STREAMLINED ENVIRONMENTAL REMEDIATION CHARACTERIZATION USING REMOTE SENSING TECHNIQUES: CASE STUDIES FOR THE U.S. DEPARTMENT OF ENERGY, OAK RIDGE OPERATIONS

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ABSTRACT

This paper provides an overview of the DOE Oak Ridge Operations Remote Sensing Program and discusses how data from this program have assisted the environmental restoration program in streamlining site-characterization activities. Three case studies are described where remote sensing imagery has provided a more focused understanding of site problems with a resultant reduction in the need for costly and time-consuming, ground-based sampling approaches.

I. BACKGROUND

The U.S. Department of Energy (DOE) Oak Ridge Operations Environmental Restoration Program began in 1984 when Resource Conservation and Recovery Act corrective measures and closures regulations were the principal drivers for mitigating contaminant releases from disposal areas that had received hazardous and mixed wastes. Since that period, the restoration program has expanded dramatically in scope and regulatory emphasis to include remediation of numerous Oak Ridge Reservation (ORR) waste sites and decontamination and decommissioning (D&D) of hundreds of old DOE buildings and structures.

The cost of collecting and analyzing environmental data to address environmental remediation and D&D problems is a major portion of the total DOE Oak Ridge annual budget. Until 1992, the typical method for site characterization was the use of land-based sampling techniques involving manual sample collection and analytical lab analysis. Such characterization methods were slow and costly. For example, the remedial investigation for one 60-acre waste area at Oak Ridge National Laboratory (ORNL) took four years to complete and cost $45 million. In the past three years, however, the methods for remedial investigation have seen a substantial shift to the use of screening-based characterization, including remote sensing. The reasons for this shift were: (1) DOE and their regulators realized that too much time was being spent on studying site contamination problems, with little progress in actual cleanup, (2) there has been a dramatic decrease in the funding available for conducting environmental restoration activities, and (3) regulators and DOE became more willing to accept the higher level of uncertainty in screening-level data for making many preliminary remedial decisions.
As a result of the increased emphasis on screening-level characterization methods, the DOE Oak Ridge Operations Remote Sensing Program was formerly established in 1992 as a technical support organization that provided planning and implementation of remote sensing data collection using both conventional and classified methods. The program is funded by the DOE Headquarters Office of Environmental Management and is directed by the DOE Oak Ridge Operations (DOE-ORO) Office. Implementation support is provided by Lockheed Martin Energy Systems. The following case studies describe how the support of the Oak Ridge Remote Sensing Program has improved the efficiency of three Oak Ridge environmental restoration projects. Although many other examples exist, these three cases represent a good cross section of the type of support offered.

2. CASE STUDY: BURIED TRENCHES AT OAK RIDGE NATIONAL LABORATORY

2.1 Introduction

Solid Waste Storage Area (SWSA) 4 is located in the DOE ORNL complex and covers approximately 23 acres. In the 1950s, SWSA-4 received a variety of low- and higher-activity radioactive waste including transuranic wastes, all buried in unlined trenches or augur holes. During the period 1955 through 1963, SWSA-4 was designated as the Southern Regional Burial Ground for the U.S. Atomic Energy Commission. Approximately half of the waste received at SWSA-4 in the 1950s originated at ORNL, while the remainder of waste came from a number of off-site locations.

The legacy of waste disposal practices at SWSA-4 has resulted in a major environmental remediation concern due to shallow groundwater contamination from radionuclides with subsequent release to off-site surface streams through a series of seeps. Water sampling data in White Oak Creek, downstream of SWSA-4, indicate that these releases contribute approximately 35% of the total off-site contribution of radioactive strontium and 20% of the tritium contribution. Reducing the flow of these contaminants requires the precise location of the trenches that contribute the highest percentage of contaminants and the undertaking of remedial actions to contain and isolate the buried waste from surface and subsurface water. Unfortunately, most of the operational records that provided locational information were destroyed in a fire and only sketchy and unverified information remained. This situation left the remediation program at an impasse, with limited ability to evaluate feasible remedial action and pollution reduction options.

Realizing this information gap problem, the Oak Ridge Operations Remote Sensing Program offered assistance in using remotely sensed multispectral and thermal imagery to accurately map the spatial locations of trench boundaries providing the needed information for site remedial investigations. The following is a discussion of the techniques and results of this effort.

2.2 Data Collection

Remotely sensed data were collected through several DOE-Headquarters-sponsored programs that involved multiple U.S. government agencies. Primary data collection programs included the Environmental Task Force (ETF), the Strategic Environmental Research and Development Program (SERDP) Waste Site Study, and the Government Applications Task Force (GATF). Each had a mission to demonstrate the utility of remotely sensed imagery to detect and locate buried waste trenches under a variety of conditions and to analyze the phenomenology underlying the signatures observed on thermal imagery. Data collected included a combination of historical imagery, multispectral remote sensing data,
and ground truth data to evaluate the accuracy of remotely sensed data and to understand the thermodynamics of trench cooling/heating.

Historical data were obtained from federal photographic archives and included both large- and small-scale aerial photography and remote sensing data. These data did not provide a complete historical perspective but included random coverage of the period 1942 (prior to DOE occupation of the site) to the present.

A thermal imagery collection was used to detect differential thermal patterns that would be indicative of the differences in soil density and moisture between trenches and nontrench soils. Multispectral remote sensing from instrumentation such as the Daedalus DS-1268 was used to obtain thermal imagery. Daedalus DS-1268 data was obtained during 1992 and 1994 by EG&G Energy Measurements, Inc., using DOE-owned equipment. Spatial resolution of 1.5 to 3 m per pixel was obtained.

"Ground truth" experiments were conducted during 1994 and involved extensive measurements of soil temperature, soil moisture, and meteorological conditions. These data were collected and analyzed to understand the physical processes that produce the trench signature observed on thermal imagery. Arrays of ground sensors were set up at the SWSA-4 study site to collect data on the surface and near-surface conditions in the trench and in an adjacent control location. The type and configuration of sensors were:

- **Soil temperature**: measurements of soil temperature were recorded at several points inside and outside the trench at depths of 1 in. and a vertical profile at 4, 6, and 10 in.
- **Thermal radiance**: infrared (IR) transducers were used to assess the emitted energy in the longwave IR band (8 to 14 μ) over the trench and nontrench areas.
- **Soil-moisture**: an array of instruments recorded soil water potential (i.e., moisture) at a 2 in. depth, both inside and outside the trench.

### 2.3 Results

Through analysis and fusion of the combination of historical photography, thermal imagery, and ground truth data, the Oak Ridge Operations Remote Sensing Program was able to derive an accurate trench map of SWSA-4 that could be used by the remediation manager to delineate trench boundaries. A reproduction of this map is shown in Figure 1.

Statistical analysis of the ground truth data indicates the nature of the thermal signature of the trench areas. Both the thermistor and radiometer data show that the differences between a trench area and the control area (i.e., nontrench area) are most evident at night with the trenches typically cooler. Soil moisture measurements showed that the trench area generally exhibits greater soil moisture than the control area, which may account for the observed thermal differences. The data also show that the spatial variation in temperature within a trench is larger than the variation between trenches, suggesting the need for multiple observations. During the daytime hours, the thermal difference was not adequately discernible.

The SWSA-4 results indicate nighttime thermal imagery can be successfully employed to help delineate waste trench areas at known sites under a variety of conditions; however, one must consider site ground cover when planning a thermal survey. SWSA-4 is characterized by mowed grass fields and similar ground cover for both the trench and non-trench areas, which simplifies data interpretation. Similar studies at other DOE sites with nonhomogeneous surface conditions (varying species of vegetation) indicate that analysis of thermal behavior is more complex and thermal image signatures are difficult to predict. Consistent thermal signatures were associated with sites where the surface conditions are more
Natural Color Ortho-Photography of Solid Waste Storage Area (SWSA) 4

Trench Features Overlay for Solid Waste Storage Area (SWSA) 4
homogeneous, whereas sites with mixed and complex vegetation can exhibit different behavior. Furthermore, even if no buried waste were present, disturbed soil typically exhibited the thermal signature observed at the trenches. Thermal imagery must be co-analyzed with other historical and "ground truth" information to provide positive confirmation of trench presence or absence.

2.4 Summary

The results of this study have benefited DOE in two ways: First, the study provided information that will be used directly in the remediation and monitoring of SWSA-4. Second, the project demonstrated a method for using thermal imagery to assist in the detection and location of buried waste trenches. The methods demonstrated in this project should be applicable to buried waste at, potentially, hundreds of similar sites in the coming years.

Previous ground-based field investigations at SWSA-4 identified two individual seep areas that contribute over 90 percent of the radioactive strontium releases from the study area. The trench map derived from remote sensing data was the key factor in pinpointing localized sources feeding these major seeps. Current remedial actions are focusing on controlling these few sources and will provide a cost-effective interim action to reduce strontium-90 releases and off-site risk. Without the remote sensing results, the ability to quickly and effectively pinpoint the locations of the individual sources would have been lost. The alternative for controlling releases (i.e., cap the whole site, collect and treat surface water) would cost in excess of $5 million more than the current action of controlling the sources directly.

The procedures demonstrated here can be applied to numerous other waste sites where remedial action is necessary to stop the migration of contaminants from burial trenches. 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. Direct boring into contaminated trenches may also present unique safety risks to the worker and environment. Even though the 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 imagery data, it is possible to locate the buried material with greater precision, reduce the ground sampling requirements, and ensure greater safety in the clean-up process.

3. CASE STUDY: CLINCH RIVER ENVIRONMENTAL MONITORING PROGRAM

3.1 Introduction

The Clinch River is the main receiving stream for discharges from point and nonpoint sources on the DOE ORR. Two major surface water tributaries to the Clinch River that provide the majority of the contaminant flux from DOE sites: White Oak Creek and Poplar Creek.

Quantifying the impacts of these inflows to the off-site environment is a major DOE concern. Specifically, knowledge of the spatial extent and hydrodynamics of the inflow mixing zones is necessary to adequately design water sampling programs for detecting off-site contamination flow by surface water and for ensuring that adverse health risks are not present. Since the Clinch River is the major integrator of all groundwater and surface water contamination from the ORR, delineation of inflow mixing zones (spatial extent and temporal variations) is required to develop efficient sampling plans to monitor actual contaminant levels both prior to remediation of on-site waste areas and for long-term monitoring. At the mixing zone, contaminant inflows are of the highest concentration (i.e., least dilution) and thus may
present the greatest risk concern. This case study utilized the analysis of remotely sensed thermal and visible imagery to assess drainage systems on the DOE ORR into the Clinch River. In addition, this study was also designed to incorporate both image-derived and in situ ground truth information for use in modeling the surface-water transport of contaminants. The modeling work is crucial to understanding the mixing zones.

This project demonstrated that it is possible to map aqueous mixing processes through the use of remotely sensed imagery.

3.2 Data Collection

Over the past several years, remote sensing imagery of the DOE ORR has been collected by several groups working on various environmental problems. This project used remote sensing datasets collected by the DOE Oak Ridge Operations Remote Sensing Program in 1992 and 1994 and topographic datasets collected by the Lockheed Martin Energy Systems Geographic Information Systems and Spatial Technologies (GISST) Program in 1994 and 1995.

Since the main goal of this project was to perform a preliminary analysis of thermal mixing of the main tributaries to the Clinch River from the ORR using remote sensing imagery, it was necessary to extract various remote sensing information covering the confluences of the tributaries with the Clinch River. Some additional watershed analysis was performed using digital terrain data. The dataset of most utility was the long-wave-band thermal infrared (IR) imagery, available from both night and daytime aerial surveys during April 1992 and in March 1994. These surveys were conducted by EG&G Energy Measurements, Inc., using DOE-owned equipment that included a Daedalus DS-1268 multispectral scanner. During these surveys the confluences of White Oak and Polar creeks were remotely sensed at a spatial resolution of 1.5 to 3 m per pixel.

3.3 Results

Daedalus imagery collected in 1992 and 1994 was used to analyze and delineate the mixing zones at both White Oak Creek and Poplar Creek. Figure 2 illustrates the mixing zone of the White Oak Creek inflow to the Clinch River as seen on 1994 Daedalus thermal imagery. Statistical analysis of the imagery for White Oak Creek was also performed to assess the distribution of thermal differences in the area of the inflow. Analysis of the pixels throughout the mixing zone (starting at the source of the inflow and extending 200 m downstream) revealed the following results:

<table>
<thead>
<tr>
<th>River Condition</th>
<th>Pixel Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow: warmer than river</td>
<td>Saturated pixels: high mean and low variance</td>
</tr>
<tr>
<td>Initial mixing: larger areas of uniform temperature</td>
<td>Bimodal distribution with high variance</td>
</tr>
<tr>
<td>Continued mixing: high variability in pixel values</td>
<td>Decrease in mean, high variance</td>
</tr>
<tr>
<td>Mixing complete: ambient river temperature</td>
<td>Decrease in mean and variance</td>
</tr>
</tbody>
</table>

The Daedalus imagery indicates that the thermal mixing patterns of the tributaries to the Clinch River vary markedly from date to date and from night to day. Thermal plumes are very prominent in some imagery, allowing ready characterization of surface thermal mixing zones. On other occasions, surface
Thermal mixing zones are poorly delineated or below the detection limits of the sensor. The dramatic differences in thermal mixing patterns from dataset to dataset may be attributable to a number of factors, including:

- Day/night differences in thermal inertia;
- Flow and water depth differences of the Clinch River caused by changes in releases from an upstream hydroelectric dam (Melton Hill Dam);
- Differences in velocity and sediment loads of the two streams and their tributaries;
- Differences in current and preceding meteorological events, including precipitation, air temperature, and atmospheric parameters; and
- The 3-D character of each stream (water depth profiles) in the vicinity of the stream confluences.

Although it is clear that mixing patterns vary greatly due to a combination of factors such as those listed above, these factors were not fully evaluated in the initial study and more work is required to understand their effect. Thermal imagery can, at most, capture the mixing regimes upon a limited number of specific occasions. To create an effective water sampling plan for monitoring contaminant transport, use of models is essential (1) to characterize mixing zones at other times and stream conditions and (2) to select both optimal times and optimal locations for collection of monitoring samples.

### 3.4 Summary

This project demonstrated an approach that is applicable to monitoring any run-off or effluent entering a neighboring body of water, provided that the plume exhibits a thermal or spectral signature observable on imagery. Some examples of where these methods could be used include:

- Waste water or cooling water from major industrial facilities or power plants;
- Potentially polluted streams or rivers entering a bay, inlet, or other coastal waters;
- Heavy metals found in the soils from mining operations carried by surface run-off into nearby rivers, streams, or lakes; and
- Any military storage or production facility, such as munitions depots, military training areas, motor pools, or petroleum storage, where surface run-off has the potential to carry contaminants into adjacent bodies of water.

Although the project was successful in demonstrating the utility of thermal remote sensing as a quick and efficient tool for mapping temperature patterns of tributary inflows, more work is planned to fully utilize the datasets for optimizing the Clinch River sampling program. This planned evaluation effort includes both modeling and "ground truth" work.

Modeling will use 3-D techniques, because thermal imagery alone provides only the surface mixing patterns (essentially two dimensions). The model of choice for this evaluation is a 3-D version of ALGE—a code developed by Alfred Garrett of Savannah River Technology Center which solves vertically integrated momentum, mass, and energy conservation equations to predict the movement and dissipation of thermal plumes discharged into cooling lakes, rivers, and estuaries. ALGE was developed specifically for applications where high resolution is needed, and imagery is available for cell-to-cell comparisons with code predictions. The 3-D version of ALGE will be used in this study to capture the effect of deeper and more turbulent waters. The sensitive parameters of the code include: plume depth, flow rate, and turbulence. In addition, a sediment module is under development and will be incorporated in the 3-D code in order to model the movement and settlement patterns of sediments. Sensitive parameters include: nature of the sediment and particle size.
In order to calibrate and validate the mathematical modeling of the river mixing process, several "ground truth" datasets will be collected. In addition to validating imagery-based models, "ground truth" measurements will determine the unique contribution of imagery-derived data. The experiment will focus on several parameters of interest including: surface water temperature, ambient air temperature, vertical profiles of water temperature and turbidity, river flow and stage data, weather data, and relevant information sediment contaminant levels. Vertical profile measurements (temperature and turbidity) will be conducted 2 to 3 times during the project under a wide variety of flow conditions at four distinct zones: (a) in the creek, (b) upstream of mixing zone in the Clinch River, (c) in the mixing zone, and (d) downstream of the creek/river confluence (well mixed).

4. CASE STUDY: ASSESSMENT OF ROOFTOP INTEGRITY AT K-25 BUILDINGS

4.1 Introduction

The DOE Oak Ridge K-25 Site is a former DOE uranium enrichment plant that contains several large process buildings with roof areas ranging from 20 to 45 acres (8 to 18 hectares). These buildings have been in place for 40 to 50 years and are now showing signs of age deterioration in many structural components. For example, the roofs are deteriorating, resulting in large water leaks to the interior and rusting and deterioration of the metal roof decking. This situation presents safety concerns for workers who must walk on roof surfaces and who work within the buildings due to the potential for roof collapse. Environmental concerns also exist because these former process buildings are now used as storage areas for hazardous wastes and should remain dry inside.

To replace or repair all K-25 roofs as a single project, given their large size, would be extremely cost prohibitive. To effectively address repair and replacement, a logical program of roof assessment and prioritization is required. Roof site assessment activities include a variety of tasks such as determining the current condition of the existing rooftop, estimating remaining lifetime, evaluating potential for rooftop collapse, characterizing the rooftop in terms of potential impacts to human and material safety, determining the need for roof repair, repair planning, and waste disposal and management of existing roof materials in the event of roof repair. A typical roof assessment utilizes a variety of tools such as infrared thermography, other instrumented nondestructive moisture sensors, visual inspection and data gathering, structural integrity analysis, and engineering feasibility analysis addressing repair and replacement options. For large roofs such as those at K-25 and numerous others within the DOE complex, use of traditional land-based assessment tools is lengthy and costly and involves extensive in situ building inspection, data gathering, and analysis.

At the K-25 Site, an initial project is currently under way to investigate the use of non-intrusive remote sensing data in the characterization of aging rooftops. The project will assess the utility of remote sensing as a roof screening tool to direct on-site inspectors to suspect rooftops and roof trouble spots to minimize cost and maximize efficiency of on-site engineering assessments. This information is essential to monitor structural deterioration in order to plan building replacement, to establish proper building waste material disposal procedures, and to evaluate potential rooftop failure. The principal focus of this study will be to determine if remotely sensed thermal signatures can substitute or supplement ground-based video thermography. This particular project will not directly address the efficacy of using remote sensing to monitor roof integrity over long periods of time, but the study may lead to approaches that could be used in long-term monitoring and detection of changes in structural roof integrity.
Natural Color Ortho-Photography (1993) of K-31 Rooftop

Predawn Thermal IR Imagery (Daedalus AADS-1268, 1994) of K-31 Rooftop

Left: Daedalus Predawn Thermal IR
Right: Rooftop Survey (Wet Areas Shown)

2.0 Enlargement of Southwest Corner of K-31 Rooftop
4.2 Data Collection

Investigative efforts to date have focused on a comparison of traditional and remote sensing assessment methods for the K-31 process building at the K-25 Site. Remote sensing data are being examined for possible correlations with roof assessment measurements made for DOE by Jacobs Engineering using conventional ground-based methods. The K-31 building was built in 1944 to cover a process building that housed a 24-hour-per-day operation. The roof is a shallow slope, built-up roof with an area of approximately 68,748 m² (740,000 ft²) and was last re-roofed in 1980. The Jacobs Engineering roof survey (July 1994) found many sections of the roof to be heavily or moderately saturated with moisture, concluded that the roof condition indicates almost total roof failure, and recommended complete replacement.

Land-based measurements of K-31 were made by Jacobs Engineering during July 1994 using walkover video thermography. Remote sensing of the thermal infrared spectrum was conducted by EG&G Energy Measurements during March 1994 using DOE-owned equipment, including a Daedalus 1268 multispectral scanner. Remote sensing was conducted at an altitude of 2,000 ft above ground level for a spatial resolution of 1.5 m per pixel.

4.3 Results

Since the thermal and structural properties of a roof change over time as the structure ages and degrades, thermal anomalies can be indicative of roof decay and intrusion of water into roof components. Thermal signatures will provide thermal characterization of rooftops, including evidence of moisture, presence of standing water as pools or in outer roof layers, roof sag, structural integrity defects and deterioration by thinning materials, rust, material cracks, etc.

Figure 3 compares a partial map of wet insulation locations for the western edge of building K-31 based on the results of an infrared thermography inspection (July 1994) with Daedalus DS-1268 nighttime thermal imagery (March 1994). According to the result of the walkover survey, the western section (area 6B, 6A North, and 6A South) contains 40% wet insulation. The suspected wet areas correlate extremely well with the cooler temperatures (blue/green) in both daytime thermal imagery (Daedalus multispectral band 11) and nighttime thermal imagery. As a result of the strong visual correlation, aerial remote sensing data can generate thermal contour and thermal anomaly maps for each rooftop that substantiate and compare favorably with video thermography. Note that the thermography inspection for the K-31 rooftop was conducted over a time frame of eight evenings and involved several individuals. The airborne remote sensing sensor was able to collect rooftop temperature data for all buildings at the K-25 Site in a single aerial survey (multiple flight lines).

4.4 Summary

Because of the substantial number of large, aging DOE roofs and the shrinking federal budget for addressing these problems, roof assessment surveys by conventional means may become increasingly unattractive. The use of a cost-effective alternative must be developed. The K-31 roof survey, as well as similar work at the DOE Hanford Site, demonstrates that remote sensing provides such an alternative. Remote sensing can obtain the needed data in a fraction of the time required by conventional means and can be performed safely without worker risk from walking on roofs of questionable integrity.

In addition to the use of remotely-sensed thermography, the use of microtopography should also be examined as a tool for providing evidence of structural deformation, such as roof sag due to aging, and to
characterize the rooftops of individual buildings. Indirect methods for determining surface irregularities include using visible wavelength imagery (at low sun angles), interferometric synthetic aperture radar, or infrared (near or thermal) wavelengths (after a rainfall event). Standing water on a flat roof after precipitation indicates a depression. Roof leaks may be indicated by depressions without standing water after precipitation.

5. CONCLUSION

Recent cutbacks in funding and regulatory pressure for less study and more remedial action have resulted in a need for substantial changes in remedial investigation methods as lengthy and/or costly techniques can no longer be tolerated. The work described in this paper illustrates that remote sensing used in conjunction with "ground truth" measurements can offer a viable and cost-effective alternative to conventional land-based methods. The federally funded demonstration projects of the early 1990s have proven the merit use of remote sensing has been a tremendous success in response to this need for change. In the coming years, it is our obligation to fully develop these proven technologies, to provide environmental program managers with procedures for their usage, and to continue to market and develop their beneficial uses for site investigations and trending. In Oak Ridge, environmental restoration program managers, as well as the general Oak Ridge public, have become increasingly aware of the benefits and uses of remote sensing. With this wider level of acceptance, DOE is confident that remote sensing will become a standard practice for future environmental site-investigation projects.

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1This project involved many non-DOE and non-ORNL team members. Additional team members included the Lockheed Martin Energy Systems National Security Program Office, the Environmental Research Institute of Michigan, the Savannah River Technology Center, Los Alamos National Laboratory, and the National Exploitation Laboratory.

2The Oak Ridge Remote Sensing Program has received funding from internal Laboratory Directed Research and Development Programs and from Work For Others sponsors to first determine a methodology for using remote sensing techniques to delineate river mixing zones and then to apply the methodology to an actual site. The first project was an ORNL Laboratory Directed Research and Development Project titled, "Modeling Contaminant Migration Using Remote Sensing Analysis of Aqueous Mixing Processes." The second project was sponsored by the National Exploitation Laboratory and was titled, "Technology Office Project on the Analysis of Contaminant Transport."