAGE AREA 6 CHARACTERIZATION PLAN

To maintain operations in SWSA-6 and comply with the closure requirements outlined in DOE 5820.2 and 5480.14, it is necessary to ensure that sufficient site information is available to verify that the site will not represent a significant radiological hazard to future generations and that minimum maintenance and surveillance will be required to maintain this condition. Because SWSA-6 was established without detailed site evaluation techniques (such as those imposed on new SLB sites by DOE 5820.2 or NRC 10 CFR Part 61), a considerable portion of the site information necessary to ensure compliance was not collected before operations began and must be collected now, with burials well under way. This situation exists for essentially all of the operating and inactive DOE burial sites.

Two approaches are available for developing a characterization plan. The first, which may be more applicable to new sites, would be to gather data on all of the parameters thought to be necessary to understand the site and, using these parameters, calculate the long-term performance of the site. In many ways, this appears to be the approach suggested for siting new facilities by DOE 5820.2 and 10 CFR Part 61, as described by Siefken et al. (1982) and Lutton et al. (1982) for NRC facilities.

The second approach, which is probably more applicable to operating facilities, would be to evaluate the concerns that have surfaced during past operations and develop a characterization plan based on these concerns. During SWSA-6 operations, it has been observed that the waste in many trenches is not isolated from water, thus a limited number of remedial actions and corrective measures have been proposed and carried out. As a result of these observations, specific studies and measurements have been made which allow the development of hypothetical models for the performance of the site, which might be different from that assumed prior to operation. This approach allows the site characterization to concentrate on the parameters required to analyze the site for future performance based on operational experience.

In the case of SWSA-6, the methodology adopted for planning the characterization of the site has been to (1) identify all existing information regarding the characteristics of the site, (2) develop conceptual models that describe our current understanding of the site, and (3) develop a plan for obtaining the additional site information required to validate the conceptual models and allow future pathways analysis and performance assessment of the site. At present, the first step in the methodology has been completed (Boegly 1984). This report, which corresponds to the third step, describes the conceptual models suggested for SWSA-6 on the basis of the currently available site information (step 2) and the requirements for completing the site characterization.

Following collection and analysis of the site information, preliminary pathways analysis and performance assessment can be conducted to determine whether the site will meet the assumed performance objectives, and if not, what corrective measures would have to be incorporated into the site to provide the necessary assurances that closure can be achieved. Section 3 describes briefly the methodology used in conducting a pathways analysis and performance assessment.

3. PATHWAYS ANALYSIS AND PERFORMANCE ASSESSMENT

To provide reasonable assurance that the performance objectives will be met, reliable predictions of site performance are required for periods of time extending at least 500 years into the future or for as long as the waste has the potential to affect public health adversely. To this end, a pathways analysis must be performed to define the modes and extent of radionuclide migration from the site and to assess its probable impact on current and projected populations and nearby facilities. Should the results of the site characterization and the pathways analysis show conditions that could jeopardize attainment of the performance objectives, corrective measures may be implemented in SWSA-6.

The pathways analysis to support the SWSA-6 performance assessment will include three major phases (see Fig. 5). The development of conceptual models to define the potential pathways to man constitutes the first phase of the analysis. For SWSA-6, this development phase has been completed in some areas, but the majority of the conceptual models need characterization data to be finalized. The conceptual models will serve as a basis for the development of the numerical models to quantify the pathways.

The second phase of the analysis includes the selection of appropriate numerical codes to quantify contaminant migration along the pathways of interest and the calibration of the numerical models. During the calibration phase, the values of the modeling parameters are adjusted within the probable ranges, using sensitivity analyses and comparisons of simulation results with existing conditions.

In the last phase of the analysis, parameters and/or scenarios describing future events are defined and used as the basis for simulating the possible release of contamination from the disposal units. Simulations of contaminant migration along the pathways of interest are performed and contaminant concentrations at locations of probable exposure are calculated for various times during the postclosure period. Doses to man are then evaluated for various modes of exposure. Due to the predictive nature of this part of the analysis,

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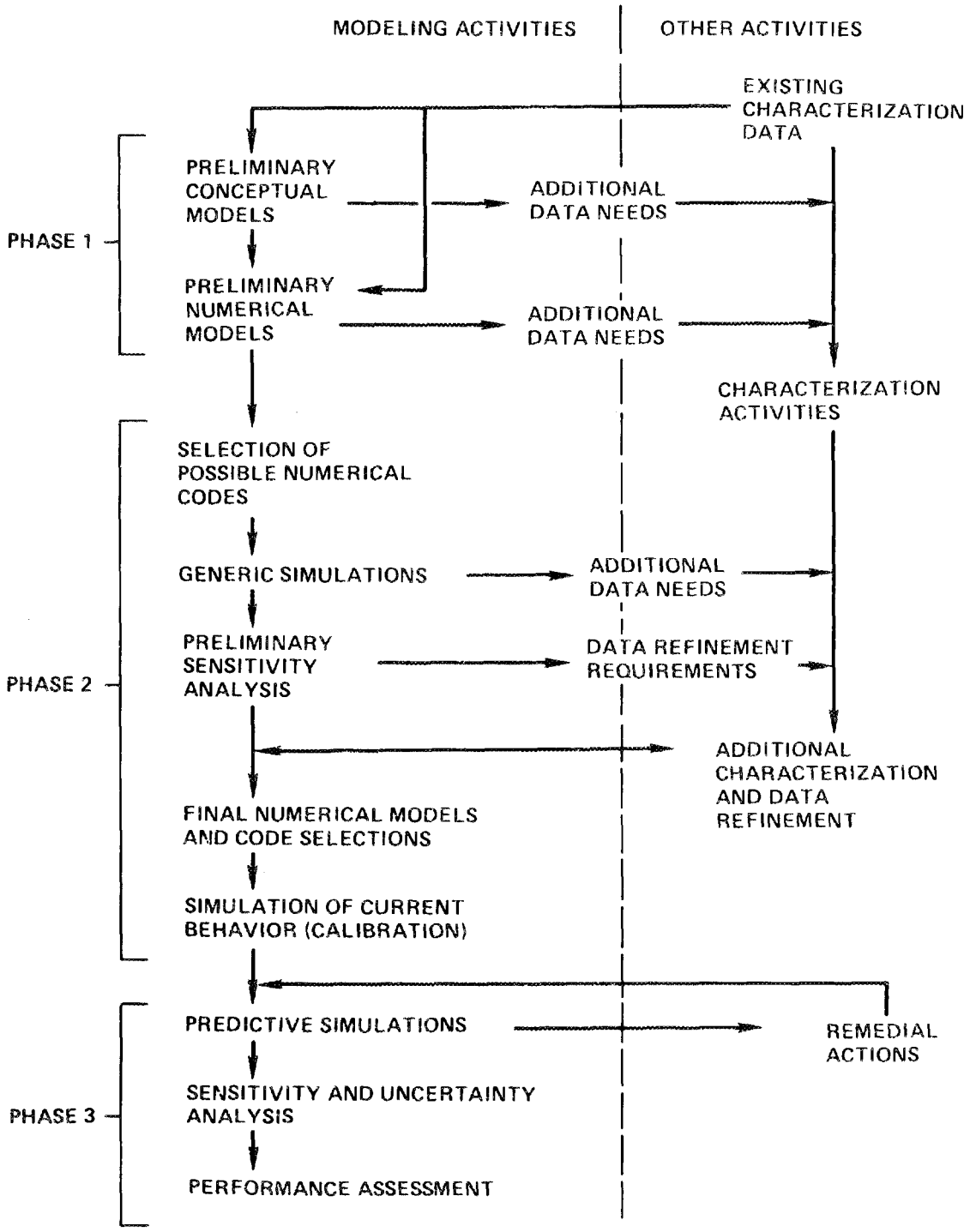

Fig. 5. Flow chart of modeling activities for SWSA-6 pathways analysis and performance assessment.

large uncertainties are generally associated with the model results. To allow reliable interpretation of the results, these uncertainties would be carefully evaluated using sensitivity and uncertainty analysis. Well-established methodologies and analytical tools are available for this purpose.

Figure 6 illustrates, generally, a two-step transport of contaminants from the disposal site to man. The first step involves the transport of contaminants from possible release points (burial trenches, auger holes, or surface spills) to environmental compartments (air, soil, surface water, and groundwater). The transport modes for this step, referred to as transport pathways, are site specific and their analysis requires in-depth site characterization. Conversely, the modes of transport for the second step, which involves transport from the environmental compartments to man, are less site specific and their analysis probably can be performed largely on the basis of generic data, given the site-specific results for the first step of the transport process. The modes of transport for this second step are referred to as exposure pathways.

For analysis of each pathway and predictive simulation of site behavior, data are necessary to characterize fully the site-specific source terms, the modes of contaminant transport to the environment, and the exposure pathways. The following sections briefly describe the information needed to analyze the two steps of contaminant transport (Fig. 6), that is, the transport and exposure pathways.

3.1 TRANSPORT PATHWAYS

Possible mechanisms for the transport of contaminants from the sources to offsite and onsite environmental compartments are outlined in Tables 1 and 2 respectively. Contaminants can be released from the trenches or auger holes via the influx and efflux of infiltrating water, the emanating of gaseous (volatile) species, and resuspension into the air after disruption of the trench cover. A characterization

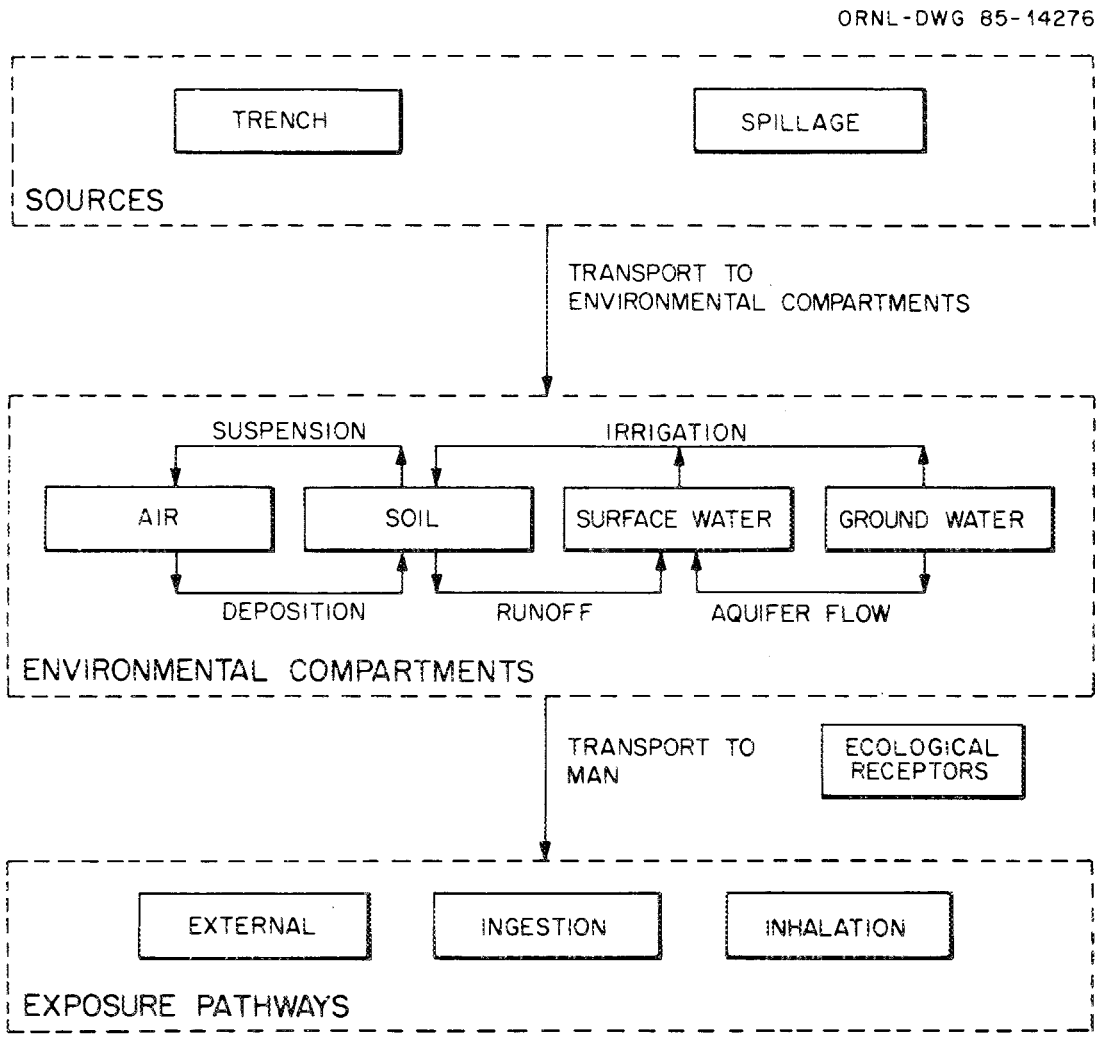

Fig. 6. Summary of sources, environmental compartments, and exposure pathways for shallow land burial of low level waste.

Table 1. Transport mechanisms from sources to offsite environmental compartments

Environmental compartment	Source		
	Trench	Spillage	Secondary[a]
Air	Suspension of particulates (atmospheric transport) Emanation of volatiles (atmospheric transport)	Suspension of particulates (atmospheric transport)	
Soil			Irrigation from surface water and groundwater Deposition from air
Surface water	Runoff	Runoff	Discharge from groundwater
Groundwater	Infiltration		

[a]Transport mechanisms between environmental compartments.

Table 2. Transport mechanisms from sources to onsite environmental compartments

Environmental compartment	Source		
	Trench	Spillage	Secondary[a]
Air	Suspension of particulates	Suspension of particulates	
	Emanation of volatiles		
Soil	Overflow/ deposition	Direct deposition	Irrigation from surface water and groundwater
	Erosion Human disruption[b]		
Surface water	Runoff	Runoff	Discharge from groundwater
Groundwater	Infiltration		

[a]Transport mechanisms between environmental compartments.
[b]Includes activities such as plowing and construction.

of the modes of contaminant release requires the determination of the fluxes of contaminated water, air, and gases out of the trenches. Since human activities can influence some of the contaminant release rates, the fluxes should be defined both during the institutional control period, and during the postinstitutional period, when maintenance and control of the site will have ceased.

The pathways analysis should consider two time periods: a near-term period (e.g., 100 years), during which time the site will be actively maintained and controlled, and the long-term period (e.g., after 100 years and for as long as the waste remains hazardous), when control and maintenance will have ceased. During the near-term period, conditions at the site are expected to be similar to the present ones or to be improved as a result of remedial actions. The site characterization data are therefore expected to be representative of the conditions at the site during that period, and field measurements can be used to estimate source terms and transport characteristics. For the long-term period, major variations in the vegetative cover, integrity of the disposal units, demography, site hydrogeology, and other controlling factors will make it necessary to use hypothetical scenarios to analyze the pathways. These scenarios will be designed based on present data and will incorporate probable variations in the major parameters. Ranges of uncertainty in the data and scenario parameters will also be defined, to generate the maximum ranges of uncertainty in the predictive results. The latter ranges are generated through a sensitivity and uncertainty analysis.

3.1.1 Groundwater Transport Pathways

Groundwater transport is considered the most significant pathway for the migration of radionuclides and hazardous constituents from SWSA-6. The release mode for groundwater transport of contaminants out of the trenches or auger holes is by the efflux of infiltrating water that has leached radionuclides and hazardous constituents from the waste. At SWSA-6, both vertical infiltration of water through the trench caps and lateral influx through the trench walls have been

observed. Estimates of these fluxes are therefore necessary to characterize the release modes for groundwater transport and are, therefore, discussed in Sect. 4.3.

Modeling of the groundwater pathway for SWSA-6 requires the largest modeling effort by far. Conceptual and numerical models will have to be finalized to serve as the basis for selecting appropriate numerical codes. A wide variety of codes are currently available to treat the flow regimes that occur at SWSA-6. The numerical models will have to be calibrated against actual field conditions and predictive simulations will have to be performed. The results will be used in the analysis of the water pathway for which groundwater is a secondary source. The results will also be used in the analysis of the exposure pathways described in Sect. 3.2. Because the uncertainties related to the results of the groundwater pathways are expected to be the largest in the analysis and may propagate into the analysis of the other pathways, they need to be carefully evaluated. Uncertainty analysis methods are available for this purpose.

3.1.2 Surface Water Transport Pathways

This type of pathway involves the release of contaminants from the disposal units to the surface water system and the subsequent transport of contamination by surface water to a point of probable exposure. Release to the surface water system could result either from the overflow of contaminated leachate from a trench or from the reemergence or discharge of contaminated groundwater into the surface water system (indicated as a secondary source in Tables 1 and 2). Although unlikely during the period of institutional control, overflow and overland transport of particulates from the trenches could be considered a potential transport mechanism if the results of erosion studies show that total erosion of the trench cap is possible within the timeframe of the analysis (i.e., as long as the waste remains hazardous).

3.1.3 Air Transport Pathways

Air pathways involve the release of contaminated particulate material or volatiles from the disposal site into the atmosphere and the transport of contamination by wind to a location of probable exposure. During operation of the site and the subsequent institutional control period, the likelihood of this mode of release occurring is considered remote since the waste is placed below the earth's surface and covered with soil as soon as possible. Following the period of institutional control, reexposure of the waste could result from natural causes, such as wind and water erosion of the trench cover, or as a result of human (or animal) intrusion, such as digging or excavation. To assess the probability of waste exposure due to natural causes, results of erosion studies are necessary.

3.2 EXPOSURE PATHWAYS

This discussion of the exposure pathways focuses on models and data needs for estimating radiation doses resulting from external exposures to radionuclides contained in the environmental compartments and from internal exposures due to the intake of radionuclides transported from the compartments to man (see Table 3). The models and methods described below assume that information about radionuclides in each environmental compartment has been provided by the transport models. This information should include the identity and the time-dependent concentration of each radionuclide present by solubility class (insoluble, soluble, and very soluble) and, for airborne radionuclides, particle size. External exposure pathways considered include immersion in contaminated air; exposure to a contaminated ground surface and to the trench contents; exposures to surface water via swimming and wading, boating, shoreline use, and bathing; and exposures to groundwater via bathing. Internal exposure pathways considered include inhalation of contaminated air and ingestion of contaminated foodstuffs [crops, fish, drinking water, and products (milk and beef) from livestock that eat contaminated crops and drink

Table 3. Modes of exposure via environmental compartments

Exposure pathway	Environmental compartment			
	Air	Soil	Surface water	Groundwater
External	Immersion	Ground surface Trench contents (on-site)	Swimming/wading Boating (off-site) Shoreline Bathing	Bathing
Inhalation	Breathing			
Ingestion		Crops Products from livestock that eat crops	Drinking water Products from livestock that drink water	Drinking water Products from livestock that drink water

contaminated water]. Many of the ingestion pathways require transport of the radionuclides from the environmental compartments to the foodstuffs. This type of transport is included in the dose-assessment models for foodchain pathways, rather than in the models for environmental transport in air, soil, surface water, and groundwater. Although the discussion that follows is mainly directed at radionuclides, similar approaches can be developed for calculating internal exposures for chemical contaminants (external exposures are probably not a major consideration for chemical contaminants).

3.2.1 External Exposure

External exposures result from radiation (primarily photons) emitted from sources outside the body. For shallow-land burial of LLW, external exposures can result from radionuclides in air, soil, and water. In reality, radionuclides will be transported between the environmental compartments by various mechanisms, such as suspension from soil to air, deposition from air to soil, runoff from soil to water, deposition by irrigation from water to soil, and migration from the surface soil to subsurface soil. In this discussion, we assume that appropriate transport models will give concentrations of radionuclides in each compartment as a function of time.

Various pathways of external exposure to radionuclides in the environmental compartments are possible. Appendix C discusses in greater detail the models and data needed to analyze the following pathways: unshielded outdoor exposures to radionuclides in the air or deposited on the ground; indoor exposures to radionuclides in the air, deposited on the ground, or deposited on building surfaces; swimming, wading, bathing, boating, and shoreline exposures; and exposures to activity in soil and trench contents.

3.2.2 Internal Exposure

Internal exposures result from radionuclides taken into the body via inhalation of contaminated air and ingestion of contaminated

foodstuffs. Dose equivalent rates to man from such exposures can be calculated using a model of the form

$$CDE_j = \sum_i \sum_p I_{ip} \, DCF_{ijp} \quad ,$$

where

CDE_j = committed dose equivalent rate (rem per year) to organ j from intake of all radionuclides via all pathways,

I_{ip} = intake rate (microcuries per) of radionuclide i via pathway p, and

DCF_{ijp} = dose conversion factor (rem per microcurie) for organ j due to intake of radionuclide i via pathway p.

A committed dose equivalent is the dose equivalent that will be received over a specified time period (usually 50 or 70 years) as a result of an acute intake of radionuclides. The numerical value of a dose conversion factor depends on the identity, chemical form (solubility), and, for inhalation, the particle size of the radionuclide taken into the body. The literature includes tabulations of dose conversion factors for adults and children for different radionuclides, solubilities, and particle sizes.

The major effort in estimating dose equivalent rates from internal exposures lies in evaluating the intake rates, I_{ip}, for the various pathways involved. In general, the intake rate via any internal exposure pathway can be expressed as

$$I_{ip} = \bar{C}_{ip} \, U_p \, \exp(-\lambda_{ir} t_D) \quad ,$$

where

$\bar{C}_{ip}$ = the concentration (microcurie per unit mass or volume of material) of radionuclide i for pathway p,

U_p = human intake rate (mass or volume per year) of material for pathway p,

λ_{ir} = radioactive decay constant (1/time) of radionuclide i, and

t_D = delay time between harvest and consumption of material for pathway p.

Generic estimates of human intake rates of air and various foodstuffs are available in the literature, but site-specific values of the intake rates may be needed for a realistic dose assessment. Radioactive decay constants of most radionuclides are well known. Delay times between the harvest and consumption of foodstuffs, which can vary from essentially zero to a few months, also are reported in the literature. Appendix C discusses in greater detail some of the models and data needs for analyzing the following pathways: breathing contaminated air; drinking contaminated water or milk; and eating contaminated fish, vegetation, or beef.

4. SOURCE-TERM CHARACTERIZATION

To predict the short- and long-term future performance of a LLW disposal site for SLB, it is necessary to understand the nature (both chemical and physical) of the waste, the rate at which contaminants (radionuclides or hazardous materials) are released from the bulk wastes, and the meteorologic, geologic, and hydrologic characteristics of the site. As is discussed in Sect. 3, there are a number of mathematical models which can adequately provide such predictions once all of the needed data are available. The basic problem at existing disposal sites is one of determining what information exists, or can be developed, to provide source-term input to the transport models. Development of a realistic and defensible source term, a component of all transport models, for SWSA-6 is an important and high-priority task.

Two types of source terms are required to conduct a performance assessment: those for the transport pathways (see Sect. 3.1), and those for the exposure pathways (see Sect. 3.2). For the transport pathways, the source terms are the mass fluxes of contaminants in the transporting medium (air, surface water, groundwater). For the exposure pathways, the source terms are provided by the results obtained from analysis of the transport pathways (i.e., the contaminant concentrations at a given point at a specified time).

4.1 METHODOLOGY FOR DEVELOPING SWSA-6 SOURCE TERMS

The most common approach to determining a source term is to determine the inventory of each contaminant present and assume that the contaminant is released at some specified rate (EPRI 1983; EPRI 1984). This type of approach requires an accurate determination of the total amount of each contaminant present, some estimate of release rate (or leach testing of representative waste samples), and assumptions relative to the physical and chemical form of the wastes. The presence and type of packaging material used can also be a consideration. For most existing LLW disposal facilities, including SWSA-6, this type of

detailed inventory information or representative samples is not available (MacKenzie et al. 1985; Dayal et al. 1985a). This is especially true for potentially hazardous chemical wastes, since knowledge of these contaminants seems to have received little attention at radioactive waste disposal sites before now.

Two types of disposal operations have been performed in SWSA-6: disposal in trenches and disposal in auger holes (Sect. 1.2). As a result of these disposal practices, most of the radioactivity is located in the auger holes, and most of the waste volume is in the trenches (Appendix A). Because the auger hole design was developed to handle higher-activity wastes, the auger holes were located in areas of SWSA-6 where the water table was deepest and the possibility of groundwater contacting the waste was considered minimal. The design of the auger holes does not allow the placement of wells or sampling points within the disposal units, as was the case for the trenches. In most instances, the auger holes are capped with concrete and may also have been filled with soil, making it difficult to obtain liquid samples from the holes, if any liquid exists, that is. Thus, SWSA-6 can be considered to be made up of disposal units containing large volumes of low-activity wastes (trenches) and localized clusters of units containing small volumes of high-activity wastes (auger holes) (Fig. 3).

Because the current inventory system does not include information on potentially hazardous constituents in buried wastes and because concerns have been expressed regarding the validity of the records, the use of inventory records for estimating the source term from the trenches may not be the preferred approach. Since it is possible to sample and analyze trench water, the best approach may be to estimate the groundwater source term by using leachate concentrations and water flux through the trenches. On the other hand, water samples probably cannot be taken from the auger holes, thus another approach will be required. It appears that the best approach to determining the groundwater source term from the the auger holes will be an inventory and release rate methodology, using estimates of release rates based on

knowledge of chemical form and packaging of the wastes. (Since there are fewer shipments disposed of in the auger holes, it should be possible to obtain this information more accurately than can be done for the trenches). For air and surface water pathways the source term can be estimated using release factors and some average contaminant concentration derived from the volume and quantity of the disposed of contaminant.

4.1.1 Groundwater

The approach selected for estimating the groundwater source term for the trenches is to measure the contaminant concentrations in the trench leachates and combine this information with the groundwater flux, to yield a source term. This approach has the added advantage of automatically focusing the performance modeling directly on mobile contaminants (i.e., those found in the leachates) and avoids the requirement for detailed knowledge of the contaminant inventory. The contaminant concentration in the leachate may be limited by contaminant inventory, solubility, or leach/dissolution rate from the buried waste. It is probable that all of these limits could be effective in controlling the leachate concentration of some of the different contaminants at the SWSA-6 site. Thus, deriving an accurate description of a source term for the trenches will be a significant effort requiring considerable sampling and analysis and hydrologic modeling.

This approach will not be satisfactory for the auger holes, since the methodology used in constructing and operating the auger holes, as well as exposure considerations, appear to preclude drilling wells into the waste. The source term for wastes in the auger holes (a much smaller volume than in the trenches but containing much of the radioactivity) will be estimated based on existing inventory data and groundwater flux. Since the inventory data may be inaccurate and incomplete, it will be important to drill monitoring wells near the clusters of auger holes (Fig. 3) to detect the presence or absence of contaminants that may have moved from the holes. Although the auger

holes contain most of the activity, the location of these holes (in the upper reaches of the facility where the water table is deep), and the nature of the wastes (sealed sources, metal parts containing induced activity, etc.) should minimize the potential for release of radionuclides from these disposal units. In using this approach, a detailed analysis should be conducted to maximize the accuracy of the inventory data for these disposal units and to obtain additional information on the physical and chemical form of the auger hole wastes.

4.1.2 Air and Surface Water

The following methodology is proposed to define the source term for air and surface water transport pathways. Typical unit waste masses (TUWM), representing the average content of radionuclides and hazardous constituents in the waste masses disposed of in the trenches and auger holes, will be constructed from available records and ongoing waste characterization studies. These TUWM and, as mentioned previously, the results of erosion studies and water budgets will serve as the basis for constructing the source terms for the air and overland water transport pathways. They will also constitute a portion of the framework for delineating the source terms for the auger hole groundwater pathways. The following section is a brief description of the status of the ORNL waste inventory system which would be used to determine the TUWMs.

4.2 ORNL WASTE INVENTORY SYSTEM

Prior to initiation of the DOE Solid Waste Management Information System (SWIMS) in 1976, minimal information was recorded on the radionuclide content of the wastes buried in SWSA-6; however, some volume estimates were maintained (Bates 1983). Up to now, essentially no information has been requested on waste form or chemical and physical characteristics (other than radionuclide) for the wastes. Existing information (mainly for the period after 1976) consists of individual generators, best estimates of the total activity and

principal nuclides present in each waste shipment. Often, radionuclide estimates are reported as less-than values, or by descriptions such as "mixed fission products" or unidentified radionuclides. Thus, many isotopes that might be anticipated in the waste, based on past ORNL research and development activities, are not identified in the inventory. Furthermore, depending on the nature of the estimates, the total quantity of radionuclides buried may be higher or lower than the inventory data indicate.

It is possible that wastes containing contaminants now listed as being hazardous materials were buried in SWSA-6 prior to enactment of the Resource Conservation and Recovery Act of 1976 (RCRA). ORNL records do not provide information on which to base estimates of the amount or types of hazardous materials that may have been buried. Since 1980, wastes known to contain hazardous materials have been excluded from burial in SWSA-6 (Personal communication, T. Oakes, 1983).

Waste generation information has been entered into a computerized data base maintained by the ORNL Operations Division. Data on volume (entered in one of five different classifications), radioactivity (as a total amount and as individual nuclides), type of disposal unit (trench or auger hole), and location (identification number of trench or auger hole and position within the disposal unit) are entered into the data files for each individual shipment. Appendix A provides data retrieved from the ORNL data base on individual radionuclides buried in trenches or auger holes.

Since the input to the ORNL data base consists of estimates of the amount of activity and principal radionuclides in the waste shipment, concern has been expressed regarding the accuracy and completeness of the inventory. The lack of information on waste form or chemical speciation of the radionuclides could lead to erroneous conclusions regarding the availability of some of the radionuclides for environmental transport. As a result of these concerns, an attempt has been made to contact the originators of some of the waste shipments to get an indication of the chemical form and containerization of the

wastes and the accuracy of the estimates (Personal communication, S. D. Van Hoesen, 1985). Preliminary findings indicate that the generators feel that the volume estimates are good and that considerable information is available on the chemical form of the radionuclides, but that the numbers reported for radionuclide content were very rough and represent only best guesses.

Regardless of the accuracy or completeness of the inventory data, some interesting findings regarding the burial operations in SWSA-6 can be obtained from the existing data (see Appendix A). First, of the total activity reported as being buried in SWSA-6 (250,000 Ci), about 62% is represented by the 155,000 Ci of europium isotopes [control plates from the High Flux Isotope Reactor (HFIR)] buried in auger holes in 1980 and 1981; this means that 62% of the total reported radioactivity in SWSA-6 is contained in five auger holes (Nos. 235, 236, 251, 252, and 272). Second, of the total activity buried in SWSA-6 during the period 1977 to 1984, 91% is contained in the auger holes and only 9% in the trenches (Table A.3). During the same period, however, about 1% of the reported waste volume was buried in the auger holes and 99% in the trenches (Table A.4). Thus, the trenches contain a large proportion of the volume but only a fraction of the activity, whereas the very small volume of waste in the auger holes contains most of the activity. These findings indicate that SWSA-6 can be considered to be composed of relatively small areas in which large concentrations of radioactivity are present (auger holes), with the balance of the site containing large volumes of low-activity wastes (trenches). Using the information in Appendix A to calculate an average curie content per cubic foot of waste buried, the auger holes contain 34.8 Ci/ft^3 and the trenches 0.03 Ci/ft^3 of the wastes buried.

5. STATUS OF INFORMATION ON CHARACTERISTICS OF SWSA-6

As stated earlier, the ultimate goal of the characterization plan for SWSA-6 is to outline the information needed to establish that the site will meet the stated performance objectives. During the 35 years that SLB has been performed in the Conasauga Shale, information has been accumulated that suggests that certain conceptual models can be developed to describe the geology and hydrology of the SWSA-6 site. Unfortunately, although a considerable amount of information is available, additional information will be required to demonstrate that SWSA-6 will meet DOE closure requirements. This section of the planning document attempts, in general terms, to describe the site characterization information both currently available and being developed for SWSA-6. For ease in compiling this plan, the current information has been divided into geology and soils, hydrology, and geochemical areas; it should be emphasized, however, that all of these disciplines are interactive, and, as a result, some of the information described in one category would also be used in another (e.g, soil chemistry).

5.1 GEOLOGY AND SOILS

5.1.1 Geology

Understanding three-dimensional groundwater movement and rock-water interactions at SWSA-6 demands knowledge of site-specific geologic structural and chemical systems. Specifically, several different types of information are required: (1) The origin and characteristics of fractures (i.e., a planar fabric) needs to be delineated. This is especially important because permeability is believed to be strongly controlled by a secondary porosity formed by fracture networks. (2) The geochemistry (including sorption/desorption properties) of any materials (rock matrix, fracture surfaces, and fracture filling minerals) that may come in contact with potentially contaminated groundwater needs to be characterized. Hydrologic data

from the Engineered Test Facility (ETF) site in SWSA-6 suggest that there may be downward vertical flow into unweathered bedrock. (This is discussed in Section 5.2.3.4). Studies associated with the hydrofracture site show that bedrock may act as a retardant if the appropriate mineralogy is present (Haase et al. 1985). Therefore bedrock geochemistry becomes an integral part of groundwater characterization or retardation studies. (3) The dynamics of saprolite formation needs to be better understood, and the character of the bedrock-saprolite/saprolite-soil interface needs to be determined. During saprolite formation, carbonate cement is leached from bedrock. Examination of saprolite fabrics, however, shows no collapse structures resulting from a volume change, and, presumably, the leaching results in overall increased porosity. The geochemical behavior of the residuum is expected to differ from that of fresh bedrock. In addition, the interfaces between soil and saprolite and between saprolite and bedrock are not necessarily planar or sharp and do not necessarily correspond to hydrologic boundaries.

The first two types of information may be predicted from regional geologic models or from detailed geologic studies from other nearby sites and refined by site-specific detailed geologic studies. Such refinement is often necessary when the scale of required data is less than 100 m. For example, geologic models describe depositional environment; rock provenance; and subsequent diagenetic, thermal, and structural histories. These models allow one to predict rock type, rock body shape, and orientation and a generalized mineralogy, porosity, and structural fabric but do not give information on specific location, morphology, or chemical characteristics of these features, which may vary from within 0.1 to 50 m. Characterizing the saprolite requires site-specific investigations. Therefore, for the purpose of this study, site-specific detailed data and generalized geologic models are needed.

In addition to improving our understanding of local geologic systems, these geologic studies will supplement hydrologic and soils characterization and will provide data necessary for the numerical

models discussed in Sect. 4 (Transport Modeling and Pathways Analysis) and the hydrology section (Sect. 5.2) of this report.

5.1.1.1 Site-Specific Information Currently Available. Very few site-specific geologic data from SWSA-6 exist, and available data are concentrated primarily at the ETF site (approximately 1200 m^2) (Fig. 7). Because available data are concentrated in a few isolated locations, they give little or no indication of lateral variability in geologic parameters. ETF data are gathered from three sources: boreholes - sample cores and geophysical logs; shallow geophysical surveys - seismic refraction and reflection, electrical resistivity, and ground-penetrating radar; and experimental trench photographs. In addition, photographs are available from the French Drain project and from waste trenches constructed after August 1984. These data provide minimal information on clay mineralogy (core samples), depth to the soil bedrock interface (geophysical surveys), depth to the Maryville/Rogersville contact (geophysical logs), and a qualitative description of deformation styles (photographs). All ETF wells except ETF 16 are too shallow and have too few recoverable core logs and no geophysical logs to be of use. Also, the geophysical log package for ETF 16 is too limited to describe more than general lithologic changes. A complete package would provide considerably more information. In addition, the borehole deviation of well ETF 16 is not known; therefore, quantitative thickness and relative orientation information can not be determined. No site-specific geochemical or petrologic studies have been conducted on any of the geologic units that underlie SWSA-6.

5.1.1.2 Site-Specific Information Currently Being Developed. At present, three different types of data acquisition are being investigated for use in geologic studies of SWSA-6 (Fig. 7). The first involves interpretation of a seismic survey line located along the western boundary of SWSA-6 that was acquired for oil and gas exploration. The line will provide control on large-scale lithologic structures (depths of 100 to 4000 m) and thus constrain cross section

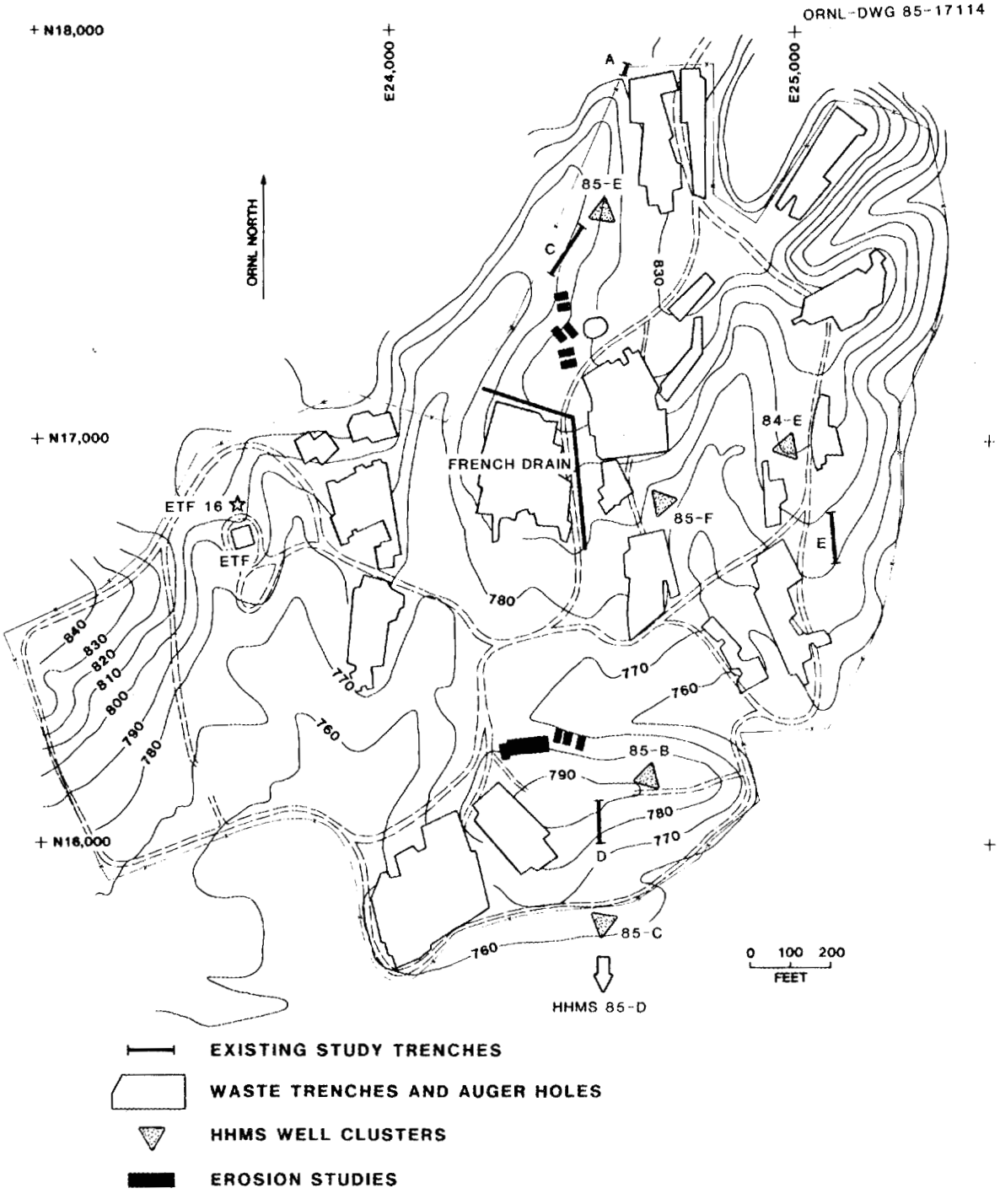

Fig. 7. SWSA-6 showing location of existing trenches, auger holes, and shallow explemental trenches.

interpretations and help predict regions of more intense deformation (and, thus, probably enhanced secondary porosity). This is the first opportunity ORNL has had to make interpretations from laterally continuous subsurface data. Seismic data on shallow horizons (less than 1000 m) need to be reprocessed to achieve better resolution of geologic structures.

The second data group would be collected from geophysical logs run on a package of four (possibly five) Hydrostatic Head Monitoring System (HHMS) well clusters. Well locations were picked to provide stratigraphic continuity between clusters. Interpretation of the the geophysical logs will provide information on lithologies, large-scale structures, and fracture systems at the well sites. The only rock samples available from these boreholes will be from cuttings, not from cores. Therefore, little information may be derived on fracture geochemistry because fractures are poorly preserved in cuttings. Initially, seven well clusters were planned to characterize SWSA-6. Because of monetary constraints, however, the construction of three of the clusters has been postponed; initial construction of the remaining four clusters may begin during late 1985. Thus, at present, no HHMS well clusters will be drilled either to characterize the northern area of SWSA-6 or to determine along-strike structural and stratigraphic variations.

The third data group is collected from a series of strike-perpendicular trenches that approximate a grid north-south traverse across SWSA-6. Geologic structures (bedding, joints, folds, and faults) were measured at a scale of 1:120. Preliminary results show two primary fracture sets, one of which is roughly strike-perpendicular, the other, strike-parallel. The dominant set appears to be strike-perpendicular. This orientation does not match hydrologic transmissivity results which show increased strike-parallel transmissivity. Preliminary results also suggest that the southern portion of SWSA-6 shows an increased degree of deformation, with a greater intensity of folding and faulting. This work is still

preliminary, and additional field work includes mapping strike-parallel trenches, as well as conducting tests at trench sites to examine qualitatively the influence of fractures in concentrating groundwater movement. Unfortunately, little room exists in SWSA-6 for the construction of additional study trenches. Hence, it is not possible to construct relatively complete strike-parallel and strike-perpendicular transects across SWSA-6.

Although measurements of fractures in saprolite give statistical results of fracture orientations, little information on the primary character of fractures may be determined from this type of analysis. Understanding original fracture development in bedrock is essential to understanding the character of altered fractures in saprolite. Unfortunately, these details are either obscured or destroyed in the weathering process and must be examined in fresh bedrock, in this case, as oriented core retrieved from boreholes.

A complete fracture analysis at SWSA-6 incorporates several different approaches that include field mapping, geophysical log analysis, and core analysis. In addition, remote sensing techniques can be used to map larger-scale fracture networks.

5.1.1.3 Use of Data from Other Regions Within the DOE Reservation. Available data from the DOE reservation that would be appropriate for SWSA-6 investigations are collected from Melton Valley to the east of SWSA-6 and from Bear Creek Valley (Table 4). Both valleys underlie rocks of the Conasauga Group and are in approximately the same structural positions in adjacent thrust sheets (The Copper Creek thrust sheet - Melton Valley, and the White Oak Mountain thrust sheet - Bear Creek Valley). Before reservation-wide data may be used, several questions need to be answered:

1. What is the lateral continuity of stratigraphic facies and diagenetic packets? Correlation with Melton Valley requires continuity on the scale of hundreds of meters and correlation with Bear Creek Valley requires continuity on the scale of hundreds of kilometers.

Table 4. Geologic data available from the DOE Reservation

Information available	Comments
Stratigraphy and petrography, minor structure	
Davis et al. 1984 Haase, 1983 Haase et al. 1985a Haase et al. 1985b Haase (in prep.) Rothschild et al. 1984 Vaughan et al. 1982	Bear Creek and Melton valleys; in addition to geologic descriptions, summary core logs are presented in these reports.
de Laguna et al. 1968	Joy 1 well data. Melton Valley; borehole deviation unknown.
Structure	
Sledz and Huff 1981	Joint study. Parts of Melton and Bear Creek valleys; minor correlation with other planar fabrics
ORNL photographs (1950-present)	Pits and Trenches, Melton Valley; only qualitative information. Interpreted photographs not presented in any report
Dreier 1985[a]	Three balanced cross sections perpendicular to strike across entire reservation
Dreier 1985[a]	Field work, Melton Valley (limited area), measured all observed fabrics, 1:1200
Dreier 1985[a]	Field work, West Bear Creek Valley; reconnaisance study of structural fabrics, 1:2400.
de Laguna et al. 1958	Pit 4, Melton Valley; primarily bedding planes data, few fold axes, no fault measurements, no fracture information
Zucker 1985. Senior Thesis; The University of Tennessee Ossi 1979. MS Thesis; The University of Tennessee.	Joint and fabric study, East Pine Ridge; Rome formation in the K-25 area; points out possible regional structural differences between the White Oak Mountain and Copper Creek thrust sheets.

Table 4. Continued

General Geology	
Stockdale 1951	Immediate X-10 area, 1:1200
Law Exxon Nuclear Site Report	West Bear Creek Valley

Information Currenlty Being Developed[b]	
Y-12 Characterization wells	Bear Creek Valley; 1000 ft; continuous core; complete geophysical log package. (Haase, Dreier)
(HHMS) wells	Melton Valley (SWSA 5, Pits and Trenches); complete geophysical log package. (Dreier)
Hydrofracture research	Three additional DM wells for hydrologic monitoring; well to Knox formation underneath the Copper Creek Thrust Sheet. (Haase, Stow)
Porosity and permeability tests	Melton Valley; Conasauga core.(Haase)
Reconnaissance field study	K-25 (Ketelle)

[a]Work done by C. Zucker under the supervision of R. B. Dreier from 12/84 to 6/85. At the present time, this work is unpublished.

[b]Names of principal investigators are given in parentheses following the comment.

2. What is the variation in (paleo) fluid composition within and between thrust sheets? Fluid composition and local chemical environments determine whether a mineral will be precipitated along a fracture (or fluid pathway) and, if so, the composition of that fracture-filling mineral. Therefore, correlation of fracture mineralogy data requires continuity on the scale of hundreds of meters for Melton Valley and tens of kilometers for Bear Creek Valley (or less if fluid migration or fracture formation occurred after thrust movement).

3. What is the degree of influence tear faults have in creating independent structural subdomains? Most "major" drainages oblique to ORNL east-west coordinates are assumed to represent tear faults. Tear faults may either independently rotate all preexisting structural fabrics or fabrics may be developed in association with movement along tear faults. Each alternative results in substantially different orientations and types of fabrics across tear faults.

Completed studies provide information on stratigraphic continuity within the reservation. Additional work is in progress to further our understanding of the stratigraphy and to characterize paleo fluid/rock interactions. At present, no data exist to allow discrimination between structural domains. A best-guess approach, in the absence of concrete data, assumes that lateral stratigraphic and fluid differences are minimal within and between separate thrust sheets and that structural subdomains surround probable high-angle faults.

5.1.1.4 Geologic Interpretation of SWSA-6. Figures 8 and 9 present a plane view and cross section geologic interpretation of SWSA-6.

Rock type is assumed to have a strong influence on topography. Thus, geologic contacts were placed at discontinuities in topographic expression. In addition, Fig. 8 also shows trends of topographic depressions that are presumed to be structurally controlled and that probably represent either minor thrusts or oblique tear faults.

The cross section (Fig. 9) is constrained primarily by two control points. These are outlined in bold in Fig. 8 and have been determined from geophysical logs (well ETF-16) or from field checking (Maynardville/Knox contact south of SWSA-6). Assumptions in cross

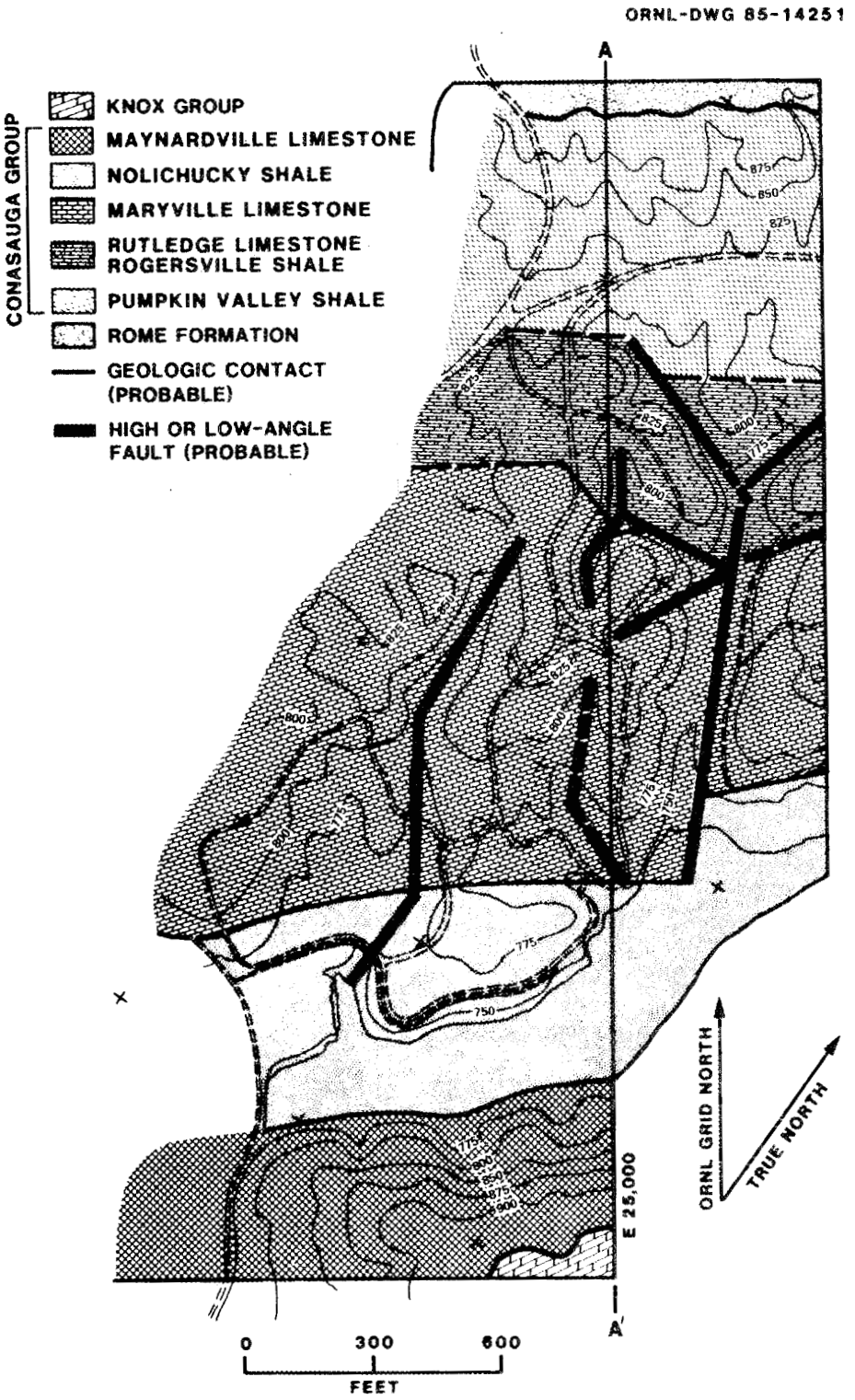

Fig. 8. Geologic map of SWSA-6.

ORNL-DWG 85-14252

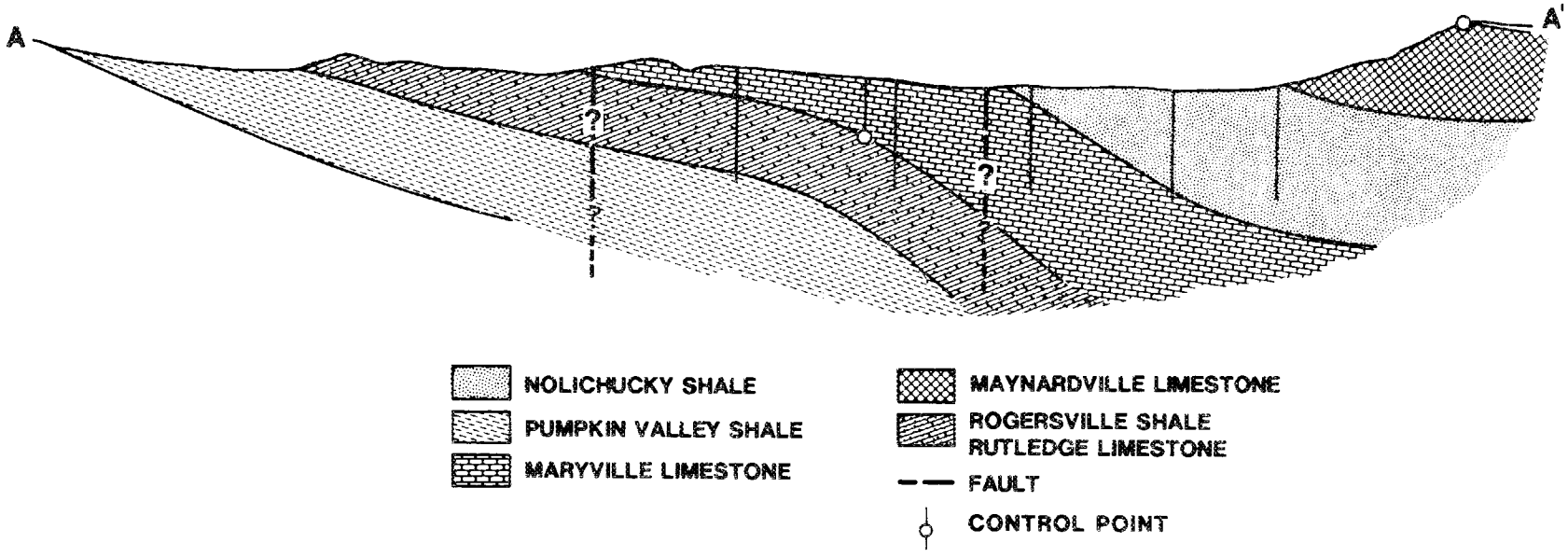

Fig. 9. Geologic cross section through SWSA-6.

section construction include the following: (1) thickness of Conasauga members is taken from Joy 2 well data, located southeast of the burial grounds in Melton Valley; (2) bed dips are derived by combining assumed bed thickness with map patterns; and (3) lithologic thicknesses remain constant.

Available data do not allow for validation of these assumptions. Lithologic thicknesses probably will vary, especially in the shale members, because of structural duplication. In addition, because geologic contact placement relies only on topographic expression, contact location is not exact and may vary by tens of meters. In turn, variations in geologic contact locations alter the three-dimensional attitude of lithologic units. Therefore, precise orientations of lithologic units remain unknown.

Correlation of soil types with bedrock lithologies suggests that the Maryville has a larger areal extent than shown in Fig. 8, and regions mapped as being Nolichucky shale may actually be Maryville limestone. This modified outcrop pattern may be the result of either (1) a decrease in Maryville bedding planes dips or (2) a duplication of the Maryville section through thrusting. The second alternative is also implicitly supported by Joy 2 well core data (Haase et al. 1985) and by structural fabric analysis measured in trenches in SWSA-6. Both interpretations create problems because they reduce the total thickness of the overlying Nolichucky shale. Therefore, at present, identification of lithologies underlying the current active trenches is not possible, and predictions of chemical and physical properties of these regions cannot be made because these characteristics vary with lithology. Discrimination of the Nolichucky shale and Maryville limestone will not be possible until geophysical log data from SWSA-6 are available. Problems associated with orientation uncertainties cannot be overstated, because potential flowpaths are commonly located at lithologic contacts or within particular lithologic horizons, as is discussed in the following section.

5.1.1.5 Regions of Possible Increased Porosity and Permeability. Other work on the DOE reservation highlights at least three possible regions of increased porosity and permeability: (1) Joy 2 well data suggest that the Upper Maryville shows increased deformation with respect to surrounding formations. At present, it is not known if there are particular horizons of increased deformation. Interpretation of photographs from the ETF site and from current waste trenches (Fig. 10) suggest that at least the southern portion of SWSA-6 shows a similarly high degree of deformation. In addition, the central and northern portions of SWSA-6, although not highly folded or faulted, contain extensive fracture systems. Pervasive deformation in Conasauga Group members is expected in Melton Valley because shales and interbedded carbonates are very susceptible to the applied stresses commonly observed in thrust sheets. (2) Contacts between carbonate and shale units may localize solution cavities and thus increase porosity. In SWSA-6, this may develop at the Rogersville shale/Maryville limestone and at the Maryville limestone/Nolichucky shale contacts. (3) Possible high-angle tear faults within SWSA-6 (Fig. 8) may act either as a conduit or as a barrier to groundwater. A fault near Trench 7 in the pits and trenches area appears to be a barrier to fluids. However, although the fault itself may act as a barrier to fluid movement, increased deformation spatially associated with faults may increase local porosity and permeability.

5.1.2 Soils

Investigations of soil (including the underlying residuum) are required to understand the site characteristics influencing isolation of the waste and long-term stability of the disposal site. Much of the general information on local soils can be obtained from published sources (USDA 1942, 1981). However detailed, site-specific studies should be performed to understand the geochemical and hydrological processes and to support the site performance assessment and closure planning efforts.

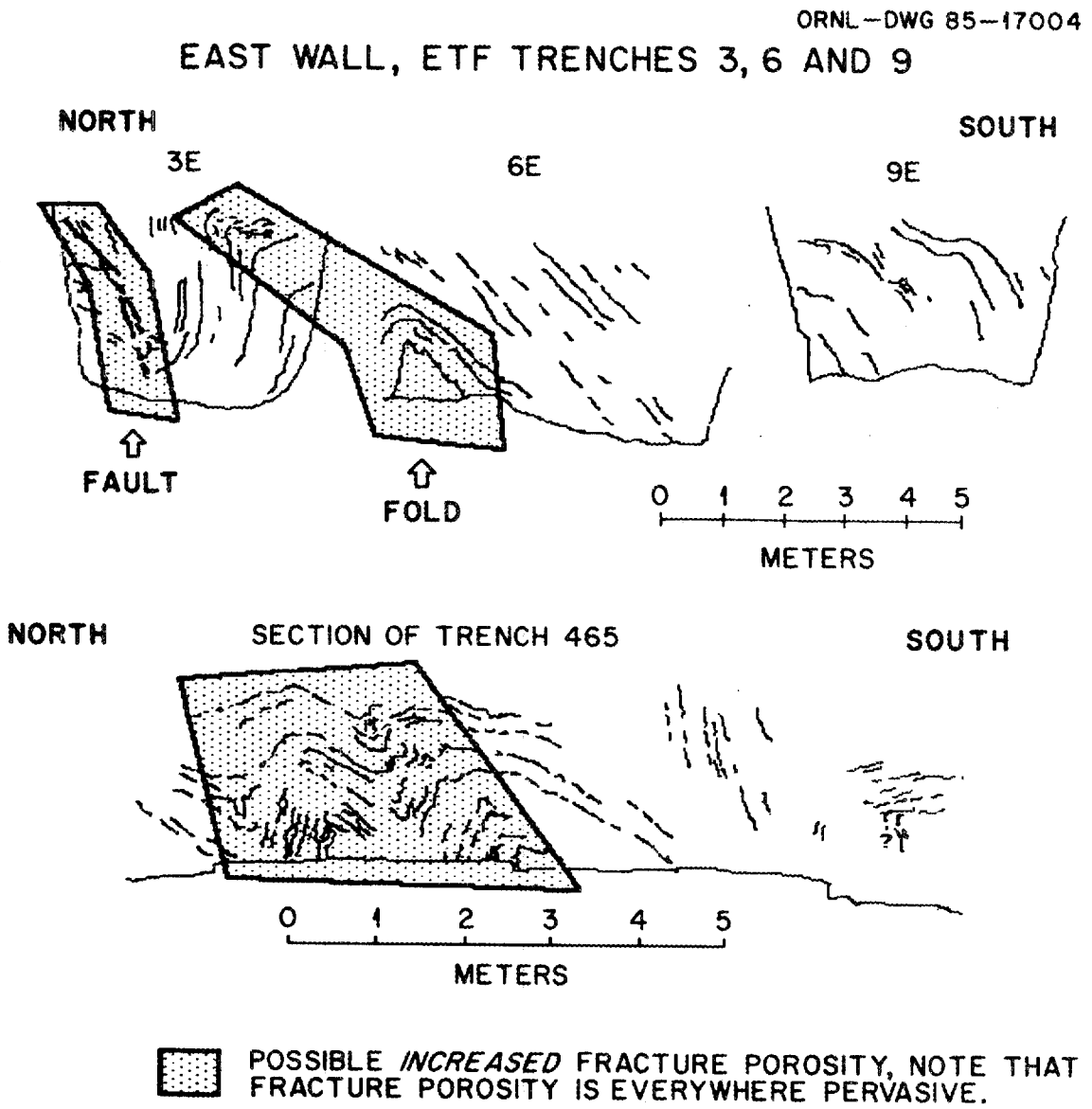

Fig. 10. Comparison of interpretations from ETF and current waste trench photographs.

Soils are composed of solid, aqueous, and gaseous phases. The composition, distribution, and spatial arrangement of the three phases influence the soil characteristics, including geochemical, hydrological, and structural properties. For example, the solid phase of soil often acts as a purifying filter for contaminated water containing dissolved and colloidal materials. Such retardation of contaminants released from wastes is governed primarily by physical and chemical properties, including mineralogy, soil solution composition, and hydraulic conductivity. The hydrological properties, such as flow path and velocity, are related to the structural development and texture of the soil. Soil development is also related to the geomorphology and bedrock geology of the site. Therefore, reliable assessment of site performance depends upon the comprehensiveness of the acquired basic data related to soil, geological, and hydrological characteristics.

The type of soil at a given place depends on the lithology of the area (bedrock), the soil forming processes which have taken place, the rate at which these processes occurred, and the time elapsed since soil formation began. The nature and intensity of soil-forming processes at particular sites depends on soil forming-factors. Therefore, soil surveying and mapping of a given site is a most valuable tool for understanding the general soil properties of the site. The soil survey provides information regarding soil type, slope, vegetation, natural drainage, associated soils, depth of bedrock, susceptibility to erosion, flooding hazard, and detailed profile description. The soil map produced can be used to select and estimate the suitable areas for trenches within the site boundary. A soil survey of SWSA-6 was conducted in the spring of 1985 and a soil map (Fig. 11) was developed indicating the presence of 10 soil mapping units (Table 5). Some of the soil mapping unit descriptions may be subject to change when laboratory analyses of the soils are completed (Lietzke and Lee, in press).

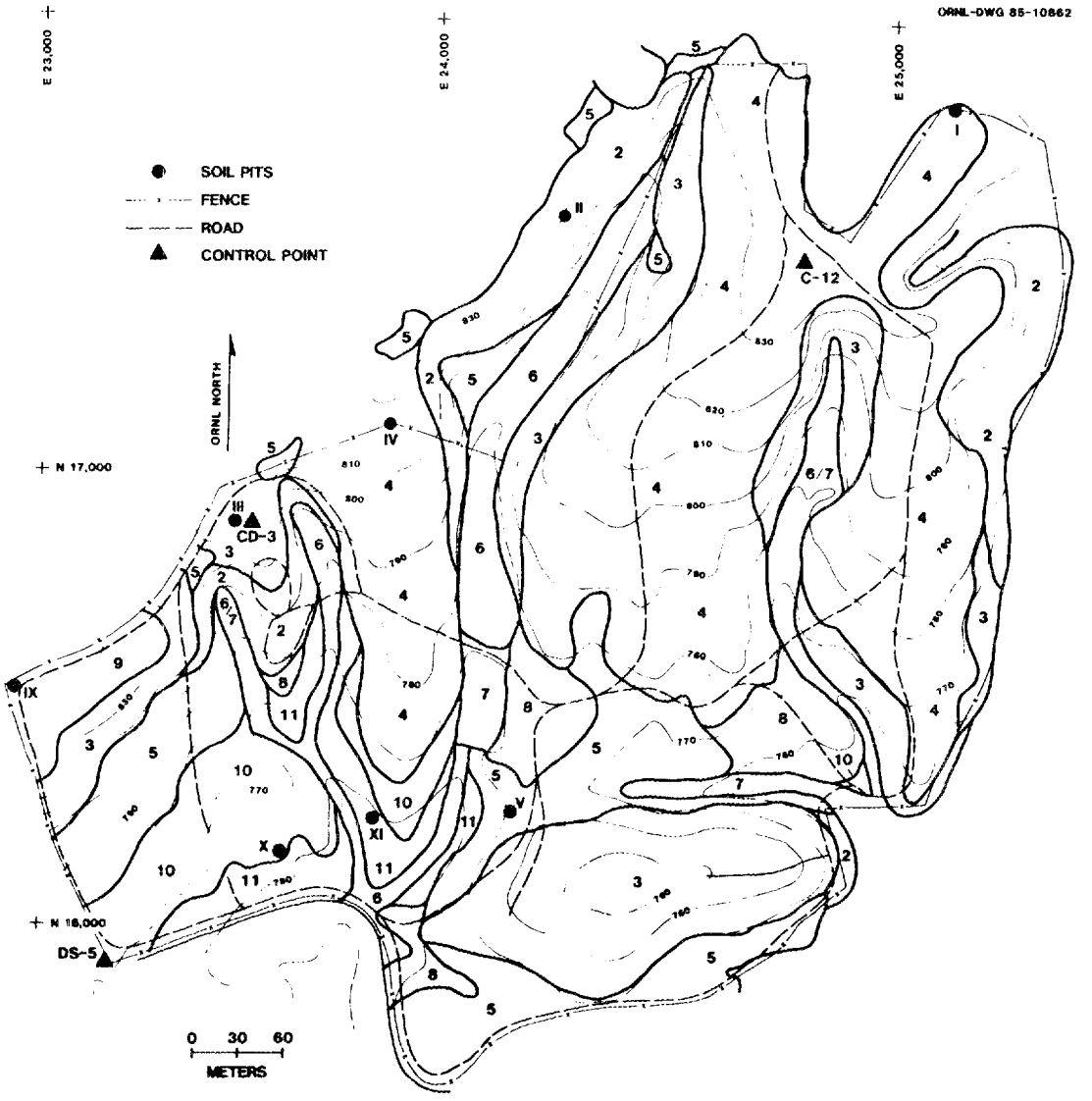

Fig. 11. Soil Map of SWSA-6 Area (See Table 5 for Soil Mapping Unit Descriptions).

Table 5. Classification of soils in the SWSA-6 area

Pedon No. (mapping unit)	Family classification	Soil series
1	Dystric Eutrochrepts, loamy-skeletal, mixed, thermic, shallow	Petros variant[a]
2	Typic Dystrochrepts; loamy-skeletal mixed, thermic	Petros variant[b]
3	Ruptic-Ultic Dystrochrepts; loamy-skeletal mixed, thermic	Litz[c]
4	Typic Hapludults; clayey, mixed, thermic	Muse[c]
5	Typic Fragiudults; fine-silty, mixed, thermic	Leadvale [d]
5	Typic Hapludults; fine-silty, mixed, thermic	Shelocta[e]
6	Typic and Aeric Fluvaquents; fine-silty, mixed, thermic	SPND[e]
7&8	Typic Udorthents; loamy-skeletal, mixed, thermic	SPND[e]
9	Typic Paleudults; fine-silty, siliceous, thermic	Turbeville[f]
10	Ruptic-Aquultic Dystrochrepts; loamy-skeletal, mixed, thermic	SND[g]
11	Aquic Hapludalfs; clayey, mixed, thermic	Tupulo

[a]Soil has morphology of Petros but Petros occurs on acid Pennsylvania shales.
[b]Too deep to the Cr for Petros. The morphology is similar to Petros but the geologic formation is not.
[c]Soil temperature regime is thermic rather than mesic.
[d]Mixed rather than siliceous mineralogy.
[e]SPND = soil profile not described.
[f]This series does not have a silt capping.
[g]SND = series not designated.

5.2. HYDROLOGY

5.2.1 Rationale for Hydrologic Characterization

In evaluating the overall environmental performance of an SLB waste management facility such as SWSA-6, characterization of the hydrologic system serves several purposes. Hydrologic transport of dissolved contaminants is probably the most important mode of contaminant migration from SLB facilities in humid climates. Information on the volume of water coming into contact with the waste and the mode and duration of such contact is needed, together with data on waste leaching behavior, to predict the rates of release of dissolved contaminants into hydrologic transport. Potential contaminant migration pathways (i.e., subsurface flow paths and surface streams) need to be delineated. Flow rates and mixing characteristics along these pathways must be known to predict the extent of dilution and physical retardation of contaminant transport. Hydrologic data may also be needed in evaluating the potential for soil erosion to lead to waste exhumation, and, thus, to exposures via atmospheric or hydrologic transport of particulates and direct exposures to contaminated surfaces.

5.2.2 Estimation of Contaminant Release Rates

In environmental pathways modeling, the rate of contaminant release into hydrologic transport is sometimes assumed to be a constant function of time, and conservatively high release rates are assumed. A more realistic approach to estimating contaminant release would be to estimate this quantity as a function of the quantity of liquid available to effect the release, the rate of supply of liquids, and the waste solubility or leaching characteristics. The hydrologic source term could be defined empirically or by applying a mathematical model of the physicochemical processes involved in waste leaching.

The hydrologic quantities of potential importance for estimating contaminant release rates include the rate of fluid supply to the waste disposal unit (i.e., a trench or auger hole), the rate of seepage from the disposal unit, the volume of fluid in contact with the wastes in

the disposal unit, and the fluid residence time in the disposal unit. Some containerized liquid wastes have been disposed of in SWSA-6, but the majority of the wastes are solids (Webster 1976), so waste liquids probably are not a major contributor to contaminant transport. Water may enter waste disposal units (and thus come into contact with the solid wastes) in one of the following ways:

1. Rain or surface runoff from surrounding areas enters open waste-disposal trenches during the period that the trenches are receiving wastes. Berms are constructed around open trenches to divert runoff, so direct entry of runoff should occur only when the diversion berms are breached.

2. Precipitation or runoff can infiltrate through the trench cap, particularly through subsidence cracks or depressions in the trench cap.

3. Some waste may come into direct contact with groundwater in waste disposal units that intersect a high water table.

4. Lateral inflow of subsurface stormflow may occur above the permanent water table (i.e., the surface below which all voids are saturated and at which water is under atmospheric pressure) when infiltrated precipitation becomes perched and moves downslope or downdip along fracture zones, soil "pans," bedding planes, or other macropore features.

Field observations suggest that all of the listed mechanisms probably contribute water to SWSA-6 waste trenches. Saturated conditions have been observed in the lower portions of many trenches (Webster 1976), and water levels in trenches tend to be higher than the water table in surrounding wells (Davis and Stansfield 1984). This apparent "bathtub effect" might indicate that more water infiltrates through trench caps (e.g., as a result of differential settlement of wastes and subsequent cracking of trench caps) than through adjoining soils, but the preferred explanation is that lateral inflows collect in the waste trenches in the aftermath of storm events.

Water-budget calculations, such as have been done for similar sites on the Oak Ridge Reservation (ORR) (see Rothschild et al. 1984a), can provide estimates of the volume of water, on a unit-area basis,

that infiltrates the soil and eventually leaves the site as surface-water discharge or groundwater inflow. A rough estimate of the volume of water involved in leachate generation can be obtained by assuming that all of the computed infiltration into SWSA-6 will enter the waste trenches and contact the waste. A more realistic estimate of flux into the trenches could be obtained by using the water-budget results in computing the infiltration flux for the land areas that contribute flow to waste-disposal units.

Water-budget calculations have not been done specifically for SWSA-6, but regional water budgets and water budgets calculated for such nearby sites as SWSA-7 (Rothschild et al. 1984a) could be used in rough calculations of environmental transport of SWSA-6 contaminants. A site-specific water budget could also be calculated for SWSA-6. Available meteorological data (i.e., precipitation measurements from the site and non-site-specific measurements of air temperature, solar radiation, etc.) described by Boegly (1984) are adequate for calculating a site-specific water budget. Additional information needed to calculate a site-specific water budget includes data on soil-moisture retention and storage characteristics of site soils, trench caps, and trench contents; measurements of seasonal groundwater-level fluctuations and groundwater fluctuations in response to storms; and flow measurements in the surface streams draining the site. Some of the soil-moisture characteristics data developed for SWSA-7 (Rothschild et al. 1984a) may also be applicable to SWSA-6, but new measurements are needed for trench materials and for soil units not present at SWSA-7. The necessary measurements of groundwater fluctuations are also yet to be made. Surface-water-flow measurement has recently begun on streams draining the site (see Sect. 5.2.4).

Another approach useful for obtaining quantitative estimates of the volumes of water entering waste trenches is mathematical modeling of the processes of infiltration and subsurface flow in the region above the water table. This approach is significantly more complex than the use of water-budget results but should yield somewhat more defensible estimates of influent water volumes and should permit estimates of the duration of water/waste contact under both fully and

partially saturated conditions. Unfortunately, the extreme complexity of the flow medium that exists in the soil and saprolite will make it difficult to characterize the flow regime fully or to represent it accurately in a deterministic mathematical model.

Specific information that would be needed to support mathematical modeling of infiltration and lateral flow in the unsaturated zone includes the following:

1. Measurements of the vertical hydraulic conductivity of SWSA-6 soils and trench surfaces over a wide range of moisture contents. Data for some soils in SWSA-6 and nearby areas have been reported by Luxmoore et al. (1981), Luxmoore (1982), Davis et al. (1984), Boegly (1984), and Watson and Luxmoore, but additional in-situ measurements are needed to characterize other SWSA-6 soil units and the variability that exists within units.

2. Detailed descriptions of SWSA-6 soils and saprolite are needed to delineate the soil structures and geologic structures likely to perch water or otherwise to conduct subsurface flow in the region above the water table. The recently completed soils mapping (Sect. 5.1.2) provides the needed information on the occurrence of paralithic contacts and other soil structures that may conduct lateral flow. Sledz and Huff (1981) have described bedrock jointing patterns in the Conasauga Group on the ORR; recent site-specific investigations of SWSA-6 saprolite structures (see Sect. 5.1.1) supplement their data.

3. Direct measurements of lateral inflow into trenches are needed both to improve conceptual understanding of lateral inflow processes and to provide data sets for model validation. Tracer tests that will be done in the ORNL subsurface transport processes research project may provide some of the necessary information. It may also be possible to use data on the performance of the French drain area of SWSA-6 (Davis and Stansfield 1984) to estimate the spatial and temporal distribution of lateral inflows to the French drain, to delineate the areas that continue to contribute to the lateral inflow to the waste trenches, and to determine how geologic structure and topography affect the spatial distribution of lateral inflow. The French-drain data set could also be suitable for use in validating a model of infiltration and lateral flow at SWSA-6. Additional observations of lateral flow may be needed, particularly if the subsurface-flow site and French-drain area are found to have atypical soil or geologic conditions.

4. Field measurements of additional hydrologic characteristics of SWSA-6 soils (e.g., relationships between moisture content and matric potential) are needed as a basis for modeling. Rothschild et al. (1984b) derived moisture characteristic curves for several soil units at the SWSA-7 site. Additional data for soils in other parts of Melton Valley may become available during FY 1986 as a result of ORNL research (K. Watson, personal communication, 1985).

Meteorological data requirements for infiltration modeling are generally similar to those for water-budget calculations. Measurements of temporal variations in rainfall intensity (e.g., at 5-min intervals) during storms might also be needed, however. Meteorological measurements should be continued at existing monitoring stations (Boegly 1984), to ensure the availability of appropriate meteorological data.

5.2.3 Delineation and Characterization of Groundwater Pathways

5.2.3.1 Conceptual Basis. Observations at LLW disposal facilities sited over Conasauga Group bedrock on the ORR suggest that the dominant pathway for offsite transport of waste constituents from SWSA-6 is subsurface flow to surface streams which carry the waste constituents offsite (Webster 1976). Thus, characterization of the SWSA-6 groundwater flow system is a critical element in evaluating the potential for offsite exposures from SWSA-6. Groundwater flow system characterization should be aimed at reliable determination of the directions of possible contaminant movement and estimation of flow rates and velocities along contaminant transport pathways.

Boegly (1984) has recently reviewed available information on SWSA-6 hydrogeology. Research and waste-disposal investigations in other parts of the ORR have also yielded a great deal of non-site-specific information on Conasauga Group hydrogeology, much of which probably is applicable to SWSA-6. These various investigations have also led to the formulation of conceptual models of groundwater flow in the Conasauga Group that help to guide efforts to characterize the SWSA-6 groundwater flow system.

A key feature of all current conceptual models of subsurface flow in the Conasauga Group is the notion that permeability due to primary porosity is quite low and that secondary porosity is almost entirely responsible for the Conasauga's water-transmitting capabilities. Secondary porosity in the Conasauga is associated with bedding planes, joints, faults, folds, and fractures, some of which are slightly enlarged as a result of the dissolution of carbonate. Transmissivity is greatest parallel to geologic strike (Webster 1976), suggesting that preferred flow paths are associated with a strike-joint set described by Sledz and Huff (1981) or with the intersections of bedding planes with the strike-joint set (Smith and Vaughan 1985b). Small-scale folds and faults formed during regional geologic deformation have also been found to be zones of unusually high transmissivity that act as conduits for groundwater flow and contaminant transport parallel to geologic strike (Olsen et al. 1983; Rothschild et al. 1984a; Smith and Vaughan 1985a) and may form local impediments to flow perpendicular to strike (Olsen et al. 1983).

Above the water table, the flow medium probably cannot be treated as an equivalent porous medium because (as is discussed in Sect. 5.2.2) the majority of flow in this zone appears to be carried by discrete geologic and soil structures (e.g., bedding planes, fractures, soil "pans"). Below the water table, however, the high density of joints and fractures in the saprolite generally makes it possible to treat the flow medium as an equivalent porous medium. The unweathered bedrock also can probably be treated as an equivalent porous medium, with somewhat lower hydraulic conductivity (Rothschild et al. 1984a) and somewhat greater anisotropy (Webster 1976) than the saprolite.

While groundwater flow patterns are controlled primarily by the hydraulic properties of the soil and rock, topography also exerts a strong influence. Water-level monitoring in the vicinity of radioactive waste disposal sites in Melton Valley has shown that the groundwater table is relatively shallow (i.e., within 0 to 12 m of the ground surface) and, as is typical of humid regions, is generally a subdued reflection of surface topography (Webster 1976; Rothschild et

al. 1984a). Some of the water that infiltrates in upland areas percolates down to low-permeability surfaces where it becomes perched and (unless it is diverted downward by a waste trench, French drain, high-angle fault, or other highly transmissive geologic structure) flows laterally to nearby watercourses, where it contributes to storm flow. Similarly, flow of groundwater below the water table seems to be predominantly a near-surface phenomenon in which groundwater follows short flowpaths in local flow systems and discharges to nearby streams (Rothschild et al. 1984c). Thus, most groundwater that is recharged in SWSA-6 probably discharges to the surface streams that drain the site or to White Oak Lake.

Some shallow groundwater may penetrate to greater depths, particularly along tear faults or other geologic structures that cut across stratigraphic boundaries. Very little is known about the extent of vertical water movement on the ORR (Rothschild et al. 1984c), and investigations of vertical flow are needed to improve the overall understanding of the hydrologic system and to predict the environmental transport of radionuclides from several major ORR waste disposal facilities. Local topographic relief on SWSA-6 is great enough, however, to induce virtually all of the SWSA-6 recharge to remain in local groundwater-flow systems. Thus, if deep flow occurs from SWSA-6, it probably involves only a small fraction of the disposal area's groundwater. Also, groundwater travel times from SWSA-6 along deep flowpaths to sites of possible offsite groundwater use or to a regional groundwater discharge area [identified by Rothschild et al. (1984c) as the Clinch River] would be very great.

5.2.3.2 Unsaturated-Zone Transport Paths. Except in areas of SWSA-6 where wastes are in direct contact with the water table, a portion of the contaminant travel pathway occurs in the unsaturated zone. Characterization of unsaturated-zone phenomena has been discussed in Sect. 5.2.2. Information on unsaturated-zone hydrology is also needed to evaluate contaminant transport through the unsaturated zone from waste-disposal areas to receiving waters.

Due to the "bathtub effect," contaminated fluids exiting waste trenches or auger holes are generally under positive pressure. Thus, downward hydraulic gradients will cause much of the contaminated water to be delivered to the water table, although some water probably moves down inclined surfaces (such as bedding planes) to discharge to streams and swales. To support a quantitative evaluation of transport along this pathway, information is needed on the proportions of contaminated water following each of these pathways, transport velocities, and the extent of fluid contact with sorptive media during transport.

Direct measurement of the properties of the unsaturated flow medium immediately below trenches and auger holes is not practicable. However, characterization activities discussed in Sect. 5.2.2 would provide generic information on the character of the unsaturated flow medium. In addition, to provide a basis for estimating the flux of contaminated fluids in the unsaturated zone, water-level fluctuations should be monitored in those waste trenches fitted with monitoring wells. Temporary gauging devices installed at close intervals along surface watercourses would identify the reaches that receive the most subsurface storm runoff and would thus identify high unsaturated-zone flows. Measurements of stream tritium concentrations at closely spaced measuring stations would help indicate which ones of these reaches are receiving flows from waste disposal areas. Repetition of the stream-gravel survey conducted by Cerling and Spalding (1981) would also help determine which ones of the high-seepage reaches are receiving contaminated inflows.

Most of the information on transport paths in the unsaturated zone that can be obtained through these activities is qualitative. However, based on this information, it should be possible to derive reasonable estimates for the hydrologic properties of unsaturated-zone transport pathways for use in hydrologic modeling. Estimates of unsaturated-zone fluxes based on monitoring of trench water levels would be very useful in parameterizing and calibrating a hydrologic model.

5.2.3.3 Aquifer Properties. Data on the water-transmitting properties, hydraulic storage properties, and effective porosity of saturated geologic media are needed for calculating contaminant

transport velocities and for constructing models of the groundwater flow system. An extensive data set exists on the saturated hydraulic properties of the Conasauga Group on the ORR. Numerous field measurements have been made of the equivalent porous-medium hydraulic conductivity and transmissivity (i.e., water-transmitting properties) of jointed Conasauga Group saprolite and bedrock. Reported values for the water-transmitting properties of the Conasauga vary over about two orders of magnitude (Rothschild et al. 1984a). Differences between the water-transmitting properties of different geologic settings (e.g., different geologic formations within the Conasauga) have not been discerned, and most of the variability seems to be attributable to local differences in the extent of structural deformation and to such factors as the number of joints intersected by a particular well. There are fewer measurements of hydraulic storage parameters (i.e., storage coefficient or specific yield) and effective porosity.

Measurements of the anisotropy of the Conasauga have been reported by Smith and Vaughan (1985b), who interpreted aquifer pumping test results as indicating that transmissivity resulting from regional jointing is three to five times greater parallel to bedrock strike than is transmissivity perpendicular to strike; however, zones of locally more intense fracturing (e.g., along small-scale folds and faults) oriented parallel to strike can increase the apparent anisotropy measured in field tests. There have been several observations of the hydrologic significance of these folds and faults, but there are no unequivocal direct measurements of their hydrologic properties. Data on the hydraulic conductivity and effective porosity of these structures would be needed to evaluate the velocity of contaminant transport through the "conduits" formed by these structures, and data on their hydraulic storage properties would also be needed to support numerical modeling of the groundwater flow system.

5.2.3.4 Hydrostatic Head Distribution. Data on the distribution of hydrostatic head (i.e., groundwater elevations in wells) are needed to locate the water table, to define groundwater flow systems, to evaluate hydraulic gradients along potential paths of contaminant

movement, and to provide a data set for use in model calibration. Delineations of the groundwater table and its fluctuations are needed to determine the vertical distance between waste trenches and the water table and to calculate a water budget.

An extensive network of groundwater-monitoring wells has been installed on SWSA-6 (see Boegly 1984) and numerous water-level measurements have been made, but many of the available water-level data are of doubtful validity, either because well designs were inappropriate or because needed information on well construction is not available (Webster et al. 1981). The existing water-level data must, therefore, be interpreted selectively. Some of the existing wells on SWSA-6 should be sealed and capped, because they are not sources of useful data and they may act as vertical conduits for contaminant movement.

Delineation of the permanent water table (i.e., the surface below which all voids are saturated and at which water is under atmospheric pressure) in the Conasauga Group presents a challenge. Wells that encounter perched groundwater above the permanent water table may show significantly higher water levels (and more dramatic water-level fluctuations) than nearby wells that do not intersect perched groundwater zones, and it is difficult to distinguish between water-level elevation differences that are due to perched water and those that are due to real differences in the elevation of the water table (e.g., on either side of a hydraulic barrier in the subsurface). Wells that are cased and sealed through the water table and are open (or screened or slotted) only below the water table do not measure hydrostatic head conditions at the water table but at discrete intervals below the water table, where hydrostatic heads may be greater or lower than at the water table due to vertical components of flow. Past well-construction practices at SWSA-6 have compounded the problem of delineating the water table (Webster 1976); it is difficult to determine the significance of the water levels measured in deep wells that have long, open intervals (or that have long, gravel-packed intervals above relatively short screens) or in wells that are perforated through their entire depths. Wells that are perforated through their entire depths probably accumulate lateral inflows from

the region above the water table, and water-level determinations in these wells do not indicate true water-table conditions. For example, the 1965 depth-to-groundwater map used in locating waste trenches (Lomenick and Wyrick 1965) is based on data from several wells of this type and significantly underestimates the depth to the permanent water table in a few parts of SWSA-6.

Data presented by Webster and McMaster (in press) can be interpreted as indicating that at least 13 SWSA-6 wells (Nos. 371 to 373, 375, 378, 379, 382 to 384, TR1 to TR3, and TR12) are true water-table wells (i.e., their screens intersect the water table). Thus water levels measured in these wells are reliable indications of groundwater table elevation. Wells 367 to 370, 374, 376, 380, 381, and 385 to 388 are technically piezometers in that their slotted intervals are below the water table, but they are screened closely enough to the water table to make them reasonably reliable indicators of the water-table elevation. Figure 12 is a contour map of the water table below SWSA-6, based on water-level measurements for these 25 wells on May 23, 1983, the date having the highest groundwater levels reported by Webster and McMaster (in press). Most of the wells in the ETF and 49 trenches areas can also be used to delineate the water table, if water levels in all wells are measured synchronously.

Piezometer installations are also important components of a monitoring-well network. Wells open at discrete intervals below the water table are needed to define the three-dimensional distribution of hydrostatic head, to track vertical movement of contaminants, and as facilities for tests to measure aquifer hydraulic properties. The most useful information on three-dimensional head distribution can usually be obtained from a network of well clusters, each cluster consisting of a water-table well and one or more deeper piezometers. The components of a well cluster are located in close enough proximity that the well cluster measures a vertical hydrostatic head profile at a single map location. There is one piezometer cluster on SWSA-6, comprising ETF wells 13, 14, and 15 (Boegly and Davis 1983). Water-level monitoring in this piezometer cluster has indicated a downward hydraulic gradient

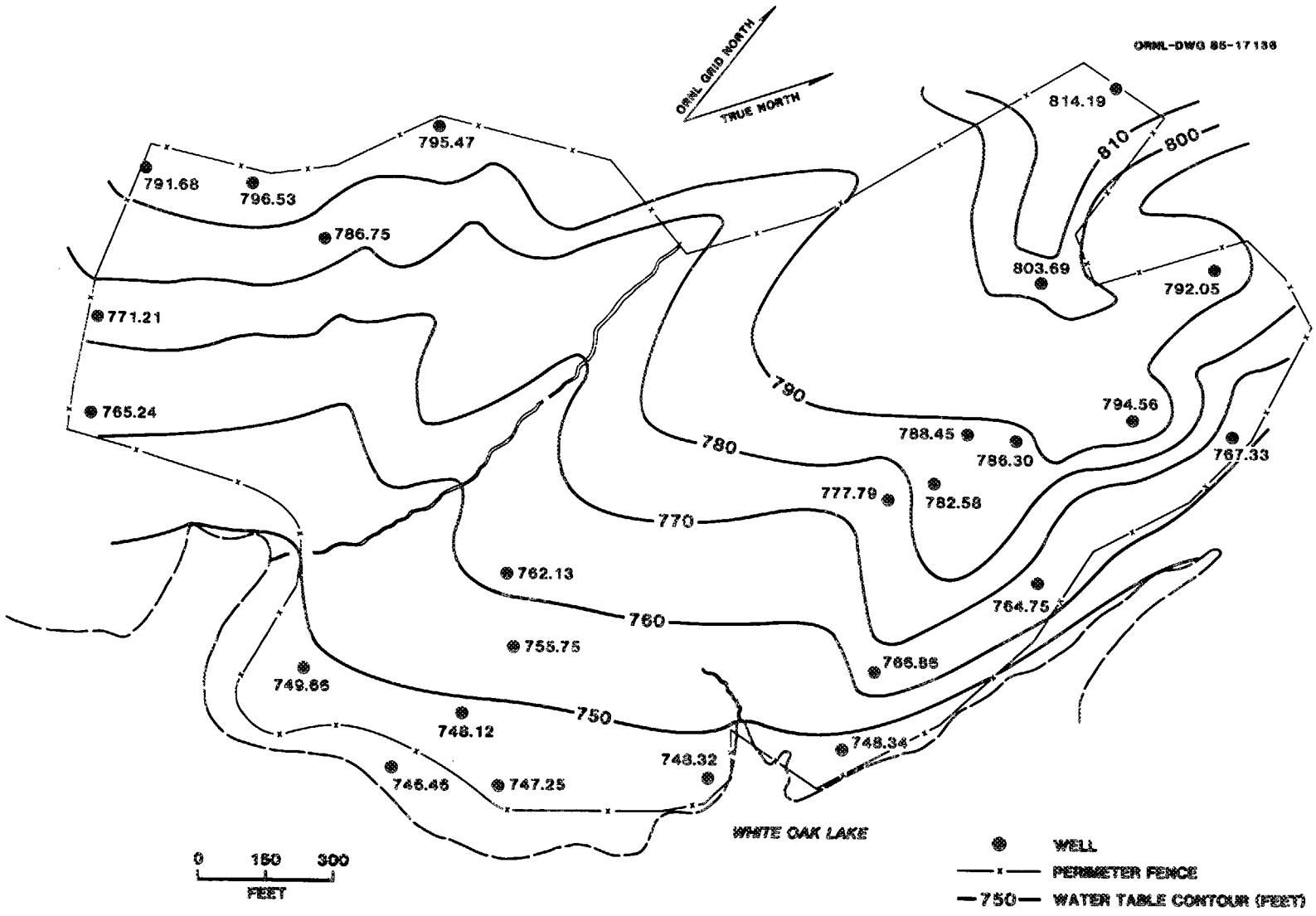

Fig. 12. Water table map of SWSA-6.

between the two shallower piezometers (at 14.2- and 28.8-m depths) and the 76.4-m-deep piezometer and suggests that groundwater in a brecciated zone at the intermediate depth may be under slight confining pressure (Davis et al. 1984). The evidence for a downward gradient in this piezometer cluster would be consistent with deep groundwater recharge from upland portions of the site, and it underlines the need for additional well-cluster installations to aid in tracing shallow and deep groundwater flow (and contaminant transport) paths in the SWSA-6 area.

Four to seven new piezometer clusters are to be constructed on SWSA-6 over the next few years as part of an effort to define the three-dimensional distribution of hydrostatic head under Melton Valley. Each of these piezometer clusters will include wells open at depths of about 15, 60, and 120 m. These new piezometers should help to ascertain the extent of deep recharge and the character of downdip flow along bedding planes. They should also help to determine whether deep groundwater flow systems are discharging in the White Oak Lake area. Additional well and piezometer clusters are needed, however, primarily at depths of 30 m or less, to permit three-dimensional characterization of flow paths near waste-disposal areas.

5.2.3.5 Flow-Path Chemistry. Data on natural groundwater chemistry can be useful in delineating groundwater flow systems (Freeze and Cherry 1979), as well as in defining chemical conditions that may influence contaminant solubility or sorption. Where contamination has already occurred, chemical analyses of groundwater are needed to define the character and extent of contamination due to waste disposal, and they can be helpful in delineating flow patterns. The status of existing information related to SWSA-6 groundwater chemistry is discussed in Sect. 5.3.2.

5.2.4 Surface-Water Hydrologic System

Information on the surface-water system to characterize transport of contaminants along surface-water flow paths that carry waste contaminants to White Oak Lake and off site. In addition, surface-water data are generally more accessible than other types of

hydrologic data, so data on surface waters are often important as indirect evidence concerning other elements of the hydrologic system. Whereas the other components of the hydrologic cycle often can only be characterized using indirect methods, surface watercourses can be located on a topographic map, channelized surface flows can be gauged directly, and acceptable surface-water samples can be collected for chemical analysis without great difficulty or expense.

Boegly (1984) reported that only limited data were available on SWSA-6 surface hydrology. Watercourses and watersheds had been delineated; a flooding hazard analysis had been done; flow and water chemistry data were available, but only for streams draining the ETF area; and one significant ^{90}Sr seep had been identified in the 49-trench area by analyzing gravels in the streambeds for sorbed radionuclides. Flow data were available for a stream (BG6E) (which drains part of SWSA-6 as well as large areas outside SWSA-6), for White Oak Creek at White Oak Dam, and for the Clinch and Tennessee rivers, which are the offsite receiving waters for SWSA-6 discharges (Rothschild et al. 1984c). During the spring of 1985, temporary surface-water gauging facilities were installed near the mouths of stream BG6E and two unnamed drainages in the central portion of SWSA-6; thus, all definable watercourses that drain SWSA-6 are now gauged (E. Davis, personal communication, 1985).

At least one year's streamflow data are needed to support water budget calculations or other modeling of SWSA-6 hydrology. (Precipitation and groundwater levels should be measured for the same year.) In addition, temporary gauging devices at closely spaced intervals along watercourses could be used in identifying areas of high inflow. Monitoring during and after storm events would identify sites of storm inflow from flow paths above the permanent water table, and monitoring during base-flow periods (e.g., in the spring, when groundwater levels are relatively high) would identify sites of groundwater discharge. Data on tritium concentrations of waters collected from closely spaced stations would assist in locating areas where subsurface contaminant transport pathways intersect the ground

surface. Migration of tritium is not retarded by adsorption on soil or rock, so tritium monitoring allows relatively early detection of zones of contaminant movement. Significant concentrations of tritium have been reported from a stream (near the ETF) which was not yet contaminated with strontium or cesium radioactivity; the tritium appears to have been associated with subsurface discharges from nearby waste trenches (Vaughan et al. 1982), indicating that tritium monitoring may be a useful tool for locating subsurface transport pathways. Similarly, useful information on contaminant discharge sites might be obtained from monitoring surface waters for any nonradioactive contaminants present in the wastes or from repeating the Cerling-Spalding (1981) stream-gravel survey.

5.3 GEOCHEMISTRY

The major purpose of geochemical characterization is to support pathways-analysis activities geared toward developing a performance assessment of the SWSA-6 site. In this discussion, the technical discipline "geochemistry" is construed to encompass both the chemical aspects of the site geologic components (soils, bedrock, and groundwater) and the chemistry of the emplaced radioactive and other waste constituents. The performance assessment will require values for a number of site aspects, including geochemical data to quantify the source term and site retardation of radionuclides and hazardous materials, in order to define probable releases of contaminants from the site. SWSA-6 is an active LLW disposal site, and, therefore, information will be needed to describe the performance of the variety of wastes already emplaced in both trenches and auger holes on the site, as well as that of additional wastes placed in the site until closure. Thus, a considerable body of information, including an estimation of associated uncertainties and ranges of expected or possible variance, will be needed for the pathways analysis, rather than single values for each parameter.

Two aspects of the site geochemistry are dominant in controlling site performance. These are the release of contaminants from the waste and the subsequent retardation of these mobilized constituents by site soil components. The information needed to define the source term has been described in Sect. 4. Retardation is primarily due to the sorption process affecting solubilized species along the release pathway from the trench or auger hole to the environment, although particulate filtration by the soil could be important in some cases.

Some of the existing geochemical information for the SWSA-6 site has been compiled and summarized in a recent report (Boegly 1984). Most of the existing soil and groundwater data are from a study of a small area (0.3 ha) of the SWSA-6 site which was developed for a field demonstration of an ETF (Davis et al. 1984). Some additional data have been collected during trench grouting studies (Spalding et al. 1985). Unfortunately, no geochemical studies were reported as a part of the original site evaluation (Lomenick and Wyrick 1965).

As a part of ongoing ORNL studies related to the siting of a new SWSA-7, a considerable amount of information has been gathered concerning the soils and geochemistry of an area of the Conasauga Group approximately 3 km east of SWSA-6 (Rothschild et al. 1984a; Lee et al. 1984; Davis et al. 1984). This information may be transferable to applicable geologic and soil units in SWSA-6.

5.3.1 Soil Chemistry

Most of the chemical information describing SWSA-6 soils is from a series of trenches at the ETF. The soils were described (Boegly 1984) as being highly leached strongly acidic. The mineralogy of samples from several wells at the ETF (Davis et al. 1984) shows typical clay constituents: illite, chlorite, and lesser amounts of smectite and vermiculite. If the soils at the ETF portion of the SWSA-6 site are representative of the soils throughout the site, then sufficient initial soil characterization information may already be available. It would be highly desirable, however, to confirm this assumed similarity by characterization of additional soil samples.

Since the contaminant release pathway may include the weathered part of the underlying strata, the geochemistry of the weathered bedrock (saprolite) and groundwaters within this strata will also be important. The ETF is situated in the Maryville formation of the Conasauga Group (Davis et al. 1984). The rock cores are described as being silty interclastic limestone interbedded with mudstone and shale.

5.3.2 Surface-Water and Groundwater Chemistry

The chemical composition of the ambient (uncontaminated) site surface waters and groundwaters is needed to characterize the geochemical properties of the existing site. The chemical composition (concentration of Na^+, K^+, Mg^{++}, Ca^{++}, Cl^-, SO_4^-, HCO_3^-, etc.) and the solution parameters (pH and Eh) play important roles in determining the contaminant leachability from wastes contacted by site water and in establishing the mobility of solubilized contaminants in groundwater. This geochemical information is also needed to understand the changes in water chemistry which may occur in the trenches from the dissolution of bulk waste components or from biological activity involving waste organics, such as paper or wood. It additionally helps us understand the water chemistry changes which may occur as the leachate moves away from the trenches or auger holes through the site soil, saprolite, or bedrock.

The chemistry of surface waters and groundwaters from several wells at the ETF are reported by Davis et al. (1984). The surface waters were described as being near neutral in pH. The chemical composition of the surface waters was not reported. The shallow groundwaters were described as being low in total dissolved solids, having low electrical conductivity, and being neutral or alkaline in pH. In general, the limited information available indicates that both surface waters and shallow groundwaters are typical dilute, unbuffered groundwater solutions at near-neutral pH. No information on deeper groundwater from the bedrock strata was reported.

Although no information was collected on background water quality (either surface water or groundwater) in SWSA-6 prior to initial waste

burials, it was possible to obtain some indication of groundwater quality in an area of SWSA-6 that was reported to be unaffected by previous waste burial operations. Vaughan et al. (1982) sampled wells in the ETF area prior to initiation of experimental waste burials. The results indicated that all of the wells sampled have calcium as the dominant cation (approximately 80% of the total) and bicarbonate as the dominant anion (approximately 90% of the total). The calcium-carbonate water was reported to be typical of limestone terrains, while the high silicon dioxide (SiO_2) level reflects the high pH and silt content of the Maryville limestone. Magnesium was the next most abundant cation, indicating the presence of some dolomite or high-magnesium calcite.

It seems likely that additional groundwater information will be required to characterize the SWSA-6 site water chemistry in sufficient detail to support the pathways analysis. The limited groundwater chemistry data available are from the ETF site, which comprises only a small portion of the SWSA-6 site. Additional groundwater sampling, and possibly bedrock groundwater sampling and geochemical characterization, will probably be necessary. It may not be possible to assume that all waters at the SWSA-6 site, including perched water tables, have the same geochemistry.

5.3.3 Waste Leachates

No information on the leachate (trench water) for the trenches at SWSA-6 was included in Boegly (1984). Although some of the existing trenches are reported to have had wells installed, no extensive sampling and analysis program has been carried out to study radionuclide leaching and migration. Some limited sampling and analysis of SWSA-6 trench solutions for ^{3}H and ^{90}Sr have been conducted, but the results have not been published. An active program to sample a number of the wells repeatedly and analyze the leachate solution will be necessary.

No information describing any solution in existing SWSA-6 auger holes was reported in Boegly (1984), and it seems likely that none exists. Since the auger holes are backfilled with soils and capped

with concrete, no ready mechanism exists for subsequent sampling or even determination of the presence or absence of groundwater in the auger holes. Some monitoring wells exist near some of the auger holes; however, no sampling of these wells is reported.

Although no leachate composition data are currently available for SWSA-6, it has been reported that trench leachate geochemical parameters can be quite different from those of the ingressing groundwater due to reactions with the emplaced wastes. Dayal et al. (1984, 1985a) report trench leachate compositions for solutions from the Maxey Flats LLW site. The leachate's geochemical parameters were drastically changed from background groundwater parameters. Due to anerobic digestion of the organic waste in the trenches, the leachates were highly reducing (as low as -400 mv) and neutral to mildly acidic, due to increased dissolved CO_2. Dissolved organics and chelating agents were also present. As the leachate migrated away from the trench, the leachate geochemical parameters began to revert to more typical groundwater conditions (Dayal et al. 1985b), and iron (II) oxidized and precipitated. The leachate composition and geochemical parameters are of importance to the performance assessment since dissolution from the wastes and subsequent retardation in the soil/groundwater system of many radionuclides and hazardous materials will be profoundly influenced by the geochemical conditions.

5.3.4 Retardation

Retardation of radionuclides or hazardous materials dissolved in trench leachate solutions, either in the trenches or as the solutions migrate away from the trench, may result from sorption of the dissolved species (either ionic or neutral) by the site soils [Lutton et al. 1982; NRC 1983]. The sorption reactions may be ion exchange (usually reversible and rapid), chemisorption (sometimes poorly reversible and slow), and surface adsorption (usually more important for nonionic species). The degree of retardation relative to the groundwater migration is usually expressed as a retardation factor ($\underline{R}$), which is

related to the experimentally measured sorption equilibrium distribution coefficient (K_d) by the relationship

$$\underline{R} = 1 + K_d(d/p),$$

where

$\underline{R}$ = retardation factor (dimensionless)
K_d = distribution coefficient (L/kg)
d = bulk density of geologic media (kg/L)
p = porosity of geologic media (dimensionless).

This expression is rigorously valid only when K_d is independent of dissolved species concentration, the sorption process is thermodynamically reversible, and a single species exists in solution. These conditions are seldom met in most practical applications; therefore, judgment must be exercised in designing the experiments to be used to measure the retardation and in extrapolating small-scale laboratory test results to predictions of geologic-scale behavior of materials.

Very limited information describing radionuclide sorption in the soil/groundwater system of SWSA-6 is given in Boegly (1984). Elements tested which would be expected to be present as cations (Am, Sr, Cs, Co, Fe, and Sr) generally showed high to very high sorption ratios in batch contact experiments; R values ranged from ~100 to ~1,000 L/kg for Sr and Co, and from ~1,000 to ~100,000 L/kg for Am, Cs, and Fe. The one element which would be expected to be present as an anion, iodine, was reported to show appreciable sorption, having R values of ~1 to ~30 L/kg. Anions are not usually well sorbed in geologic systems.

The radionuclide sorption information for the SWSA-6 soil/groundwater systems reported on may be insufficient to support realistic pathways analysis modeling. Additional laboratory measurements of radionuclide and hazardous materials sorption will be necessary to permit accurate and realistic pathways analysis modeling.

5.4 SOIL EROSION POTENTIAL

The site-specific potential for soil erosion to lead to waste exhumation must be evaluated as a part of the performance assessment. The frequency and intensity of rainfall are the main hydrologic factors in soil-erosion potential, which also depends on soil conditions, large- and small-scale site topography, and vegetative cover. Because the detachment and transport of eroded sediment are essentially hydrologic and hydraulic processes, however, additional hydrologic measurements can be useful in evaluating soil erosion potential at a specific site.

The Nuclear Regulatory Commission staff has recommended (Siefken et al. 1982) that soil-erosion potential at proposed LLW disposal sites might be evaluated by measuring sediment yields to streams that drain the sites. The main advantage of this approach is that it yields measurements of actual soil removal, rather than estimates (which are subject to uncertainty due to model error). These direct measurements are applicable only to site conditions at the time of measurement, however, and do not indicate how erosion potential might change under different site management practices or after native vegetation invades the site. Also, sediment yields do not always indicate the soil loss since upland channels can either capture and retain soil particles, or, conversely, they can erode themselves, yielding overestimates of soil loss. Therefore, considerable interpretation must go into estimates of soil loss.

A second approach to evaluating soil-erosion potential would be to apply the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1965), an empirically derived formula for predicting farmland soil erosion as a function of six factors characterizing the intrinsic erodibility of the soil, climate (i.e., rainfall intensity), slope angle, slope length, vegetative cover, and other site management practices. Although the USLE has been validated in a variety of field situations and has been modified from its original form so that it can be applied to nonagricultural settings, predictions made using the USLE

with published estimates of the individual input factors are less reliable than site-specific erosion measurements.

The approach being used to evaluate the soil-erosion potential at SWSA-6 is to make direct, onsite measurements of sediment yield and to relate the results to slope, measured rainfall intensity (or the intensities of simulated rainfall events applied to the surface), soil characteristics, vegetation, and microtopography. In essence, the experiments upon which the USLE was originally based are being replicated at the SWSA-6 site. ORNL is currently performing site-specific erosion studies on soil plots at SWSA-6. The intent of this effort is to calibrate the USLE to site conditions at SWSA-6 and other SLB sites in Melton Valley (R. Clapp, personal comm., 1985). This effort should provide the best-achievable estimates of soil-erosion potential at SWSA-6.

The USLE is designed to estimate sheet erosion only; soil losses due to gully formation and the resulting erosion are problematic. The CREAMS hydrologic model (Chemicals, Runoff, and Erosion from Agricultural Management Systems) which has the USLE built into it plus a gully-formation submodel, should be evaluated for estimating gully and rill erosion in SWSA-6.

6. ACTIVITIES PROPOSED TO COMPLETE THE CHARACTERIZATION OF SWSA-6

The current status of information on SWSA-6 has been summarized in Sect. 5. The purpose of this section is to describe studies that must be undertaken to obtain the missing information necessary to characterize SWSA-6 for compliance with DOE 5820.1. For planning purposes, it was assumed that data collection and analysis would be completed within two years of plan initiation. Based on our current understanding of the site (through conceptual models) it is apparent that a considerable research effort will be required to obtain the information. It should also be mentioned that the studies outlined below may have to be revised as the results of initial data collection become available. This may be especially true in the development of the source term (for both the chemical and the hydrologic aspects), since the approach suggested is a departure from traditional source-term analysis. However, it is anticipated that sufficient flexibility has been built into the proposed research and development programs to allow alternative approaches to be used as backup, if necessary.

6.1 PATHWAYS ANALYSIS

The pathways analysis to support the SWSA-6 performance assessment will include three major phases (see Fig. 5). The development of conceptual models to define the potential pathways to man constitutes the first phase of the analysis. As indicated previously, this development phase has been completed in some areas (e.g., exposure pathways) but the majority of the conceptual models need characterization data to be completed. The numerical models to be used to quantify the pathways will be developed based on the conceptual models.

The second phase of the analysis includes the selection of appropriate numerical codes to quantify the contaminant migration along the pathways of interest and the calibration of the numerical models.

During the calibration phase, the values of the modeling parameters are adjusted within the probable ranges, using sensitivity analyses and comparisons of simulation results with existing conditions.

In the last phase of the analysis, parameters and/or scenarios describing future events are defined and used as the basis for simulating the possible release of contamination from the disposal units. Simulations of contaminant migration along the pathways of interest are performed and contaminant concentrations at locations of probable exposure are calculated for various times during the postclosure period. Doses to man are then evaluated, assuming various modes of exposure. Due to the predictive nature of this part of the analysis, large uncertainties are generally associated with the model results. To allow reliable interpretation of the results, these uncertainties would be carefully evaluated, using sensitivity and uncertainty analysis. Well-established methodologies and analytical tools are available for this purpose.

The Conasauga Group is known to be hydraulically heterogeneous and anisotropic, with differing flow regimes occurring in the matrix, the bedding planes, the joint sets, and the local geologic features. The relative importance of each flow regime as well as the spatial distribution of hydraulic and geochemical properties (e.g., primary and secondary porosity, anisotropic values of hydraulic conductivity, unsaturated conductivity-moisture-suction characteristics, storativity, dispersivity, distribution factors, water-table fluctuations, moisture content, and chemistry of the medium-water system) need to be evaluated.

The conceptual model of the site hydrology includes at least two zones (or layers) in the subsurface. Because they play different roles in the site hydrology and contaminant transport process, these zones may require different numerical treatment. The zone above the water table includes both unsaturated and saturated (local perched water table) materials. It also includes the majority of the waste material. The hydrologic role of this zone is to transmit the water infiltrating at the surface down to the water table, thus providing a recharge for the saturated zone. The results sought in the analysis of

this zone are estimates of vertical and lateral water fluxes through trenches or auger hole areas and the areal distribution of the vertical fluxes at the bottom boundary of the zone (i.e., the aquifer recharge at the water-table elevation). The portion of this recharge that has been in contact with the waste would be assigned leachate concentrations to provide source-term values to the saturated zone model (see Sect. 6.2.3).

The role of the saturated zone is to transmit water laterally from its recharge area to its discharge area. Modeling of the saturated zone is proposed to be handled using a two-dimensional, vertically averaged, saturated flow and transport model. Such a model would not accommodate discrete layers having contrasting hydraulic properties, but available data do not indicate that this capability is needed for modeling the Conasauga Group. Several available computer codes for two-dimensional groundwater flow simulation include capabilities for modeling contaminant transport, so this flow-modeling approach would be compatible with transport modeling. The boundaries of the model would be located on groundwater divides and groundwater discharge surface-water bodies. The aquifer recharge in the simulated domain would thus be provided by the estimates of vertical fluxes obtained in the water-budget analysis of the upper zone. Source terms would be applied at the cells of the model corresponding to groups of trenches or groups of auger holes. The numerical model would provide estimates of concentration distributions in time and space for use in the pathways and dose analysis.

To characterize the overland transport pathway, the results of a water-budget analysis are necessary to estimate runoff value at the site and the part of the runoff that reaches White Oak Lake via the surface water pathways only (i.e., without infiltrating and reemerging).

The most likely pathway for the migration of contaminants from the trenches to the surface water system is through the subsurface. Reemergence of groundwater in the surface water system is evidenced in SWSA-6 by the existence of a seep in a streambed and by groundwater discharge to White Oak Lake. Shallow and deep flow paths may exist in

SWSA-6. The shallow flow paths leading to reemergence of groundwater are controlled by discrete local geologic features. The mapping of such features and of the reemergence locations with respect to the major disposal locations in SWSA-6, as well as the characterization of the hydraulic role of the features in the geohydrology of SWSA-6, is essential to the characterization of the surface water pathways.

6.2 SOURCE TERM

6.2.1 Sampling and Analysis of Trench Leachates

As discussed earlier, most of the trenches at SWSA-6 have had a well installed in the downgradient end of the trench. Many of these wells have been damaged or destroyed during routine operation or maintenance (grass cutting, excavation, backfilling). However, it will be possible to install new wells as needed in the trenches and obtain samples of the trench leachate (if any exists) for use in calculating a source term. Not only will leachate analyses be required but also some estimate of the amount of water entering and leaving the trench will be required.

Sampling and analysis of SWSA-6 trench water is a critical aspect of the source-term determination. The concentration of the radionuclides and hazardous materials (metals and organics) in the leachates must be known in order to calculate the releases which may occur over time. A sufficient number of trenches must be sampled to develop statistically significant average concentration values and to evaluate the ranges of concentrations which may be encountered. Because encountered of the wide variety of LLW placed in the trenches since 1969 and which will continue to be placed until the site is closed, as well as the multiplicity of disposal methods, it seems likely that a number of trenches must be sampled to get a satisfactory measurement of leachate radionuclide and hazardous materials concentrations.

Initially, ten trenches will be selected for sampling, and it is anticipated that based on the results of the initial samples, three or four trenches can be selected for more detailed evaluations. In

addition, initial uncertainties as to the direction of groundwater flow through the trench (lateral or transverse) and seasonal variation in groundwater flux will necessitate repeated sampling of the wells to quantify the ranges of concentration values to be encountered over time.

Trench leachate samples will be collected anerobically, that is, with as little contact with air as possible. Samples should be taken from various depths of each well in order to detect organic contaminants which might be water-emissible and might float on the surface of the leachate. The leachate pH, Eh, alkalinity, and temperature should be measured on a parallel sample in the field. After the samples are received in the laboratory, they should be promptly analyzed for major and minor cations and anions, as well as for radionuclides. Alpha, beta, and gamma counting techniques should be used as appropriate to detect and then quantify the radionuclides present. Because of the wide range of radionuclides in the wastes at SWSA-6, practical experience will have to be gained in the analytical program in order to develop the concentration values of the more significant radionuclides with a degree of precision which will satisfy the pathways analysis needs. Analyses should be completed for total dissolved inorganic carbon, total dissolved organic carbon, and for chelating organics. Other analyses should be performed as appropriate. If appreciable quantities of dispersed solids are present, filtration and examination of the solids might be desirable.

6.2.2 Auger Hole Water Sampling and Analysis

It is unlikely that leachate samples can be obtained from the auger holes. Solid, high-activity wastes have been placed in these holes and then the holes have been backfilled with soil and sealed with a concrete plug. If any auger holes can be identified as having accessible leachate, they will be sampled.

Wells in the vicinity of the auger hole clusters will be sampled to determine if contaminants have leached from the auger holes. Since most of the existing wells are located away from the auger holes, a number of additional wells will be installed as close to the auger

holes as possible, to enable water sampling during the period in which site characterization is being performed. Sampling and analysis of samples will be similar to that described for trench leachates in Sect. 6.2.1. If contaminants are not detected in the initial samples, efforts will be directed toward verifying the accuracy of the inventory of radioactivity in the auger holes such that reported release factors or leaching tests can be coupled with estimates of potential inflow and outflow of water through the auger hole to estimate the source term.

6.2.3 Groundwater Flux through Trenches and Auger Holes

A water-budget approach supported by field measurements and a simulation model will be used to estimate the various flow components going into and through waste-disposal units. Using this approach, incoming precipitation is distributed among surface water and groundwater discharge, change in moisture storage within both the saturated and unsaturated zones, evapotranspiration losses, and deep seepage of groundwater. Water-budget components are expressed by unit area and are compared with field results, to assure their validity. For evaluating flow into and away from a waste disposal unit, as well as mean residence time, the contributing area for the waste-disposal unit is determined and coupled with the estimated generation of lateral subsurface inflow through trench or auger hole walls, vertical infiltration, and saturated zone flow through any wastes present at depths greater than the water-table depth. Monitoring of changes in water storage within waste-disposal units will be used to verify water-budget calculations of both inflow and outflow rates. For specific disposal units, determination of drainable porosity can be used to relate an observed change in water level to the change in the quantity of water stored. Observations on the decline of water levels within trenches or auger holes can be used to verify the relationship between water level and flow rate. Analysis of rising water levels in waste-disposal units, if observed, will provide a basis for quantifying shallow lateral subsurface inflow. Thus, detailed water-budget calculations for individual disposal units can be used as the basis for

estimating both the average contact time between the wastes and water, the amount of water and waste in contact, and the flux of water away from the unit.

It is likely that a range of conditions exists and that some waste-disposal units are never in contact with water, while others have water present much of the time. These considerations, together with others (e.g., geologic, geochemical), must be combined to estimate overall transport. This general synthesis is described further in Sect. 6.4.1.

6.3 GEOLOGY AND SOILS

6.3.1 Geology

Geologic characterization tasks may be divided into five groups: core wells; geophysical studies; shallow trench characterization; laboratory analysis; and data interpretation and management. Data acquired from these tasks will increase our basic understanding of geologic processes that were or are active in SWSA-6 and will provide physical boundaries for and constrain numerical models of SWSA-6. Both types of information, process understanding and modeling requirements, are necessary to fully characterize the geologic features of SWSA-6 and to predict the long-term stability of this region.

6.3.1.1 Site Characterization Activities

Core wells

A core well to characterize stratigraphy and fractures should be placed south of Whiteoak Lake, as close as possible to the Nolichucky-Maynardville contact so that a complete section of the rocks that underlie SWSA-6 can be sampled. Joy 2 well data suggest that total depth of the well would be approximately 1100 ft. This depth estimate may be altered after retrieval of geophysical logs from the hydrostatic head wells.

A core well to characterize tear fault will be drilled at a nonvertical angle so that it will intersect the fault at a high angle. It will be cored so that the borehole walls are smooth (this is essential for packer installation). Subsequently, packers will be installed to partition off the interval surrounding the fault, and hydrologic tests will be run on this interval. Where this core well will be located depends on results of the geophysical surveys. Topography suggests the presence of several high-angle faults. If this is supported by the surveys, one fault will be chosen to be investigated as a general case. The well location will be placed so that the well intersects the fault at a high angle and for ease in well construction. Thus, the well location may be near any of the high-angle faults outlined on the geologic map (Fig. 8).

All core wells must have a complete set of geophysical logs run on them to complement and extend the usefulness of core data. Additional wells may be required to sample potentially complex fracture networks.

Geophysical studies

Recommended geophysical methods to conduct shallow geophysical ground surveys include those used in the SWSA-7 characterization study (Rothschild et al. 1984) and may be divided into seismic (refraction and reflection) and electrical (very-low-frequency-electromagnetic resistivity, spontaneous potential, electromagnetic resistivity, and electrical resistivity) methods. Geophysical transects should cut across possible high-angle tear faults and should follow all existing roads, to maximize coverage.

Reprocessing seismic data in shallow depth intervals of 0-1000 m will improve resolution of geologic structures, which now do not show sufficient resolution.

Shallow trench characterization

To establish a complete photographic record of all trenches; photographs should be shot at a scale and angle so that geologic structures preserved in the saprolite can be documented. Photographs

should be taken of all trenches dug by operations and of trenches dug specifically for the SWSA-6 closure plan.

To continue field mapping additional trenches should be constructed perpendicular and parallel to geologic strike and should sample as much of the SWSA-6 area as possible. (See Sect. 5.1.1.2 for more description.) Tests to determine whether radionuclides or groundwater is concentrated along particular structural planes may either be tracer tests, accomplished by induced flow outside of a trench, or a detector may be used to measure count variations with respect to various planes. These tests can be performed on the two existing trenches in SWSA-6 (trenches D and E, Fig. 7).

Possible geophysical transects, outcrop sites, and core well locations, as well as existing data locations and existing trench locations, are shown in Fig. 13.

Laboratory analysis

Core samples should be prepared for slabs, thin sections, and geochemical analysis (can include stable isotope and fluid inclusion analysis) and possible porosity and permeability tests. These analyses should also include thin section petrography and core porosity and permeability tests.

Data interpretation and management

Activities in the area of data interpretation and management should include interpretation of core fractures characteristics, all orientation analyses (including those performed using the SCAT method), interpretation of fracture networks (SLAR data), geophysical log analysis, interpretation of geophysical surveys, interpretation of seismic data, and development (or improvement) of available software for geologic interpretation.

SWSA-6 data needs and the tasks necessary to obtain these data are summarized in Table 6. Essentially, the data will provide information on overall geologic characteristics and specific information on fracture networks. Because primary geologic characteristics influence

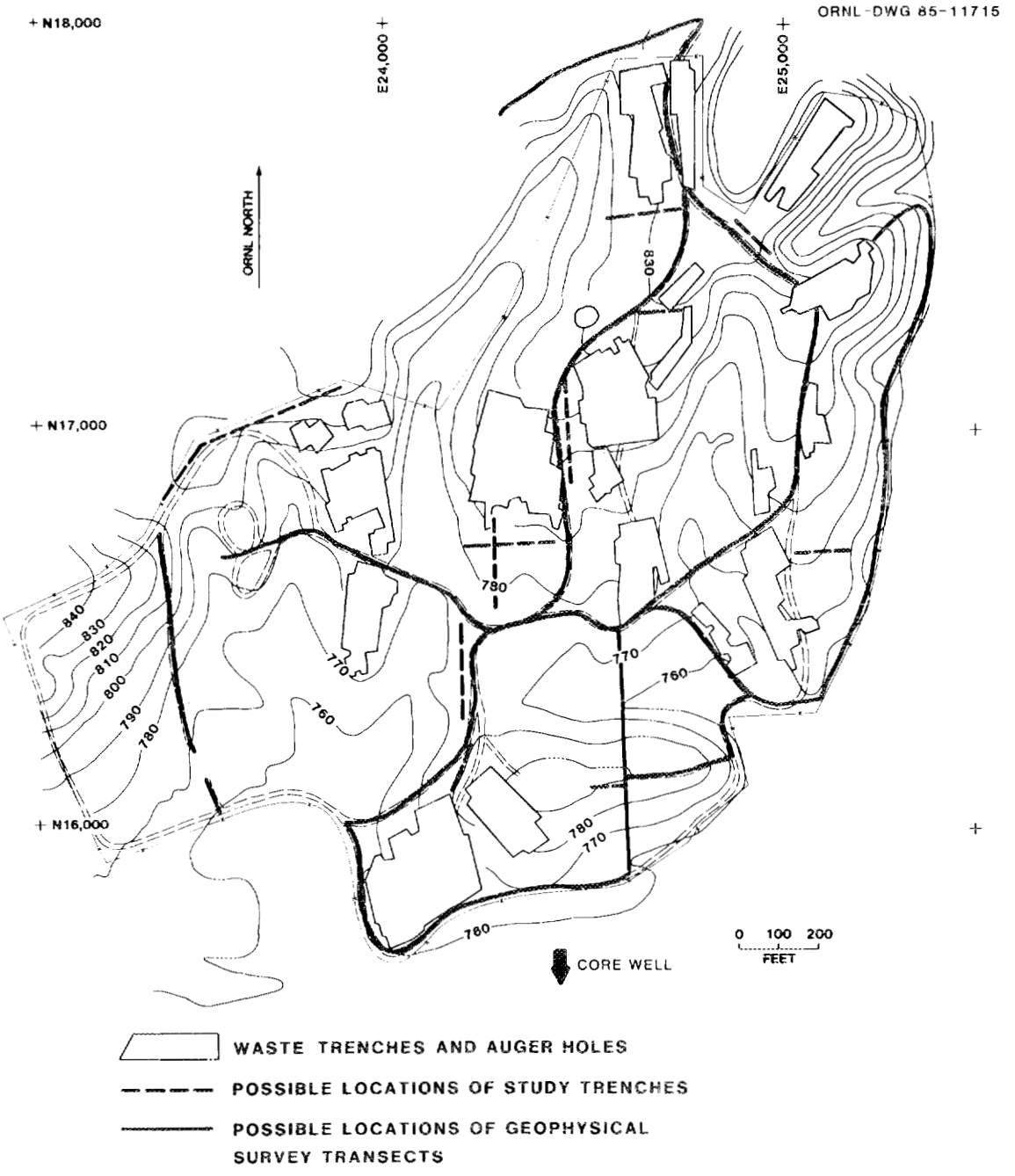

Fig. 13. Map of SWSA-6 showing proposed locations of geophysical transects, core wells, and shallow trenches.

Table 6. Data needs for SWSA-6 geological characterization

Type of information	Method of acquisition
General	
Rock type	Geophysical logs, core
Rock body shape and orientation	Deep seismic data, geophysical logs and core from several wells
Depth to saprolite and to bedrock	Shallow geophysical ground surveys
High-angle fault location and orientation	Geophysical ground surveys
Structural sub-domains	Mapping, geophysical logs and core from several wells
Saprolite processes	Continuous sampling from soil-saprolite-bedrock(core), standard soil sampling
Tests for Data Use from Other Regions	
Stratigraphic continuity	Comparison of core and geophysical log data from Melton and Bear Creek valleys
Fluid continuity	Comparison of stable isotope characteristics, comparison of groundwater geochemistry from widely separated monitoring wells
Tear-fault influence	Geophysical logs, core and hydraulic tests in well(s) that penetrate faults at an oblique angle to fault orientation
Matrix Characteristics	
Mineralogy	Core
Porosity	Geophysical logs, core tests, in situ hydraulic tests
Permeability	Core tests that are in conjunction with in situ hydraulic tests

Table 6. Continued

Type of information	Method of acquisition
Fracture Characteristics	
Identification and orientation of different structural fabrics	Mapping, geophysical logs, core
Porosity of each fabric type (conduit or seal)	In situ hydraulic tests (poor resolution?), tests on core
Density	Geophysical logs, mapping, core
Extent (through going or not)	Mapping
Morphology	Core
Mineralogy of fracture-filling material	Core
Origin	Core

[a]In this case, a fracture is defined as any semiplanar feature, such as a fracture, joint, fault, or bedding plane, that may increase the total porosity and permeability of the country rock and thus enhance fluid movement. This is a considerably broad definition of fracture.

soil development, groundwater transport, and groundwater geochemistry, these data will supplement soils, hydrology, and geochemistry studies. Specifically, processes involved in the transformation from bedrock, to saprolite, to soil will be better understood and structural fabrics, which appear to strongly control groundwater movement, will be characterized. In addition, at least two types of potential water/rock interactions (i.e., water/rock matrix interactions and water/fracture-filling minerals interactions) will be characterized. If bedrock groundwater sampling is conducted or if there is any potential for downward vertical flow of groundwater into bedrock, then it is essential that these water/rock interactions be understood. If not, meaningful interpretations cannot be made of bedrock groundwater geochemistry.

6.3.2 Soils

6.3.2.1 Physical and Engineering Properties. The measurements of soil physical parameters provide the data base needed for hydrological and engineering calculations. Among the physical properties considered most useful for site characterization are texture, porosity, structure, moisture retention, and dynamic properties of the soils. These parameters describe the size distribution of the primary soil particles, the degree to which these particles are packed, the nature of the secondary arrangement of the primary particles, water-holding capacity and potential, and engineering properties (consistency, plasticity, shear strength, and compaction). These properties can sometimes be correlated with water retention and movement, field moisture regime, solute transport, and soil erosion. The measurements of engineering properties are considered important in constructing facilities and designing trenches for maximum sidewall stability.

The different textural separates in soils are classified into various-sized groups (sand, silt, and clay) on the basis of their equivalent diameter. Sand and silt fractions do not exhibit marked

physical activity and may be considered the skeleton of the soil. Clay is a surface-active fraction with a high degree of chemical and physical activity. Clay soils have a tendency to be plastic and to swell and shrink, depending on moisture and salt content and mineralogical composition; they are also likely to have a low permeability. Textural information is available in the soil survey report, and laboratory tests will improve accuracy of the field data. The texture of the soils in SWSA-6 varies from clay loam to sandy loam. Such a wide variation of textural classes within the survey area and with depth is expected because the present soil textures are the result of the soil-forming factors. The variation with depth is caused by clay translocation and secondary mineral formation during pedogenesis and by the inherited texture of lithologic strata.

Porosity, a percentage of pore space calculated from the real and bulk specific gravity, gives the volume percentage of the pore space but does not characterize the size of the pores. The porosity varies with the size of particles and the state of aggregation. The size distribution of pores can be determined from the moisture-tension curve that relates the amount of water in the soil in equilibrium with tension forces applied.

6.3.2.2 Chemical and Mineralogical Properties. Detailed chemical and mineralogical characterizations of SWSA-6 soils and weathered parent rocks are required for understanding the retardation behavior of radionuclides, soil solution and groundwater chemistry, and physical and engineering properties. Since the release pathway of the radionuclides and hazardous components of the emplaced wastes may include the underlying weathered bedrock strata, chemical and mineralogical characterization of the rock samples is also required. Such investigations will support the pathways analysis modeling and site performance assessment for the closure plan.

About 10 to 20 bore hole samples should be collected from predetermined locations. The selection of the bore hole locations will be made in conjunction with overall planning of hydrological and

geological investigations. The laboratory chemical and mineralogical investigations of soil and rock samples include hydrogen ion activity, carbonate content, exchangeable acidity and base saturation, cation exchange capacity, amorphous iron and aluminum contents, and semiquantitative mineralogical composition.

Soil minerals are the discrete units which comprise crystalline and amorphous inorganic solid phases inherited and/or produced by the weathering of parent rocks. The parent rocks (limestone and shale) are composed of detrital and authigenic minerals. Minerals, especially in the clay fraction, control the permeability, moisture-density relationship, cohesion, shrink-swelling, soil solution composition, exchange capacity and retardation factor, and other fundamental properties of soils and bedrock. Because clay minerals fill void spaces such as fractures, vesicles, and fissures, they are probably the dominant cause of the retardation of radioactive and nonradioactive contaminants and fluid flow within the hydrologic compartment.

Mineralogical analyses are normally performed on whole soil and bedrock and/or specific size fractions of the samples, such as sand, silt, and clays. Prior to the particle-size separation, carbonate minerals and organic matter will be removed by using sodium acetate and hydrogen peroxide treatments respectively. The sand, silt, and clay fractions will be separated by wet sieving, sedimentation, and centrifugation. Free iron oxides in the clay fraction will be removed using the citrate-bicarbonate-dithionite treatment. The free iron oxides removed from samples are defined as being amorphous materials which provide chemical sorption sites for trace heavy metals. Cation exchange capacities related to cesium fixation and strontium retention by the clay fractions will be determined, to provide an estimation of smectite and vermiculite contents. The amount of illite will be calculated from total potassium content and kaolinite will be estimated using differential scanning calorimetric analysis. The clay and silt fractions will be examined using X-ray diffractometry after various chemical and thermal treatments. Mineral phases in the fracture or micropore filling materials will be determined using scanning electron microscopy and electron microprobe analysis.

6.4 HYDROLOGY

6.4.1 Recommended Approaches for Synthesizing Information

A recommended program for characterizing SWSA-6 hydrology has been selected from the "menu" of alternatives outlined in Sect. 5.2. The main criteria for selecting a particular approach to be included in this program are (1) a high probability of its being successfully completed within the constraints of the resources that can realistically be expected to be available, (2) its technical defensibility, and (3) the expected accuracy of the results. The remainder of Sect. 6.4.1 describes the recommended approaches for synthesizing field data, in order to yield the input data needed for pathways analysis. Section 6.4.2 lists the measurements that should be made as part of the hydrologic characterization program, and Sect. 6.4.3 lists the facilities and equipment that must be installed on SWSA-6 to support the field measurement program.

An empirical approach should be used in estimating the quantities of radionuclides released into hydrologic transport (i.e., the hydrologic transport source term). The optimum method for deriving this estimate appears to be a hybrid of the water-budget approach and the physical-modeling approach described in Sect. 5.2.1. Water-budget calculations and field measurements of trench water levels and trench water chemistry would be the basis for models that estimate the hydrologic-transport source term. Initial estimates of the volume of water entering waste-disposal units from infiltration would be derived from water-budget estimates of unit-area infiltration over the SWSA-6 watershed. These estimates would be refined (by applying some sort of statistical model) to account for the observed effects on trench-water levels of such factors as the landscape position of the waste disposal unit, geologic setting of the waste-disposal unit, trench cover characteristics, and infiltration characteristics of the catchment area that contributes subsurface inflows to the waste-disposal unit. The volume of groundwater flowing through a trench or auger hole that intersects the permanent water table would be estimated after

groundwater flow system characterization is complete by (1) comparing the trench or auger hole base elevation with the water-table elevation to determine whether it intersects the water table and (2) using Darcy's Law to calculate the annual flux through that portion of the trench or auger hole that intersects the water table.

Flow and transport in the unsaturated zone will also need to be evaluated semiempirically, as it is impractical to expect that sufficient information can be collected in one year to support deterministic modeling of this zone. Rates of outflow from waste-disposal units can be estimated semiempirically from analysis of the dependence of trench-water-level fluctuations on waste-trench hydraulic characteristics, measured hydraulic characteristics of the unsaturated zone, and site water-budget parameters. The proportions of infiltration that contribute to short-term subsurface storm runoff and long-term saturated-zone groundwater flow can be estimated using stream hydrograph separation.

Modeling of saturated-zone groundwater flow is an integral part of characterizing the hydrologic system. This modeling can be done at several different levels of complexity. The simplest type of modeling is the use of informed professional judgment (i.e., the application of conceptual models) to draw water-table contour maps and flow nets. Models range upward in complexity to numerical flow models that simulate three-dimensional saturated and unsaturated flow phenomena in media whose hydraulic properties are heterogeneous in space. The appropriate level of complexity for modeling a given site is determined based on data availability, site complexity, and the intended uses of the model output. The appropriate level of modeling complexity for SWSA-6 appears to be implementation of a two-dimensional numerical model of saturated flow. Such a model would not accommodate discrete layers with contrasting hydraulic properties, but available data do not indicate that this capability is needed for modeling the Conasauga Group. Several available computer codes for two-dimensional groundwater-flow simulation include capabilities for modeling contaminant transport, so this flow-modeling approach would be compatible with transport modeling.

It is probably reasonable to neglect deep recharge in modeling the SWSA-6 groundwater-flow system, if for no other reason than that neglect of deep recharge is conservative with respect to offsite exposures from SWSA-6. (If all of the groundwater is assumed to discharge to the White Oak Creek drainage, all of the radionuclides in this discharge would be predicted to leave the ORR much faster than if they followed longer, deeper flow paths.) Thus, White Oak Lake and the creek grideast of SWSA-6 probably can form one boundary of the model domain (a constant-head boundary), and the "bottom" of the model domain can be defined as the depth below which water does not seem to participate in flow paths to the White Oak Creek drainage. Boundaries on the north and west edges of the model domain will be somewhat more difficult to define, but they should be located far enough from SWSA-6 so that the boundary conditions imposed on these boundaries do not artificially control model-predicted hydraulic heads in the area of interest. Areal recharge to the groundwater system would not be modeled directly (i.e., by implementing a mathematical model of the unsaturated zone), but nodal recharge values would be estimated from water-budget calculations of rates of trench leakage and infiltration below undisturbed areas. The model would assume an anisotropic flow medium, punctuated by higher- and lower-permeability geologic structures.

6.4.2 Site Characterization Activities

The activities listed below should be undertaken to provide information needed to support the analysis proposed in Sect. 6.4.1.

- The regular program of meteorological measurements should be continued, including various observations at the ORNL meteorological towers and precipitation measurements on the SWSA-6 area.

- Groundwater levels in all suitable groundwater observation wells should be measured monthly. Groundwater-level data are required for calibrating the SWSA-6 groundwater model and for estimating changes in groundwater storage for the water-budget analysis. More frequent measurements may be needed during a limited period or in a limited area to support studies of trench-water dynamics and/or to support transient calibration of the groundwater flow model. This may involve 40 to 50 wells, including at least 30 existing wells and the 12 proposed new wells.

- Waste-trench water levels should be measured monthly in all trenches that have monitoring wells. Data on fluctuations of trench water levels are needed in water-budget analyses and in analyses of inflow to waste-disposal units.

- Measurement of discharge at the mouths of all SWSA-6 streams should continue. Streamflow data are needed to support water-budget calculations, calibration of the groundwater flow model, and calculations of offsite contaminant transport. Hydrograph separations should be performed on several storm hydrographs from each stream, to facilitate estimations of the relative contributions to storm runoff of groundwater below (i.e., base flow) and above the water table.

- Measurements of water levels in and discharges from the French drain should be continued. These measurements are needed to support water-budget calculations and to support the analysis of flow in the unsaturated zone, particularly flow into waste-disposal units.

- Soil water storage should be measured quarterly, to support water-budget analyses. More frequent measurements are desirable, if resources permit.

- Detailed short-term (e.g., 2 to 3 months) studies of trench-water dynamics should be carried out in five to ten trenches representing different landscape positions and soil types. Continuous measurements should be made of trench water levels during the test period. Also, field observations of the infiltration of overland runoff should be made during at least one storm event.

- Measurements should be made of the hydraulic properties (i.e., drainableporosity and sidewall hydraulic conductivity) of waste trenches. Porosity data are needed for water-budget analysis, and data on porosity and hydraulic conductivity are needed for analysis of trench-water dynamics. One way to make the necessary measurements would be to flood four or five waste-filled trenches, measuring the volume of water flowing into the trench and the rise and recession of trench water levels during and after the flooding. To provide accurate data on waste-trench porosity, reliable data on the dimensions of the trenches selected for this testing will be required. Also, to enhance the value of the water-level recession measurements, it would be desirable to work with trenches for which information on sidewall geology is available.

- A field survey of site wells should be conducted to identify all wells that are not useful for groundwater monitoring but that may (due to damage, well construction features, or location) contribute to cross-contamination or hydraulic disturbance. Information on problem wells is needed to interpret the site hydrologic system, as some wells may be responsible for hydrologic or chemical anomalies that cannot be otherwise explained by modeling.

- Tritium concentrations at stream-gauging stations should be measured under a variety of flow conditions. Tritium data will be useful in determining the relative contributions of subsurface storm runoff and true groundwater flow to transport of contaminants

from waste-disposal units. Some samples should be 24-h composites during base-flow periods. At each site, there should be at least one attempt to sample for tritium during a major storm runoff event.

- The vertical hydraulic conductivities of trench cover soils and in situ soils should be measured to supplement the available data on soil hydraulic conductivity from the SWSA-7 area and from earlier work on SWSA-6. Optimally, there should be a total of about 30 measurements each on trench cover materials (selected to represent a wide range of trench ages) and natural soils. Double-ring infiltrometer measurements are appropriate for these purposes.

- An induced-gradient groundwater tracer test should be performed in a group of wells that does not seem to be influenced by any discrete folds or faults. The primary purpose would be to measure apparent dispersion due to the movement of groundwater between fractures and the lower-permeability rock matrix. Measurements of this phenomenon are needed so that the effects of "matrix diffusion" on contaminant transport can be accurately reflected in subsurface contaminant-transport modeling.

- Temporary flow-gauging devices at various locations along the watercourses during base-flow periods will be used to estimate the amount of groundwater discharge occurring along discrete stream segments. The findings of this activity would be useful in locating hydraulically important geologic structures and in determining how to treat the streams in the groundwater flow model.

- Single-hole hydraulic conductivity tests (i.e., slug tests) should be performed in all appropriately constructed SWSA-6 wells. The purposes of this activity would be (1) to ascertain that the existing data set on the hydraulic properties of

Conasauga Group rocks is adequate for modeling SWSA-6, (2) to discern any areal trends or patchiness in the distribution of hydraulic conductivity on SWSA-6, and (3) to determine whether observed geologic differences (i.e., differences in lithology, saprolite vs. unweathered bedrock, or in density of jointing) can be correlated with differences in hydraulic conductivity. This is not a critical activity because there is strong evidence that an assumption of fairly uniform hydraulic conductivity will be adequate for first-cut groundwater flow modeling.

- Conduct an aquifer pumping test and a groundwater tracer test in a selected "typical" fold or fault structure. The aquifer pumping test results could be interpreted to yield estimates of the transmissivity and hydraulic storage parameter (i.e., specific storage or storage coefficient) of the structure. These are the parameters needed to characterize the structure in a two-dimensional, vertically integrated groundwater flow model. The tracer test results would yield an estimate of the hydraulic diffusivity of the structure and might be interpreted to yield information on matrix diffusion along the flow path. These parameters could be used in analytical modeling of contaminant transport along the structure. By manipulating the data from the two tests, it would also be possible to derive estimates of hydraulic conductivity and effective porosity of the structure, which are needed for some modeling applications.

6.4.3 Requirements for New Onsite Installations

- Install one additional recording rain gauge, preferably in the eastern half of SWSA-6. A gauging device in the eastern half of the site would permit monitoring of precipitation variability within the SWSA-6 area.

- Upgrade temporary stream gaging stations to permanent status.

- Install piezometers (typically about 100 ft deep) adjacent to four existing wells, to create four 2-well clusters. Holes should be made available for water chemistry sampling before the inside casing is installed and should be geophysically logged.

- Install up to 12 additional water-level observation and chemical sampling wells at a typical depth of 50 ft. Telescoped casing is probably unnecessary; finished inside-casing diameter should be 2 to 4 in. Some of these wells will be used to obtain information on groundwater levels and radiochemical data in the vicinity of the auger holes.

- Install new in-trench monitoring wells in as many as ten waste trenches representative of different landscape positions, initial waste inventories, waste age, etc. Typical well depth is 14 ft. Unusual construction conditions will largely dictate construction details.

- Install ten neutron-probe access tubes, distributed over the different major soil map units in the SWSA-6 watershed, for soil moisture measurements.

6.5 GEOCHEMISTRY

Based on existing information and the anticipated data requirements for pathways analysis and site performance assessment, additional geochemical investigations will be required. These investigations include the following:

- Sampling and analysis of uncontaminated site groundwaters (water table and perched water tables, if any), to determine background groundwater composition and geochemical parameters. Establishment of the background geochemistry of site surface water and groundwater is prerequisite to interpreting the leaching behavior

of the trench and auger hole wastes and identifying changes in geochemistry as water passes through the waste and soils.

- Sampling of site groundwater and surface water to determine the extent of existing contaminant migration through, or retardation by, the site soils. At this time, some analyses have been reported on samples removed from selected wells in SWSA-6 (Boegly 1984). However, the data are not sufficient to establish the movement of contaminants; especially nonradioactive components. New-water level and piezometer wells installed in SWSA-6 as part of the planned hydrologic studies will be sampled to establish a more detailed description of the extent of contaminant transport in SWSA-6. This type of information will be useful in identifying groundwater pathways (Sect. 5.2.3.5) and determining the ability of the site soils to retard the transport of contaminants.

Samples will be analyzed for gross alpha, beta, and gamma activity. Using these initial data, appropriate analytical methodology will be used to quantify the concentration of individual radionuclides present at significant levels in the samples. Total organic carbon analyses will be performed to test for the presence of organics and, subsequently, chromatographic or other techniques will be used to identify and quantify the concentration of hazardous organics present. Inductively coupled plasma spectrometry and atomic adsorption techniques will be used to identify the presence and measure the concentration of hazardous metal components in the samples. Because of the appreciable cost and time involved in a complete analysis of water samples, the contaminants to be studied in future analyses will be carefully selected. The scope of the effort for this activity can only be established as the initial contaminant data become available.

- Laboratory measurement of radionuclide and hazardous materials sorption in the site soil/groundwater and site bedrock/groundwater systems. Experimental work is necessary to develop retardation factor

values which quantify the retardation of important radionuclide and hazardous materials by site components. In the case of radioactive contaminants, chemical and hydrologic retardation can delay the transit time from the source to accessible environments, thereby allowing a portion of the radioactivity to decay. These experiments will employ samples of site soil, weathered bedrock, groundwater, and leachate under appropriate geochemical conditions. The site soil and weathered bedrock samples used will be subsets of the samples obtained for the determination of physical and chemical properties (see Sect. 6.3.2). Laboratory batch-contact experiments will be conducted under site release-pathway-specific geochemical parameters, to measure sorption isotherms (sorption ratios as a function of concentration) for the important radionuclides and hazardous materials. Sensitivity tests under variations or extensions of site geochemical parameters may also be conducted. Additional batch contact tests will explore sorption/desorption disequilibrium, to confirm the inherent conservatism of the batch-contact sorption ratio values. Laboratory once-through column chromatographic tests will be conducted to measure retardation factors directly and confirm the values calculated from batch-contact sorption ratios. These column tests will also explore possible multiple speciation and sorption/desorption disequilibrium effects on the retardation factor values.

Selection of the radionuclides and/or hazardous materials to be studied under this activity and determination of the amount or depth of study required will be an iterative process involving other site activities. As specific contaminants are identified which could be considered to be major dose contributors upon release, or to be in violation of some regulatory requirement, greater attention will be directed toward accurately quantifying the retardation behavior of these contaminants in the site geologic system.

In addition to the geochemical investigations outlined above, there are other studies in which geochemistry will play a major role. These tasks are described in greater detail in Sect. 6.2 (Source Term) and include the following activities:

- Sampling and analysis of wells near the auger holes, to determine the radionuclide and hazardous materials content (see Sect. 6.2.2).

- Sampling and analysis of trench leachates, to determine the radionuclide and hazardous materials content, as well as the leachate composition and geochemical parameters (see Sect. 6.2.1).

6.6. SOIL EROSION POTENTIAL

Sheet and gully erosion are of greatest concern during and immediately following the period over which institutional control will be exercised over the closed site. Following this period, natural succession will result in the invasion of forest species, with resulting changes in site erosion performance. Although the goal of the current ORNL studies on erosion includes an evaluation of the effects of crop cover, it is doubtful that meaningful results will be obtained within the time suggested for the characterization studies. It is therefore proposed to use the CREAMS model and the measured SWSA-6 site data to estimate what the long-term effect of reestablishing natural conditions will be on the long-term erosion potential of the site.

7. COSTS AND SCHEDULES FOR OBTAINING CHARACTERIZATION DATA

Section 6 describes the additional information needed to characterize the SWSA-6 site, to assure compliance with DOE orders 5820.2 (Radioactive Waste Management) and 5480.14 (the CERCLA Program). Based on an evaluation of the current status of knowledge regarding the performance of SWSA-6 (Sect. 5) additional information is needed to develop a source term for contaminants leaving the trenches and auger holes; define the site-specific geology (stratigraphy, petrography, characterization of fracture networks and other zones of increased porosity, etc.); provide additional information on the chemical, mineralogical, and physical properties of site soils; determine the hydrologic component of the source term (groundwater flux and wastewater contact time); determine the parameters necessary to characterize groundwater transport pathways; and evaluate geochemical parameters related to contaminant release (source term) and the retardation of contaminant transport. For planning purposes, it has been assumed that the characterization can be completed within two years.

Currently, DOE is funding a number of regional environmental evaluations related to past and future waste disposal operations at Oak Ridge nuclear facilities. For example, as part of the DOE-funded evaluations, wells are being installed to monitor the hydrostatic head distribution of groundwater in Melton Valley and provide groundwater monitoring facilities. Where these existing or proposed installations can be used to supply information for the characterization plan, the costs of drilling the wells has not been included in the overall cost of characterizing SWSA-6; only the costs of specific studies related to the use of these wells is included. As a result, the costs in this section do not reflect the total cost that would be incurred if the additional studies were not ongoing.

7.1 SOURCE TERM AND GEOCHEMISTRY

Geochemical information is needed as a part of the source-term definition and to serve as input to transport modeling of water and contaminants. Concerns expressed regarding the incompleteness of the current waste inventory records and the lack of data on nonradioactive contaminants indicate that the use of a total inventory-release-factor approach probably will not produce a defensible source term for modeling SWSA-6. Rather, a source term based on trench water analyses, coupled with estimated volumetric throughput and residence times, will be developed. This approach requires considerable sampling and analysis for radioactive and nonradioactive contaminants. Samples will also be obtained from existing and newly installed wells in SWSA-6, to provide geochemical information on site groundwater in the vicinity of the trenches and auger holes that will be useful in evaluating contaminant migration.

Although limited in extent, some leach testing of LLW will be conducted in an attempt to establish a relationship between current and future trench water contaminant concentrations.

Estimates of costs and schedules for the subtasks outlined above are included in Tables 7 and 8. Because little is known at this time regarding the radioactive and nonradioactive contaminants present in trench or auger hole water, these estimates may have to be revised once initial data are accumulated.

Table 7. Tasks, time, and manpower needed for source term and geochemistry analyses

Subtask	Time (months)	Staff (FTEs)
1-Characterize trench water	12 - 24	0.25
2-Extent of migration	6 - 12	0.25
3-Waste leaching	12	0.25

Table 8. Estimated costs for gathering source-term and geochemistry data, by subtask and fiscal year

Subtask		FY 1986	FY 1987	Total
1		125,000	100,000	225,000
2		50,000	75,000	175,000
3		25,000	25,000	50,000
	Total	200,000	200,000	400,000

7.2 GEOLOGY

Geologic characterization can be divided into five subtasks: core wells, geophysical studies, shallow trench characterization, laboratory analysis, and data management and interpretation (see Tables 9 and 10). For planning purposes, it has been assumed that most of this work (subtasks 1 through 4) will be done under subcontract with outside organizations. However, although most of the work would be done outside of ORNL, a considerable Laboratory involvement will be necessary to oversee the performance of the subcontracts and to provide the coordination necessary to ensure that schedules and data needs are met.

7.3 SOILS

Soil samples will be obtained from selected locations in SWSA-6 and analyzed for physical, chemical, and mineralogical properties. Chemical laboratory measurements will include pH, exchangeable bases and acidity, cation exchange capacity, mineralogical composition, and retardation of contaminants by SWSA-6 soils. Physical properties such as porosity, bulk density, texture, structure, moisture retention, compressive strength, cohesion, and shear strength will also be determined. This information will be used in modeling groundwater transport and in evaluating site stability. Tasks, manpower requirements, and costs for obtaining additional soils information are given in Tables 11 and 12.

Table 9. Tasks, time, and manpower needed for geology data gathering

Subtask	Time (months)	Staff (FTEs)
1-Core wells (2)	3	Contract
2-Geophysical studies	12	Contract
3-Shallow trench characterization	3	Contract
4-Laboratory analysis	12	Contract
5-Data interpretation	24	0.5

Table 10. Estimated costs together data, by subtask and fiscal year

Subtask	FY 1986	FY 1987	Total
1	40,000	35,000	75,000
2	30,000	25,000	55,000
3	5,000	5,000	10,000
4	10,000	20,000	30,000
5	50,000	70,000	120,000
Total	135,000	155,000	290,000

Table 11. Tasks, time, and manpower needed to conduct soil studies

Subtask	Time (months)	Staff (FTES)
1-Soil chemical and mineralogical properties	12	Contract
2-Soil physical properties	12	Contract
3-Sampling and sample preparation	24	0.2

Table 12. Estimated costs for soils studies, by subtask and fiscal year

Subtask		FY 1986	FY 1987	Total
1		10,000	20,000	30,000
2			20,000	20,000
3		20,000	30,000	50,000
	Total	30,000	70,000	100,000

7.4 HYDROLOGY

As indicated in Sect. 6.4, a number of the hydrology needs will require further evaluation. For planning purposes, four general areas have been defined as subtasks. These are basic hydrology, trench-water dynamics, surface-water studies, and meteorology. By far, the most important of these subtasks are those dealing with trench-water dynamics (hydrologic component of the source term), and basic hydrology (hydrologic transport). The majority of the effort during the characterization period will be devoted to these subtasks. However, some effort will be required to continue measurements related to the surface-water component of the water balance. In addition, it will be necessary to continue to operate and maintain the meteorological stations in SWSA-6 and to compile information for the basic hydrology and trench-water dynamics subtasks (see Tables 13 and 14).

Costs for installing some of the necessary piezometer wells and monitoring wells for this task are not included in the estimates reported in Table 14. Ongoing programs related to environmental compliance and restoration of ORNL facilities will provide the necessary installations. The cost of trench wells to be used to develop the source term (See Sect. 6.4) is included in Table 14.

Table 13. Tasks, time, and manpower needed for hydrology studies

Subtask	Time (months)	Staff (FTEs)
1-Basic hydrology	24	0.5
2-Trench-water dynamics	18 - 24	0.5
3-Surface water	24	0.1
4-Meteorology	24	0.1

Table 14. Estimated costs for hydrology studies, by subtask and fiscal year

Subtask	FY 1986	FY 1987	Total
1	120,000	95,000	215,000
2	130,000	100,000	230,000
3	5,000	5,000	10,000
4	5,000	5,000	10,000
Total	260,000	205,000	465,000

7.5 PATHWAYS ANALYSIS

Preliminary estimates of time, staff, and costs required for the various activities related to site modeling and pathways analysis are indicated in Tables 15 and 16. Only the modeling activities that are coincidental to or that shortly follow the site characterization activities [i.e., the activities included in Phases 1 and 2 of the overall performance assessment program (see Fig. 6)] are included in this plan. The other activities (Phase 3), which are closely tied to any remedial action program, cannot be costed at this time. Subtask 1 (Table 15) will include a preliminary analysis of data collected during initial stages of the site characterization, refinement of conceptual and numerical models, and selection of appropriate codes. Subtask 2

Table 15. Tasks, time, and manpower needed for pathways analysis studies

Subtask	Time (months)	Staff (FTEs)
1-Data analysis, refinement of conceptual models	12	0.2
2-Sensitivity analysis	12	0.2
3-Generic simulations/preliminary simulation of current behavior	6	0.5

Table 16. Estimated costs for pathways analysis studies, by subtask and fiscal year

Subtask	FY 1986	FY 1987	Total
1	20,000	40,000	60,000
2	10,000	70,000	80,000
3	———	100,000	100,000
Total	30,000	210,000	240,000

(Table 15) should be initiated as soon as characterization activities for a given pathway are near completion. The plan assumes that preliminary modeling activities for simulation of current behavior (Phase 3) will not be initiated until at least one year of data collection is completed.

7.6 PROJECT COORDINATION AND MANAGEMENT

To coordinate the various site characterization efforts and ensure that work progresses on schedule, it is anticipated that about 0.5 FTE will be required each year (Table 17). This individual will also be responsible for preparing a final characterization report on SWSA-6. Estimated costs are given in Table 18.

Table 17. Tasks, time, and manpower needed to many characterization efforts

Subtask	Time (months)	Staff (FTEs)
1-Project management	18	0.5
2-Report preparation	6	0.5

Table 18. Estimated costs for management of characterization efforts, by subtask and fiscal year

Subtask	FY 1986	FY 1987	Total
1	40,000	75,000	115,000
2	———	25,000	25,000
Total	40,000	100,000	140,000

7.7 SUMMARY

Based on the estimates developed for the individual subtasks in this plan, Table 19 presents the total subtask costs for each of the fiscal years during which the plan would be carried out and the totals for the overall characterization effort. Note that (1) not all of the costs are included in this tabulation, since ongoing studies in SWSA-6 related to ORNL's Environmental Restoration and Facilities Upgrading program will incur some of the costs of monitoring wells and piezometers in the hydrology subtask; (2) some installations (surface-water weirs, wells, meteorological station, etc.) already existed or were installed during the development of the plan; and (3) some parts of the plan were conducted before or during the time the plan was being finalized (for example, soil mapping and water level measurements).

Table 19. Summary of SWSA-6 characterization costs, by task and fiscal year

Task	FY 1986	FY 1987	Total
1. Source term and geochemistry	200,000	200,000	400,000
2. Geology	135,000	155,000	290,000
3. Soils	30,000	70,000	100,000
4. Hydrology	260,000	205,000	465,000
5. Pathways analysis	30,000	210,000	240,000
6. Project coordination and management	40,000	100,000	140,000
Total	695,000	940,000	1,635,000

7.8 SCHEDULES

Figure 14 presents the proposed schedule for performing the subtasks defined in the development of this plan. For planning purposes, it has been assumed that it will take two years to install needed facilities, collect data, analyze data, and prepare a characterization report. Availability of funding may dictate modifications in the proposed schedule.

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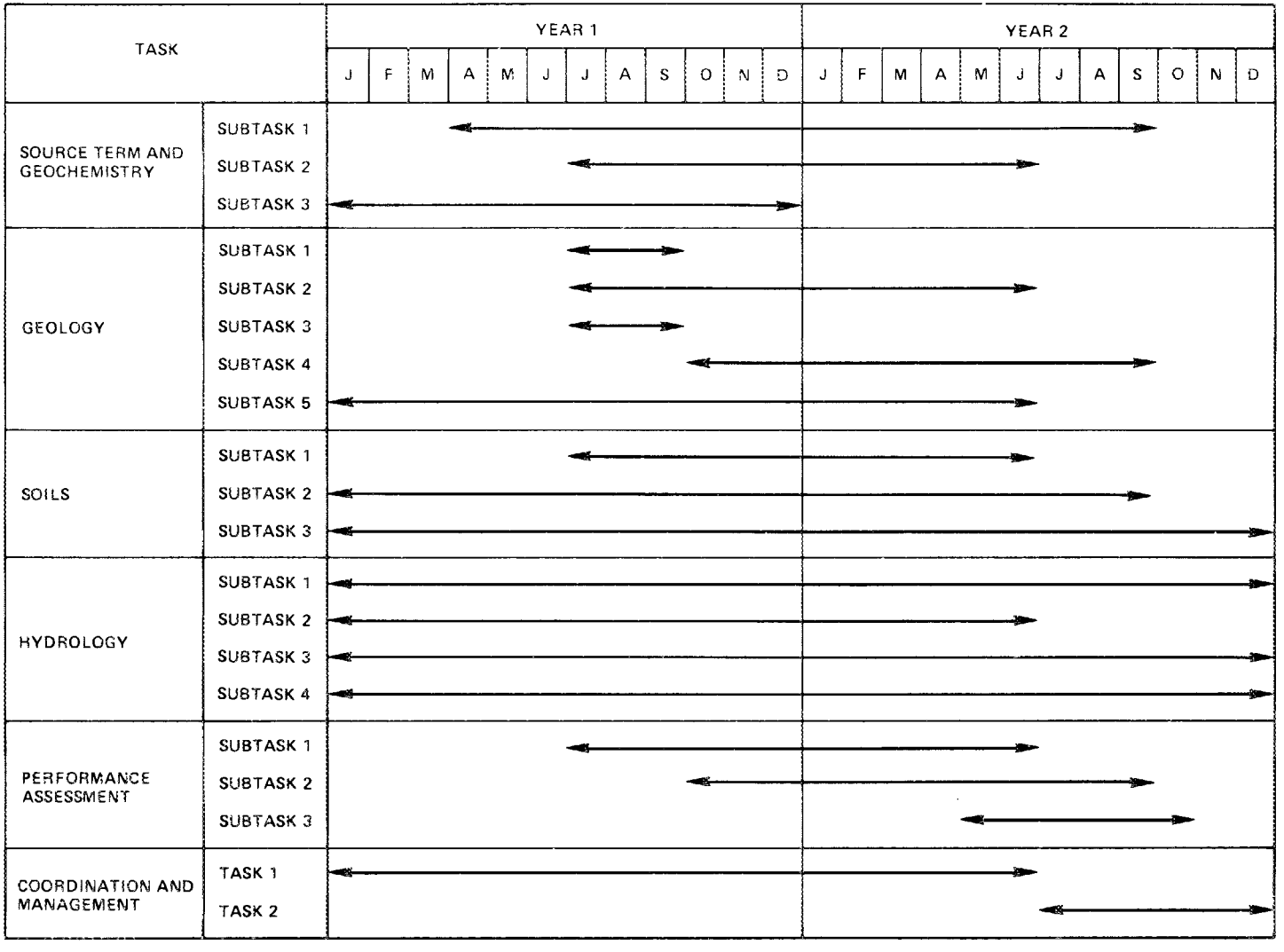

Fig. 14. Schedule for SWSA-6 characterization activities.

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APPENDIX A
OAK RIDGE NATIONAL LABORATORY LOW-LEVEL WASTE INVENTORY

Appendix A

OAK RIDGE NATIONAL LABORATORY LOW-LEVEL WASTE INVENTORY

To model hydrology and performance, it will be necessary to establish a source term for the contaminants in Solid Waste Storage Area 6 (SWSA-6). The derivation of the source term requires information related to the radionuclide content and the date on which the waste was buried, the chemical form of the radionuclides, and some estimate of the rate of dissolution of the nuclides. This section of the plan presents the currently available information regarding the volume and activity level of the low-level wastes (LLW) buried in SWSA-6.

The ORNL Operations Division maintains a computerized inventory of all waste shipments to SWSA-6. Prior to contacting the ORNL Operations Division for LLW disposal service, the waste generator must fill out a form which identifies the waste classification, type of waste, and the number and type of waste container (Fig. A.1). Although this form requests a list of the principal isotopes in the waste, in many cases, this is only an estimate, and past experience has shown that the estimates are often on the high or conservative side. Thus, the total activity values obtained by summing up the individual disposals may be higher than what is actually buried.

Since the first burials were conducted at SWSA-6 in 1971 the nature of the information entered into the ORNL record system has been modified a number of times. Initially, waste information was entered into the system using what was called MOD 1 input. For MOD 1, only data on waste volume were stored, although fissile waste was noted and entered separately. MOD 1 input was used for SWSA-6 data until 1975. Starting in 1975, inventory data were input using what was called MOD 2, which consisted of information on volume (both combustible or noncombustible and compactible or noncompactible) and the activity content of the waste using certain nuclear material codes. The major shortcoming of the data input is the lack of information on radionuclides other than those included on the special nuclear materials lists. MOD 2 was used for only a short time (1975 to 1976).

REQUEST FOR STORAGE OR DISPOSAL OF RADIOACTIVE SOLID WASTE OR SPECIAL MATERIALS

REQUESTER: EXECUTES THIS SECTION BEFORE ARRANGING MATERIAL TRANSFER

DATE	ORIGIN OF WASTE BLDG. IF ORNL	REQUESTER'S SIGNATURE	EMPLOYEE NO.	PHONE NO.	OFFICE AND BLDG. NO.	CHARGE NO.

TOTAL VOLUME CU. FT.	COMBUSTIBLE VOL. CU. FT.	WEIGHT LBS	ACCOUNTABILITY MM NUMBER	TOTAL CURIES IN WASTE BEST ESTIMATE

WASTE CLASSIFICATION (CHECK ONE)

1. ☐ TRU OR 233U (> 10 μ Ci/Kg) - Retrievable Storage
   ☐ TRU OR 233U (< 10 μ Ci/Kg)
2. ☐ URANIUM/THORIUM
3. ☐ FISSION PRODUCT
4. ☐ INDUCED ACTIVITY
5. ☐ TRITIUM
6. ☐ BETTA-GAMMA TRU OR 233U (> 10 μ Ci/Kg) - Retrievable Storage
   ☐ BETA-GAMMA TRU OR 233U (< 10 μ Ci/Kg)
7. ☐ ALPHA
8. ☐ LANDFILL
9. ☐ TEMPORARY STORAGE
10. ☐ OTHER _____

TYPE OF WASTE (CHECK ONE)

1. ☐ BIOLOGICAL (BW)
2. ☐ CONTAMINATED EQUIPT. (CE)
3. ☐ DECONTAMINATION DEBRIS (DD)
4. ☐ DRY SOLIDS (DS)
5. ☐ SOLIDIFIED SLUDGE (SS)
6. ☐ NOT CLASSIFIED (NC)

BRIEF DESCRIPTION _____

	CHARGE NO.
☐ CONSTRUCTION	
☐ RENOVATION	
☐ DECONTAMINATION & DECOMISSIONING (D&D)	

CONTAINER(S) INDENTIFICATION (INDICATE NUMBER OF EACH)

1. ☐ 55 GAL SS DRUM
2. ☐ 30 GAL SS DRUM
3. ☐ 4 1/2" WALL CONCRETE CASK
4. ☐ 6 IN. WALL CONCRETE CASK
5. ☐ 12 IN. WALL CONCRETE CASK
6. ☐ 55 GAL BI DRUM
7. ☐ 30 GAL BI DRUM
8. ☐ WOOD OR METAL BOX
9. ☐ OTHER
10. ☐ GI CAN
11. ☐ PLASTIC
12. ☐ DUMPSTER
13. ☐ NONE
14. ☐ CASK NO. _____
    ☐ WALL THICKNESS _____ IN.
    ☐ SHIELDING MATERIAL _____

PRINCIPAL ISOTOPES BEST ESTIMATE

1. QUANTITY _____ ☐ GRAMS ☐ CURIES, IDENTITY _____
2. QUANTITY _____ ☐ GRAMS ☐ CURIES, IDENTITY _____
3. QUANTITY _____ ☐ GRAMS ☐ CURIES, IDENTITY _____
4. QUANTITY _____ ☐ GRAMS ☐ CURIES, IDENTITY _____

REQUESTER'S COMMENTS FOR THOSE HANDLING WASTE IN FIELD

HEALTH PHYSICIST: EXECUTES THIS SECTION BEFORE MATERIAL TRANSFER

RADIATION DATA

BETA-GAMMA FOR PACKAGE _____ mrem/hr. _____ IN. OR FOR SHIELDED CASK _____ mrem/hr. _____ IN.

SURFACE CONT. _____ dpm (β-γ) _____ dpm (α). NEUTRON READING _____ mrem/hr.

HP SURVEYOR'S COMMENTS FOR THOSE HANDLING WASTE IN FIELD

	HP'S SIGNATURE	PHONE NO.

STORAGE AREA FOREMAN: COMPLETES AND SENDS COPY TO ORIGINATOR AFTER HANDLING WASTE

ACTION TAKEN CHECK ONE

WASTE WAS ☐ STORED, ☐ BURIED, ☐ COMPACTED, ☐ OTHER _____

LOCATION SWSA NO.	DATE

FACILITY Check One ☐ BUILDING ☐ WELL ☐ RAVINE ☐ TRENCH ☐ ON GROUND ☐ OTHER

WASTE DESCRIPTION	FACILITY NUMBER	SWSA ATN

LOCATION WITHIN FACILITY

FFD FFY COMP. NO. LAYER FILE RANK

FISSILE WASTE DATA

WELL FULL ☐ YES ☐ NO

CRITICALITY COMMITTEE APPROVAL FOR GRAMS

BALE NO.

COMMENTS FROM SWSA FOREMAN REGARDING WASTE AND/OR OPERATION

FOREMAN'S SIGNATURE

DISTRIBUTION WHITE - STORAGE AREA FOREMAN RETAINS
BLUE - COMPLETED AND RETURNED TO ORIGINATOR
CANARY - RETAINED BY ORIGINATOR

UCN 2822
(3 2 80)

Fig. A.1. Form used at ORNL for shipment, storage, or disposal of solid radioactive waste.

In 1976, the National Low-Level Waste Management Program established a nationwide data retrieval system called SWIMS (Solid Waste Information Management System) for DOE-generated LLW (Batchelder 1980). At this time ORNL initiated MOD 3 data input, which included more detailed information on radioisotopes in the waste and provided output that was compatible with SWIMS requirements. SWIMS required that LLW volumes and activity levels be itemized into eight nuclide categories: transuranium (TRU), uranium/thorium, fission product, induced activity, tritium, beta-gamma TRU, alpha, and other. Two of these nuclide categories (TRU and beta-gamma TRU) are retrievably stored in facilities outside of SWSA-6 and are not of concern in developing this plan (Bates 1983). A more detailed description of the eight nuclide categories is given by Batchelder (1980). Data on the chemical and physical forms of the radionuclides, which would be useful in evaluating potential leachability, have not been required in the data input.

Although not entered into the inventory system, a written log is kept of the dates the disposal units (trenches and wells) are excavated and the time at which the units are filled and covered (Table A.1). The log also contains information regarding the intended use (such as for storage of high- or low-activity wastes) of the disposal unit. Table A.1 summarizes the number (and intended uses) of the trenches and wells filled in SWSA-6 up to mid-1985 (T. Grizzard, personal communication, 1985).

The early portions of the ORNL inventory system do not record the amount of specific radionuclides buried; however, there are estimates of the total amount of activity buried in SWSA-6. Based on existing reports it is estimated that about 470,000 ft^3 of waste containing 41,000 Ci was buried during the period prior to 1977 (Bates 1983).

Since 1977, MOD 3 information on the amount of radioactivity in each of the seven nuclide categories (by totals and by individual nuclides) has been required for each waste shipment to the SWSAs. Table A.2 shows that a total of 211,000 Ci of radioactivity was

Table A.1. Solid Waste Storage Area 6 trenches and auger holes (Data from Tom Grizzard, June 1985)

Depth (inches)	Nos. at each depth
AUGER HOLES (WELLS)	
High-Activity Wells	
10	7
12	6
18	21
24	22
30	44
36	156
47	185
Solvent Wells	
30	20
47	16
Fissile Wells	
24	1
36	21
47	35
Total Number of Wells = 534 (approx. 18 ft deep)	
TRENCHES	
Low-Activity Trenches	175
Low-Activity Bales	5
High-Activity Trenches	48
Asbestos Trenches	33
Fissile Trenches	4
Lead Trenches	1
Animal Trenches	193
Experimental Trenches	12
Total Number of Trenches = 471 (10 to 17 ft deep)	

Table A.2. Radionuclide inventory in SWSA-6 for the period 1977 to 1984 (MOD 3)

Radionuclide	Activity (curies) Trenches	Wells or auger holes	Totals[a]
Am-241	3.44	0.150E-03	3.44
Am-243	0.400E-04	0.106E-04	0.506E-04
Be-10	0.213	400.	400.
Bk-249	0.999E-06	0.000	0.999E-06
C-14	258.	0.999E-06	258.
Cd-113M	0.002	3.00	3.00
Cf-252	0.009	0.000	0.009
Cm-242	0.499E-05	0.000	0.499E-05
Cm-244	6.08	0.000	6.08
Co-60	9950.	22200.	32200.
Cs-134	4.42	0.000	4.42
Cs-137	645.	4460.	5110.
Eu-152	7.12	50900.	50900.
Eu-154	3.34	72600.	72600.
Eu-155	0.0500	31300.	31300.
Fe-55	0.755	10.0	10.8
H-3	4320.	2790.	7110.
Na-22	0.541	0.000	0.541
Ni-63	0.00100	0.000	0.00100
Np-237	0.000449	0.299E-06	0.000450
Pm-147	59.7	85.0	145.
Pu-238	0.0270	0.00189	0.029
Pu-239	0.135	0.103E-04	0.141
Pu-242	0.00500	0.000	0.00500
Ru-106	10.0	0.000	10.0
Sm-151	3.25	200.	203.
Sn-121M	0.500	9.00	9.50
Sr-90	251.	2720.	2970.
Tc-99	36.2	0.612	36.8
Th-232	2.46	0.083	2.54
U-233	227.	0.000	227.
U-235	5.56	0.015	5.57
U-238	205.	0.445	205.
Zr-93	5.11	18.5	23.6
Unid	1650.	5690.	7340.
Totals	17,500	193,000	211,000

[a]Numbers do not add up because of rounding and method of data entry.

transferred to SWSA-6 during the reporting period 1977 through 1984. It should also be noted that of the 211,000 Ci buried since 1977, 155,000 Ci was europium isotopes (73.5%), 2,970 Ci was ^{90}Sr (1.4%), 5,110 Ci was ^{137}Cs (2.4%), 32,200 Ci was ^{60}Co (15.3%), and 7,110 Ci was ^{3}H (3.4%). These nuclides make up 96% of the total activity buried during the period 1977 to 1984; the remaining 8,400 Ci is listed as unidentified or comprises smaller amounts of other nuclides. Table A.3 gives an account of the radioactivity buried in SWSA-6 by calendar year.

Information on the total volume of waste buried in SWSA-6 is summarized in Table A.4. This table shows that since 1977 about 90% of the total waste volume was disposed of in the trenches and the remaining 10% in the auger holes or wells. Note that the data in Table A.4 are given by calendar year, whereas the data reported previously by Boegly (1984) are given by fiscal year (Oct. 1-Sept. 30).

An attempt is being made to determine if additional information on radionuclide content and chemical form of the isotopes can be obtained by interviewing the waste generators. Due to manpower limitations and other factors, such as the time interval since the waste was generated and the retirement of some of the generators, it is not apparent what additional information could be gathered. It could be that additional information can only be obtained for large-curie-content sources, most of which were placed in the auger holes.

Table A.3. Radioactivity buried in SWSA-6

Calendar year	Activity in trenches (Ci)	Activity in wells or auger holes (Ci)	Totals
1977	700	3,300	4,000
1978	1,700	2,100	3,800
1979	1,100	4,300	5,400
1980	400	58,000	58,400
1981	200	114,000	114,200
1982	200	7,700	7,900
1983	3,300	2,700	6,000
1984	9,600	1,900	11,500
Total (1977-1984)	17,200[a]	194,000[a]	211,000[a]
Prior to 1977[b]			41,000
Total for SWSA-6			252,000

[a]Data do not add up because of rounding.

[b]Pre-1977 data from Bates (1983) are given by fiscal year.

Table A.4. Volume of low-level waste buried in SWSA-6

Calendar year	Trenches	Volume in wells or auger holes (ft^3)	Totals
1977	66,400	800	67,200
1978	69,600	800	70,400
1979	74,000	700	74,700
1980	69,900	900	70,800
1981	48,800	500	49,300
1982	45,700	600	46,300
1983	60,300	600	60,900
1984	76,700	800	77,500
Total (1977-1984)	511,000[a]	5,700[a]	517,000[a]
Prior to 1977[b]			470,000
Total for SWSA-6			987,000

[a]Numbers do not add up because of rounding.

[b]Pre-1977 data from Bates (1983) are given by fiscal year.

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APPENDIX B
CLIMATOLOGY DATA SOURCES

Appendix B

CLIMATOLOGY DATA SOURCES

To assess short- and long-term performance it will be necessary to obtain detailed records of meteorological observations. Information on precipitation (amount, intensity, and frequency), wind speed and direction, humidity, solar radiation, and air temperature, is critical to developing an understanding of the hydrology of the site and performing the necessary risk and performance assessments required to ensure compliance with regulatory guidelines. In general, it is suggested that at least one year of on-site measurements be obtained (Siefken et al. 1982).

The type of meteorologic information currently being taken in the vicinity of SWSA-6 is presented in Table B.1, along with the period of time for which records exist.

Meteorological stations operated by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), exist in the city of Oak Ridge and at the Knoxville Airport (McGhee Tyson) (USDOC 1987). The Knoxville Station is located about 32 km (20 miles) southeast of SWSA-6 and measurements have been taken since 1942 (ORO-99 1953); measurements at the Oak Ridge Station [about 14 km (9 miles) northeast of SWSA-6] were initiated in May 1967 (USDOC 1982).

In addition to the NOAA stations, ORNL installed three meteorological towers in 1982, to provide measurements of wind speed and direction (Boyle et al. 1982). Two of the towers are 30-m (100-ft) tall, and the third is 100-m (330 ft) tall. All of the towers are equipped to measure wind speed and direction, temperature, and humidity at 10 and 30 m. The tallest tower can also provide these measurements at 100 m. Precipitation-measuring devices (rain gages) were installed in conjunction with the towers. Data are stored in a data base operated by the ORNL Environment and Safety Division (Personal communication, J. B. Murphy, March 11, 1985).

Table B.1. Meteorological stations in the vicinity of SWSA-6

Station description	Location	Period of record	Measurements
Knoxville[a]	McGhee Tyson Airport	1942-present	Precipitation
		1942-present	Wind
		1942-present	Temperature
		1942-present	Temp. Gradient
		1942-present	Humidity
Oak Ridge	City	1947-present	Precipitation
		1947-1979	Wind
		1947-present	Temperature
		1947-present	Temp. Gradient
ORNL Towers A and B	ORNL	1982-present	Precipitation
		1982-present	Wind
		1982-present	Temperature
		1982-present	Temp. Gradient
ORNL Tower C	ORNL	1982-present	Precipitation
		1982-present	Wind
		1982-present	Temperature
		1982-present	Temp. Gradient
		1982-present	Humidity
		1982-present	Solar Radiation
USGS	SWSA-5	1975-present	Precipitation[b]
USGS	SWSA-6	1976-present	Precipitation[b]
ETF	SWSA-6	1980-present	Precipitation[b]
EPCOR	SWSA-6	1985-present	Precipitation
		1985-present	Temperature
		1985-present	Humidity
Bldg. 1505	ORNL	1984-present	Solar Radiation

[a]Measurements also exist for the period 1871 till the station was moved to McGhee-Tyson.
[b]Precipitation gages are not equipped to measure snowfall.
[c]At various times, meteorological measurements have been made at the Y-12 plant, K-25, an early X-10 station, and the tower shielding facility (ORO-99, ORNL-xxxx).

Sources: ORO-199; Boyle; USDOC; ORO-99; Oakes group, Davis; USGS Open-File Report 82-254.

During the period of December 1975 to January 1976 rain gages were installed in SWSA-5 and SWSA-6 by the U.S. Geological Survey as a part of their hydrogeologic investigations (Webster 1982). In 1980, an additional rain gage was installed in SWSA-6 as a part of the Engineered Test Facility (ETF) (Boegly and Davis 1983). Thus there are two recording rain gages in SWSA-6 at present and one gage located approximately 0.6 km distant in SWSA-5.

In the near future (summer 1985) an additional rain gage will be installed in SWSA-6, northwest of the ETF site (EPCOR experiment); this gage will have the capacity to measure snowfall (Personal Communication, E.C. Davis, March 6, 1985). When this new gage is installed, a decision may be made to discontinue the readings at the ETF site in favor of those of the new gage. The types of information to be collected at the EPCOR station are included in Table B.1

Prior to 1982 solar radiation levels had not been measured at any of the ORNL meteorological stations. However, the addition of a solar cell at ORNL Tower C and the installation of a gage on the roof of Building 1505 at ORNL in 1984 should provide sufficient information to allow estimates of evapotranspiration.

Sufficient information exists regarding precipitation at SWSA-6 from on-site measuring stations (although there are no continuous records for some of the gages), and long-term precipitation data have been recorded at nearby stations in Oak Ridge and Knoxville. Although there are no on-site measurements of wind speed and direction, considerable data exist (and are being gathered in the vicinity of SWSA-6 that should supply the necessary information for characterization studies. If there are any deficiencies in the meteorological information, it is a lack of solar radiation data at the SWSA-6 site. The solar radiation measurements recently initiated, however, may be sufficient for estimating evapotranspiration from SWSA-6.

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APPENDIX C
DOSE ASSESSMENT MODELS

Appendix C

DOSE ASSESSMENT MODELS

C.1 EXTERNAL EXPOSURES

C.1.1 Unshielded Outdoor Exposure to Radionuclides in the Air and on Ground Surfaces

The dose equivalent rate $DE_j(out)$ (rem per year) to organ j due to unshielded outdoor exposures to all airborne and surface-deposited radionuclides can be estimated using a model of the form

$$DE_j(out) = [\sum_i (DCF_{ijA}\ C_{iA}) + R_S \sum_i (DCF_{ijS}\ C_{iS})]\ f_0 \quad ,$$

where

DCF_{ijA} = dose conversion factor (rem per year per microcuries per meter) for organ j from exposure to radionuclide i that is assumed to be uniformly distributed throughout a semi-infinite atmospheric cloud,

C_{iA} = concentration (microcuries per meter) of radionuclide i in air.

R_S = dose reduction factor due to ground roughness effects (assumed to be radionuclide independent),

DCF_{ijS} = dose conversion factor (rem per year per microcurie per meter) for organ j from exposure to radionuclide i that is assumed to be uniformly distributed over an infinite ground surface,

C_{iS} = concentration (microcuries per meter) of radionuclide i on ground surface,

f_0 = fraction of the year that the exposed individual is assumed to be outdoors.

Organ- and nuclide-specific dose conversion factors are available in the literature for both the air immersion and the ground-surface exposure pathways. For given radionuclide concentrations in air and on the ground surface, the only site-specific variables in the model are the ground-roughness factor, R_S, and the outdoor residency, f_O. Recommended values of R_S are available in the literature for various types of terrain.

C.1.2 Indoor Exposures to Radionuclides in Air and on Ground Surfaces

The dose equivalent rate $DE_j(in)$ (rem per year) to organ j due to indoor exposures to all airborne and surface-deposited radionuclides can be estimated using a model of the form

$$DE_j(in) = [\sum_i (DCF_{ijA}\ C_{iA}) + R_S \sum_i (DCF_{ijS}\ C_{iS}\ RF_{iS})]\ f_I \quad ,$$

where DCF_{ijA}, C_{iA}, R_S, DCF_{ijS}, and C_{iS} are as defined in the previous equation for outdoor exposures,

RF_{iA} and RFU_{iS} = dose reduction factors for indoor exposure to radionuclide i that is either airborne or deposited on the ground surface,

f_I = fraction of the year that the exposed individual is assumed to be indoors.

In addition to the surface-roughness factor, R_S, and the indoor residency, f_I, the dose reduction factors RF_{iA} and RF_{iS} are site-specific variables in the model, given appropriate environmental concentrations of radionuclides. The dose reduction factors reflect the shielding provided by a building when the exposed person is inside. These factors depend on the spectrum of photons emitted by radionuclide i, the thickness and composition of the building materials in the walls and ceiling, the effective radius of the building, the building ventilation rate, and the deposition velocity of radionuclide i

on inside and outside building surfaces. Generic values of dose reduction factors for airborne and surface-deposited radionuclides are available in the literature and can be used in many dose assessments. If more precise values are needed or if most of the photons involved have energies below a few hundred kiloelecton volts, then simple models and computer codes are available for estimating dose reduction factors for specific radionuclides and particular building characteristics.

C.1.3 Exposures to Radionuclides Distributed in Soil and to Trench Contents

Radionuclides that are deposited on ground surfaces will penetrate the surface via infiltration of rainwater, for example, and will produce a distribution of activity that varies with depth in subsurface soil. Environmental transport models are used to describe this distribution.

The dose equivalent rate $DE_j(out)$ (rem per year) to organ j due to exposures to all radionuclides distributed in subsurface soil can be estimated using a model of the form

$$DE_j(out) = (\sum_i DE_{ijS'})\ f_0 \quad ,$$

where DE_{ijS}' is the dose equivalent rate from radionuclide i in soil and is obtained as

$$DE_{ijS'} = \int_x^x DCF_{ijS}(x)\ C_{iS}(x)\ dx \quad ,$$

where x and x are the lower and upper boundaries (m) respectively of a subsurface soil region with depth-dependent distribution $C_{iS}(x)$ (microcurie per cubic meter) of radionuclide i, and DCF_{ijS} is the dose conversion factor (rem per year per microcurie per cubic meter) for organ j from exposure to radionuclide i that is assumed to be uniformly distributed over an infinite plane surface at depth x in

soil. Dose conversion factors as a function of depth in soil are available in the literature. As before, f_0 is the fraction of the year during which outdoor exposures occur; this parameter is the only site-specific variable contained in the model.

For indoor exposures to radionuclides that are distributed with depth in soil, we have by analogy with the results for ground-surface exposure that

$$DE_j(in) = (\sum_i DCF_{ijS'}) \; RF_{iS}] \; f_I \quad ,$$

where RF_{iS} is the dose reduction factor from building shielding and f_I is the fraction of the year spent indoors. The ground roughness factor R_S is not needed for exposures to activity below the ground surface.

Exposure to trench contents is a special case of the model for arbitrary distributions of radionuclides with depth in soil. In this case, the source region can be regarded as an infinite slab of finite thickness determined by the vertical extent of the trench contents, and the radionuclide concentration can be regarded as being uniform throughout the slab. The dose equivalent rates DE_{ijS}' for uniform slab sources of given concentration can be obtained directly from tabulations in the literature.

C.1.4 Swimming in Contaminated Water

The dose equivalent rate (rem per year) to organ j from all radionuclides due to swimming in contaminated water is given by a model of the form

$$DE_j = (\sum_i DCF_{ijW} \; C_{iW}) \; f_W \quad ,$$

where

DCF_{ijW} = dose conversion factor (rem per year per microcurie per meter) for organ j from exposure to radionuclide i that is assumed to be uniformly distributed throughout an infinite water medium,

C_{iW} = concentration (microcurie per meter) of radionuclide i in water,

f_W = fraction of the year spent swimming.

Organ- and nuclide-specific dose conversion factors for immersion in contaminated water are available in the literature. For given radionuclide concentrations in water, the parameter f_W is the only site-specific variable in the model.

C.1.5 Bathing, Wading, and Boating in Contaminated Water

The formula for swimming exposures also can be applied to bathing, if correction factors are specified to account for the different geometries involved. For bathing, the above equation can be used with an additional dose reduction factor of the form $(1 - \exp[-u_i R])$, where R is the radius of the volume of the bathing water and u_i is an effective linear absorption coefficient for radionuclide i in water. This dose reduction factor can be defined generically.

Wading and boating exposures conceptually involve exposure of organs above the water to radionuclides that are uniformly distributed in an infinite slab of water of finite depth. Thus, dose equivalent rates to organs from wading and boating can be estimated using a model similar to that for exposures above contaminated soil. In these cases, water would replace soil as the host medium. Also, the formulation for boating would require an additional dose reduction factor to account for shielding by the boat; a generic value probably can be used for this dose reduction factor.

C.1.6 Exposures to Contaminated Shoreline

The dose equivalent rate (rem per year) to organ j from exposures to all radionuclides on a contaminated shoreline may be estimated by a model of the form

$$DE_j = (\sum_i DCF_{ijS}\, C_{iS})\, W_S\, f_S \quad ,$$

where

DCF_{ijS} = dose conversion factor (rem per year per microcurie per meter) for organ j due to exposure to radionuclide i that is assumed to be uniformly distributed over an infinite ground surface,

C_{iS} = surface concentration (microcurie per meter) of radionuclide i on the contaminated shoreline,

W_S = shoreline factor that gives the fraction of the infinite ground-surface dose to be used for the particular type of shoreline being considered,

f_S = fraction of the year spent on the shoreline.

Values of W_S for different types of shoreline (e.g., canals, rivers, lakes, oceans, and tidal basins) are available in the literature. Values of C_{iS} are assumed to be given by appropriate transport models, and the DCF_{ijS} are the dose conversion factors used to evaluate ground-surface exposures. Again, the parameter f_S is the only site-specific variable in the model.

C.2 INTERNAL EXPOSURES

Internal exposures result from radionuclides taken into the body via inhalation of contaminated air and ingestion of contaminated foodstuffs. Dose equivalent rates to man from such exposures can be calculated using a model of the form

$$CDE_j = \sum_i \sum_p I_{ip} \, DCF_{ijp} \quad ,$$

where

CDE_j = committed dose equivalent rate (rem per year) to organ j from intake of all radionuclides via all pathways,

I_{ip} = intake rate (microcurie per year) of radionuclide i via pathway p,

DCF_{ijp} = dose conversion factor (rem per microcurie) for organ j due to intake of radionuclide i via pathway p.

A committed dose equivalent is the dose equivalent that will be received over a specified time period (usually 50 or 70 years) due to an acute intake of radionuclides.

The numerical value of a dose conversion factor depends on the identity, chemical form (solubility), and, for inhalation, the particle size of the radionuclide taken into the body. Tabulations of dose conversion factors for adults and children are available in the literature for different radionuclides, solubilities, and particle sizes.

The major effort in estimating dose equivalent rates from internal exposures lies in evaluating the intake rates, I_{ip}, for the various pathways involved. In general, the intake rate via any internal exposure pathway can be expressed as

$$I_{ip} = \bar{C}_{ip} \, U_p \, \exp(-\lambda_{ir} t_D) \quad ,$$

where

$\bar{C}_{ip}$ = the concentration (microcuries per unit mass or volume of material) of radionuclide i for pathway p,

U_p = human intake rate (mass or volume per year) of material for pathway p,

λ_{ir} = radioactive decay constant (1/time) of radionuclide i,

t_D = delay time between harvest and consumption of material for pathway p.

Generic estimates of human intake rates of air and various foodstuffs are available in the literature, but site-specific values of the intake rates may be needed for a realistic dose assessment. Radioactive decay constants of most radionuclides are well known. Delay times between harvest and consumption of foodstuffs, which can vary from essentially zero to a few months, also are reported in the literature. The remainder of this subsection discusses models and data needs for calculating radionuclide concentrations in various materials.

C.2.1 Breathing Contaminated Air

The concentration of radionuclide i in inhaled air (microcuries per cubic meter) is given by

$$\bar{C}_{iA} = C_{iA} (f_O + RF_i f_I) \quad ,$$

where

C_{iA} = concentration (microcuries per meter) of radionuclide i in outdoor air,

f_{OD} = fraction of year spent outdoors,

RF_i = ratio of indoor to outdoor air concentrations of radionuclide i,

f_I = fraction of year spent indoors.

The fractions of the year spent outdoors and indoors are the same as in the models for external exposures. The term RF_i arises because indoor air concentrations may differ significantly from outdoor air concentrations. At equilibrium, this dose reduction factor depends on the building ventilation rate, the deposition velocities of radionuclide i on indoor building surfaces, the areas of the indoor building surfaces, and the building volume. The parameters f_O, f_I, and RF_i are the site-specific variables in this model.

Use of this concentration in the intake rate equation requires that U_A, the human breathing rate, be expressed in cubic meters per year. Human breathing rates for several exertion levels and classes of persons are available in the literature and can be applied on a site-specific basis. The delay time, t_D, is set to zero for inhalation exposures.

C.2.2 Drinking Contaminated Water

The concentration of radionuclide i in drinking water (microcuries per liter) is given by

$$\bar{C}_{iW} = C_{iW} (1 - TF_{iW}) \quad ,$$

where

C_{iW} = concentration (microcuries per liter) of radionuclide i in surface water or groundwater

TF_{iW} = fraction of radionuclide i removed from surface water groundwater by water treatment processes.

Values of TF_{iW} may be between zero and one, depending on the type of water treatment used and the particular chemical element involved.

Use of this concentration in the intake rate equation requires that U_W, the human water consumption rate, be expressed in liters per year. Generic water consumption rates for several classes of persons are given in the literature. Values of t_D may be between zero and a few days. The parameters TF_{iW}, U_W, and t_D are site-specific variables in the model for intake rates, given appropriate environmental concentrations.

C.2.3 Eating Contaminated Fish

The concentration of radionuclide i in fish (microcuries per kilogram) is given by

$$\bar{C}_{iF} = C_{iW} B_{iF} \quad ,$$

where

C_{iW} = concentration (microcuries per liter) of radionuclide i in surface water

B_{iF} = bioaccumulation factor (liters per kilogram) defined as the ratio of the concentration of radionuclide i in fish (microcuries per kilogram) to its concentration in water (microcuries per liter).

Generic bioaccumulation factors for the various types of fish and other aquatic foods are available in the literature.

Use of this concentration in the intake rate equation requires that U_F, the human consumption rate of fish, be expressed in kilograms per year; generic consumption rates are available in the literature. Values of t_D may be between zero and a few months. The parameters B_{iF}, U_F, and t_D are the site-specific variables in the model for intake rates.

C.2.4 Eating Contaminated Vegetation

The concentration of radionuclide i in edible vegetation (microcuries per kilogram) is given by

$$\bar{C}_{iV} = C_{iA}\, D_{iA}\, (r/Y_V)\, (\lambda_{ir} + \lambda_{iw})^{-1}\, (1 - \exp[-(\lambda_{ir} + \lambda_{iw})t_V] +$$

$$= C_{iW}\, D_W\, (r/Y_V)\, (\lambda_{ir} + \lambda_{id})^{-1}\, (1 - \exp[-(\lambda_{ir} + \lambda_{id})t_V] +$$

$$= C_{iS}\, B_{iV} \quad .$$

where

C_{iA} = concentration (microcuries perimeter) of radionuclide i in air,

D_{iA} = deposition velocity (meters per day) of radionuclide i from atmosphere onto ground surface,

r/Y_V = density-normalized interception fraction (meters per kilogram) for vegetation type V,

λ_{ir} = radioactive decay constant (liters per day) of radionuclide i,

λ_{iw} = weathering removal rate constant (liters per day) for radionuclide i deposited from atmosphere onto vegetation,

t_V = growing season (day) for vegetation type V.

C_{iW} = concentration (microcuries per liter) of radionuclide i in irrigation water,

D_W = average rate of irrigation (liters per meter per day) during growing season,

λ_{id} = weathering and runoff removal rate constant (liters per day) for radionuclide i deposited onto vegetation by irrigation water,

C_{iSD} = concentration (microcuries per kilogram) of radionuclide i in soil root zone,

B_{iV} = concentration ratio (microcuries per kilogram) of vegetation per microcurie per kilogram of soil) for uptake of radionuclide i by edible portion of vegetation type V.

This equation applies to various types of vegetation, including leafy and nonleafy vegetables, grains, grasses, and silage. Given the concentrations of radionuclides in air, irrigation water, and soil, all the other parameters in this model are site specific. Only generic values are available in the literature for the different types of vegetation. Values of r/Y_V may differ for deposition from air and for deposition from irrigation water.

Use of this concentration in the intake rate equation requires that U_V, the human consumption rate of vegetation type V, be expressed in kilograms per year. Values of t_D may be between zero and a few months. Both of these variables are site-specific. It also might be desirable to include a term to account for radionuclide removal during food processing. The concentration in vegetation is also used in calculating concentrations in milk and beef.

C.2.5 Drinking Contaminated Milk

The concentration of radionuclide i in milk (microcuries per liter) is given by

$$\bar{C}_{iM} = [(\sum_V f_V \bar{C}_{iV} Q_V) - (C_{iW} Q_W)] F_M \exp(-\lambda_{ir} t_M) \quad ,$$

where

f_V = fraction of a cow's daily intake of vegetation that is of type V,

$\bar{C}_{iV}$ = concentration (microcuries per kilogram) of radionuclide i in vegetation type V,

Q_V = consumption rate (kilograms per day) of vegetation type V by cow,

C_{iW} = concentration (microcuries per liter) of radionuclide i in water,

Q_W = consumption rate (liter per day) of water by cow,

F_M = milk transfer coefficient (days per liter), defined as the average fraction of a cow's daily intake of radionuclide i that appears in milk,

g_{ir} = radioactive decay constant (liter per time) of radionuclide i,

t_M = average time between radionuclide ingestion by a cow and milk harvest.

The parameters f_V, Q_V, Q_W, F_M, and t_M are site-specific variables, and ranges of values for each of these parameters are available in the literature for the various types of vegetation eaten by cows.

Use of this concentration in the intake rate equation requires that U_M, the human consumption rate of milk, be expressed in liter per year. Values of t_D may be between zero and a few weeks. Both of these parameters are site-specific variables.

C.2.6 Eating Contaminated Beef

The concentration of radionuclide i in beef (microcuries per kilogram) is given by

$$\bar{C}_{iB} = [\sum_V f_V \bar{C}_{iV} Q_V) + (C_{iW} Q_W)] F_B \exp(-\lambda_{ir} t_B) \quad ,$$

where

F_V, $\bar{C}_{iV}$ Q_V, C_{iW}, Q_W, and λ_{ir} are as defined in the previous equation,

F_B = beef transfer coefficient (days per kilogram), defined as the average fraction of a cow's daily intake of radionuclide i that appears in beef,

t_B = average time between radionuclide ingestion by a cow and beef harvest.

Again, the parameters f_V, Q_V, Q_W, F_B, and t_B are site-specific variables, and ranges of values of each of these parameters are available in the literature for the various types of vegetation eaten by beef cattle.

Use of this concentration in the intake rate equation requires that U_B, the human consumption rate of beef, be expressed in kilograms per year. Values of t_D may be between zero and a few months. Both of these parameters are site-specific variables.

C.3 VARIABLES FOR SITE-SPECIFIC DOSE ASSESSMENTS

The parameters in the exposure models that can be regarded as variables for which site-specific information is needed are summarized in Table C.1. For external and inhalation exposures, these variables include dose reduction factors due to shielding and residency times for particular types of exposures. The site-specific variables for ingestion exposures include foodchain transport parameters, intake rates by humans and livestock, and time delays between contamination of foodstuffs and ingestion by man. The remaining parameters in the dose-assessment models include factors for converting concentrations or intakes to dose equivalent rates and are not subject to site-specific variations.

Table C.1. Summary of site-specific variables in environmental dose-assessment models

Exposure pathway	Site-specific variables
EXTERNAL	
Air immersion	Building shielding factors for indoor exposures Outdoor and indoor residency times
Ground surface	Ground roughness factor Building shielding factors for indoor exposures Outdoor and indoor residency times
Soil and trench contents	Building shielding factors for indoor exposures Outdoor and indoor residency times
Swimming, wading, bathing, and boating	Exposure time for different exposure modes
Shoreline	Exposure time Shoreline dose-reduction factor
INHALATION	
Breathing	Building shielding factors for indoor exposures Outdoor and indoor residency times
INGESTION	
Drinking water	Removal of radionuclides by water treatment Human intake rate Time delay from removal from surface water or groundwater to human intake
Fish	Bioaccumulation factors Human consumption rate Time delay from catch to consumption
Vegetation	Transfer factors and retention from air or irrigation water Bioaccumulation factors from soil Duration of growing season Human consumption rates Time delays from harvest to consumption
Milk and beef	Consumption rates by cows of contaminated vegetation and water Transfer factors from ingestion by cows to milk and beef Time delays from ingestion by cows to production of milk and beef Human consumption rates Time delays from production to consumption by humans

APPENDIX D
WELL DATA FOR SWSA-6

Table D.1. Records of observation wells in SWSA-6 (Webster et al., in press).

Well No.	Location: Latitude (deg., min, s)			Location: Longitude (deg., min, s)			ORNL (ft)	Grid (ft)	Depth of well (ft)	Year Completed	Casing: Diam[a] (in.)	Casing: Terminal depth (ft)	Casing: Type	Finish: Character	Finish: Depth interval	Altitude of land surface (ft above sea level)	Measuring Point: Distance above land surface (ft)	Depth to water below land surface: Period of Record (year)	Depth to water below land surface: Minimum (ft)	Depth to water below land surface: Maximum (ft)
107	35	54	18	84	19	32	N17041	E24402	122	1956	5-1/2	(?)	S	Opn	(?)	811.15	0.15	1975-83	18.66	25.43
108	35	54	21	84	19	32	N17279	E24594	125	1956	5-1/2	39	S	Opn	39-125	827.91	0.25	1975-83	28.55	32.98
109	35	54	21	84	19	33	N17330	E24499	126	1956	5-1/2	37	S	Opn	37-126	819.65	0.35	1975-83	21.53	26.28
110	35	54	21	84	19	30	N17204	E24684	123	1956	5-1/2	47	S	Opn	47-123	825.32	1.80	1975-83	29.37	31.77
267	35	54	04	84	19	37	N16118	E23221	17	1964	6-5/8	17	S	Prf	0-17	789.56	1.06	1975-81	2.98	DRY
268	35	54	06	84	19	38	N16365	E23307	20	1964	6-5/8	20	S	Prf	0-20	804.86	0.40	1975-83	2.23	DRY
269	35	54	06	84	19	41	N16511	E23104	20	1964	6-5/8	20	S	Prf	0-200	846.59	0.77	1975-83	3.55	DRY
272	35	54	05	84	19	35	N16221	E23520	8	1964	6-5/8	8	S	Prf	0-8	769.51	1.20	1975-83	0.13	DRY
274	35	54	05	84	19	37	N16210	E23347	19	1964	6-5/8	19	S	Prf	0-19	787.01	0.82	1975-83	8.12	DRY
276	35	54	08	84	19	31	N16211	E23895	6	1964	6-5/8	6	S	Prf	0-6	758.53	0.80	1975-83	+0.19	4.62
277	35	54	10	84	19	28	N16207	E24182	21	1964	6-5/8	21	S	Prf	0-21	773.47	0.82	1975-83	9.27	DRY
278	35	54	13	84	19	30	N16552	E24223	11	1964	6-5/8	11	S	Prf	0-11	775.22	0.00	1975-83	3.07	DRY
279	35	54	14	84	19	31	N16696	E24205	10	1964	6-5/8	10	S	Prf	0-10	779.27	1.95	1975-83	2.70	7.48
284	35	54	13	84	19	34	N16750	E23983	17	1964	6-5/8	17	S	Prf	0-17	785.67	2.62	1975-83	6.53	14.76
313	35	54	11	84	19	38	N16798	E23605	20	1964	6-5/8	20	S	Prf	0-20	801.42	1.36	1975-83	16.00	19.49
351	35	54	08	84	19	27	N15977	E24188	27	1964	6-5/8	27	S	Prf	0-27	776.09	1.32	1975-83	14.63	DRY
317	35	54	15	84	19	31	N16766	E24328	14	1964	6-5/8	14	S	Prf	0-14	792.32	0.25	1975-83	4.21	DRY
318	35	54	19	84	19	34	N17225	E24323	15	1964	6-5/8	15	S	Prf	0-15	799.34	3.95	1975-83	4.38	DRY
343	35	54	19	84	19	24	N16763	E25010	24	1964	6-5/8	24	S	Prf	0-24	788.92	0.88	1975-83	12.83	DRY
345	35	54	15	84	19	22	N16361	E24881	11	1964	6-5/8	11	S	Prf	0-11	756.59	0.67	1975-83	2.81	8.47
346	35	54	14	84	19	25	N16435	E24631	17	1964	6-5/8	17	S	Prf	0-17	772.17	1.60	1975-83	2.81	8.47
347	35	54	15	84	19	26	N16531	E24604	16	1964	6-5/8	16	S	Prf	0-16	776.49	0.00	1975-83	2.00	12.77
350	35	54	12	84	19	23	N16152	E24649	17	1964	6-5/8	17	S	Prf	0-17	769.08	0.88	1975-81	8.26	DRY
351	35	54	11	84	19	22	N16028	E24661	24	1964	6-5/8	24	S	Prf	0-24	777.63	1.19	1975-83	10.23	DRY
355	35	54	20	84	19	26	N16909	E24991	19	1964	6-5/8	19	S	Prf	0-19	797.38	0.95	1975-83	8.84	DRY
356	35	54	13	84	19	28	N16481	E24451	9	1964	6-5/8	9	S	Prf	0-9	772.02	0.73	1975-83	1.11	9.10
358	35	54	10	84	19	25	N16090	E24448	18	1964	6-5/8	18	S	Prf	0-18	794.07	1.32	1975-79	17.23	DRY
359	35	54	19	84	19	26	N16904	E24867	19	1964	6-5/8	19	S	Prf	0-19	785.90	0.88	1975-81	5.00	11.78
361	35	54	11	84	19	26	N16904	E24156	8	1964	6-5/8	8	S	Prf	0-8	769.70	2.13	1975-81	1.51	DRY
362	35	54	10	84	19	36	N16588	E23718	8	1964	6-5/8	9	S	Prf	0-8	775.54	2.74	1975-83	4.62	6.96
363	35	54	09	84	19	34	N16420	E23748	4	1964	6-5/8	4	S	Prf	0-4	763.97	2.61	1975-83	0.11	3.43
364	35	54	09	84	19	33	N16407	E23838	8	1964	6-5/8	8	S	Prf	0-8	767.73	2.60	1975-83	0.20	DRY
365	35	54	09	84	19	35	N16454	E23681	6	1964	6-5/8	6	S	Prf	0-6	767.72	2.15	1975-83	0.98	4.39
366	35	54	25	84	19	29	N17467	E24926	23	1975	6-5/8	23	S	Prf	0-23	837.15	3.26	1975-83	22.20	DRY
367	35	54	27	84	19	30	N17723	E25901	69	1977	3	69	P	Slt	59-69	841.70	2.50	1977-83	47.33	54.96
368	35	54	24	84	19	26	N17348	E25155	39	1977	3	39	P	Slt	29-39	819.50	0.00	1977-83	22.88	26.85
369	35	54	23	84	19	31	N17476	E24805	48	1977	3	48	P	Slt	38-48	838.24	2.76	1977-83	33.14	37.84
370	35	54	22	84	19	27	N17145	E24981	34	1977	3	34	P	Slt	24-34	806.96	3.74	1977-83	19.09	23.59
371	35	54	16	84	19	21	N16293	E25090	30	1977	3	30	P	Slt	20-30	765.40	2.70	1977-83	16.50	DRY
372	35	54	17	84	19	22	N16570	E25042	33	1977	3	33	P	Slt	23-33	773.99	2.41	1977-83	7.63	17.11
373	35	54	21	84	19	23	N16945	E25208	34	1977	3	34	P	Slt	24-34	784.05	1.45	1977-83	17.99	26.43
374	35	54	26	84	19	25	N17462	E25346	31	1977	3	31	P	Slt	21-31	781.28	2.22	1977-83	13.08	20.99
375	35	54	08	84	19	40	N16935	E23521	26	1977	3	26	P	Slt	16-26	813.63	2.57	1977-83	16.88	22.30
376	35	54	08	84	19	38	N16584	E23479	35	1977	3	35	P	Slt	25-35	806.46	3.04	1977-83	18.10	24.22
377	35	54	08	84	19	40	N16610	E23297	56	1977	3	56	P	Slt	46-56	836.62	2.98	1977-83	36.29	46.44
378	35	54	06	84	19	41	N16474	E23092	60	1977	3	60	P	Slt	50-60	842.15	2.95	1977-83	45.53	DRY
379	35	54	04	84	19	38	N16156	E23206	37	1977	3	37	P	Slt	27-37	792.13	0.77	1977-83	16.77	29.90
380	35	54	03	84	19	36	N15977	E23320	31	1977	3	31	P	Slt	21-31	772.55	2.25	1977-83	4.08	18.21
381	35	54	10	84	19	28	N16248	E24266	35	1977	3	35	P	Slt	25-35	777.59	2.51	1977-83	12.82	24.69
382	35	54	05	84	19	27	N15814	E24025	21	1977	3	21	P	Slt	11-21	763.34	2.36	1977-83	10.94	19.67
383	35	54	13	84	19	21	N16165	E24895	33	1977	3	33	P	Slt	23-33	769.38	2.12	1977-83	20.46	25.98
384	35	54	10	84	19	26	N16131	E24377	46	1977	3	46	P	Slt	36-46	791.77	0.20	1977-83	31.63	40.82
385	35	54	26	84	19	35	N17903	E24669	45	1977	3	45	P	Slt	35-45	841.27	2.53	1977-83	19.21	27.84
386	35	54	19	84	19	27	N16892	E24828	12	1978	3	12	P	Slt	(?)	779.19	2.85	1978-83	0.05	4.93
387	35	54	20	84	19	27	N16986	E24886	11	1978	3	11	P	Slt	(?)	786.35	3.45	1978-83	2.08	7.41
388	35	54	21	84	19	27	N17111	E24888	12	1978	3	12	P	Slt	(?)	788.61	3.70	1978-83	0.16	5.34
TR-1	35	54	09	84	19	25	N16002	E25475	47	1976	4	47	P	Slt	22-47	784.25	0.00	1977-81	32.21	40.98
TR-2	35	54	09	84	19	23	N15872	E24541	20	1976	4	20	P	Slt	13-20	764.65	1.35	1977-83	13.08	DRY
TR-3	35	54	07	84	19	24	N15762	E24331	23	1976	4	23	P	Slt	13-23	760.25	2.85	1977-83	10.26	17.58
TR-12	35	54	08	84	19	25	N15946	E24377	34	1976	4	34	P	Slt	24-34	779.60	2.00	1978-83	27.13	DRY

[a] 1 ft = 0.3 m; 1 in. = 2.54 cm.

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