DEVELOPMENT OF AN IN SITU SUBSURFACE RADIOACTIVITY DETECTION SYSTEM - THE "RADCONE"

R. A. Marton, L. R. Taylor, K. L. Wilson
The Earth Technology Corporation
Long Beach, California 90807

ABSTRACT

Development of a unique in situ subsurface radioactivity detection system is described. This system, named the "Radcone," adapts gamma-ray well logging instrumentation for deployment by electronic Cone Penetration Testing (CPT) equipment. The system will allow in situ identification of gamma-emitting radionuclides in soils and measurement of real-time activity profiles more rapidly, safely, and efficiently than is possible with conventional methods. Downhole instrumentation components are encapsulated in a 4.4-cm diameter stainless steel housing that prevents intrusion of groundwater and soil particles and accommodates the mechanical stresses resulting from penetration, but does not severely attenuate gamma radiation. The calibrated system can collect data for gross gamma counts, dosage, or identity and abundance of specific radionuclides. Spectral analysis can provide information on radionuclides such as fission products, activation products, and members of the uranium and thorium decay series. The Radcone can be used to map subsurface radioactivity profiles during site investigations and remedial action programs at either contaminated or potentially suitable low-level and mixed waste sites.

INTRODUCTION

Land disposal and other operations involving low-level and mixed radioactive wastes can contaminate soils and groundwater with radioisotopes which may threaten human health and the environment. Evaluating the nature and extent of such contamination is a necessary part of site assessments and remedial investigations at sites where low-level radioactive wastes are present. Evaluations usually involve soil sampling programs and groundwater monitoring well installations which can entail significant health physics/personnel protection measures and high costs associated with collecting, analyzing, and disposing of contaminated materials from the drilling and sampling operations.

This paper presents the current status of research undertaken by The Earth Technology Corporation to develop a unique in situ testing system which can identify gamma-emitting radionuclides in subsurface soils and measure activity profiles rapidly, safely, and efficiently. Initial laboratory and field testing of the probe housing and electronic system has yielded positive results. Detailed calibration of the system is ongoing.

The nature of the probe and the system used for deployment of the detector are based on Cone Penetration Testing (CPT) technology--hence, the "Radcone" system. By merging the Radcone system's radioactivity mapping capabilities with the capabilities of proven CPT techniques, a single in situ testing system which can provide both radiologic and geologic data can be deployed at low-level and mixed waste sites to facilitate efficient site assessments and remediation. Since the system does not require drilling, no potentially contaminated drill cuttings are generated for handling and disposal and the potential for personnel exposure is minimized.

The Radcone system, including detectors and instrumentation, the deployment system, and operational procedures, is outlined in the following sections. This is followed by a discussion of Radcone applications and data interpretation, which illustrates the flexibility of the tool and the benefits of performing integrated analyses with other CPT tools.

THE RADCONE SYSTEM

Detectors and Instrumentation

The Radcone detection system consists of a downhole probe, nuclear instrumentation module (NIM) components for signal processing and power supply, and a PC-based multichannel analyzer. A block diagram of the probe and instrumentation configuration, including linkage between the various components, is shown in Fig. 1.

Downhole probe components are mounted in a streamlined (4.4 cm O.D.) stainless steel casing behind the cone tip. Approximately half of the surface area of the casing along the length of the detector is covered by thin (4.2mm thickness) stainless steel "windows" to reduce attenuation and allow detection of lower energy gamma-rays. The thicker half of the casing provides structural support during penetration. A schematic diagram of the probe, including the detector, electronics, and casing, is shown in Fig. 2.

While other types of detectors such as plastic scintillators (suitable for direct dosage measurements) may be used with the system, the probes are currently designed for thallium-activated sodium iodide (NaI(Tl)) crystals of various lengths. The crystal is optically coupled to a photomultiplier tube as an integral assembly. Attached to this assembly is a circuit board containing the voltage divider string, preamplifier, and high voltage supply. A

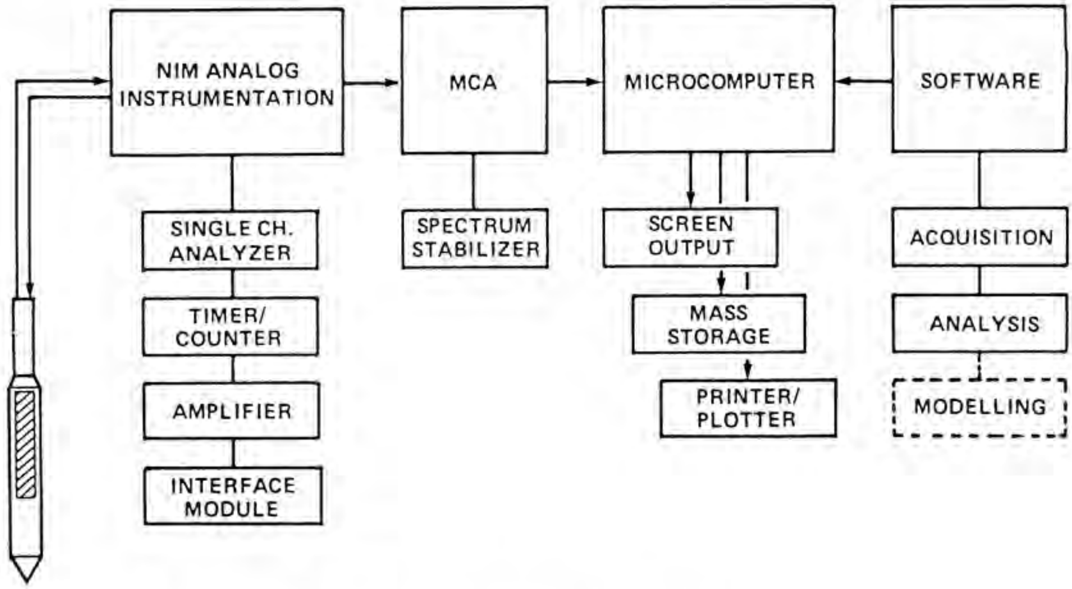

Fig. 1. Radcone System Configuration.

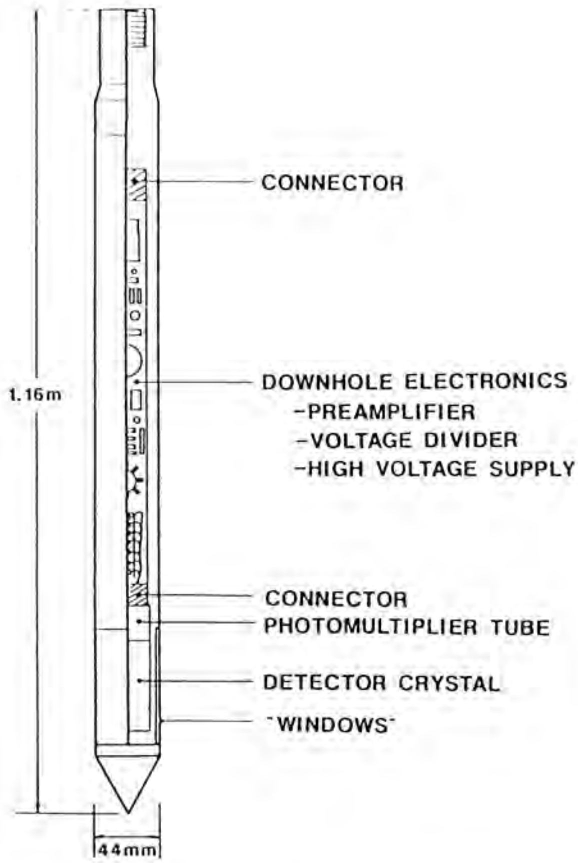

Fig. 2. Radiation Detection Probe.

single coaxial cable connects the downhole probe to the surface through lengths of penetrometer rod, relaying the measured signal and supplying low voltage DC current.

At the surface, the signal is processed for either gross count or spectral analysis. The pulse signal from the probe is decoupled from the DC voltage supply by a custom-designed interface NIM module. After amplification, the signal can be split and processed in several ways depending on whether gross count, spectral, or both types of analyses are desired. A rugged personal computer (PC) is used with a card that contains an analog to digital converter (ADC), single channel analyzer (SCA), multichannel scaler (MCS), and dual-ported memory. The PC card will allow gross count analysis of the signal or, by converting the PC into a multichannel analyzer (MCA), spectral analysis. An additional PC card provides digital spectrum stabilization by adjusting the ADC gain and zero offset when changes in the peak shape or position are detected for gamma-ray peaks produced by radionuclides external to the probe or sources implanted in the probe. If gross count screening of the signal is desired while maintaining the MCA mode of the PC, the signal can also be processed utilizing SCA and computer-controlled dual counter/timer NIM components. A digital current integrator may be added for direct integration of the phototube current when used with a plastic scintillator. This provides a signal proportional to dose rate; the plastic scintillator's response to gamma-radiation is similar to human tissue's response. The PC and a printer/plotter are also available for further data manipulation, storage, and output.

The fully calibrated system can collect data for gross gamma counts, identity and abundance of specific radionuclides, and dosage. Gamma-emitting radionuclides present at low-level and mixed waste sites include fission pro- ducts, activation products and members of the uranium and thorium decay series. Potentially important radionuclides with decay intensities greater than 10 percent of decays are listed in Table I along with their half-lives and decay energies. Radionuclide inventories and activities will vary from site to site.

Typical Radionuclide Characteristics

Routine data reduction for dosage-correlated measurements or gross-count measurements can be performed on site. Spectral data reduction and analysis and more sophisticated 3-D mapping of contaminant distribution require significantly more time and are more appropriately performed on an office-based micro- or minicomputer system but can be performed on site if necessary.

The complexity and accuracy of the calibration procedures is proportional to the complexity and accuracy of the required measurements. A semi- quantitative estimate of the probe's response and attenuation of gamma energies can be obtained by making measurements while varying the position of a point source relative to the probe. For gross count and spectral measurements, calibrations can be done utilizing annular calibration sleeves with distributed radionuclides or calibration facilities such as those maintained by the Technical Measurements Center at Grand Junction, Colorado (1). For precise spectral analysis, decomposition of the spectra by computer may be necessary, using a set library spectra for the various radionuclides obtained from experimental sites or fabricated calibration sleeves. Dose rate measurements can be calibrated by utilizing the NaI(Tl) detectors response to various gamma-ray energies calculated by the above methods and intergrating the pulse height spectra.

Deployment System

The probe is deployed using relatively conventional Cone Penetration Test (CPT) equipment with minor modifications. CPT systems have been utilized for foundation investigations, stratigraphic profiling and other applications for more than 50 years and are well proven in a variety of soil and terrain conditions. The depth of penetration which can be achieved by the CPT is dependent in part on local subsurface conditions (e.g., difficulty in penetrating very dense gravelly soils, boulders, hard bedrock, etc.), but penetration depths on the order of 100 meters have been achieved and penetrations on the order of 30 to 40 meters are typical.

The CPT deployment system is illustrated schematically in Fig. 3. The basic components of the system include a high-capacity hydraulic load frame mounted on a 6-wheel drive truck providing a reaction mass of roughly 19.5 metric tons. The truck is hydraulically jacked and leveled to provide maximum capacity. The probe is advanced by adding 1-meter sections of 3.5-cm diameter high-strength hollow rods through which the instrument cable is pre-strung and continuously attached to the detector and instrumentation system. All hydraulic and electrical power systems are onboard the vehicle so that peripheral support is usually not required.

The entire working area of the CPT vehicle is enclosed and ventilated thereby minimizing the potential for exposure of the operator(s) to excessive radiation levels. Upon completion of a sounding, the rods and probe are withdrawn through a special rod washing unit using disposable elastomeric wipers and high pressure steam to decontaminate exposed components.

Condensate from the decon system can be collected in drums for later treatment and/or disposal after being analyzed. The Radcone can monitor itself for probe contamination as well as vertical cross-contamination of soils during deployment.

TABLE I

Typical Radionuclide Characteristics

Radionuclide	Half-life(days)	Decay Energy(keV)	Decay Intensity(%)
K-40	4.75E11	1460	11
Co-60	1,921	1173, 1332	100,100
Cs-137	11,042	661	85
Pb-214	0.019	295, 352	19, 37
Bi-214	0.014	609, 1120, 1765	43, 14, 15
Ac-228	0.26	338, 911, 965-9	12, 27, 21
Pb-212	0.44	239	45
Tl-208	0.0021	583, 2614	30, 36
Nb-95	35	766	100
Zr-95	65	724, 756	44, 55
Ce-144	284	133	11
Zn-65	244	1115	51
Ce-141	33	145	48
La-140	1.7	329, 487, 816,1596	18, 43, 22, 95
Ag-110m	253	658, 678, 707, 764	95, 11, 17, 22
I-131	8.1	364	81
Ru-103	40	497	86
Co-58	71	811	99
Ba-140	13	30, 537	14, 20
Cs-134	749	569, 605, 796	15, 98, 85
Ru-106	367	512	21
Fe-59	45	1099, 1292	56, 43
Sb-125	986	428, 463, 601, 636	29, 10, 18, 11
Mn-54	303	835	100
Sn-126	3.65E7	88	37
Eu-152	4,745	122, 344, 1408 (and more)	28, 27, 21
Eu-154	3,102	123, 723, 1274 (and more)	41, 20, 36
Co-57	270	122, 136	85, 11
Kr-88	0.12	196, 834, 2392 (and more)	26, 13, 35

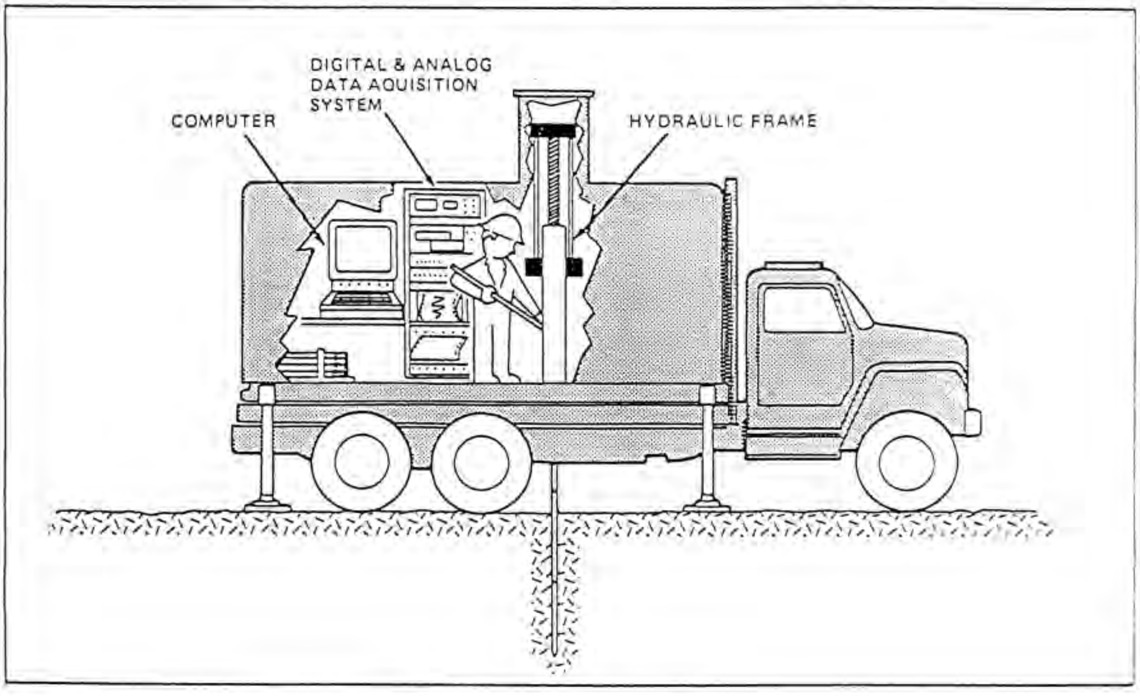

Fig. 3. CPT Deployment System.

System Operational Procedures

The probe is advanced at a constant penetration rate of approximately 1 to 2cm/sec during which time the gross gamma count rate is monitored. Penetration is halted at selected depth intervals for a sufficient period of time (several minutes) to allow collection of data - either a standard time period for dosage-correlated measurements with a plastic scintillator or until a statistically valid number of total counts to provide meaningful gamma-radiation spectral analysis has been collected. Depth intervals at which measurements are taken depend upon the magnitude, extent and distribution of measured radioactivity and can be optimized in the field to provide the necessary level of detail. The total amount of time required to perform a vertical profile to a depth of 15 meters with measurements at 1.5-meter intervals is on the order of 90 minutes.

Routine health physics procedures are followed in the field. This includes continuous ambient air monitoring inside the CPT vehicle and screening of penetrometer rods and probes with a survey meter following withdrawal and decontamination using the rod washing system.

APPLICATIONS AND INTERPRETATIONS

The CPT-deployed Radcone provides a rapid, economical means of gathering not only gross count or spectral gamma-radiation information but also a wide-ranging suite of complementary data from other subsystems which are applicable to low-level and mixed waste site investigations. Of particular importance is the ability to provide enhanced operator safety and to "preassess" the subsurface environments for other investigative techniques which, by necessity, disturb the in situ conditions and might bring contaminants to the surface. In combination with existing software and analytical techniques the Radcone data can be rapidly processed, displayed, and used to make decisions affecting the environmental consequences of site investigation and remediation activities.

A significant benefit of using the CPT vehicle for deployment of the Radcone is the capability of performing conventional CPT soundings in parallel with radioactivity profiling. In fact, in most cases it will be preferable to perform a CPT sounding with an electronic-friction cone prior to deploying the Radcone because: (1) stratigraphic data are provided which are potentially useful in evaluating potential locations for contaminant migration, and (2) a pre-determination of the subsurface soil profile identifies hard-to-penetrate zones and other situations where pushing the more costly Radcone "in the blind" may cause problems, and those occurrences are avoided when a hole in pre-punched. Monitoring with a radiation meter at the surface will detect potential contamination of CPT equipment as it is withdrawn from soils.

Use of the electronic cone penetrometer and interpretation of CPT results is described extensively in literature and will not be presented in detail here (2, 3, 4, 5). In brief, the CPT is an extremely useful in situ test method for evaluating stratigraphy, geotechnical properties and strength para- meters. Correlations of CPT data to various properties are widely accepted. Moreover, modern CPT equipment utilizing computer-based data acquisition and analysis provides capabilities for real-time or rapid onsite interpretation and plotting of data.

A variety of other in situ measurement tools and probes can be deployed with the CPT system to provide useful data for site and contaminant characterization at low-level and mixed waste sites. For example, at each vertical sounding location physical soil properties and other subsurface data can be either directly measured in situ, indirectly determined by correlations, or measured in the field or laboratory from retrieved samples (see Table II).

A broad range of potential applications for which the Radcone system is well-suited include:

- Pre-screening drilling locations prior to sampling programs or installing monitoring wells to assess health physics requirements and evaluate handling requirements for drill cuttings, or estimating radiation dosage levels to which workers may be exposed during excavation operations
- Profiling of sites where soil or groundwater contamination from LLW is suspected
- Detailed three dimensional mapping of the distribution and extent of radioactive contamination at known waste sites (plume-and-source tracking, contaminant migration studies, esti- mating boundaries and volumes for remedial action, etc.)
- Establishing radioactive baselines at existing or potential low- level or mixed waste sites.

Subsurface drilling (i.e., auger, rotary methods) is a typical method for site investigations. At sites where contamination includes low-level waste, it is often not known beforehand where contamination is located and what health and safety measures will be required for drilling or other excavation (e.g., trenching). Using the CPT-deployed Radcone, a "pre-drilling" program can be performed to confirm both the levels of contamination and the general vertical and areal distribution of the radionuclides. Detection can be by gross count or by spectral analysis depending on the needs of the specific survey. Because no cuttings are produced by the CPT operation, essentially no contaminants are brought to the surface and minimal protection and peripheral support is required. General health and safety planning as well as specific worker safety are greatly enhanced over the current methods of auger drilling. In addition, direct in situ measurements at the horizons of interest are made rather

TABLE II

CPT Probes for Waste Site Evaluation

Type of Probe	Data Provided
Electronic Friction Cones o Piezocone o Self-Grouting Cone o Miniature Cone	Stratigraphic Profiles and Engineering Property Correlations
Seismic Velocity Probe	Downhole Seismic Surveys
Conductivtiy Probe	Electrical Conductivity Profiles
Sampling Probes	Discrete Soil Gas or Groundwater Samples
Radcone	Subsurface Radioactivity Profiling - Identification of Radionuclides

than relying on extrapolations based on surface geophysical surveys.

Investigations at a single site (e.g. pond, pit, landfill) are usually aimed at determining migration of radionuclides away from a source both laterally and vertically. Often the groundwater table is near the base of the burial site and migration of contaminants through porous soils, weathered rock materials, and young alluvial deposits toward potable water sources is a prime concern. CPT soundings using Radcone and other CPT tools can very accurately depict vertical profiles and gather samples of liquids and gas present in the various horizons. For example, Fig. 4 illustrates the concept of correlating radiation profiles with electronic friction resistance and cone tip resistance soundings collected through the same profile. The figure simulates radioactive contamination of ground water perched above an impermeable layer.

Where investigations are required over a broad area (several hundred acres or many square miles) numerous soundings can be performed in an integrated network to create cross-sectional profiles and subsurface distribution maps (e.g. isopach, iso-intensity, concentration). Existing software (MINEPAK®) is used to store data as it is retrieved from the field and to pro- cess these data using appropriate geostatistical methods to produce contour maps, cross-sections, fence diagrams, perspective views, and other graphics. This capability is currently being developed for "real time" field usage to give guidance on drilling locations for monitoring wells or line locations for shallow geophysical surveys.

As new low-level and mixed waste sites are developed or as remedial action is undertaken at existing sites, baseline radiation levels for specific radionuclides prior to "site disturbance" need to be established. Using the CPT-based Radcone at surveyed locations, profiles measuring spectral intensity at the various soil horizons can be made to establish an existing baseline condition. Repeated measurements as the project is undertaken will allow changes in background levels to be noted inexpensively and accurately so that mitigation measures can be instituted as appropriate.

SUMMARY

Field operations at sites with radioactive contamination require special care in order to protect workers and operators and to provide recommendations which will lead to a safe environment at such sites in the future. The CPT-based Radcone is an important tool which can rapidly and inexpensively help provide this special care. Because operations are conducted remotely and do not bring contaminated soils or liquids to the surface, the Radcone is an excellent reconnaissance tool to precede required drilling and sampling or excavation and treatment. Equipment and instrumentation are off-the-shelf and fully proven for deployment in a range of environments. Detection capabilities for spectral analysis allow most common radionuclide inventories to be evaluated. Applications described above are required by the U.S. Department of Energy and its major prime contractors at sites across the United States.

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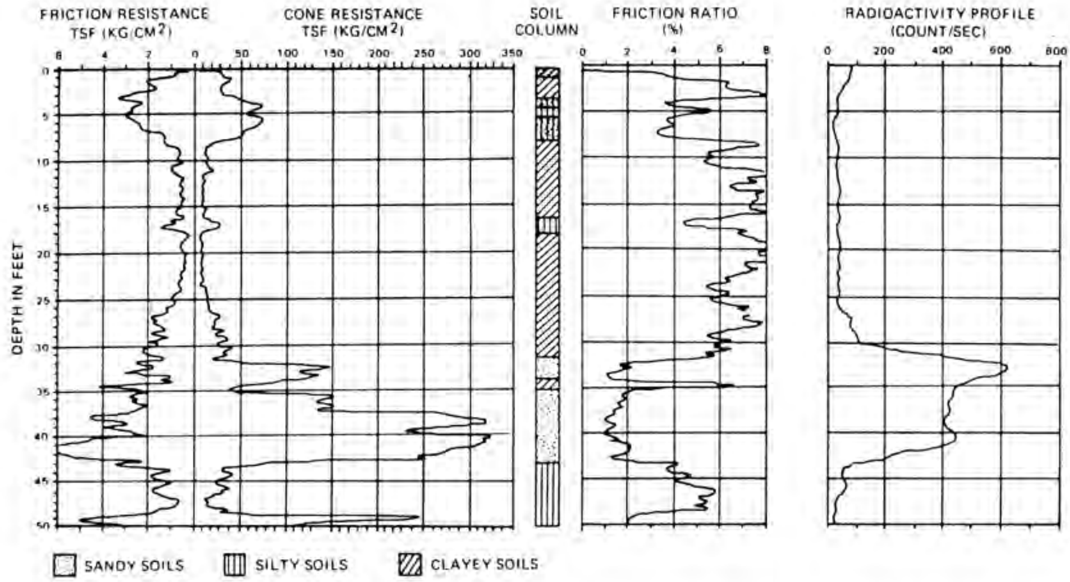

Fig. 4. Cone Penetration Test Data, Interpreted Stratigraphic Profile, and Radioactivity Profile from Radcone Sounding at the Same Location.

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