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

The 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. Descriptions have been provided for three case studies in which 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.

1. BACKGROUND

The U.S. Department of Energy (DOE) Oak Ridge Operations Environmental Restoration Program began in 1984. At this time, Resource Conservation and Recovery Act (RCRA) 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 Environmental Restoration Program has dramatically expanded in scope and regulatory emphasis scope to include remediation of numerous Oak Ridge 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, e.g., for one 60-acre waste area at Oak Ridge National Laboratory (ORNL), a four-year and $45 million remedial investigation was conducted. 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 saw that too much time was being spent on studying site contamination problems while there was 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 formally established in 1992. The Program was implemented to provide a technical support organization for planning and implementation of remote sensing data collection, using both conventional and classified methods. The Program is funded by the DOE-Headquarters (HQ) Office of Environmental Management and is directed by the DOE Oak Ridge Operations 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 for 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 ORNL

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 wastes, including transuranic wastes, all of which were 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 resulted in a major environmental remediation concern due to shallow groundwater contamination from radionuclides with subsequent release to site surface streams through a series of seeps. Water sampling data in White Oak Creek downstream of SWSA-4, indicated that these releases contributed approximately 35-percent of the total off-site contribution of radioactive strontium and 20-percent of the tritium contribution. Reducing the flow of these contaminants would require 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. Unfortunately, most of the operational records that provided locational information were destroyed in a fire and only sketchy and unverified information remained. This 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. This assistance would provide 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-HQ sponsored programs that involved multiple U.S. government agencies. Primary data collection programs included the Government Applications Task Force (GATF), the Environmental Task Force (ETF), and the Strategic Environmental Research and Development Program (SERDP) Waste Site Study. 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 high and low spatial resolution aerial photography and remote sensing data. This data did not provide a complete historical perspective, but did include random coverage of the period 1942 (prior to DOE occupation of the site) to the present.

Thermal imagery collection was used to detect differential thermal patterns that would be indicative of the differences in soil density and moisture that are characteristic of trench disposal. Multispectral remote sensing from instrumentation, such as the Daedalus 1268, which was used to obtain thermal imagery. Daedalus 1268 data was obtained during 1992 and 1994 by EG&G Energy Measurements using DOE-owned equipment. Spatial resolution of 1.5 to three meters per pixel were 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 produced 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 choice and configuration of sensors were:

- Soil Temperature: Measurements of soil temperature were recorded at several points inside and outside the trench at depths of one inch and a vertical profile at four, six, and 10 inches.
- Thermal Radiance: Infrared transducers were used to assess the emitted energy in the longwave Infrared band (8-14 microns) over the trench and non-trench areas.
- Soil-Moisture: An array of instruments recorded soil water potential (i.e., moisture) at two-inch 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 indicated the nature of the thermal signature of the trench areas. Both the thermistor and radiometer data showed that the differences between a trench area and the control area (i.e., non-trench area) was most evident at night, with the trenches typically cooler. Soil moisture measurements showed that the trench area generally exhibited greater soil moisture than the control area, which may account for the observed thermal differences. The data also showed that the spatial variation in temperature within a trench was larger than the variation between trenches, suggesting the need for multiple observations. During the daytime hours, the thermal difference was not readily discernible.

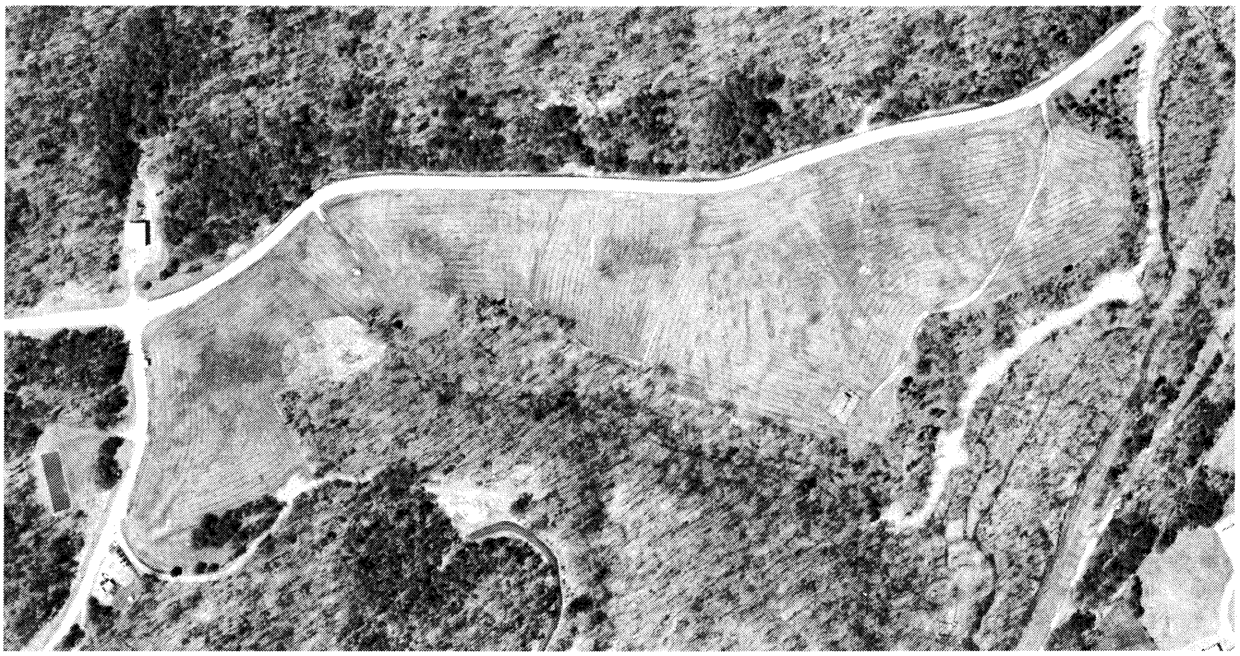
The SWSA-4 results indicate that nighttime thermal imagery can be successfully employed to help delineate waste trench areas at known sites under a variety of conditions; however, one must consider site ground cover when planning a thermal survey. SWSA-4 is characterized by mowed grass fields and similar ground cover for both the trench and non-trench areas. This simplifies data interpretation. Similar studies at other DOE sites with non-homogeneous surface conditions (varying species of vegetation) indicate that analysis of thermal behavior is more complex and that thermal image signatures are difficult to predict. Consistent thermal signatures are associated with sites where the surface conditions are more homogeneous, whereas sites with mixed and complex vegetation can exhibit different behavior. Furthermore, even if no buried waste was 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

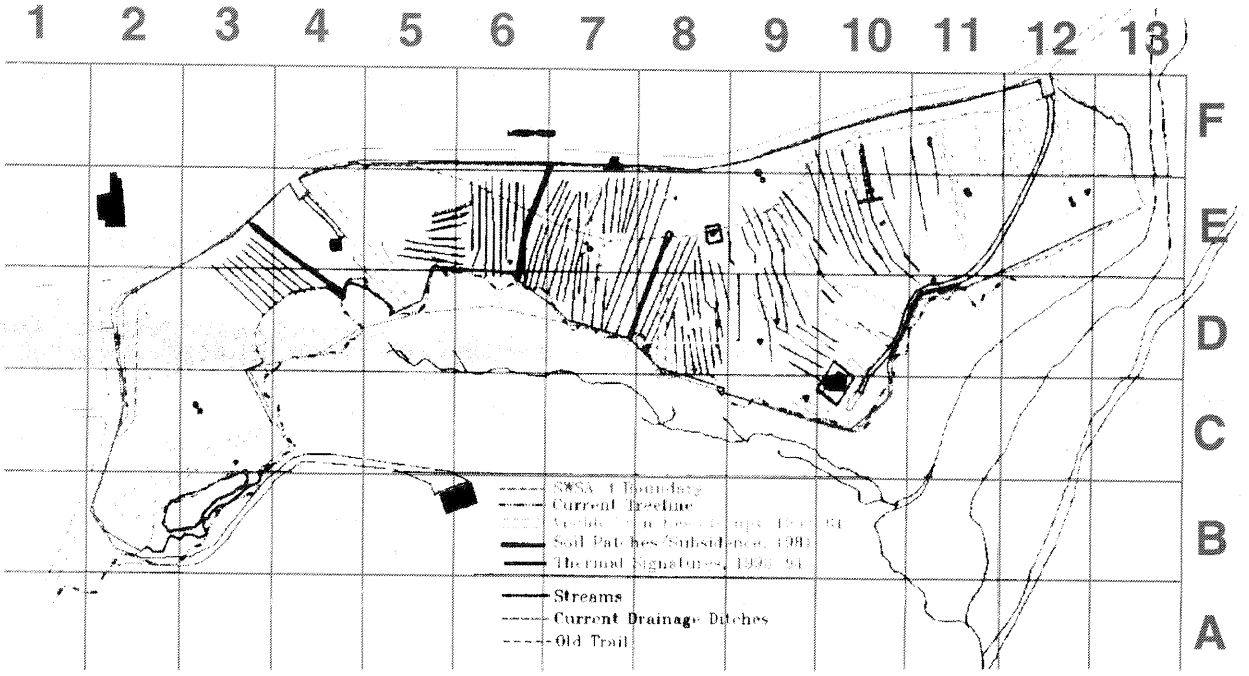
The results of this study have benefited DOE in two ways. First, the study provided information that will be used directly in the remediation and monitoring of SWSA-4. Second, the project demonstrated a method for using thermal imagery to assist in the detection and location of buried waste trenches. 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 investigation 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 directly controlling the sources.

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



Natural Color Ortho-Photography of Solid Waste Storage Area (SWSA) 4



Trench Features Overlay for Solid Waste Storage Area (SWSA) 4

Figure 1. Solid Waste Storage Area 4, Derived Trench Map

trenches may also present unique safety risks to the worker and environment. 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 imagery data, it should be 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 point and nonpoint sources discharges from the DOE Oak Ridge Reservation (ORR). Two major surface water tributaries to the Clinch River 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 onsite 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 proved that, through the use of remotely sensed imagery, it is possible to map aqueous mixing processes.

3.2 Data Collection

Over the past several years, remote sensing imagery has been collected of the DOE ORR 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 imagery, available from both night and daytime aerial surveys during April 1992 and March 1994. These surveys were conducted by EG&G Energy Measurements using DOE-owned equipment that included a Daedalus 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 three meters 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 meters downstream) revealed the results as shown in Table 3.

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

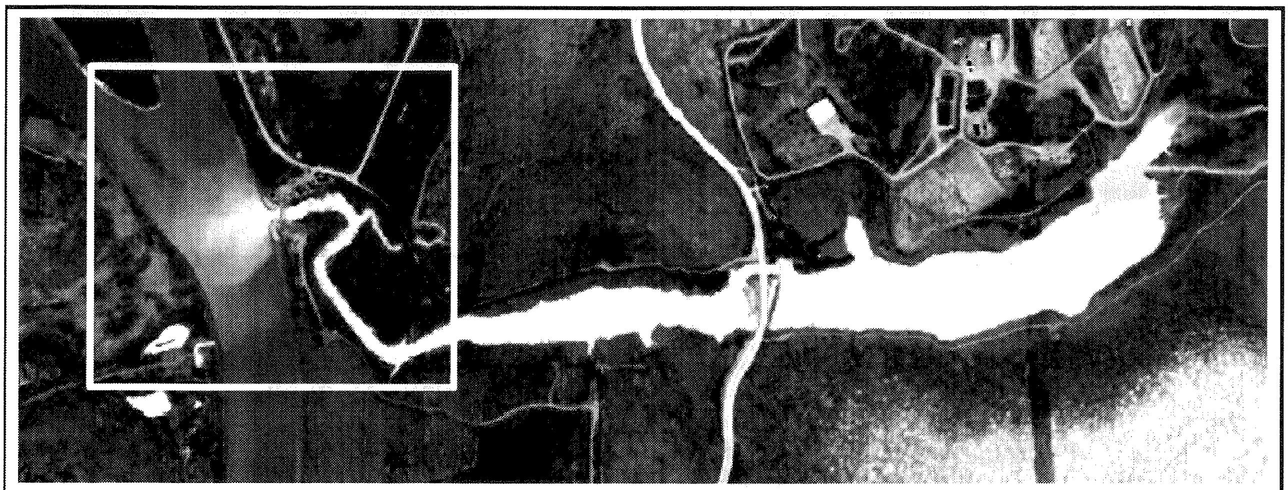
- day/night differences in thermal inertia;
- flow and water depth differences of the Clinch River due to changes in releases from an upstream hydroelectric dam (Melton Hill Dam)
- differences in velocity and sediment loads of the two streams and their tributaries;
- differences in current and preceding meteorological events, including precipitation, air temperature, and atmospheric parameters; and
- the three-dimensional 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) in order to select both optimal times and optimal locations for collection of monitoring samples.

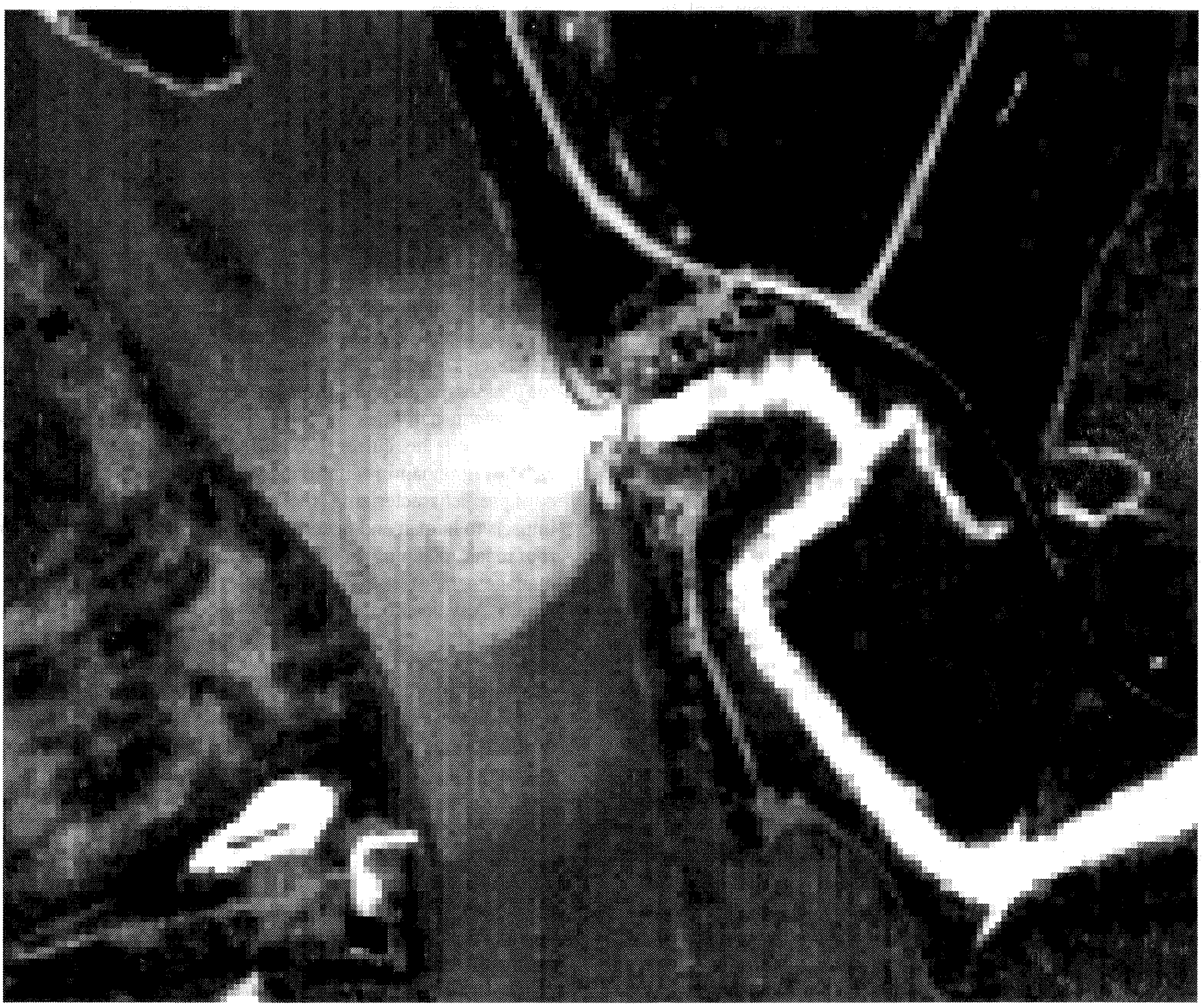
3.4 Summary

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 monitoring of:

- waste water or cooling water inflows from major industrial facilities or power plants;
- potentially polluted streams or rivers entering a bay, inlet, or other coastal waters;



Predawn Thermal Infrared Imagery of White Oak Creek and Clinch River
(Daedalus AADS-1268, April 15, 1992)



Magnified Thermal Mixing Zone of White Oak Creek and Clinch River

Figure 2. White Oak Creek and Clinch River Mixing Zone, Thermal Imagery

River Condition	Pixel Statistics
Inflow: Warmer Than River	Saturated Pixels: High Mean and Low Variance
Initial Mixing: Larger Areas of Uniform Temperature	Bimodal Distribution with High Variance
Continued Mixing: High Variability in Pixel Values	Decrease in Mean, High Variance
Mixing Complete: Ambient River Temperature	Decrease in Mean and Variance

Table 3. Statistical Analysis Results

- heavy metal contaminated run-off due to mining operations; and
- run-off from military storage or production facilities, such as munitions depots, military training areas, motor pools, or petroleum storage, which carries 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 uses three-dimensional techniques, whereas thermal imagery alone provides only the surface mixing patterns (essentially two dimensions). The model of choice for this evaluation is a three-dimensional version of ALGE, a code developed by Alfred Garrett of Savannah River Technology Center (SRTC), 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 to code predictions. The three-dimensional 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 to the three-dimensional 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 on sediment contaminant levels. Vertical profile measurements (temperature and turbidity) will be conducted two to three times during the project under a wide variety of flow conditions at four distinct zones: (1) in the creek, (2) upstream of mixing zone in the Clinch River, (3) in the mixing zone, and (4) 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 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 presents safety concerns for workers who must walk on roof surfaces and for workers who work within due to the potential for roof collapse. Environmental concerns also exist as 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 Site 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, planning repairs, and performing 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 non-destructive 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 the K-25 Site and numerous other sites 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 underway 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.

4.2 Data Collection

Investigative efforts to date have focused on comparison of traditional and remote sensing assessment methods for the K-31 Process Building at the K-25 Site. Remote sensing data is being examined for possible correlations with roof assessment measurements made for DOE by Jacobs Engineering using conventional ground-based methods. Building K-31 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 m^2 (740,000 ft^2) and was last re-roofed in 1980. The Jacobs Engineering roof survey (July 1994) indicated that many sections of the roof were heavily or moderately saturated with moisture. It was concluded that the roof condition indicated almost total roof failure, and recommendations were made for 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 feet above ground level for a spatial resolution of 1.5 meters 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 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 4 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 1268 nighttime thermal imagery (March 1994). According to the results of the walkover survey, the western section (Areas 6B, 6A North, and 6A South) contains 40-percent 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, remote sensing data can generate thermal contour and thermal anomaly maps for each rooftop that substantiate and compare favorably with video thermography. It should be noted 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).

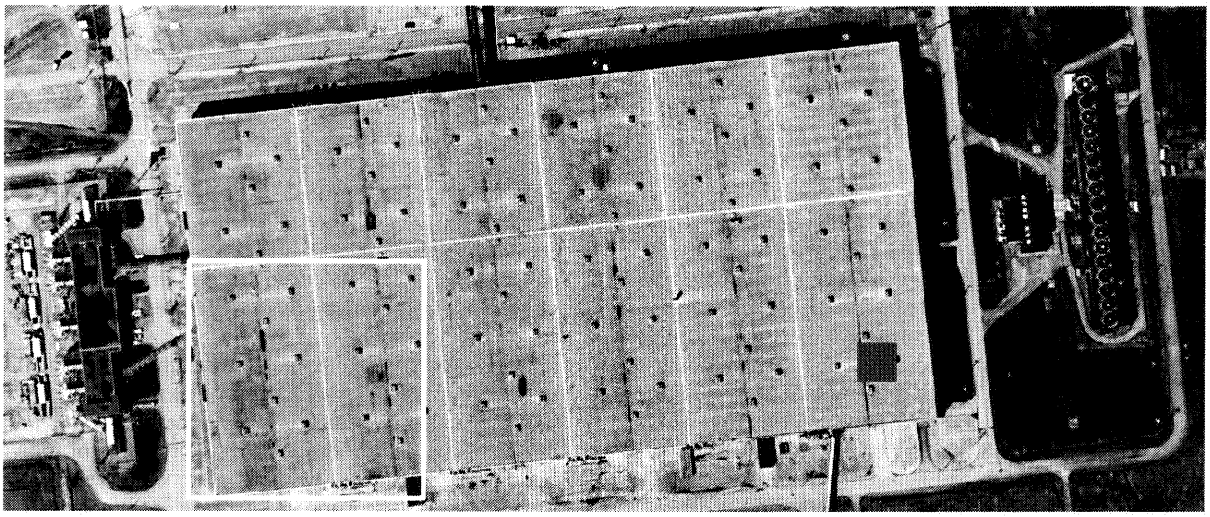
4.4 Summary

Due to 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.

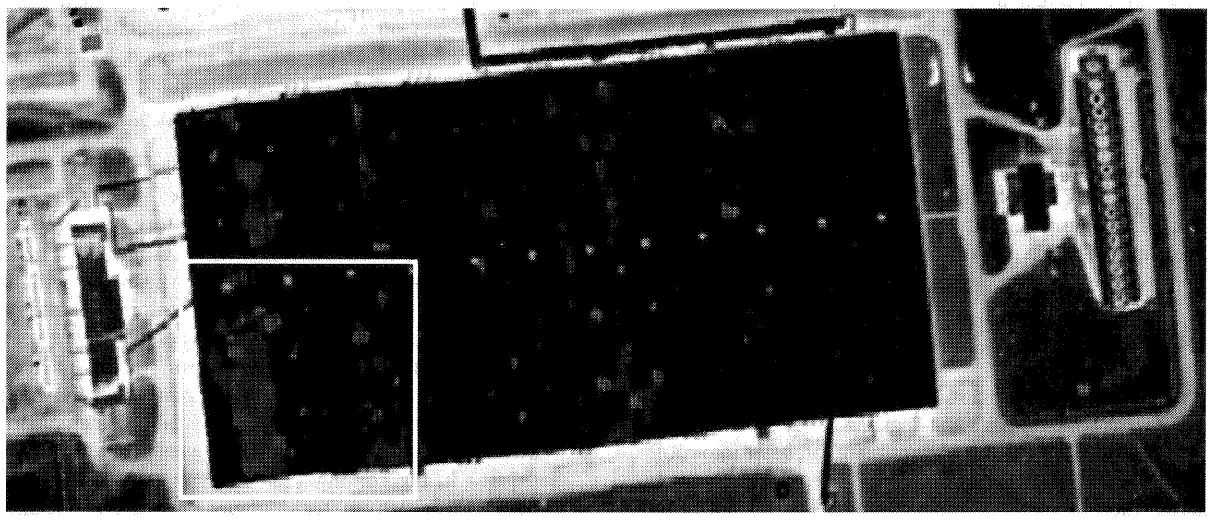
In addition to the use of remote-sensed thermography, the use of micro-topography should also be examined as a tool for providing evidence of structural deformation, such as roof sag due to aging, and to characterize the rooftops of individual buildings. Indirect methods for determining surface irregularities include using visible wavelength imagery (at low sun angles), interferometric Synthetic Aperture Radar (SAR), 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

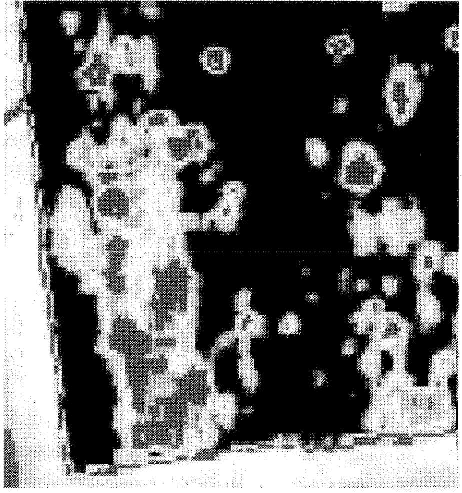
Recent cutbacks in funding and regulatory pressure for less study and more remedial action have resulted in a need for substantial changes in remedial investigation methods as lengthy and/or costly techniques can no longer be tolerated. The work described in this paper illustrates that remote sensing, 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 of remote sensing. In the coming years, it is our obligation to fully develop these proven technologies, 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.



Natural Color Ortho-Photography (1993) of K-31 Rooftop

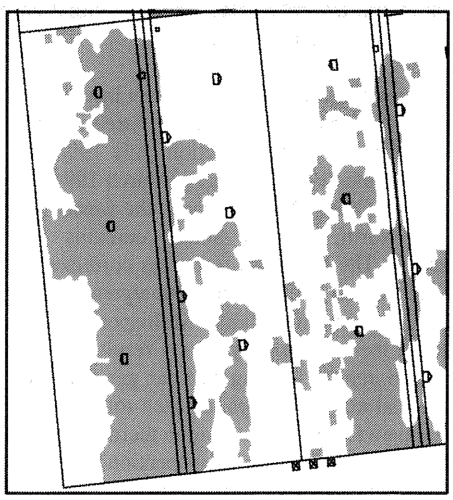


Predawn Thermal IR Imagery (Daedalus AADS-1268, 1994) of K-31 Rooftop



Left: Daedalus Predawn Thermal IR

Right: Rooftop Survey (Wet Areas Shown)



2.0 Enlargement of Southwest Corner of K-31 Rooftop

Figure 4. K-31 Rooftop, Comparison of Walkover and Remotely Sensed Thermal Imagery