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# A NON-TRADITIONAL IN SITU VITRIFICATION DEMONSTRATION FOR MIXED WASTE APPLICATIONS AT THE LOS ALAMOS NATIONAL LABORATORY

Brett Campbell
Geosafe Corporation

Gordon Huddleston and Bob Balhiser
MSE-TA

Marja Springer, and Deba Daymon
Los Alamos National Laboratory

## ABSTRACT

MSE Technology Applications, Inc., in conjunction with DOE's Subsurface Contamination Focus Area (SUBCON) and (MSE-TA), is conducting an evaluation of non-traditional in situ vitrification (NTISV) technology as a potential remedy for treatment of the mixed-waste-contaminated absorption beds at Material Disposal Area-V (MDA-V) site. Project participants from the Los Alamos National Laboratory (LANL) selected an inactive absorption bed for the site to be treated during the second phase of the demonstration project. The first phase was conducted in a nearby non-radioactive contaminated location that was simulated to represent a portion of the actual absorption bed. The LANL Environmental Division is providing support and services for the demonstration project. MDA-V contains three absorption beds that received laundry effluent and research-derived liquids from 1945 to 1978. The absorption beds and the soils below them contain various radionuclides, heavy metal and organic contaminants.

A competitive procurement of NTISV technologies selected an advanced NTISV technology involving joule-heated melting within the subsurface for demonstration at the MDA-V site. The GeoMelt technology was developed and is being demonstrated by Geosafe Corporation of Washington State. Advancements over the traditional ISV technology include performance of subsurface startup and melting, and employment of a new "planar" melting method. The demonstrations are being performed using Geosafe's commercial large-scale equipment.

The project involves the performance of two large-scale demonstration melts. The first demonstration, termed the "cold" demonstration, was performed in an uncontaminated simulated absorption bed and was completed in April of this year. A second "hot" (radioactive) demonstration melt is currently planned for March of 2000 and will be performed within LANL's MDA-V's Absorption Bed #1 at Technical Area 21. The project is designed to demonstrate the GeoMelt technology's capability to treat both the contaminated bed contents and underlying contaminated soil to a depth of 6.7 m. The melting process will result in destruction and removal of all organic contaminants within the target treatment zone, and immobilization of heavy metals and radionuclides with a high integrity vitrified (glassy rock-like) monolith.

The successful demonstration of NTISV at LANL is expected to provide a useful technology for the general remediation needs of EM-40 (complex-wide) including specific site remediation needs of LANL for remediating buried waste and other waste configurations.

The cold demonstration was completed successfully resulting in achieving all of the objectives established for the cold demonstration. Based upon the results of the cold demonstration, approval to proceed with the hot demonstration has been received. The hot demonstration will be performed during the second quarter of FY 2000. The results of the cold demonstration test will be reported in this paper and presented at the conference, as well as a status of the progress of the hot demonstration.

Funding for this project was provided through the DOE Federal Energy Technology Center at the Western Environmental Technology Office under DOE Contract Number DE-AC22-96EW96405. LANL, as the host site, provided funding for their site support.

## NTISV PROCESS DESCRIPTION

ISV is a mobile, thermal treatment process that involves the electric melting of contaminated soils, sludges, or other earthen materials and debris in situ for the purpose of permanently destroying, removing, and/or immobilizing hazardous and radioactive contaminants. Geosafe currently offers the ISV technology in four different application configurations, collectively called GeoMelt™ vitrification technologies. The four GeoMelt treatments include: 1) GeoMelt-ISV for in situ treatment, 2) GeoMelt-Staged ISV for treating materials that have been staged for processing, 3) GeoMelt-Stationary Batch for repetitive melt cycling at a single location, and 4) GeoMelt-Continuous vitrification for material feeding and melt withdrawal at a stationary facility.

Historically, conventional (or traditional) ISV involved processing the soil/waste matrix in a top-down fashion. A horizontally oriented melt is established between four electrodes using a series of horizontal starter paths placed between the electrodes in the soil near the surface to pass electrical current and dissipate the joule heat necessary to melt the surrounding soil. Once molten, the soil becomes sufficiently conductive to support the flow of electrical current, thereby dissipating enough joule heat to propagate the melting process. By the application of continued power through the melt, the soil adjacent to and below the melt becomes molten. The addition of power is continued to the melt until such time that the melt has encompassed the entire treatment volume from grade down to the desired depth.

When electrical power is shut off, the molten mass solidifies into a vitreous and crystalline, rock-like monolith with unequaled physical, chemical, and weathering properties compared to alternative solidification/stabilization technologies. Individual melts in excess of 7 m deep, 12 m in diameter and up to 1,000 tonnes can be formed. Off gases generated by the process are contained under a steel hood covering the treatment area and are drawn to an off-gas treatment system.

Upon cooling, a highly durable vitrified product is formed that consists of a mixture of glass and crystalline materials in a monolithic block. The resulting product is typically ten times stronger than concrete and is extremely leach resistant. Organic contaminants such as dioxins, pesticides, and PCBs are destroyed by the process. Heavy metals and radionuclides are retained in the melt and immobilized in the resulting product. The ISV process has been used commercially to successfully treat all contaminant types (volatile and semi-volatile organics, heavy metals, and radionuclides) and all types of soil media (sands, silts, clays, and sludges). ISV is also distinguished by its ability to tolerate significant amounts of debris within the treatment zone. Types of debris previously processed by ISV in commercial operations include scrap metal, steel drums, concrete, asphalt, wood, plastic, paper, protective clothing, HEPA filters, and general construction demolition debris. Individual melts can typically accommodate thousands of tonnes of debris. The process produces a product similar in appearance to natural obsidian with outstanding physical and chemical characteristics, weathering and leaching resistance, and life expectancy.

A competitive procurement of NTISV technologies resulted in the selection of an advanced NTISV technology offered by Geosafe Corporation, termed GeoMelt (Planar) ISV, which involves joule-heated melting within the subsurface. The technology is an advancement based on Geosafe's GeoMelt vitrification technology which has been widely demonstrated and very successfully applied on a commercial basis within the U.S., Australia and Japan. In this process, the horizontal array of starter paths used between four electrodes in traditional ISV is replaced with vertically-oriented planes of starter material between two pair of electrodes. The planes can be positioned at the desired depth and separation within the subsurface. The separation of the starter planes allows two relatively independent melts to form during the initial stages of the process. This allows significant control of the initial melt process so that it can be focused for optimal treatment of the waste zone. Moreover, because the melts are separated laterally during their initial stages of development, the treatment volume can be processed without the build-up of large gas volumes below the melt, which potentially could pass through the melt. This approach allows for the maintenance of approximately twice the amount of permeable zone around the two melts, which aids in the controlled transport of any gases generated during processing to the off-gas treatment system. Any gases generated from hazardous materials during processing are either pyrolyzed during melting, or are removed to the off-gas treatment system. By the time the melts have grown sufficiently to merge, all volatile materials (e.g. – mainly water) will have been effectively and safely removed from the treatment zone.

## NTISV PROJECT DESCRIPTION

The NTISV project involves the performance of two large-scale demonstration melts. The first "cold" demonstration was performed in a simulated absorption bed (see Figure 1), which contained no radioactive contamination. The simulated absorption bed was designed and constructed to represent the actual MDA-V absorption beds as closely as possible. This simulation included the use of similar construction materials (i.e.: cobbles, gravel and sand), as well as the use of surrogate chemicals for radionuclides of interest. It is planned that a second "hot" (radioactive) demonstration melt will be performed within MDA-V's Absorption Bed #1 at MDA-V. This particular absorption bed received liquid effluent primarily from a radioactive laundry facility, as well as intermittently from research facilities and contains a wide variety of organic, heavy metal and radioactive contaminants.

A target treatment depth of 6.7-m was established for both demonstrations, which will demonstrate the GeoMelt technology's capability to treat both the contaminated bed contents and underlying contaminated soil. The melting process will result in the destruction and removal of all organic contaminants within the target treatment zone, and immobilization of heavy metals and radionuclides within a high integrity vitrified monolith.

The demonstrations involve monitoring to gather performance data pertinent to evaluation of the technology for various applications at LANL and throughout the DOE Complex. Specific performance data is being gathered relative to the technology's treatment effectiveness on the contaminants present at the site. In addition, data is being gathered relative to reliability of equipment and all aspects of costs related to application of the NTISV technology.

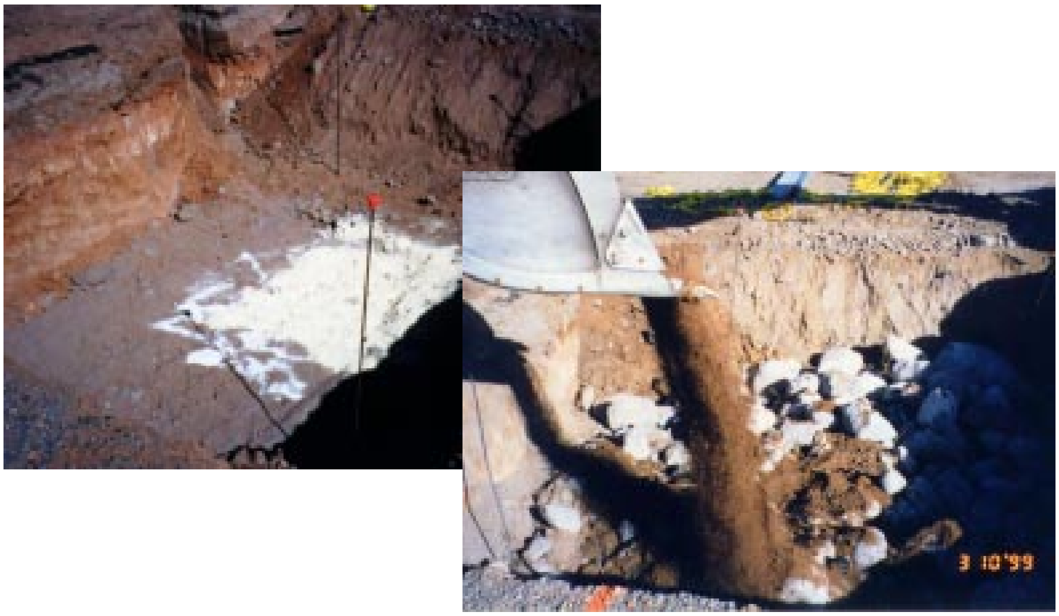


Figure 1. Construction of a Simulated Liquid Effluent Absorption Bed

The general objectives established for the NTISV project include:

- demonstrate the ability to safely and successfully install planar starter paths significantly below grade within the native Bandelier Tuff formation
- demonstrate the ability to process the materials placed into the cold demonstration bed and present within absorption bed #1 at MDA-V
- confirm that the physical dimensions of the melts meet or exceed the desired treatment volumes
- obtain process performance information necessary to optimize the processing configuration and operational parameters, as well as increasing the cost effectiveness
- confirm that the geochemical data of the various components processed during the cold demonstration compare with the anticipated geochemical conditions in the hot demonstration

- characterize the vitrified products by performing homogeneity evaluations, as well as product quality (TCLP & PCT) leach tests

- obtain costing data to enable estimation of large-scale remediation costs of the MDA-V, and to compare costs to the target level of $800/ton or less

To qualify for the non-traditional aspect of the ISV procurement, Geosafe chose to employ the planar-ISV approach coupled with a subsurface start-up, which had not previously been tested on an application like the MDA-V absorption beds. Other innovative applications being demonstrated during both the cold and hot demonstrations included the use of overburden and dynamic disruption.

Overburden, as used in this application, serves to increase the efficiency of the melting process (Geosafe 1999). Heat losses, which otherwise would escape in the plenum area of the hood and then be removed through the off-gas treatment system in a conventional top-down approach are minimized by the overburden. Use of overburden has been shown to increase the thermal efficiency of the melting process by up to 30%. This can provide significant cost savings both by reducing the power costs and by shortening the amount of run time to complete a given treatment volume. The use of overburden also provides protection from the effects of a melt disturbance that may occur when treating highly heterogeneous or liquid-bearing wastes.

Dynamic disruption of the soil surrounding the target treatment volume is a method employed to ensure that the contents of the simulated absorption bed are completely incorporated into the melt during the treatment process (see Figure 2). Disruption of the surrounding soil is accomplished by using a hydraulic hammer to vibrate a steel probe down into the soil column. By disrupting or loosening the surrounding soil, the soil is enabled to feed into the surface of the developing melt(s). When treating soils that are structurally strong, such as the native tuff at the LANL site, it is possible for vertical walls to be formed as the melt progresses downward. By breaking up the tuff prior to treatment, the sloughing of the adjacent soil into the melt is promoted, as well as eliminating the potential for a steep wall of soil to cleave off and fall into the subsided area.

## COLD DEMONSTRATION PREPARATION

Initial activities, which included preparation of test specific documentation and a site specific health and safety plan, as well as review and approval of Geosafe's health and safety program and procedures, were initiated during the fall of 1998. Following approval of the working documents required for the LANL site, preparation of the test site by LANL-ER was performed. During the excavation of the test area, low

Figure 2. Dynamic Disruption In and Around the Area to be Treated

levels of hydrocarbons found in diesel fuel were detected in the soil. The contaminants were determined to be the result of an above ground diesel storage tank that had been located over the test area and had since been removed. The identification of the low level contamination dictated that LANL-ER prepare a voluntary corrective measure plan for approval by the New Mexico Environmental Division, which covered treatment of the organic species during the cold demonstration (LANL 1999).

To form the simulated absorption bed for the cold demonstration, an amount of soil great enough to form the 3-m by 4.6-m by 1.8-m deep target volume was removed. Prior to commencing backfilling of the absorption bed, 6.5-kg of cesium carbonate and 30-kg of cerium oxide were added to the floor of the excavation to serve as surrogates for radionuclides that are present within the actual absorption bed. The cesium carbonate was added to represent cesium-137, whereas the cerium oxide simulated the presence of refractory radionuclides such as plutonium, uranium and strontium. Inclusion of these surrogates within the absorption bed allowed investigators to determine the level of homogeneity within the vitrified product, as well as its resistance to leaching. The surrogates added to the floor of the simulated absorption bed can be seen in Figure 1.

Materials used to backfill the excavation, which formed the simulated absorption bed, were selected based upon similarity in size and composition to the expected contents of the actual absorption beds. Construction of the simulated absorption bed can be seen in Figure 1. Backfilling of the simulated bed consisted of first placing a layer of cobble that ranged in diameter from 0.15 to 0.61-m. at depth of 1.2 to 1.8-m below grade. A 0.3-m layer of gravel followed by a similar thickness of sand was used to fill the excavation from the top of the cobble to a depth of 0.6-m below grade. The excavation was then filled to grade using native tuff from the LANL site. This completed the construction of the simulated absorption bed that would be treated during the cold demonstration.

Once construction of the simulated absorption bed was completed, assembly of the GeoMelt equipment and preparation of the test area were performed for application of the subsurface GeoMelt-planar approach. This included the following steps of preparation of the target treatment volume:

- dynamic disruption in, around, and below the area to be treated
- installation of the four electrodes , which was performed by Applied Geotechnical Engineering and Construction, Inc (AGEC) of Richland, WA
- injection of two vertically oriented starter planes by AGEC
- installation of a 0.76-m layer of gravel overburden

Assembly and installation of an off-gas hood was then completed over the target treatment volume. Interconnection of the off-gas pipe and electrical and instrument cables from the hood to the GeoMelt equipment was then completed prior to initiating the operational phase of the cold demonstration.

## COLD DEMONSTRATION OPERATIONS OVERVIEW

Prior to initiating the melting process, the off-gas treatment system was started and allowed to stabilize (MSE 1999). The power supply system was brought on-line at 1407 hrs on 4/16/99. The melting process continued for 185.7-hrs at which time all of the melting objectives had been met. Power to the melt was terminated at 0735 hrs on 4/24/99. The average power level input to the melt during processing was 971 kW including the graduated start-up. Excluding the graduated start-up period, wherein the power level was slowly increased up to the desired level, the average power input was 1033 kW. The total energy consumed to produce the melt was 165,600 kWh.

Four graphite electrodes, which are used to carry the electrical power into the treatment volume, were initially inserted into the soil to a depth of 3.3-m during the preparation activities and placed in a gripped or stationary mode. The electrodes were released once the developing melts reached the depth equal to the bottom of the electrodes and allowed to independently feed downward via gravity. Shortly after the initial movement, the electrodes were re-gripped using the pneumatic gripping device on the feeders. This was done to ensure that the electrode depths remained relatively close and to ensure that the feeding of the electrodes proceeded in a controlled manner. It is important to ensure that the electrodes are not exposed to excessive force or wear as they are a critical element of the melting process.

To ensure that the electrode feeding could be controlled during the remainder of the run, a crane was used to lower the electrodes typically once per day for the remainder of the demonstration.

The final electrode depths all reached or exceeded the target depth of 6.7 m. The exact depths were: A1– 6.96-m, A2 – 7.06-m, B3 – 7.11-m, and B4 – 7.09-m.

## COLD DEMONSTATION RESULT SUMMARY

The cold demonstration phase of the NTISV project was highly successful based upon the results obtained. The demonstration confirmed that the subsurface GeoMelt-planar ISV process is capable of meeting the depth and treatment effectiveness objectives for the MDA-V site, in an efficient and reliable manner. The demonstration was productive in generating field scale data that could be used to evaluate the approach for use on the MDA-V absorption beds as well as other similar applications at LANL and other DOE sites. The process converted the simulated absorption bed into a vitrified product that exhibits excellent durability (resistance to leaching) and stability, which will maximize the long-term performance of the waste form. In addition, because of the excellent leach resistance property of the product, the need for long-term monitoring should be minimized.

The starter path injection method utilized was highly successful. Two 2.1-m long vertical starter planes were installed by injection below the simulated absorption bed at the depth of 2 to 2.9-m below grade. The installation of these two starter planes was conducted safely and to the specifications required to enable initiation of subsurface melting. The initial GeoMelt process start-up and continued processing of the simulated absorption bed proceeded smoothly. The ability to successfully inject the starter material into the subsurface is an approach, which could greatly increase the depth capabilities of GeoMelt applications. Injection of the starter path materials had previously not been performed prior to this project.

A simulated absorption bed was configured according to the specifications identified in as-built drawings of the actual MDA-V beds. An increase in the size range of the cobbles placed in the simulated bed (relative to the drawings) was made based upon observations made during actual excavation activities within the MDA-V beds. Some minor differences in the surrounding soil stratigraphy of the cold demonstration area existed as compared to the actual MDA-V, due to limited availability of uncontaminated areas near the site selected for the hot demonstration. However, the small variations in the soil stratigraphy did not affect the melting process or the quality of the product.

Post-test examinations indicated that the entire target volume and its contents were successfully treated and incorporated into the resulting vitrified monolith. The 3-m by 4.6-m area was configured from grade down to a depth of 1.8-m to represent the absorption beds found within the MDA-V. A subsidence volume of 4.9-m by 4.9-m wide at the surface with a depth of 2.6-m existed after completion of the cold demonstration. The subsidence volume was created from the incorporation of the absorption bed materials and the subsequent volume reduction of these materials as they are converted into a vitreous product. In addition, the majority of a 0.76-m layer of overburden gravel (that existed above grade prior to treatment) was also incorporated into the melt. Thus, the entire target volume was incorporated downward into the melt, which resulted in the development of a large subsidence volume that was later backfilled with clean soil.

Observations made when the completed product was exhumed indicated that all of the contents of the simulated absorption bed comprising the target treatment volume were incorporated into the vitrified product, including the large (up to 0.6-m diameter) cobble.

The entire top surface of the vitrified product was exposed one month after processing was completed. In addition, two sides of the cooled melt were exposed down to a depth of approximately 5.5-m. The dimensions of the vitrified product were measured to be 7.6-m in the east/west direction and 7-m in the north/south direction (see Figure 3). In addition to the data provided above, this also confirms that the target treatment area (3-m by 4.6-m) was treated and incorporated into the melt. In regards to the depth of treatment, all four of the electrodes used in the melting processed exceeded the target depth of 6.7-m.

Data was gathered in many areas during the cold demonstration that will facilitate the successful completion of the hot demonstration. Many activities associated with the cold demonstration were being performed for the first time on the media specific to the LANL site. Because sites vary significantly from one to another, the need to gather operational data to allow "fine tuning" is a typical requirement. The approach used during the cold demonstration was to simulate the hot demonstration application in as many ways as possible such that the data produced would be representative for use on the subsequent hot demonstration. In this way, Geosafe was able to gain the maximum amount of knowledge in regards to the operation and application of the system on the hot demonstration.

An excellent vitrified product was produced by the cold demonstration. The product was sampled in order that various analyses could be performed to evaluate product quality. The analyses included the determination of the quantities of surrogates (cesium and cerium) that are present within the product, the degree of mixing (or homogeneity) of the surrogates within the product, and the degree of leachability of the surrogates out of the product. A piece of the vitrified product can be seen in the lower left corner of Figure 3.

Figure 3. Vitrified Monolith Created During the Cold Demonstration

Samples of the vitrified product were analyzed to determine the concentration of the cesium and cerium surrogates immobilized within the product. During the preparation of the simulated absorption bed, surrogates representing radionuclides contained within the MDA-V were added to the bottom of the simulated bed (at the 1.8-m depth). Cesium for ($Cs^{137}$) and cerium (for transuranics) were added in concentrations sufficient to allow the determination of mixing efficiency of the surrogates within the vitrified product. Enough of the cesium and cerium were added to raise the concentration from background concentrations of 3.5 ppm and 110 ppm, respectively in the soil, to concentrations of 33-ppm cesium and 248-ppm cerium in the vitrified product (see Table I). The concentrations of surrogates found within the vitrified product also indicates that all of the surrogates were retained within the vitrified product and not volatilized to the off gas or transported into the surrounding soil.

Table I. Radionuclide Simulant Concentrations in the Native Soils and in the Vitrified Monolith

| | Cesium | Cerium |
|---|---|---|
| Background Concentration in Native Soils | 3.5 ppm | 110 ppm |
| Amount of Simulant Added to Test Area | 6.5 kg | 30 kg |
| Uniform Concentration Throughout the Monolith | 33 ± 0.7 ppm | 248 ± 3 ppm |

To determine how well the surrogates were incorporated into and distributed within the resulting vitrified product, five samples were collected from a portion of the melt and submitted for complete digestion and analysis. Homogeneity testing of these samples resulted in a values of 33 ± 0.7 ppm for cesium and 248 ± 3 ppm for cerium. This indicates that all of the surrogates present in the simulated absorption bed were incorporated downward into the developing melt and distributed uniformly throughout the resulting product. This is typical within a GeoMelt-created product due to the convective flow patterns that develop within the melt. Hotter regions within the melt, which occur around the four electrodes, cause molten material to flow upward and then outward and downward into the cooler regions. This flow pattern is the reason that contaminants (or surrogates), that may be localized initially in the soil column, become effectively distributed throughout the entire melt volume.

Leach testing was also performed on the cold demonstration product to evaluate its resistance to leaching. Five random samples were submitted for product consistency (PCT) and toxic characteristic leach procedure (TCLP) testing. In all cases, the results indicated that none of the surrogate compounds were present in the leachate at or above the detection limits of the analytical procedures (see Table II). For the TCLP analysis, all five of the samples were reported at less than 0.29 ppm for cerium and less than 0.056 ppm for cesium.

Table II. Results of Leach Testing Performed on the Vitrified Product

| Leach Test Method | Cesium Simulant | Cerium Simulant |
|---|---|---|
| TCLP | <0.29 mg/L | <0.056 mg/L |
| PCT | <0.011 g/m$^2$ | <0.036 g/m$^2$ |

Likewise, the results of the PCT analyses indicated that the concentration within the leachate was less than 0.002 ppm for cerium and less than 0.006 ppm for cesium, which when normalized on a surface area to unit mass of the finely ground product results in levels of <0.011 g/m$^2$ and <0.036 g/m$^2$ for the cesium and cerium, respectively (MSE 1999). The data gathered from the two leach tests exceeds the criteria established for the test, as well as that of any other type of immobilization technology, including high-level waste melters. The high level of product quality is possible due to the fact that no melt additives are required to lower the melting temperature during GeoMelt processing. In addition, the soils present at the LANL site contain a very high concentration (>90 wt %) of glass forming compounds, which serve to make a very high quality and durable vitrified waste form.

All major components of the GeoMelt ISV system operated as designed throughout the duration of the demonstration. Only two minor equipment problems were encountered during the cold demonstration. Both of the minor equipment problems were resolved easily without hindering the cold demonstration.

Performance data was gathered on individual pieces of equipment such that "fine tuning" or minor modifications can be made prior to initiating the hot demonstration. The adjustments that have been identified will allow for an efficient, safe and cost effective application during the hot demonstration.

Gases exiting the thermal oxidizer were sampled continuously during the cold demonstration for oxygen (O2), carbon monoxide and dioxide (CO and CO2), and total hydrocarbons (THC). These compounds are routinely monitored when treating hydrocarbons as they either measure:

- a component required for combustion (O2)
- a combustion product (CO and CO2)
- the presence of any untreated organics (THC)

The O2 and the CO2 levels were typical discharge levels when measuring at the discharge of the thermal oxidizer. The propane fuel combustion process depletes the O2 level from 20.9 wt % down to approximately 15-wt %. Likewise, 5 to 8 wt % CO2 is generated from the combustion of the fuel. The total hydrocarbons measured were between 0 and 1 ppm during the demonstration.

The level of carbon monoxide, which is generated as a result of partial combustion, was evolved at a level typically between 15 and 65 ppm, which is approximately equivalent to the emissions coming from a standard automobile. Typically, these levels are of no concern from a health and safety and environmental release standpoint.

All phases of the cold demonstration were conducted safely and according to all of the applicable components of LANL's integrated safety management program. Although the GeoMelt process uses high levels of power, generates significant amounts of molten soil subsurface, and requires the use of cranes, drill rigs and high-pressure injection equipment, no accidents or near accident occurred during the cold demonstration.

Cost data collected during the cold demonstration indicated that the direct costs of the cold demonstration operations amounted to $684/ton (this includes the labor, equipment costs, consumables, propane, and electrical energy used during the 8-day run). This cost per ton is below the established unit cost criteria established for the hot demonstration of $800/ton of treated soil. It is expected that the cost/ton of the hot demonstration will be equal to or less than that of the cold demonstration due to increased efficiency with larger scales of application. The planned target volume for the hot demonstration is twice the volume than that of the cold demonstration.

## REFERECES

Proc. Spectrum '98 International Conference on Decommissioning and Decontamination and on Nuclear and Hazardous Waste Management, Denver, Colorado, Sept. 13 – 18, 1998, American Nuclear Society.

LANL, "Voluntary Corrective Measure Plan for Consolidated Potential Release Site 21-027(d)-99," LA-UR-99-1613, Los Alamos National Laboratory (1999)

MSE, "Final Report – Cold Demonstration of Non-Traditional In Situ Vitrification at the Los Alamos National Laboratory," ECCP-11, MSE Technology Applications, Inc. 1999