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**Government Applications Task
Force Ground Truth Study
of WAG 4**

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Government Applications Task Force Ground Truth Study of Waste Area Grouping 4

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ABBREVIATIONS

ANOVA	Analysis of variance
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DOE	U.S. Department of Energy
DP	Drive point
ER	Environmental Restoration
GATF	Government Applications Task Force
GISST	Geographic Information Systems and Spatial Technologies
IR	Infrared
LANL	Los Alamos National Laboratory
MSL	Mean Sea Level
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
RMSE	Root Mean Square Error
SERDP	Strategic Environmental Research and Development Project
SRTC	Savannah River Technology Center
SWSA	Solid Waste Storage Area
TOPACT	Technology Office Project on Analysis of Contaminant Transport
TRU	Transuranic
USDA	United States Department of Agriculture
WAG	Waste Area Grouping

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EXECUTIVE SUMMARY

The Government Applications Task Force (GATF) Buried Waste Project was initiated as a field investigation and verification of the 1994 Strategic Environmental Research and Development Program's Buried Waste Identification Project results. The GATF project team included staff from three U. S. Department of Energy (DOE) Laboratories [Oak Ridge National Laboratory (ORNL), Los Alamos National Laboratory (LANL), and the Savannah River Technology Center (SRTC)] and from the National Exploitation Laboratory. Concurrent studies were conducted at waste areas located within each of the three DOE laboratories to demonstrate the effective uses of remote sensing technologies. The three locations were selected to assess differences in buried waste signatures under various environmental conditions (i.e., climate, terrain, precipitation, geology, etc.).

This report documents the field investigation (ground truth) results from the 1994–1995 GATF Buried Waste Study at ORNL's Waste Area Grouping (WAG) 4. The analysis of ground truth data showed that, for sites with a uniform grassy ground cover (such as WAG 4), nighttime soil temperatures were slightly cooler and soil moisture was greater within a waste trench. Both *in situ* sensors and thermal infrared (IR) measurements from the IR radiometers confirmed this temperature difference. This study has demonstrated that thermal remote sensing technologies have the potential for identifying buried waste trenches. However, the observed trench signatures are dependent on the depth of soil cover and the time of year when the measurements were taken.

1. INTRODUCTION

This report documents the Government Applications Task Force (GATF) Buried Waste Project. The project was initiated as a field investigation and verification of the 1994 Strategic Environmental Research and Development Program's (SERDP) Buried Waste Identification Project results. The GATF project team included staff from three U. S. Department of Energy (DOE) Laboratories [Oak Ridge National Laboratory (ORNL), Los Alamos National Laboratory (LANL), and the Savannah River Technology Center (SRTC)] and from the National Exploitation Laboratory. Similar studies were conducted at each of the three DOE laboratories to demonstrate the effective uses of remote sensing technologies. The three locations were selected to assess differences in buried waste signatures under various environmental conditions (i.e., climate, terrain, precipitation, geology, etc.). After a brief background discussion of the SERDP Project, this report documents the field investigation (ground truth) results from the 1994-1995 GATF Buried Waste Study at ORNL's Waste Area Grouping (WAG) 4. Figures for this report are located in Appendix A.

2. BACKGROUND INFORMATION

The SERDP Buried Waste Project analyzed historical photography and thermal imagery of WAG 4 at the Oak Ridge Reservation (ORR) to identify potential locations of buried waste trenches and pits. The SERDP project identified individual trench location information from stereoscopic analysis of historical aerial photography and trench signature analysis from daytime/nighttime thermal imagery at a site where few records exist. Using this information, the project constructed a composite trench map that compared data across all images (Fig. 1). The historical photography, spanning 14 collections, was obtained from several US Government archives: the US Department of Agriculture (USDA), the National Aerial Photography Program (NAPP), and the Tennessee Valley Authority (TVA). All imagery was black and white panchromatic aerial photography. The scale varied from 1:12,000 to 1:43,200. All archival data was available only in hard copy, either as photographic prints or as transparencies. Figures 2 through 8 depict a time series progression showing site activity from 1952 to 1981 using aerial photography. Detailed information for each photograph is listed in Table 1. High resolution Daedalus 1268 multispectral scanner imagery (1992 and 1994) was available for the WAG 4 area from the Oak Ridge Environmental Management Remote Sensing Program. The Daedalus 1268 scanner, which has been used frequently over Oak Ridge and other DOE sites, has 12 spectral bands spanning the near ultraviolet, visible, near-infrared (IR), short-wave IR, and long-wave thermal IR wavelengths. The spatial resolution varied from 1 m to 5 m, depending on the altitude of the acquisition flight. Trench locations identified from historical photography corresponded to signatures evident in the Daedalus thermal data. The thermal imagery (8.5 microns to 12.5 microns) acquired during daytime hours showed an apparent thermal difference between the trenches and the surrounding areas (Fig. 9). This signature corresponded to temperature and soil moisture differences observed at the site through ground measurements.

Table 1. Historical Photography Information

Date	Scale	Source	Frame/Roll
4/30/52	1:18,000	TVA	15479
2/29/56	1:18,000	TVA	19006
10/27/61	1:20,000	USDA	AOA-6V-81
3/2/67	1:24,000	TVA	130-3A-10
3/21/71	1:24,000	TVA	76489
4/14/73	1:20,000	USDA	47145 173-12
3/25/81	1:24,000	TVA	2022-122

Analyses of the photography and imagery led to the identification of several prior waste disposal areas and over 80 trench features were identified. Figure 1 shows these trenches. As a follow-on to the SERDP project, the GATF Project sponsored a study to determine why the trench features were evident in the thermal imagery using trench TT19 identified at WAG 4.

3. WAG 4 SITE DESCRIPTION

3.1 BACKGROUND

WAG 4, one of 17 WAGs within and associated with ORNL, is located along Lagoon Road south of the main plant complex. Solid Waste Storage Area (SWSA) 4 is the largest unit at WAG 4, covering approximately 23 acres (Fig. 10). The trench (TT19) used in this study is located within SWSA 4.

In the 1950s, SWSA 4 received a variety of low- and high-level wastes (including transuranic wastes) that were all buried in trenches (approximately 90 to 100 trenches) or auger holes. During the period from 1955 through 1963, SWSA 4 was designated the Southern Regional Burial Ground for the Atomic Energy Commission (predecessor to the DOE). Approximately half of the waste received at SWSA 4 in the 1950s originated at ORNL, while the remainder of the waste came from a number of off-site locations (Oak Ridge Y-12 Weapons Plant, Argonne National Laboratory, Knolls Atomic Power Laboratory, Mound Laboratory, and the General Electric Company). SWSA 4 also received non-radioactively contaminated construction debris from 1959 until 1973.

Historical records for the site trenches are mainly nonexistent; waste disposal records for SWSA 4 were destroyed in a fire in 1957. The primary surviving record of the trench locations is a line map constructed from interviews with site workers (Fig. 11). Radioactive wastes reported to have been disposed of include absorbent paper, clothing, glassware, scrap metal, dirt, filters, lumber,

irradiated piston rings, oils, powders, wire, depleted uranium, animal carcasses used in biological experiments, a few large pieces of equipment, and a small metal building.

Some waste materials were buried in metal, wooden, plastic, fiber, or concrete containers (Fig. 12); others were dumped into the trenches without containers (Fig. 13). Reports also indicated that drums containing explosive material such as elemental sodium (which tends to explode upon exposure to water) may be present in some of the trenches at the site. Wastes were placed in unlined trenches and shallow auger holes or temporarily stored above ground for later burial. Areas in higher elevations were used for waste burial during the winter months because high water table conditions occurred at lower elevations; the lower elevations were used during the summer when the water table was lower. The size of trenches has been estimated at 15 m to 122 m long, 3.4 m to 9.1 m wide, and 3.4 m to 4.3 m deep based on available information from remote sensing techniques, drive points, and coreholes.

3.2 ENVIRONMENTAL CHARACTERIZATION

3.2.1 Physiography and Topography

ORNL is characterized by a succession of elongated and relatively parallel southwest-trending valleys and ridges. WAG 4 is in Melton Valley, which is primarily composed of gentle (3% to 5%) southeast and east-northeast trending slopes. Maximum relief at the site is approximately 23 m; elevations range from a low of 236 m above mean sea level (MSL) at the east end to a high of 259 m above MSL at the southwest corner of the site (DOE 1995). In the area surrounding the candidate ground truth trench, sensor ground elevations range from 244.13 m above MSL to 248.22 m above MSL. Excavation and filling associated with waste disposal activities has significantly altered the original topography of the site by raising the land surface in some places, creating abrupt and steep slopes in others, and by forming depressions as a result of subsidence within burial trenches (DOE 1995).

3.2.2 Meteorology

Year-round mean temperature at ORR is approximately 14°C, with temperatures greater than 38°C and less than -18°C being unusual (DOE 1995). For the first full month of the ground truth study period (October 1995), the WAG 4 temperature ranged from -3.3°C to 25.3°C and had a mean value of 10.9°C, based on values from the WAG 4 local meteorological station. Precipitation varies seasonally, with the highest period of rainfall occurring during the winter months (i.e., January and February). Another peak in rainfall occurs in July when short, heavy thunderstorms are common. Annual precipitation at ORR averages approximately 132 cm/year (DOE 1995). Precipitation at WAG 4 during the month of October 1995 were recorded as 11.4 cm (higher than average).

3.2.3 Hydrogeology

Groundwater flow is predominantly shallow at the ORR and is controlled by topographic relief and a marked decrease in permeability with depth. Water budget estimates in undisturbed areas indicate that approximately 90% of subsurface flow occurs through the 1 m to 2 m deep stormflow zone. Infiltration tests indicate that this zone is up to 1,000 times more transmissive than the underlying unsaturated (vadose) zone. During rain, this stormflow zone becomes partially or

completely saturated, transmitting water laterally to surface water bodies. Overland flow occurs when this zone becomes completely saturated (DOE 1995).

Numerous WAG 4 trenches occupy the storm flow and vadose zones and are filled with heterogeneous materials. The entire area has a layer of construction debris for cover. The trenches have a higher transmissivity than the surrounding soil. Also, water infiltrates through the construction debris and into the trenches more quickly than it would through native soils. Thus, the trenches and the layer of debris provide two conduits for water flow that may act as a sink for shallow groundwater and storm water flow (DOE 1995).

3.2.4 Soils

Soils at WAG 4 generally are derived from the underlying clastic and carbonate bedrock and typically consist of red-yellow and red-brown silts and clays. Soil at the site is moist, low in organic content, strongly leached, and acidic (pH 4.5 to 5.7). Illite and vermiculite (clay minerals) in the soil enhance the soil's ability to retard migration of radioactive contaminants through matrix diffusion, mechanical filtering, adsorption, and ion exchange (DOE 1995).

Native soils that had been reworked and fill materials (i.e., construction debris) were imported to the WAG 4 area to accommodate operational and disposal activities. This importation resulted in altering the natural structural fabric and mineralogy of the soil in some areas, providing a random network of conduits for collection and migration of fluids throughout the area. In places, construction debris may enhance the infiltration of precipitation. However, where the debris appears to be thick, especially at the downslope ends of trenches, it may be a barrier for flow and contaminant transport (DOE 1995).

On the basis of information from previous studies and installation of drive points, the soil fill over trenches was thickest at the east and west ends of SWSA-4. It is at these locations that the thermal trench signatures were weakest or missing (Energy Systems 1995a and Huff 1996). The depth of the soil over the trench is a limiting factor for this and related studies.

3.3 DESCRIPTION OF TRENCHES

Limited information is available on the types, concentrations, and the quantities of radionuclides buried at SWSA 4. Potential wastes, based on the types of materials typically generated throughout ORNL's history, include ^{239}Pu , ^{90}Sr , ^{137}Cs , $^{242,243}\text{Cm}$, ^3H , ^{60}Co , ^{85}Kr , and ^{241}Am , as well as various uranium, thorium, and other transuranic (TRU) isotopes. However, in and around the trenches, the results of various sampling programs conducted indicate that the primary contaminants of concern appear to be ^{90}Sr , ^{60}Co , ^3H , uranium, thorium, and TRU isotopes. Of these contaminants, ^{90}Sr is the principal contaminant of concern based upon concentration, mobility, and radiotoxicity.

Figure 14 summarizes the conceptual model for source release and contaminant fate at WAG 4. The diagram shows a cross section through a typical "bathtubbing" trench. A "bathtubbing" trench resembles a sloping bathtub that collects water along its length. The water flows to the downslope end and in extreme cases overflows out of the trench. At WAG 4, the large void volume and associated high permeability in the trenches may cause many of the trenches to act as collection drains. In particular, there are two flow pathways in the conceptual model: (1) transient near-surface

flows associated primarily with storm events, and (2) shallow groundwater flows in the stable saturated-zone (Energy Systems 1995a).

The identification and location of the waste trenches was important due to the contaminants released from WAG 4. Surface water sampling data indicated that a significant quantity of contamination has been released from these burial trenches. Contamination released from the trenches accounted for 25% of the ^{90}Sr observed at White Oak Dam in the 1987 to 1994 period and about 14% of the total ORNL off-site human health risk via the drinking water pathway. ^{137}Cs is also a contaminant of concern at the site. Stemming the flow of these contaminants required precisely locating the trenches that contributed the highest percentage of contaminants and undertaking remedial actions to contain and isolate the buried waste from surface and subsurface water (DOE 1995).

4. GATF GROUND BASED MEASUREMENTS

The GATF ground truth study was conducted to determine the underlying phenomenology of why thermal imagery can identify buried waste trenches. On the basis of the 1994 SERDP Project results, trench TT19 in WAG 4 was selected as the candidate ground truth study area (Fig. 15). Previous analyses of remotely sensed data indicated strong trench signatures year-round near the vicinity of this trench. Figure 16 shows a schematic map of the area surrounding trench TT19 and the location of the various ground truth sensors. According to the SERDP trench map (Fig. 1), trench TT19 has approximate dimensions of 1.8 m to 2.4 m in width and 59.4 to 62.5 m in length. These dimensions are consistent with previous estimates of trench sizes at WAG 4.

4.1 GROUND TRUTH SENSORS AND DATA SETS

.. The suite of ground truth sensors included the following instruments:

- 24 soil surface temperature thermistors
- 10 surface soil moisture blocks
- 2 IR temperature transducers
- 1 rain gauge
- corresponding data logging/storage support equipment

A variety of meteorological sensors were also available both locally at the WAG 4 site and at a meteorological tower located less than 2 km from the site. Appendix B contains more information about the meteorological data that were collected.

Two consecutive weeks of representative ground truth data were selected from more than 10 weeks of coverage. The two week data set received detailed qualitative and quantitative analysis. All sensors were sampled every five minutes and the minimum, maximum, and average values were recorded during each sampling interval. The first data set analyzed was from the week of 10/16/95 and it consisted of 1888 contiguous data points (128 data points were lost from the recorded data at the beginning of the weekly cycle for unknown reasons). The second data set selected was from the

following week (10/23/95) and consisted of 1791 data points (231 data points contained erroneous data, probably due to data rollover between the CR-10 data logger and the supplemental data storage module).

4.2 SOIL TEMPERATURE

4.2.1 Data Collection

Twenty-three Campbell Scientific Instrument temperature thermistor probes (model 107B) were employed to measure surface soil temperature in the vicinity of trench TT19 in WAG 4. Figure 16 shows a layout diagram of the site configuration. Twenty-four sensors were originally deployed; however, one sensor (T07) was removed early in the experiment because of erratic data measurements. Based on previous field investigations at WAG 4 (i.e., topography studies, direct field observations of slight surface evidence of subsidence, and differential grass growth), the boundaries for trench TT19 were roughly delineated and several points were flagged at the site. From these location points, the axis of the trench was determined on the surface. Two transects parallel to the trench axis were selected, based primarily on the field observations of vegetation differences (e.g., density; longer, healthier grass; and slight subsidence within the perceived main body of the trench). The two transects were spaced approximately 0.96 m apart and measured 44.3 m in length.

Five sensor sites along each transect were chosen for temperature measurements. For each transect, three of the five sensors were intended to be within the boundary of the SERDP-based thermal trench signature (T18, T09, T02 in the east transect and T17, T16, T01 in the west transect), while the remaining two sensors (T03, T15 in the east transect and T07, T14 in the west transect) were specifically positioned up-slope of the trench in a non-trench area. The non-trench areas were selected as probable areas that were excavated as trenches but did not receive any hazardous waste materials. Sensor locations along the transects were separated by a variable distance of approximately 4.0 m in the non-trench area and 11.3 m to 15.5 m in the trench. Figure 17 shows the elevation and the distance cross section of the east temperature transect that revealed an elevation difference of almost 4.3 m from the up-slope, non-trench sensor (T15) and the farthest down-slope sensor (T18). The west transect exhibited a similar slope effect.

Based on the SERDP trench map (Fig. 1), it appears that the east transect (sensors T15, T03, T02, T09, and T18) fell outside the boundary of the thermal signature of trench TT19. Previous site characterization field work with drive point installations demonstrated that the apparent correlation between the SERDP trench map and trench locations was excellent. However, in certain areas within WAG 4 there were discrepancies between the SERDP trench map and drive point results. In particular, in the vicinity of trench TT19, translation errors on the order of 1.5 m to 2.4 m were observed. This observation, in conjunction with accuracy limitations of the SERDP trench map itself, could account for the east transect falling outside of the mapped trench boundary (Energy Systems 1995a).

The WAG 4 remedial investigation team installed several drive point (DP) locations (DPs 17, 18, 25, and 40) to penetrate suspect trenches and to allow for the sampling of groundwater for the determination of ^{90}Sr concentrations. The installation of DPs 17, 18, 25, and 40 were confirmed as being inside a trench (on the basis of the rate and depth of insertion of the drive rod), according to

the *Site Investigation Report for Waste Area Grouping 4 at Oak Ridge National Laboratory* (Energy Systems 1995a). Figure 18 depicts an expanded site layout diagram that includes the DP locations. Since DP 25 and the east transect sensors have similar ORNL easting coordinates, these sensors may actually be in trench TT19.

At each surface temperature site, the surface temperature probes were inserted into the ground at 2.5 cm depth; uniform placement below the ground surface was achieved using a template. The probes were inserted horizontally at the prescribed depth. Sensor cables from the probes were brought to the surface and were run along the ground surface to a Campbell Scientific Instrument CR-10 data logger (mounted in a weather-proof enclosure box on a 6-ft tripod). The data logger was powered by a gel cell marine battery that was recharged by a single solar panel. Data were stored on a removable data storage module that was manually collected weekly or biweekly and downloaded onto a PC. In addition, a cellular phone and modem were used to facilitate the process of remote data downloading and monitoring the status of instrument operation.

In addition to the ten surface temperature sensors on two transects, two sets of three temperature sensors were placed for vertical temperature profiles. One vertical profile array (T10, T11, T12) was positioned in a non-trench area, and the second array was placed within the trench boundary (T04, T05, T06). Each vertical profile consisted of three temperature sensors at depths of 10.2 cm, 15.2 cm, and 25.4 cm that were collocated within a 0.3 m radius of each other. Sensors were not placed at greater depths because health and safety requirements would require additional permits and more costly precautions at this Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)-regulated site.

Lastly, two temperature sensors were placed at a 2.5 cm depth in an up-slope control area (T19, T21) above trench TT19 and adjacent to the non-trench area. Three sensors were placed on the surface to record ambient temperatures (T13, T20, T24). Sensor T20 was left uncovered and fully exposed on the surface, while sensor T13 was shielded with an aluminum cover to minimize solar loading during the daytime. Sensor T24 was mounted on a tripod over the trench at a distance of 30.5 cm above the ground surface. The remaining two sensors (T22, T23) were originally placed in the up-slope, non-trench area at a 5 cm depth. However, midway through the experiment, T22 was moved to the up-slope moisture transect and T23 was moved to the down-slope moisture transect in order to provide temperature input data for calculation of soil water potential.

4.2.2 Data Analysis and Results

Selected surface soil temperature results from the weeks of 10/16/95 and 10/23/95 are shown in Exhibits 1 and 2. The data show several interesting relationships:

- On average, the temperature in the trench is lower than the non-trench area and much lower than the control sites.
- The trench sensors generally have cooler minima and greater variability (as evidenced by the slightly larger values for the sample standard deviation) than the non-trench sensors.
- The control sensors are generally warmer than both the trench and non-trench sensors.
- The trench and non-trench sensors have two daily cross-overs at noon (1200–1300 hours) and early evening (1800–1900 hours).
- The vertical temperature profiles show that greater depth is associated with higher temperatures and lower variability.

Exhibit 1. Summary Statistics for Thermistor Average Data (all units are °C).

a) East Transect

10/16/95 N=1888	T-15(1") Non-trench	T-03(1") Non-trench	T-02(1") Trench	T-09(1") Trench	T-18(1") Trench
Minimum	10.54	10.13	10.01	8.73	8.90
Maximum	18.27	18.70	19.28	20.15	18.50
Average	14.66	14.53	14.67	14.35	13.72
Standard Dev	1.71	1.94	2.11	2.70	2.24

b) West Transect

10/16/95 N=1888	T-14(1") Non-trench	T-07(1") Non-trench	T-01(1") Trench	T-16(1") Trench	T-17(1") Trench
Minimum	10.66	10.78	10.38	9.50	9.34
Maximum	18.85	17.99	19.13	18.54	17.61
Average	14.84	14.69	14.89	14.16	13.75
Standard Dev	1.86	1.62	2.01	2.10	1.92

c) Controls

10/16/95 N=1888	T-19(1") Control	T-21(1") Control
Minimum	9.95	10.42
Maximum	21.38	20.16
Average	15.51	15.23
Standard Dev	2.67	2.20

d) Vertical Profiles

10/16/95 N=1888	T-04(4") Trench	T-06(6") Trench	T-05(10") Trench	T-12(4") Non-Trench	T-11(6") Non-Trench	T-10(10") Non-Trench
Minimum	12.36	13.95	15.13	12.52	13.57	15.13
Maximum	16.93	17.29	18.44	17.93	17.64	17.95
Average	15.08	15.93	16.62	15.68	16.02	16.81
Standard Dev	0.99	0.73	0.58	1.17	0.87	0.68

e) Average Sensor Values by Site

10/16/95 N=1888	Average In-Trench	Average Non-Trench	Average Controls
Minimum	9.51	10.55	10.20
Maximum	18.82	18.43	20.65
Average	14.25	14.68	15.37
Standard Dev	2.18	1.78	2.43

Exhibit 2. Summary Statistics for Thermistor Average Data (all units are °C).

a) East Transect

10/23/95 N=1785	T-15(1") Non-trench	T-03(1") Non-trench	T-02(1") Trench	T-09(1") Trench	T-18(1") Trench
Minimum	10.57	10.12	9.93	8.65	8.98
Maximum	16.49	16.52	16.78	17.75	16.15
Average	13.63	13.36	13.39	13.00	12.55
Standard Dev	1.49	1.59	1.67	2.24	1.84

b) West Transect

10/23/95 N=1785	T-14(1") Non-trench	T-07(1") Non-trench	T-01(1") Trench	T-16(1") Trench	T-17(1") Trench
Minimum	10.70	10.67	10.02	9.15	9.28
Maximum	16.87	16.14	17.18	16.41	15.88
Average	13.78	13.53	13.59	12.87	12.59
Standard Dev	1.53	1.35	1.72	1.78	1.67

c) Controls

10/23/95 N=1785	T-19(1") Control	T-21(1") Control
Minimum	9.87	9.95
Maximum	18.96	17.99
Average	14.21	13.92
Standard Dev	2.20	1.88

d) Vertical Profiles

10/23/95 N=1785	T-04(4") Trench	T-06(6") Trench	T-05(10") Trench	T-12(4") Non-Trench	T-11(6") Non-Trench	T-10(10") Non-Trench
Minimum	12.00	13.43	14.34	12.02	12.95	14.29
Maximum	15.29	15.54	15.75	16.03	15.76	16.04
Average	13.74	14.54	15.05	14.24	14.52	15.29
Standard	0.79	0.51	0.31	0.90	0.61	0.40

e) Average Sensor Values by Site

10/23/95 N=1785	Average In-Trench	Average Non-Trench	Average Controls
Minimum	9.39	10.61	9.91
Maximum	16.66	16.47	18.40
Average	13.00	13.57	14.06
Standard Dev	1.81	1.48	2.03

Figures 19, 20, and 21 show the near-surface thermistor temperature data. Figure 19 displays the data for the week beginning 10/16/95. Figure 20 displays a two-day span of data in greater detail from 10/16/95 at 2200 hours through 10/19/95 at 0000 hours. Figure 21 displays the data for the following week beginning 10/23/95. Sensor values were averaged according to the location of the thermistors (trench, non-trench, and control). The strongest pattern in the data was the pronounced diurnal variation induced by solar heating. The pattern of interest for this study was the relationship between the temperature in the trench and the temperatures in the other two areas (non-trench and control). Note that the trench was consistently cooler than the control areas. The non-trench area represented temperatures midway between the trench and control cases, with temperature values closer to the trench during the day and closer to the control at night. Therefore, nighttime thermal differences offer the best hope for distinguishing trenches from the remainder of the site.

In addition to the first and second order statistics, several hypotheses tests for differences in mean values were computed on the in-trench versus non-trench sensors. Paired sample t-tests for each set of 5 sensors along a transect were computed to compare the means. When these tests were evaluated with a week's worth of data (1888 data points), each pairwise comparison was statistically significant with p-value of 0, implying significant "treatment" difference in means within or between a trench or non-trench sensor (i.e., the temperature measurements for each sensor are significantly different).

As a result of too many diurnal data points overwhelming the test, the data set was reduced from a sample size of 1888 to 288 to cover a single day's worth of data. In particular, values from 10/16/95 at 1040 hours until 10/17/95 at 1035 hours (the first day's worth of data) were used as input for a single factor analysis of variance (ANOVA).

The single factor ANOVA is a simple analysis of variance which expands on the t-test and tests the hypothesis that the means from several samples (temperature sensors) are equal. In general, ANOVA is a statistical procedure used to determine whether the means from two or more samples are drawn from normal populations with the same mean. The ANOVA results generally show that as a group, all five sensors have differing means (statistically significant) at any non-zero confidence level. If the three trench sensors (T02, T09, T18 in the east or T01, T16, T17 in the west) are compared, the means are statistically different ($p=0$). When the two up-slope sensors are tested together (for a given transect), the ANOVA results are mixed, showing that the means for T02 and T09 are marginally identical ($p=0.10$) and that the means for T01 and T16 are different ($p=0.0$). A pairwise comparison of the in-trench sensors further reveals that the individual trench sensors are statistically different in their mean measurements. If each trench sensor is compared with the two non-trench sensors, the results show that as you progress farther down slope, the difference becomes more significant. Lastly, when comparing the two non-trench sensors for either transect, there is no statistical difference in measurements from outside the trench (i.e., $p=.33$ for T03/T15 and $p=.51$ for T14/T07).

4.3 SOIL MOISTURE

4.3.1 Data Collection

Ten Campbell Scientific model 253 soil moisture sensors were employed to estimate soil water

potential in the vicinity of trench TT19 in WAG 4. Two parallel transects perpendicular to the axis of the trench were selected, each with four sensors (two in and two out of the trench) buried at a uniform depth of 5.1 cm (Fig. 22). The upper transect spanned 5 m and consisted of sensors M05, M06, M07, and M08. It was located up-slope across the trench and had an average elevation of 247.3 m. The lower transect spanned 4.2 m and consisted of sensors M01, M02, M03, and M04. It was located approximately 9.4 m down-slope from the upper transect and had an average elevation of 246.5 m. The remaining two sensors, M09 and M10, were installed in the control area. There was an elevation difference of approximately 0.8 m, due to the slope of the site, with a variable sensor spacing ranging from 0.96 m to 2.24 m, where the closest sensors were the two in-trench sensors.

The soil moisture sensors measured resistance and the soil water potential (0 bars to 2 bars) was calculated from a non-linear relationship between resistance and soil temperature. The initial ground installation of the soil moisture sensors did not include collocated temperature sensors. As a result, the soil water potential estimates were based on averages of 14 surface soil temperature probes buried at a depth of 2.5 cm, including the east transect and controls. On 10/25/95 at approximately 1400 hours, two temperature sensors (T22 and T23) were moved from the control area to each of the two soil moisture transects, relocated midway between the in-trench soil moisture sensors (M7/M6 and M3/M2) and buried at a depth of 5.1 cm. For consistency, the remainder of the 10/23/95 data set soil water potential calculations was based on the average of the 14 temperature sensors (including the relocated sensors T22 and T23). The impact of averaging the deeper sensors (T22 and T23) with the other 12 soil temperature sensors was assumed to be minimal. Comparison of T22 and T23 before and after the relocation shows a temperature delta of approximately 1°C between the two depths (for only one point in time). Nevertheless, the critical issue for this study was the relative difference in soil moisture over the site.

4.3.1 Data Analysis and Results

Selected data from two consecutive weeks (10/16/95 and 10/23/95) of the upper and lower transect surface soil moisture sensors collected at 5.1 cm depth show the relationship between the trench and non-trench areas. Figures 23 and 24 depict the soil moisture data for the selected data as a function of observation time. Individual readings are averaged within the three categories of trench, non-trench, and control. Note the steady divergence of the trench readings from the other two values as soil drying occurs. The rain event on 10/20/95 causes all three series to change abruptly, followed again by a drying process. Once the initial saturation effects of the rain event passed, the trench exhibited consistently greater soil moisture and the soil moisture difference increased over time.

The surface soil moisture data show several interesting relationships:

- All of the sensors displayed a general pattern of drying out (higher values of soil water potential) prior to the rain events on 10/20/95 from 1000 to 1200 hours (0.09 in/hr) and 10/27/95 from 0700 to 1700 hours (0.12 in/hr).
- The non-trench and control sensors were substantially dryer than the in-trench sensors.
- The non-trench and control sensors showed a greater overall rate of drying (based on the average slope of each curve).

- The non-trench and control sensors showed a greater diurnal effect of increased soil moisture during the afternoon hours (1100 hours to 1400 hours) that is somewhat positively correlated with the daily minima of relative humidity (1400 hours to 1600 hours) and negatively correlated with the daily maxima of ambient temperature (1500 hours to 1600 hours) with a lead time of two to three hours between these events.
- The lower transect sensors tended to record the greatest range of soil water potential values.
- In general, the average delta difference was greatest after several days of drying out had elapsed after a rain event. At the greatest difference, the ratio of non-trench to trench soil water potential was greater than two, indicating that the average non-trench areas can be at least twice as dry as the average trench areas.

Exhibits 3 and 4 summarize statistical parameters for each of the two transects and the controls for the two weeks of 10/16/95 (128 data points are missing due to a data dropout) and 10/23/95 (231 data points are missing because of erroneous values).

The statistical differences between individual sensors were less obvious for the soil moisture as compared to soil temperature. However, the following statistical characteristics were observed:

- The in-trench sensors (upper are M7/M6 and lower are M3/M2) recorded greater soil moisture (smaller maxima and lower averages).
- The in-trench sensors (especially M3 and M6) showed much less variability (smaller standard deviation).

In addition to the first and second order statistics above, several hypotheses tests for differences in mean values were computed on the in-trench versus non-trench sensors. Several paired sample t-tests and ANOVA tests were computed for soil moisture sensors to compare the means. In all but one case, the tests were statistically significant, with $p < 0.0001$ implying a treatment difference in the means within or between a trench or non-trench sensor. The only exception was the results for comparing in-trench sensors T3 and T6, which showed that their means were not significantly different.

**Exhibit 3. Summary Statistics for Soil Moisture Average Data for 10/16/95
(Soil Water Potential, Bars).**

a) Individual Transects

10/16/95	Lower Transect				Upper Transect				Control	
N=1888	M-01	M-02 Trench	M-03 Trench	M-04	M-05	M-06 Trench	M-07 Trench	M-08	M-09	M-10
Minimum	0.133	0.132	0.038	0.137	0.041	0.039	0.087	0.105	0.052	0.051
Maximum	0.882	0.567	0.191	0.686	0.441	0.241	0.331	0.675	0.579	0.989
Average	0.487	0.316	0.115	0.351	0.168	0.122	0.186	0.345	0.282	0.471
Standard Dev	0.204	0.107	0.039	0.159	0.107	0.053	0.062	0.136	0.123	0.228

b) Collective Transects

10/16/95 N=1888	Trench Average	Non-Trench Average	Control Average
Minimum	0.096	0.120	0.052
Maximum	0.331	0.670	0.784
Average	0.184	0.338	0.377
Standard Dev	0.058	0.133	0.169

**Exhibit 4. Summary Statistics for Soil Moisture Average Data for 10/23/95
(Soil Water Potential, Bars).**

a) Individual Transects

10/23/95	Lower Transect				Upper Transect				Control	
N=1791	M-01	M-02 Trench	M-03 Trench	M-04	M-05	M-06 Trench	M-07 Trench	M-08	M-09	M-10
Minimum	0.037	0.046	0.038	0.036	0.035	0.038	0.037	0.034	0.038	0.041
Maximum	1.838	0.905	0.257	0.945	0.527	0.450	0.553	1.133	1.190	1.722
Average	0.856	0.501	0.146	0.490	0.220	0.199	0.275	0.589	0.601	0.729
Standard Dev	0.572	0.301	0.076	0.315	0.152	0.128	0.171	0.376	0.392	0.514

b) Collective Transects

10/23/95 N=1791	Trench Average	Non-Trench Average	Control Average
Minimum	0.04	0.036	0.039
Maximum	0.539	1.098	1.452
Average	0.28	0.539	0.665
Standard Dev	0.166	0.347	0.45

4.4 THERMAL IR

4.4.1 Data Collection

Two Everest Interscience IR temperature transducers (model 4000.GL) were employed to measure radiant energy in the long-wave IR band (8 microns to 14 microns) of the electromagnetic spectrum over trench TT19. It was expected that the radiance from the trench would be different than that of the non-trench due to differences in surface soil temperature or emissivity, the spatial heterogeneity of the soil/vegetation mix (composition and structure), topography, water content, or other causes. As a result, one of the IR transducers (XD2) was specifically positioned over trench TT19 (approximately midway between the upper and lower soil moisture transects). The other transducer (XD1) was located over the non-trench area, approximately midway between the four non-trench temperature sensors. The two transducers were separated by a distance of 14.8 m and an elevation difference of 1.2 m. Each transducer had a narrow 15° field-of-view (FOV) and was mounted at a height of 1.2 m above the ground, resulting in a small nadir target spot size of 0.32 m.

4.4.2 Data Analysis and Results

Selected delta results from data acquired during the weeks of 10/16/95 and 10/23/95 of the difference of the non-trench and trench IR transducer measurements are shown in Figs. 25 and 26, respectively. The IR temperature values shown assume that the emissivity of the ground surface is fixed at 0.95. This assumption forces the surface emissivity to be both temporally and spatially invariant and ignores the fact that the surface emissivity will vary as a function of composition (amount of bare soil/ grass and grass vigor/health) and physical parameters of the surface (such as soil moisture content). Actual emissivities for vegetative surfaces are typically in the 0.95 to 0.99 range so that the actual, true surface temperatures are probably lower than the apparent temperatures measured by the IR transducers. Thus, the apparent surface temperatures shown here are upper limits.

Differences were expected in the thermal-emitted radiance between the in-trench and out-of-trench sites. Those differences were anticipated to be less a function of variation in surface emissivity than differences in surface temperature, especially since the ground cover over both the in-trench and out-of-trench IR transducer sites consisted of comparable, fully vegetated surfaces. Subsurface differences (voids, waste deposits, density differences, deteriorated backfill, moisture plumes, etc.) were probably responsible for the observed thermal differences since the atmosphere and surface emissivity were essentially identical at the two sites. In general, the following IR temperature characteristics were observed:

- Based on the limited number of two sensors, the delta differences showed a substantial amount of "noise" or fluctuation.
- For the majority of the daily diurnal cycle, the in-trench sensor was cooler than the non-trench sensor [i.e., during the hours from late afternoon/early evening (1700–1900 hours) until mid-morning/noon (1100 hours to 1200 hours) the non-trench sensor was consistently warmer than the trench sensor].
- After maximum solar heating (1200 hours to 1400 hours), the trench area was warmer than the non-trench area.

- During this same time period (1200 hours to 1400 hours), the in-trench and non-trench sensors experienced several crossovers.

The IR temperatures observed were consistent with those observed using the thermistor surface soil temperature and moisture probes. Since the trenches had a greater moisture content than the non-trench areas, they should have had a higher thermal inertia and hence would have warmed up less during the daytime and cooled off less during the night. Similarly, the non-trench areas should have had a lower thermal inertia (less moisture) and would have been relatively warmer in the daytime and cooler in the night. However, thermal inertia differences due to moisture differences do not completely explain the observed behavior. It appears the evaporation processes are causing the cooler nighttime temperatures in the moister trench areas. In addition to moisture, there were host of factors (e.g., sensor placement, local subsidence/topography, soil differences, grass placement, etc.) that also could have affected surface soil temperatures.

5. GATF RESULTS

The analysis of ground truth data showed that for sites with a uniform grassy ground cover such as WAG 4, nighttime soil temperatures were slightly cooler and soil moisture was greater within the waste trench during the Fall time frame. Both *in situ* sensors and thermal IR measurements from the IR radiometers confirmed this temperature difference. During the daytime, the thermal difference was ambiguous.

These results demonstrated that nighttime thermal imagery can be employed to help delineate waste trench areas at known sites under many, but not all, conditions. The depth of soil over the trench, the nature of the surface soil, and vegetation affected the image signature. Consistent thermal signatures were associated with sites where the surface conditions were more homogeneous, whereas a site with mixed and complex vegetation could exhibit different behavior. Furthermore, even if no buried waste was present, disturbed soil typically exhibited the thermal signature observed at the trenches. Thus, the results showed that thermal imagery can suggest the presence of waste trenches when no trenches are present. This finding would suggest that human activity had occurred at the site in the past, but wastes may not have been buried in the area. Image contextual and collateral data is necessary to distinguish such features from actual trenches of interest.

Statistical analysis of the ground data indicated the nature of the thermal signatures of the trench area. The trench area was typically cooler than the non-trench area. The spatial variation in temperature within the trench was larger than that between trench differences, suggesting the need for multiple observations. Both the thermistor and radiometer data showed that the difference between the trench and control areas was most evident at night. Soil moisture measurements showed that the trench area generally exhibited greater soil moisture than the non-trench area, which may have accounted for the observed thermal differences.

Observations at this relatively moist site during fall weather are as follows:

- With respect to the IR radiometer (longwave) measurements, the difference in apparent

temperatures was greatest during the night-time hours (the non-trench was warmer than the in-trench area). The in-trench area was cooler in the nighttime IR data, exhibiting a contrast of as much as 3°C. However, the IR delta temperature results were extremely mixed, often showing multiple crossovers and/or no difference in temperatures (on the basis of 0.5°C error bound) during the daytime (1100 hours to 1600 hours).

- The lack of in-trench/non-trench signature differentiation from the IR transducer was consistent with expectations. Radiometer measurements were directly related to two major factors influencing all remotely sensed data (minus atmospheric): variations in vegetation and soil moisture. As the surface approached full canopy coverage, the variations in soil moisture had a minimal effect on radiometer measurements. At WAG 4, the visible surface features of the in-trench and non-trench locations appeared to be somewhat similar/homogeneous, especially in terms of ground coverage and mixture of grass/bare soil.
- The thermistor data clearly demonstrated greater cooling in the trench area (especially during nighttime, with a contrast of as much as 1.5°C as compared to the non-trench area). This is an important observation explained by the thermal properties of disturbed soil within the trench as compared to the thermal properties of undisturbed soil at the control site. The vertical profile thermistor data showed less variability at greater depths and were warmer than the surface temperature at night (as expected from thermal inertia).
- The *in situ* surface temperature contrast between trench, non-trench, and control sensors was also consistent with a preliminary site survey conducted near the current experiment site at WAG 4. On 12/21/94 (at 1330–1530 hours) 31 temperature measurements were recorded with soil thermometers along two transects through previously identified SERDP thermal signature areas. Based on field observations, there were two contrasting surface types: 1) thick grass cover in depressions (probably from settlement of trench cover/fill or consolidation and/or decomposition of trench waste material) and 2) thin grass between depressions. The mean temperature difference between the two surface types was 2.7°C. The thick grass type had the lower soil temperature (probably due to longer grass and increased insulation from solar loading), greater moisture retention in the trench, and increased evapotranspiration effects.
- The moisture data clearly indicated a significant difference in soil water potential (greater in the trench), with a moisture difference of as much as three times higher soil water potential in the trench as compared to the control areas. In addition, the corresponding rate of drying was almost twice as slow in the trench. This observation could be explained by the difference in vegetation and/or soil properties of disturbed soils in the trench (porosity and compaction) as compared to the undisturbed soils at WAG 4. In addition, the trench excavation and subsidence of overfill and trench contents may have contributed to a differential preference for channeling surface water into the trenches.
- Both the thermistors and the IR radiometer observations showed cooling of several degrees in the trench indicating that the IR signature was driven more strongly by temperature effects (which themselves are highly dependent on the soil moisture content) than by changes in emissivity in the surficial soil in the scene. Thus, temperature was the major cause of radiance variations in this study.

6. BENEFITS OF REMOTE SENSING TECHNOLOGIES

The techniques developed in the SERDP Project and verified by the GATF Study can benefit DOE and other federal agencies in many ways. By applying these techniques at other hazardous waste areas, remote sensing technologies can: 1) aid site characterization by identifying potential areas of past waste disposal, 2) focus traditional ground-based sampling efforts by identifying the areas of concern within waste sites, 3) aid remediation activities by providing additional information on the locations of waste, and 4) provide long-term monitoring of remedial action effectiveness at sites that have undergone restoration.

At WAG 4, the SERDP and GATF projects aided the Environmental Restoration (ER) Remedial Investigation Team in identifying two seep areas that contributed over 90% of the ^{90}Sr release from the study area. The SERDP trench map derived from remote sensing data was the key factor in pinpointing localized sources feeding the major seeps. It is believed that control of these few sources will provide a cost-effective interim action to reduce ^{90}Sr releases and off-site risk. Without the remote sensing results, the ability to pinpoint the locations of the individual sources quickly and effectively would have been lost. The alternative for controlling releases (i.e., cap the whole site, collect and treat surface water) could have cost in excess of \$5 million more than directly controlling the sources. Thus, use of the remotely sensed data provided a significant reduction in remediation costs for this site.

The procedures demonstrated here can be applied to numerous other waste sites where the locations of waste areas are known, where remedial action is necessary to stop the migration of contaminants from burial trenches/pits, and where long-term monitoring is required. Candidate sites of this type exist at numerous DOE reservations and military facilities. The alternative to employing remote sensing technology is to rely on extensive and costly ground sampling to precisely locate the hazardous material. While use of imagery will not totally eliminate the need for ground sampling, it can substantially reduce the amount that is required. Through proper analysis of remotely sensed imagery, it should be possible to locate the buried material with greater precision, reduce the ground sampling requirements, ensure greater safety in the clean-up process, and conduct long-term monitoring of remedial action effectiveness after remediation has been completed.

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8. FURTHER INFORMATION AND CONTACTS

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APPENDIX A

FIGURES

FIGURES

1. SERDP Trench Map.
2. TVA Aerial Photograph of SWSA-4 (April 30, 1952).
3. TVA Aerial Photograph of SWSA-4 (February 29, 1956).
4. USDA Aerial Photograph of SWSA-4 (October 27, 1961).
5. TVA Aerial Photograph of SWSA-4 (March 2, 1967).
6. TVA Aerial Photograph of SWSA-4 (March 21, 1971).
7. TVA Aerial Photograph of SWSA-4 (April 14, 1973).
8. TVA Aerial Photograph of SWSA-4 (March 25, 1981).
9. Predawn Thermal Infrared Image of SWSA-4 (April 6, 1992).
10. Oblique Helicopter Photograph of SWSA-4 (January 3, 1978).
11. Historical Trench Map.
12. Buried Waste at SWSA-4 (May 22, 1957).
13. Buried Waste at SWSA-4 (November 12, 1957).
14. WAG 4 Bathtubbing Trench Conceptual Model
15. Location of Ground Truth Study Site at SWSA-4.
16. SWSA-4 Ground Truth Configuration.
17. Elevation/Distance Cross-Section for East Temperature Transect.
18. SWSA-4 Ground Truth Configuration with Drive Point Locations.
19. Surface Soil Temperature Data for the Week of 10/16/95.
20. Surface Soil Temperature Data for Two Days.
21. Surface Soil Temperature Data for the Week of 10/23/95.
22. Elevation/Distance Cross-Section for Moisture Transects.
23. Surface Soil Moisture Data for the Week of 10/16/95.

24. Surface Soil Moisture Data for the Week of 10/23/95.
25. IR Radiometer Delta for Difference in Radiance Between the Non-Trench and Trench Areas for the Week of 10/16/95.
26. IR Radiometer Delta for Difference in Radiance Between the Non-Trench and Trench Areas for the Week of 10/23/95.

Trench Map Derived from Imagery

Figure 1. SERDP Trench Map.

Figure 2. TVA Aerial Photograph of SWSA-4 (April 30, 1952).

Figure 3. TVA Aerial Photograph of SWSA-4 (February 29, 1956).

Figure 4. USDA Aerial Photograph of SWSA-4 (October 27, 1961).

Figure 5. TVA Aerial Photograph of SWSA-4 (March 2, 1967).

Figure 6. TVA Aerial Photograph of SWSA-4 (March 21, 1971).

Figure 7. TVA Aerial Photograph of SWSA-4 (April 14, 1973).

Figure 8. TVA Aerial Photograph of SWSA-4 (March 25, 1981).

Predawn Thermal Infrared Imagery
of Waste Area Grouping (WAG) 4
Oak Ridge National Laboratory, Tennessee

Daedalus AADS-1268 Scanner Flown April 6, 1992 at 4000 Feet Elevation

*Area inside WAG 4 boundary has been digitally
enhanced to emphasize trench signatures.*

Data from Environmental Restoration
Remote Sensing Program

Processing by
GIST/ORNL

Figure 9. Predawn Thermal Infrared Image of SWSA-4 (April 6, 1992).

Figure 10. Oblique Helicopter Photograph of SWSA-4 (January 3, 1978).

Figure 11. Historical Trench Map.

Figure 12. Buried Waste at SWSA-4 (May 22, 1957).

Figure 13. Buried Waste at SWSA-4 (November 12, 1957).

WAG 4 Bathtubbing Trench Conceptual Model

Uncontaminated
Drainage
Upslope

Fence Line

Road

Edge of Grassed
Area

Storm-Related
Perched Water
in Trench

Surface
"PLUMES"

Auger Holes

Normal
Water Table

SWSA 4
Tributary

More Permeable
Fracture Zones

Water Diversion
System

Figure 14. WAG 4 Bathtubbing Trench Conceptual Model

Figure 15. Location of Ground Truth Study Site at SWSA-4.

Figure 16. SWSA-4 Ground Truth Configuration.

Elevation/Distance Cross-Section for East Temperature Transect

Figure 17. Elevation/Distance Cross-Section for East Temperature Transect.

Figure 18. SWSA-4 Ground Truth Configuration with Drive Point Locations.

Calibrated Surface Soil Temperature

Figure 19. Surface Soil Temperature Data for the Week of 10/16/95.

Calibrated Surface Soil Temperature

Figure 20. Surface Soil Temperature Data for Two Days.

Calibrated Surface Soil Temperature

Figure 21. Surface Soil Temperature Data for the Week of 10/23/95.

Elevation/Distance Cross-Section for Moisture Transects

Figure 22. Elevation/Distance Cross-Section for Moisture Transects.

Calibrated Surface Soil Moisture

Figure 23. Surface Soil Moisture Data for the Week of 10/16/95.

Calibrated Surface Soil Moisture

Figure 24. Surface Soil Moisture Data for the Week of 10/23/95.

IR Radiometer Data

Figure 25. IR Radiometer Delta for Difference in Radiance Between the Non-Trench and Trench Areas for the Week of 10/16/95.

IR Radiometer Data

Figure 26. IR Radiometer Delta for Difference in Radiance Between the Non-Trench and Trench Areas for the Week of 10/23/95.

APPENDIX B

METEOROLOGICAL DATA

Year-round mean temperature at ORR is approximately 14°C (58° F), with temperatures greater than 38°C (100°F) and less than -18°C (0°F) being unusual. For the first full month of the ground truth study period (October 1995), the WAG 4 temperature ranged from -3.3°C (26.0°F) to 25.3°C (77.6°F) and had a mean value of 10.9°C (51.5°F). These figures are based on values from the WAG 4 local meteorological station. Precipitation varies seasonally, with the highest period of rainfall occurring during the winter months. Another peak in rainfall occurs in July when short, heavy thunderstorms are common. Annual precipitation at ORR averages approximately 132 cm/year (52 in/year). The WAG 4 precipitation was 4.5 in of recorded rainfall during the month of October 1995.

The WAG 4 meteorological station is located at WAG 4 proper approximately 126 m (415 ft) from the study site. This station is operated and maintained by the ER program. The SWSA-4 meteorological monitoring system at ORNL consists of a stand-alone tower and meteorological instruments connected to an electronic data logger for continuous data acquisition. With the exception of the precipitation gauges and the evaporation pan that are mounted at ground level, the meteorological instrumentation is mounted on the tower. The following paragraphs describe the instrumentation that is used to measure the indicated parameters.

- *Wind Speed:* Wind speed is measured with a Met One Northwest Model 014A wind speed sensor with a starting threshold of 1 mph and an upper range of 100 mph.
- *Wind Direction:* Wind direction is measured with a Met One Northwest Model 024 wind direction sensor with starting threshold of 1 mph and an upper range of 100 mph.
- *Temperature and Relative Humidity:* The atmosphere dry bulb temperature and relative humidity are collected using a Vaisala temperature and relative humidity sensor (Vaisala, Model HMP 35A). This sensor uses a thin-film polymer capacitive, relative-humidity-sensing element with a range of -40° to +60° C. This unit is installed in a Vaisala model 2212 HM shield to protect the sensors from solar radiation and precipitation.
- *Solar Radiation:* Solar radiation data are collected with a pyranometer (Li-Cor Model Li-200SA) which consists of a cosine high stability silicon photovoltaic detector. This instrument measures solar radiation received from a whole hemisphere (global sun plus sky radiation).
- *Precipitation:* Precipitation is measured electronically using a Qualimetrics Tipping Bucket Raingauge (Qualimetrics, Model 6011-A) with a resolution of 0.01". Precipitation is also measured using a Belfort Weighting Bucket Raingauge (Belfort, Model 5-780) with a capacity of 12" (dual-traverse).
- *Evaporation:* Evaporation is measured using a Qualimetrics Analog Output Evaporation Gauge (Qualimetrics, Model 6844-A). The sensor consists of a stilling well with the main support, the potentiometer drive, and the polypropylene floats. The sensor has a range of 0 to 5.6 inches, with an accuracy of 0.015 inches of true water, and infinite resolution. The pan consists of a Class A stainless steel evaporation pan, 10" high x 47.5" deep. The site is serviced at least weekly and water is added if the level is below ~6" and removed if above ~7.5" (as measured in the pan). This unit was in service until 12/1/95.

- *Data Logger:* Data are collected using an Omnidata Easy Logger (Omnidata, Model 800 series, Version 2.0). Power for the logger is supplied by a 12 volt gel-cell battery continuously charged by a solar panel mounted on the meteorological tower.

Table B.1. Sampling Parameters.

Meteorological Parameter	Scan Interval	Data Logger Recording Interval
Wind Speed	1 min	15 min average
Wind Direction	1 min	15 min average
Dry Bulb Temperature	1 min	15 min average
Auxiliary Temperature	1 min	15 min instantaneous
Relative Humidity	1 min	15 min instantaneous
Solar Radiation	15 min	15 min instantaneous
Pan Evaporation	15 min	15 min instantaneous
Precipitation	Pulse Counter	15 min total

The meteorological station is serviced weekly (more often during severe weather). The Data Storage Pack (DSP) is changed during the first site visit of each month. Logging must be stopped to change the DSP due to the one minute scan interval. Stopping the logger causes one 15 minute recording interval to be missed. Tables B.2 and B.3 and Figs. B-1 through B-10 summarize weather parameters for the month of October and the two weekly data sets (10/16/95 and 10/23/95).

In addition to the availability of the local meteorological station at WAG 4, ORNL has a series of weather towers. The MT2 weather tower for ORNL is located less than 1.2 km from the WAG 4 site. Temperature, pressure, relative humidity, wind speed/direction at several altitudes, precipitation, and solar radiation, are routinely measured as 15 minute averages and recorded as hourly averages (except precipitation which is totaled hourly). The most pertinent observation from these records are the air temperature at the 10 meter elevation (closest to the ground) and the wind speeds at 10 m (also closest to the ground). All of these data were available for the entire duration of the experiment.

These weather station measurements correlate well with observations made by our measurement team. For example, the daily maxima in surface soil moisture (1300–1400 hrs) are strongly correlated with minima in relative humidity.

Table B.2. Weather Summary for the Month of October.

OCTOBER	WAG 4 Local Meteorological Station–One Month							
N=2974	Wind Speed MPH AVE	Air Temp Deg C Avg	Air Temp Deg F Avg	Rel Hum % Inst	Sol Rad W/M^2 Inst	Rainfall In Sum	Pan Evap In Inst	Aux Temp Deg C Avg
Min	1.00	–3.34	25.99	31.80	0.10	0.00	0.80	–1.37
Max	16.18	25.33	77.59	99.99	870.30	0.22	3.48	28.80
Average	2.70	10.86	51.55	87.43	131.27	0.002	2.05	13.08
Stdev	2.26	6.25	11.26	18.49	215.91	0.01	0.86	6.69

Table B.3. Weather Summary for 10/16/95 and 10/23/95.

WAG 4 Local Meteorological Station–Week Beginning 10/16/95								
N=672	Wind Speed MPH AVE	Air Temp Deg C Avg	Air Temp Deg F Avg	Rel Hum % Inst	Sol Rad W/M^2 Inst	Rainfall In Sum	Pan Evap In Inst	Aux Temp Deg C Avg
Min	1.00	–3.34	25.99	33.37	0.10	0.00	1.35	–1.37
Max	9.80	20.65	69.17	99.99	866.60	0.12	1.54	23.91
Average	2.30	7.44	45.40	84.17	159.13	0.004	1.49	9.79
Stdev	1.83	6.30	11.34	21.16	235.64	0.01	0.05	6.74
WAG 4 Local Meteorological Station–Week Beginning 10/23/95								
N=672								
Min	1.00	–2.61	27.30	33.62	0.10	0.00	1.35	–1.17
Max	10.22	20.46	68.83	99.99	788.50	0.22	3.06	23.42
Average	2.52	8.62	47.52	84.76	115.06	0.002	2.15	10.32
Stdev	1.80	5.51	9.91	20.82	201.58	0.01	0.70	5.91

FIGURES

- B-1. Average Wind Speed from SWSA-4 Local Meteorological Station for the Week of 10/16/95
- B-2. Average Ambient Air Temperature from SWSA-4 Local Meteorological Station for the Week of 10/16/95
- B-3. Relative Humidity from SWSA-4 Local Meteorological Station for the Week of 10/16/95
- B-4. Solar Radiation from SWSA-4 Local Meteorological Station for the Week of 10/16/95
- B-5. Precipitation from SWSA-4 Local Meteorological Station for the Week of 10/16/95
- B-6. Average Wind Speed from SWSA-4 Local Meteorological Station for the Week of 10/23/95
- B-7. Average Ambient Air Temperature from SWSA-4 Local Meteorological Station for the Week of 10/23/95
- B-8. Relative Humidity from SWSA-4 Local Meteorological Station for the Week of 10/23/95
- B-9. Solar Radiation from SWSA-4 Local Meteorological Station for the Week of 10/23/95
- B-10. Precipitation from SWSA-4 Local Meteorological Station for the Week of 10/23/95

GATF SWSA-4 Ground Truth - Local Met Data

B-1. Average Wind Speed from SWSA-4 Local Meteorological Station for the Week of 10/16/95

GATF SWSA-4 Ground Truth - Local Met Data

B-2. Average Ambient Air Temperature from SWSA-4 Local Meteorological Station for the Week of 10/16/95

GATF SWSA-4 Ground Truth - Local Met Data

B-3. Relative Humidity from SWSA-4 Local Meteorological Station for the Week of 10/16/95

GATF SWSA-4 Ground Truth - Local Met Data

B-4. Solar Radiation from SWSA-4 Local Meteorological Station for the Week of 10/16/95

GATF SWSA-4 Ground Truth - Local Met Data

B-5. Precipitation from SWSA-4 Local Meteorological Station for the Week of 10/16/95

GATF SWSA-4 Ground Truth - Local Met Data

B-6. Average Wind Speed from SWSA-4 Local Meteorological Station for the Week of 10/23/95

GATF SWSA-4 Ground Truth - Local Met Data

B-7. Average Ambient Air Temperature from SWSA-4 Local Meteorological Station for the Week of 10/23/95

GATF SWSA-4 Ground Truth - Local Met Data

B-9. Solar Radiation from SWSA-4 Local Meteorological Station for the Week of 10/23/95

GATF SWSA-4 Ground Truth - Local Met Data

B-10. Precipitation from SWSA-4 Local Meteorological Station for the Week of 10/23/95

APPENDIX C

**LOCATION INFORMATION FOR GROUND TRUTH SENSORS
AND WELLS**

Lack of precise knowledge of trench locations at WAG 4 has put a limitation on linking locations of discharge seeps with specific sources in waste trenches. However, previous field investigations have found excellent correlation with the SERDP trench map and trench locations that could be observed in the field. In particular, many of the initial drive point locations installed during a limited site characterization corresponded well with trench features shown on the SERDP map (Energy Systems 1995a).

This appendix lists location information (ORNL easting, northing, and elevation in ft) for each of the ground truth sensors and several wells. This coordinate information is provided in order to relate the sensor locations to known drive points that actually penetrated a trench (DP 17, 18, 25, and 40) and so sensor locations could be revisited in future investigations.

Table C.1. Location Information for Ground Truth Sensors and Wells

No.	Sensor	Location	Easting (ft)	Northing (ft)	Elevation (ft)
1	T01 (West Transect, 1")	Trench	19344.61	27898.95	808.865
2	T02 (East Transect, 1")	Trench	19344.39	27902.24	808.991
3	T03 (East Transect, 1")	Non-Trench	19395.30	27902.25	813.021
4	T04 (Vertical Profile, 4")	Trench	19375.45	27899.67	811.436
5	T05 (Vertical Profile, 10")	Trench	19375.49	27899.30	811.421
6	T06 (Vertical Profile, 6")	Trench	19375.90	27899.68	811.396
7	T07 (West Transect, 1")	Non-Trench	19395.18	27899.14	813.201
8	T08	--	---	---	---
9	T09 (East Transect, 1")	Trench	19307.09	27901.40	805.341
10	T10 (Vertical Profile, 10")	Non-Trench	19402.60	27912.17	813.388
11	T11 (Vertical Profile, 6")	Non-Trench	19403.04	27911.95	813.493
12	T12 (Vertical Profile, 4")	Non-Trench	19403.15	27912.53	813.467
13	T13 (Covered)	Control	19403.06	27922.67	813.242
14	T14 (West Transect, 1")	Non-Trench	19408.63	27898.84	814.383
15	T15 (East Transect, 1")	Non-Trench	19408.62	27902.19	814.263
16	T16 (West Transect, 1")	Trench	19306.89	27898.36	805.375
17	T17 (West Transect, 1")	Trench	19263.42	27898.35	801.094
18	T18 (East Transect, 1")	Trench	19263.31	27901.29	800.950
19	T19 (1")	Control	19401.23	27923.87	813.064
20	T20 (Uncovered)	Control	19404.16	27921.53	813.342
21	T21 (1")	Control	19405.35	27919.71	813.468
22	T22 (Upper Transect, 2")	Trench	19370.92	27900.59	811.260
23	T23 (Lower Transect, 2")	Trench	19339.91	27900.30	808.565
24	M01 (Lower Transect)	<i>Non-Trench</i>	19339.63	27906.89	808.775
25	M02 (Lower Transect)	Trench	19339.86	27901.87	808.644
26	M03 (Lower Transect)	Trench	19339.96	27898.73	808.489
27	M04 (Lower Transect)	<i>Non-Trench</i>	19339.76	27893.01	808.621
28	M05 (Upper Transect)	<i>Non-Trench</i>	19371.08	27909.69	811.078
29	M06 (Upper Transect)	Trench	19370.92	27902.33	811.247
30	M07 (Upper Transect)	Trench	19370.93	27898.86	811.268
31	M08 (Upper Transect)	<i>Non-Trench</i>	19370.79	27893.19	811.617
32	M09	Control	19401.20	27919.71	813.300
33	M10	Control	19405.57	27924.03	813.386
34	XD1 tripod	Non-Trench	19401.50	27900.20	813.807
35	XD2 tripod	Trench	19352.78	27899.69	809.721
36	Rain Gauge	--	19373.74	27907.44	811.305
37	Ground Control Panel 1	---	19407.21	27866.61	816.681
38	Ground Control Panel 2	---	19219.38	27852.50	798.562

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