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Development of a Cone Penetrometer for Measuring Spectral Characteristics of Soils In Situ

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ABSTRACT

A patent was recently granted to the U.S. Army for an adaptation of a soil cone penetrometer that can be used to measure the spectral characteristics (fluorescence or reflectance) of soils adjacent to the penetrometer rod. The system can use a variety of light sources and spectral analytical equipment. A laser-induced fluorescence measuring system has proven to be of immediate use in mapping the distribution of oil contaminated soil at waste disposal and oil storage areas. The fiber optic adaptation coupled with a cone penetrometer permits optical characteristics of the in-situ soil to be measured rapidly, safely, and inexpensively. The fiber optic cone penetrometer can be used to gather spectral data to a depth of approximately 25 to 30 m even in dense sands or stiff clays and can investigate 300 m of soil per day. Typical detection limits for oil contamination in sand is on the order of several hundred parts per million.

INTRODUCTION

Cone penetrometers have been used in soils investigations for foundations and roadways for over fifty years. A typical geotechnical cone penetrometer consists of a hollow, instrumented, steel rod that is forced into the ground at a constant rate by employing hydraulic rams and a large reaction mass. The rod and conical tip are generally instrumented to measure the force the soil generates on the standard conical tip, and the force the frictional resistance of the soil produces on the side wall of the rod. Additional adaptations have permitted the measurement of the soil electrical resistivity and the pore pressure of fluids in the soil. The purpose of the present paper is to discuss new adaptations that allow the cone penetrometer to be used to measure spectral properties of soils in-situ.

An engineering cone penetrometer of modern design typically consists of a 20- to 30-ton truck equipped with all-wheel drive. Hydraulic jacks are used to lift the truck up from the ground so that all of the weight of the truck can be mobilized as a reaction mass. The hydraulic rams mounted in the truck use the reaction mass to force the penetrometer rod into the underlying soil. The electronics and computer equipment needed to readout and record data from the instruments in the rod is mounted in the van body that houses the rams (Figure 1).

The cone penetrometer is recognized in the geotechnical community as a rapid method for gaining access to the subsurface soils in order to make in-situ measurements or to recover samples of soil or groundwater. A typical cone investigation uses a 35-mm-diameter, hollow, steel rod that is forced into the soil at 2 cm/sec. A truck can generally investigate 300 m of soil in a working day. Using a 200-kN thrust the penetrometer can reach depths of at least 25 to 30 m even in dense sands and stiff clays (1).

The cone penetrometer equipped with suitable sensors is finding new applications in reconnaissance-level site investigations where contaminated soil and shallow groundwater are suspected. Cone penetrometers represent a faster, safer, and more economical alternative to drilling, sampling and sample analysis (2). Cone penetrometers produce no cuttings for disposal and a relatively simple adaptation to the ram unit allows the penetrometer rods to be cleaned as they are brought out of the ground. The penetrometer van can be adapted to maintain a cool, controlled air supply for the equipment operators. Air quality monitors located in the rod handling area assure that the van interior is a safe working area.

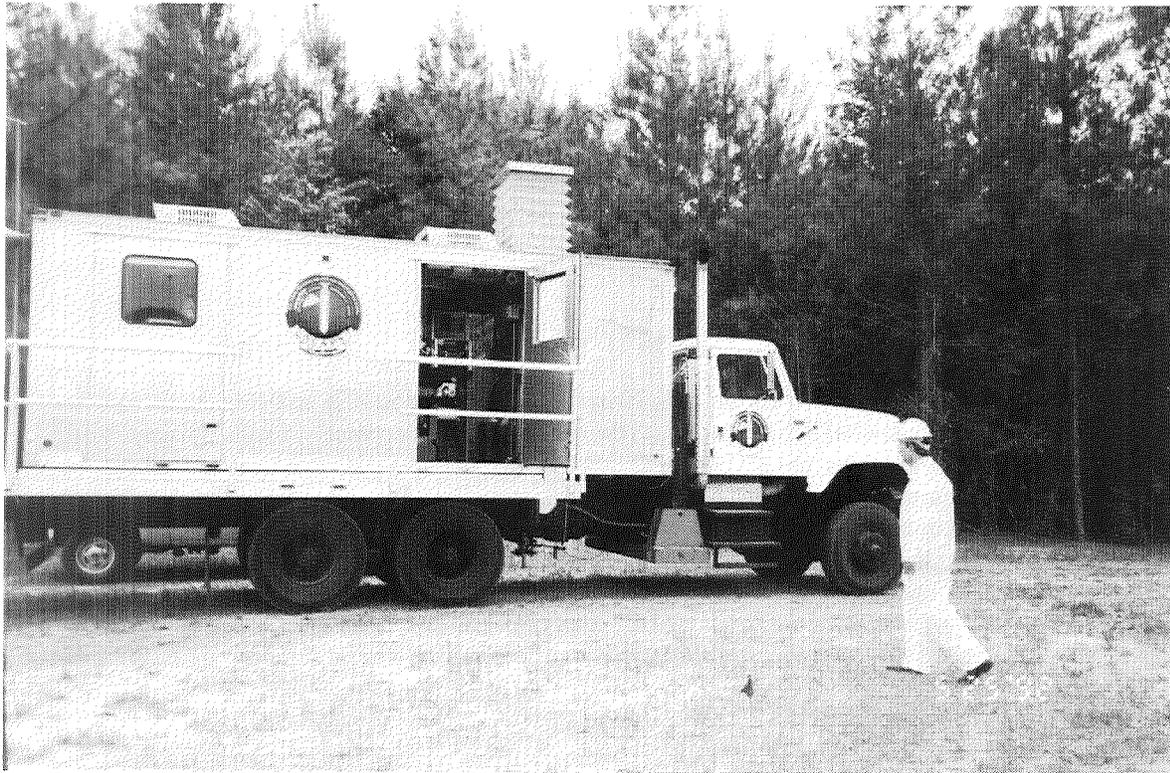


Figure 1. Photo of a penetrometer truck equipped for waste site investigations. The forward compartment houses the hydraulic rams for forcing the penetrometer rods into the ground. The rear compartment houses the instrumentation.

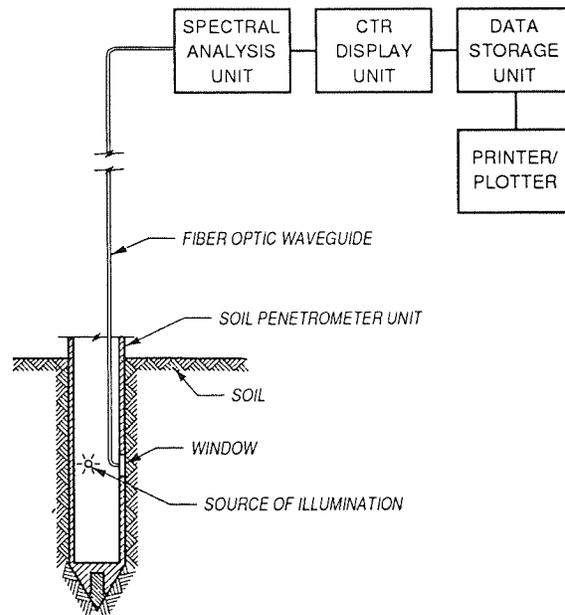


Figure 2. Schematic drawing of the system used for measuring soil spectral characteristics (after Figure 1 in U.S. Patent No. 5,128,882)

## THE FIBER OPTIC CONE PENETROMETER

The U. S. Army Toxic and Hazardous Materials Agency is directing a tri-services research effort on applications for the cone penetrometer in site characterization and has tasked the U.S. Army Engineer Waterways Experiment Station to develop the cone penetrometer equipment that will allow it to be used as a screening tool for locating contaminated soil and groundwater. As one result of research in this area, the U.S. Army has been granted a patent on a novel method for examining the spectral characteristics of soil adjacent to the penetrometer rod (3). The patent describes a method for using a window that passes through the wall of the penetrometer tube. Light from inside the penetrometer tube is used to illuminate the soil opposite the window. The light returning from the soil is captured by a fiber optic waveguide inside the penetrometer and transferred to the surface. Spectral analysis equipment attached to the end of the fiber at the surface is used to determine the energy distribution of light returning from the soil. A schematic of the system is shown in Figure 2. The spectra are displayed in near real time in the penetrometer instrument compartment and are evaluated and recorded.

The illumination source and fiber optic waveguide in the cone penetrometer can be configured in a variety of ways to measure different phenomena. The basic fiber optic system can be used as a fluorometer or as a reflectometer. Two experimental fluorometer units have been built by the Army to detect contamination from hydrocarbons in soil, one unit employed miniature UV lamps housed in the penetrometer as an excitation source and used a grating spectrophotometer as a spectral analysis unit. A single waveguide was used to carry the fluorescent signal to the surface. A second design developed in an Army and Navy cooperative effort used a pulsed nitrogen laser emitting at 337 nm coupled to a fiber as an excitation source and a fixed grating with a charge-coupled photodiode as a spectral analyzer. Both single- and double-fiber designs have been built and evaluated. The Air Force has assembled a fiber optic cone penetrometer to detect jet fuel contamination in soil. The Air Force unit uses a portable, tunable dye laser coupled to a fiber bundle and a grating spectrophotometer as a spectral analyzer.

A prototype reflectometer has been assembled by the Army to evaluate the use of reflectometry in the visible portion of the spectrum as an aid to detecting wastes (such as TNT washout and rinse waters) that have a distinctive color. The reflectometer uses a tungsten lamp coupled to a fiber waveguide to provide illumination at the window and a second fiber waveguide and a spectrophotometer as a spectral analyzer.

Because of the widespread problem of soil contamination from fuel spills or leaks and waste oil disposal, the fluorometer is currently the configuration that has the widest application. The most useful system to date is the laser-induced fluorescence (LIF) unit that uses a nitrogen laser as a UV excitation source. The components used are specified in Table 1, and illustrated in Figure 3.

The penetrometer tool that is used in the LIF system (Figure 4) is adapted from a standard penetrometer cone that would be used to measure soil strength (4). The window through the wall of the penetrometer rod and the fiber optic elements are contained in a module that rides above the standard cone. The only modification that was produced in the lower part of the penetrometer is the addition of a grouting system that allows the tip of the penetrometer cone to be ejected and grout to be pumped down through the rod to seal the hole as the penetrometer is withdrawn. With the exception of the grouting system the penetrometer tool follows the standard design with regard to the tip configuration and the area of the lower part of the rod (the sleeve) that is used for soil friction measurements.

TABLE 1

LASER INDUCED FLUORESCENCE (LIF) UNIT COMPONENTS

Illumination Source: Laser Photonics LN 1000 Nitrogen Laser (337.1 nm excitation).

Fiber Optic Waveguide: Ensign - Bickford 360 micron core fiber optic, 400 micron total diameter.

Spectral Analysis: EG&G PARC Model 1460 Optical Multichannel Analyzer; Model 1302 Fast Pulsar; Model 1229 Spectrograph; Model 1421 Photodiode Array.

Data Acquisition and Processing: Hewlett Packard Vectra 486 Computers (2) networked via Ethernet; Data Translation A/D and D/A boards; Hewlett Packard LaserJet III printer.

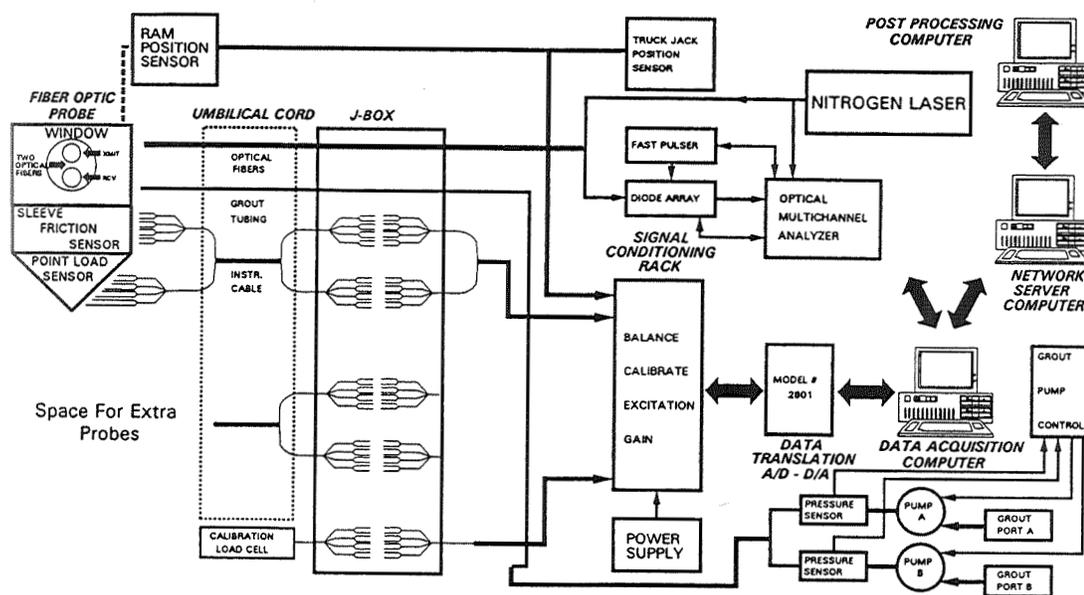


Figure 3. Layout of the instrumentation used in the laser-induced fluorescence (LIF) system.

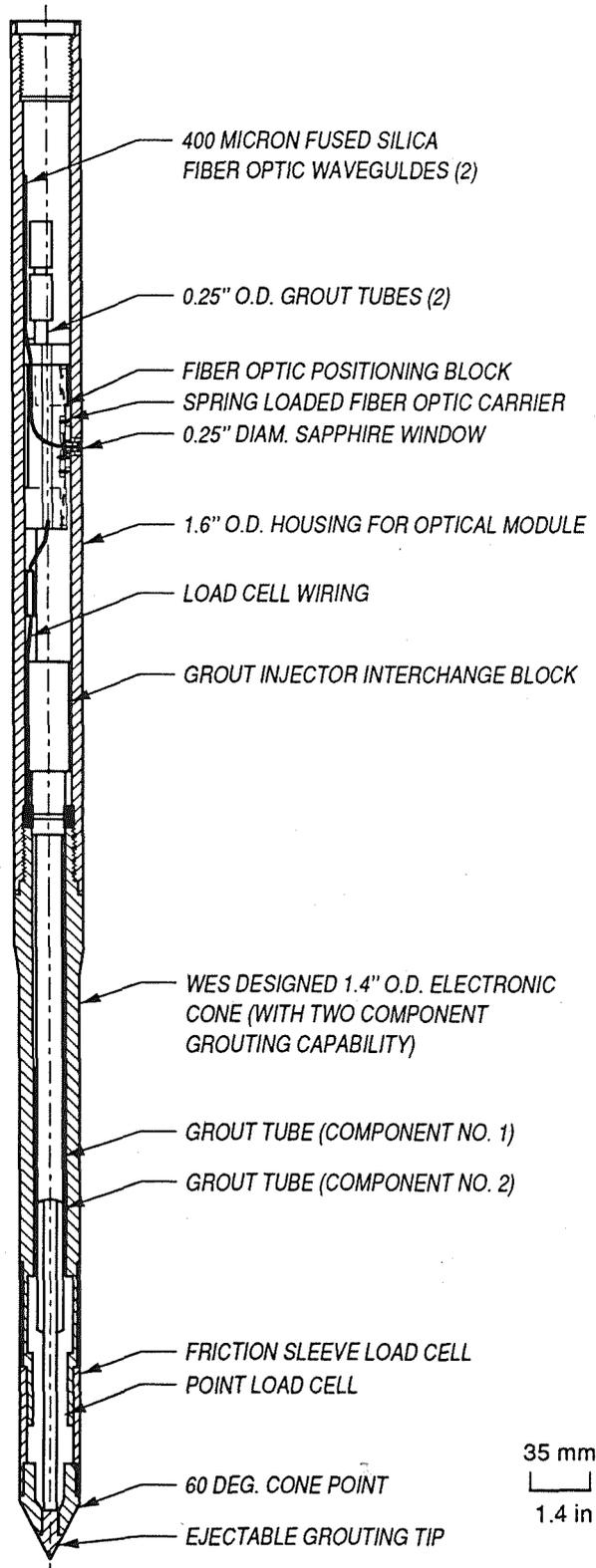


Figure 4. Cross section of the penetrometer tool showing the instrumented cone and the optical module.

The optical module (Figure 5) is designed with a replaceable sapphire window. The module consists of a fiber optic carrier that slides inside the penetrometer rod. The carrier holds two 400-micron diameter silica-on-silica fibers. The fibers are epoxied into a holder that assures that the cones of acceptance of the fibers overlap at the outer surface of the window. As the window is screwed into the carrier, the threads on the window pull the spring-loaded holder and the attached fibers into position behind the window. The wiring harness for the strain gages at the tip and sleeve of the penetrometer rod passes through slots in the optical fiber carrier. The optical fiber carrier has two stainless steel tubes inserted through it to allow the grout to be pumped down to the ejectable tip.

#### OPERATION OF THE FIBER OPTIC PENETROMETER

As in any technique that depends on spectral data for detection or quantification of a compound in a complex matrix, the detection limit depends on the response of the compound of interest and the influence of the matrix. The detection limit that can be obtained from the fluorometer when it is used to examine fuel-contaminated soil depends on the fluorophore present in the fuel (for example, polynuclear aromatic compounds in diesel fuel) and the conditions in the soil. With carefully prepared standards and heavy-grade fuels (rich in polynuclear aromatic compounds) in a sand matrix, detection limits of a few parts per million are possible (Figure 6). At many sites where free fuel is present in the soil as a non-aqueous phase liquid, low detection limits are not necessary if the objective is to determine the shape, size and depth of the mass of oil-saturated soil. The fluorometer can be used to find critical locations where the penetrometer or drilling techniques can then be used to collect soil or groundwater samples for analysis.

#### POTENTIAL APPLICATIONS FOR THE FIBER OPTIC PENETROMETER

The first application for the fiber optic penetrometer has been fluorometry for the detection of fuel in soil. Fuel residues at five sites have been mapped. By using the large volume of sensor data from the cone penetrometer and a volume mapping computer routine, a model of the contaminated soil mass can be prepared that shows the probable concentration of the fuel in the soil and the location and depth of each sensor reading. The visualization of the sensor-derived concentrations can be used in planning monitoring or remedial actions. An example of a three-dimensional plume map produced from penetrometer sensor data is shown in Figure 7.

The fiber optic cone penetrometer even in the form of a simple fluorometer offers potential for commercial applications. The U. S. Environmental Protection Agency estimates indicate that there are over two million fuel storage tanks in the United States. Surveys indicate that on an average one tank in three is leaking (5). This problem alone would justify commercializing the fiber optic cone penetrometer. The penetrometer also has uses in tracking the flow of landfill leachate and septic tank effluent. Fluorescent dyes have been used with the existing fluorometer to determine the direction and velocity of groundwater movement under a dredged material disposal area.

The fiber optic cone penetrometer will potentially become even more useful in the future as waveguides are developed that will allow broad range remote spectral studies, especially in the infrared. Development of more specific techniques using infrared, visible, and UV reflectometry can potentially expand the technological benefits. Experimental work is also underway in evaluating the use of resonance Raman spectrometry in a fiber optic cone penetrometer. Future fiber optic penetrometer applications will build upon basic designs developed during the production of the fluorometer system for the cone penetrometer (6, 7).

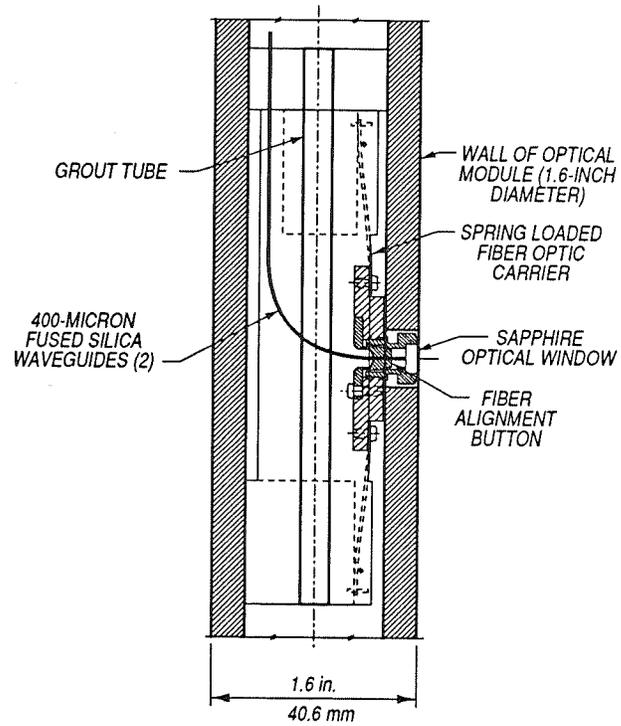


Figure 5. Detail of the fiber optic module showing the sapphire window. Note that the fibers are pulled in position as the window is screwed into place.

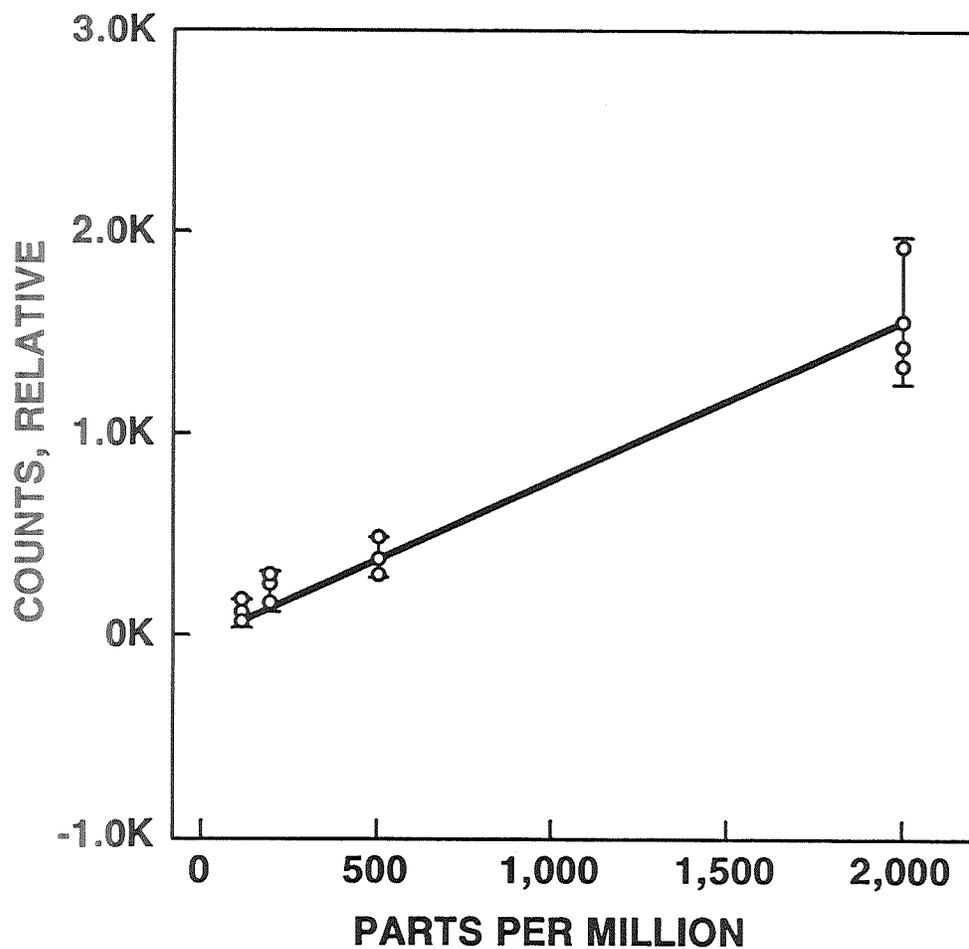


Figure 6. Typical calibration curve for fluorescence of #2 diesel fuel oil in sand. Parts per million are presented on a weight/weight basis. Error bars are +/- one standard deviation from the mean.

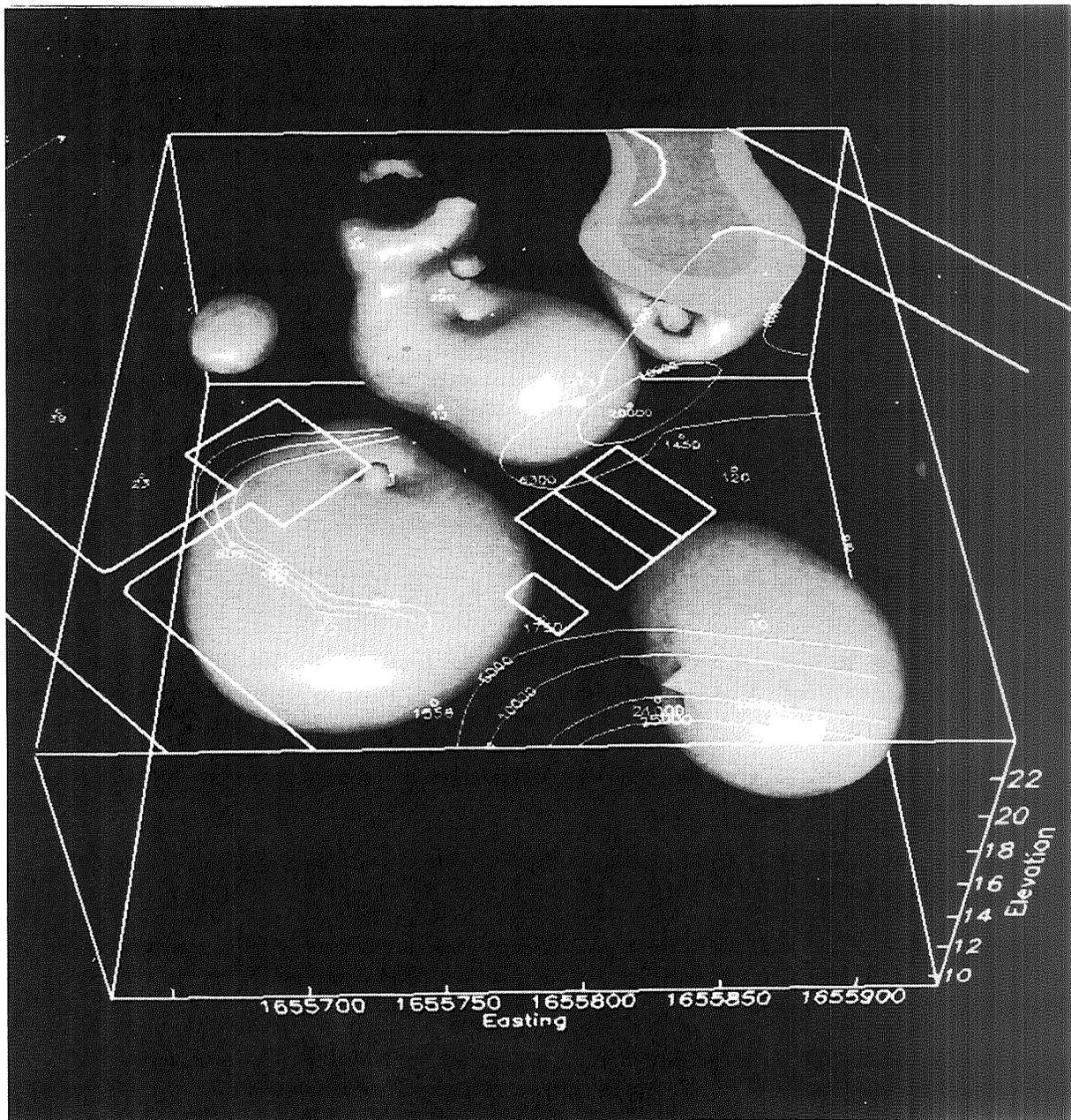


Figure 7. Block view of the masses of fuel-contaminated soil in a fuel storage area. The irregularly shaped masses are the volume of soil that fluoresced at levels equivalent to sand contaminated with over 2000 ppm of diesel fuel. The contours indicated on the surface show the concentration of hydrocarbon (measured as ppm hexane) in soil gas.

## ACKNOWLEDGEMENTS

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