Innovative Directional and Position Specific Sampling Technique Phase III

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EXECUTIVE SUMMARY

The POLO System is a major enhancement to the state of the art for subsurface environmental restoration equipment. The POLO System locates the tip position of penetrometer probes as they are placed underground while meeting the rigid constraints of environmental restoration applications. POLO is applicable to small diameter probes, does not obstruct the center of the probe, is rugged, is unaffected by the presence of steel or other magnetic material, and is capable of remote operation beneath underground tanks or foundations. The development and adaptation of the POLO System for use with penetrometers, sponsored in part by the Department of Energy, has progressed through three development phases prior to commercialization.

Phases I and II of the contract "Innovative Directional and Position Specific Sampling Technique" included the design, testing, and integration of all components of the POLO device. Although the work was conducted in a laboratory, efforts were made to simulate field conditions in terms of the scale of the components as well as the operating environment. The pre-established success criterion, which has been maintained throughout the research, was to demonstrate path tracking with a total error of less than 0.50% of the distance traveled for distances less than 70 meters. The results of Phase I tests on individual POLO components showed that the equipment met or exceeded the success criterion. The Phase II laboratory scale path tracking experiments of the integrated POLO System also met the success criterion.

The Phase III work moved the POLO System out of the laboratory and into the field. The full-scale field demonstration tested the ability of the new POLO Module to track the path of a small diameter probe as it moved underground. It was completed in two stages. The first stage was conducted for two weeks in June of 1994 in test areas located near the UTD, Incorporated home office in Newington, Virginia. The purpose of this initial field test was to debug and refine individual components, as well as the integrated POLO System, close to home and before mobilizing to a distant field site. A final field demonstration took place for two weeks in July of 1994 at an uncontaminated location of the Savannah River Site in Aiken, South Carolina. Initially the work was similar to the earlier tests in Northern Virginia. During the final week of testing, the fully integrated POLO System was demonstrated to Department of Energy personnel and invited guests from industry. Once again, the success criterion for this work was to achieve 0.50% accuracy with respect to the distance traveled for distances less than 70 meters. On the basis of the field tests and the successful field demonstration UTD is pursuing commercialization of the POLO System.

1.0 INTRODUCTION

Although progress is being made, a significant gap remains between the technical needs and the field-ready equipment for subsurface environmental restoration work. Traditionally, monitoring wells have been used for finding contamination, identifying extent of contamination, remediating, and finally monitoring sites. However, the high cost of well installation makes them an expensive option, particularly when a large area is being assessed. In addition, the rotary motion of a drill used to install a well produces significant soil movement, which can potentially expand the zone of contamination..

Penetrometers are a better alternative to monitoring wells because they combine high penetration rates with minimal subsurface disturbance. For example, it may only take 45 minutes to complete a 30 meter penetration. The push rods displace a small amount of soil in a radial direction and leave the surrounding strata intact. A wide range of sensors and sampling devices, located near the tip of the probe, are available for expedited site characterizations. Despite their advantages, locating the final position of a sensor that has been pushed a specified distance has previously been difficult and of questionable accuracy.

Figure 1 illustrates a simplified version of a typical penetrometer path. Initially the penetrometer travels in a straight line. However, striking an underground obstacle such as a pebble or boulder, root, or consolidated layer is common and causes the probe to deviate from a straight path. Once the penetrometer probe starts to wander, the unbalanced force that is produced tends to increase the deflection as penetration proceeds. As a result, the location of the final target point is uncertain, and small errors can have a significant impact on the interpretation of plume origins and other characteristics. The POLO System is the only known locator technology that can provide this critical positioning information while meeting all the constraints for environmental restoration applications. POLO is applicable to small diameter probes, does not obstruct the center of the probe, is unaffected by the presence of steel or other magnetic material, and is capable of remote operation beneath steel tanks or foundations.

To re-direct the penetrometer probe of Figure 1 back on course, directional control is required. While steerable penetrometers are not currently available, the advent of POLO provides the basis for future additions of a steerable head that will permit position specific sensing. The ability to make measurements beneath tanks, foundations, and other locations heretofore inaccessible due to safety hazards and other limitations of current technology is a key ingredient to larger plans for environmental restoration.

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Figure 1. Significant deviations from a straight path occur in typical penetrometer insertions.

2.0 DOCUMENTATION FOR NATIONAL ENVIRONMENTAL POLICY ACT

To meet the requirements of the National Environmental Policy Act (NEPA), a detailed summary of the POLO field work and its effect on the environment was developed. Documentation for each of the field sites where POLO work was conducted was submitted to the Department of Energy (DOE). The first NEPA document summarized the preliminary field trial at the Fort Belvoir Army Post in Northern Virginia. Due to extremely difficult ground conditions at Fort Belvoir, the preliminary field trial was moved to a neighboring site in Kingstowne, Virginia. The work at the alternate Kingstowne site followed the same NEPA guidelines set out for the original Belvoir site. A second NEPA document that summarized the final field demonstration at the Savannah River Site in Aiken, South Carolina was developed with the assistance of the Environmental Sciences Group of the Savannah River Technology Center. Since the environmental impacts for the field tests are minimal, both qualified as a "Categorical Exclusion" under the NEPA guidelines. DOE issued a formal authorization for the proposed field work on May 24, 1994.

None of the field work violated applicable statutory, regulatory, or permit requirements for environmental, safety, and health requirements. In addition, there was no siting, construction, or expansion of waste storage, disposal recovery, or treatment facilities. There was also no uncontrolled or unpermitted release of hazardous substances. Minimal surface disturbance was observed in the immediate area of the test equipment. However, the field tests did not permanently affect land use or physically change either site. Detailed descriptions of test procedures and test equipment are given in subsequent chapters of this report. The following discussion describes the physical layout of the two test sites.

The preliminary field test was conducted at Fort Belvoir, a U.S. Army post located along the Potomac River in Fairfax County, Virginia. Figure 2 is a photograph that shows the test site, which was located away from the river in an uncontaminated, vacant, and lightly wooded location. The ground surface was nearly level, but was adjacent to a hill where the tip of the probe could "hole-out" at the end of a test. The slope of the hill was about 20 degrees with respect to horizontal and was leaf covered or vegetated and shows no signs of significant erosion. The underground work took place within 6 meters of ground surface and above the water table in sandy clay soil. A paved roadway that had ample parking for support vehicles ran within 15 meters of the intended test site.

The Kingstowne test site was in a vacant portion of a large housing complex that was under development. After getting the approval of the developers and Miss Utility, the POLO equipment was set up along a treeless ridge that was accessible by a dirt road. The slope of the hill was about 10 degrees with respect to horizontal and was

Figure 2. The Fort Belvoir test site had tree roots, and unforeseen pebbles, boulders, and consolidated layers that were difficult to penetrate.

lightly vegetated. As shown in Figure 3, an angled push through the sandy clay soil that was free of roots and cobbles allowed the tip of the probe to "hole-out" at the end of a push.

The POLO field demonstration took place at the Savannah River Site in Aiken, South Carolina. Two neighboring test areas, with a combined size of over 1.5 hectares, (3.7 acres) were allocated for this work. The Savannah River Company (SRC) grid coordinates shown in Table 1 describe the location of corner points of each boundary line. Although portions of the Savannah River Site are heavily polluted, the POLO test site is uncontaminated, vacant, and lightly wooded with scrub pine trees. Figure 4 shows that a dominant feature of the landscape is a ravine that has a vertical cliff face nearly 10 meters high. It was originally planned to use the relief provided by this ravine to achieve conveniently located "hole-outs" for surveying. However, difficulties with ground conditions required the use of an area adjacent to the ravine which proved to be entirely satisfactory. The adjacent ground surface is flat and open, with ample space for equipment and support vehicles. A gravel road to the east of the ravine provides site access. The underground work took place within 6 meters of ground surface and above the water table. Previous penetrometer work in this area has identified the soil type as a sandy clay.

Figure 3. The Kingstowne test site was a vacant ridge that was more hospitable for penetrometer pushes.

Table 1. The SRC coordinates identify the size and location of the two test areas at the Savannah River Site.

TEST AREA	EASTING COORDINATE (feet)	NORTHING COORDINATE (feet)
1	50100	80100
	50300	80100
	50100	79900
	50300	79900
2	50450	80000
	50950	80300
	50950	79850
	50450	79850

Figure 4. The field demonstration at the Savannah River Site was planned to take place near a ravine with vertical cliff walls.

3.0 FULL-SCALE MODULE MANUFACTURE

By the end of the three phase program, four POLO Modules were built. The first two Modules were prototypes and were designed and built during earlier phases, where laboratory-scale research was conducted to evaluate individual components of the new locator system. Although the first two units had the same shape as a standard penetrometer rod, they were made of aluminum, rather than steel, to facilitate laboratory testing. Aluminum responds to strain in the same uniform way as steel except that it has a lower modulus of elasticity which allows it to bend more easily. In other words, an aluminum module that follows a prescribed path experiences the same strain levels and has the same resolution as a steel module on the same path, but the forces required to cause the deflection are much lower. By using full size POLO components made of a more flexible, but similar, material, typical problems encountered when scaling up from laboratory to field conditions were avoided.

The first POLO prototype, shown in Figure 5, was a three piece device. It consisted of an inner core that housed three pairs of strain gage circuits, a middle ring that provided an annulus for circuit completion wiring, and an outer shield to provide mechanical protection for the circuitry. This first transducer successfully recorded the bending strain along its length, which is the input to the POLO tracking algorithm. Unfortunately, when access to the strain gage circuits was required (an important but rarely required operation), the original three piece module proved difficult to disassemble. The sequence of the operations was critical. First the outer shield, then the middle ring had to be removed from the inner core. If the middle ring broke free during the removal of the shield, the strain gage circuits could be damaged.

Figure 5. The first POLO prototype had a three layer construction.

During a subsequent phase of POLO development, a second prototype POLO Module was assembled. Although its main purpose was to provide a backup to avoid delays if the primary unit was damaged, minor enhancements were included in its design. Like the original, the second prototype was made of aluminum so that it could be deflected with laboratory scale equipment. Unlike the earlier unit, small grooves were machined into the core to make room for the strain gage wiring. With this approach, the two primary parts were an inner core that contained both the strain gages and circuit completion wires and an outer shield that provided mechanical protection. The middle ring used on the original POLO Module was eliminated. Since the strain gage wiring was recessed along the core, the shield was removable without the potential for damage to the strain gage circuits.

In the third and final plan of the DOE program, full-scale POLO Modules were assembled. The full-scale POLO Modules for field use are an adaptation of the two piece prototype and are described in detail in Section 3.2, Module Manufacture and Assembly. The manufacturing, assembly, and performance experience from the first two POLO prototypes also proved useful. The final information for the mature design was derived from careful consideration of the operating constraints of a penetrometer.

3.1 Module Design

Other than displacing a small amount of soil as it moves underground, the POLO Module is a passive device that does not interact with the subsurface environment in any way. Its exclusive function is to monitor deflections (bending) at the tip of a penetrometer string. The design goals for the full-scale POLO Module are to 1) meet penetrometer operational constraints and 2) precisely measure bending.

3.1.1 Design to Meet Penetrometer Constraints

The allowable bend of a penetrometer push rod depends on the type of rod used and the applied axial load. All push rods are made of steel. Standard push rods for measuring soil properties are less than 3.8 centimeters (1.50 inches) in diameter and 1 meter (39.37 inches) in length, with a tensile strength of over 1100 MPa (160 ksi). A common push rod used to perform sampling functions has a slightly larger diameter of 4.45 centimeters (1.75 inches), a similar 1 meter (39.37 inches) length, and a smaller 414 MPa (60 ksi) tensile strength. In either case, the push rods are designed for axial loads as large as 18 metric tons (20 tons) as long as sufficient lateral support, typically from overburden, is present to prevent buckling.

There is an indirect relationship between the allowable axial loads and the deflection of a penetrometer rod. When a penetrometer push rod deflects it has a measurable curvature along its length. As the rod deflection increases, the radius of curvature decreases (creating a tighter bend). The curvature causes the metal to be strained, which imparts an additional longitudinal component to the axial load that

already exists in the part. Figure 6 shows that there is a clear tradeoff between the achievable curvature and the applied axial loads. As the deflection of the rod increases, the radius of curvature of the rod decreases, and a smaller axial load is allowable. The calculations are based on the 4.45 centimeter (1.75 inches) push rod for sampling. In many soils, the penetrometer thrust load is less than 9 metric tons (10 tons), which translates to an allowable radius of curvature of about 40 meters (130 feet). As long as the axial loads are small, which could be the case in loose unconsolidated sediments, radii of curvature as tight as 25 meters (80 feet) are negotiable without rod breakage. It should be clear from this discussion that a reasonable range of penetrometer curvatures is achievable with existing equipment, but significant equipment modifications are necessary before higher performance is realized. For the purposes of this three phase program, this analysis was used to understand the limits of safe testing conditions.

Figure 6. Curvatures in the 25-40 meter range are achievable with penetrometer rods.

The penetrometer joints which are used commercially today were designed for penetrometers being inserted with straight trajectories. Under these conditions thrust is applied as axial compression, which is carried by the shoulders of the mating rod segments as shown in Figure 7. This condition is stable and should perform very well in straight ahead insertions. Pre-tensioning by torquing the two rod sections together could be helpful to maximize the contact between the two shoulder surfaces, although this is not typically done at present.

Unfortunately, when the penetrometer rods bend, the likelihood of rod breakage at the joint increases dramatically. As the rod deviates from a straight path, a moment "M" is superimposed on the joint as shown in Figure 7. This increases the bearing load on the shoulder and decreases the stresses at the azimuth (measured around the rod axis) at which the inside of the curve occurs. At the outside of the curve, bearing load on the shoulder is decreased, with a corresponding increase in thread stresses. This can result in one of several possible failure modes: 1) Shear strength can be exceeded, "stripping" the threads; 2) Bending stresses in the threads may cause them to fail in bending; and 3) The body on which the threads are cut may fail in tension. Modes 2) and 3) are exacerbated by the stress concentration factors associated with the changes in section occurring at the roots of the threads. From this simplified analysis it can be seen that penetrometer rod joints should be modified and improved to avoid premature rod breakage.

Figure 7. The joint of a standard penetrometer rod is the weak link for directional applications.

POLO is not the primary sensor, but an enhancement to existing equipment for subsurface environmental restoration work. This concept impacted the design in numerous ways. First of all, the POLO Module conforms in size and shape to a standard penetrometer rod. In fact, the POLO Module uses standard penetrometer connections for direct attachment to push rods. Secondly, the umbilical that relays POLO information to the surface takes less than 25% of the available space at the center of the probe, an important consideration when fiber optic cables or grout tubes are also used downhole. Third, the strain gage circuits are isolated from mechanical and environmental damage in a separate waterproof compartment. Finally, all structural components are made of AISI 15-5 stainless steel, a material that combines a durable

exterior with a surface finish that resists corrosion. In summary, the POLO Module functions unobtrusively with other penetrometer sensors and in harsh underground environments.

3.1.2 Design of a Bending Transducer

The POLO Module is essentially a bending transducer. Hence, the axial forces during a penetrometer push and their potential impact on the bending measurements were fully considered. A strain gage blindly monitors the strain on the surface of a transducer and does not inherently know the difference between the strain due to an axial load or due to a bending load. However, it was found that "same sign strains", that occur from axial loads (tension or compression), could be effectively eliminated by using full wheatstone bridge circuits wired electronically in the standard "bending" configuration. The only signal that a full wheatstone bridge bending circuit is capable of measuring is differential strain. In the strain gage configuration used on the POLO Module any differential strain on the POLO Module is due to a bend and must be processed by the POLO algorithm.

It is widely known that temperature effects can also have a strong influence on the precision of strain gage measurements. Sources of temperature change could include contaminant plume influence or similar effects, but the simple frictional heat source due to pushing the rod through soil is expected to be the most common influence. In assessing the influence on POLO, it must be emphasized that it is a temperature differential between individual gages or between leadwires of a given bridge that could cause problems. To quantify these potential variations for a penetrometer in an underground environment, the thermodynamics of the penetrometer tip were considered. Based on this consideration it was determined that most of the frictional heat was concentrated near the tip, away from strain gages on the POLO Module. It was also known that after a minimum depth and to depths of several hundred feet, an underground environment maintains a steady temperature. Therefore, to a first approximation, the POLO System will operate in a constant temperature environment, where the temperature induced errors are relatively small.

To achieve high accuracy, the POLO System was carefully designed to cancel out the effects of unexpected temperature variations. The temperature induced errors could occur in two places, in the transducer itself or in the leadwires that transmit the electronic signal. For example, temperature induced measurement errors in the transducer could occur due to thermal expansion. Recall that a strain gage circuit simply monitors the strain on the surface of the transducer. If the thermal expansion of the transducer is different than that of the strain gage circuit, a temperature differential could induce an erroneous strain reading. Fortunately, it is possible to minimize the potential problems in a number of ways. To reduce errors with the POLO Module, 1) temperature compensated strain gages were used, 2) bending strain gage circuits that inherently

cancel out temperature induced errors were utilized, 3) the temperature compensation for each circuit was fine tuned by hand, and 4) a data acquisition system which minimizes the effects of temperature on the leadwires was selected.

While the ability to reject extraneous signals from axial loads and temperature differentials is important, many other subtle details were critical for the design of the POLO bending transducer. For example, the shape of the cross section was carefully considered because it controls how the POLO Module responds to an applied load. Any feature that could promote exaggerated bending in one direction was avoided. To illustrate this point, think of bending a ruler. While it is easy to bend the ruler in the direction of its thin axis, it is much more difficult to bend with respect to its long axis. Now think of bending a round pipe. Because of the symmetry of its circular cross section, the pipe resists bending in all directions. In fact, it is no more prone to bending in one direction than in any other. The POLO Module mimics the behavior of a round pipe so that it responds uniformly to an applied load, independent of its line of action.

3.2 Module Manufacture and Assembly

Figure 8 is a cutaway schematic that shows the POLO Modules that were used for the field demonstration. The entire device is made of stainless steel, is 4.45 centimeters in outer diameter, and is 1.5 meters long. Three sets of strain gages, equally spaced along an inner core, monitor bend orientation and intensity. The sets of gages from back to front are called the lag, mid, and lead gage stations respectively. Circular grooves on the core correspond to the strain gage locations and provide a gap to complete the wheatstone bridge circuits. An outer shield protects the gages and electronics. Small rings that appear as small bumps on the outer shield are present to compensate for the material taken away by the circular grooves on the core. Thread adapters on either end of the device attach directly to standard penetrometer rods. The strain gage wiring is routed to the center of the probe and bundled together for communication with data acquisition equipment at ground surface. Chapter 5 provides a detailed description of how POLO measurements are made in a field environment.

While full-scale commercialization of POLO will be accomplished in a subsequent phase, UTD continues to refine the plans for POLO manufacture and assembly. To achieve highest performance, each stage of the multi-step process is carefully monitored from a quality assurance perspective. At present, POLO units are manufactured and assembled one at a time or a few at a time. However, a preliminary plan has been established that has the capacity to reach thousands of units per year. For example, custom purchases of stainless steel in mill quantities and in sizes ideally suited to final machining have been considered and could reduce manufacturing costs substantially. This option will be pursued further as demand for POLO increases. The UTD Virginia facility currently has space which can accommodate future POLO manufacture.

Figure 8. The POLO Module has been carefully designed and constructed for uniform bending in all directions.

3.3 Module Calibration

In any type of measurement there are three potential sources of error: accidental, experimental, and systematic. Accidental errors occur because of limitations inherent to the measurement process, such as the resolution of the sensing apparatus. Accidental errors are unavoidable, but can be kept to acceptable levels by selecting appropriate equipment and maintaining it as per the manufacturer's specifications. Experimental errors occur when incorrect procedures are followed and should be eliminated from the data measurement process. Systematic errors occur due to imperfections in the instrument, but deviate from zero in predictable ways. For this reason, systematic errors can be greatly reduced, but not totally eliminated, by applying a calibration factor to the measurement being made.

The POLO calibration procedure reduces systematic errors from all components that influence a strain measurement. Misalignment of the strain gages, attenuation of the electronic signal, and the manufacturing tolerances of the steel components are a few factors that can shift a strain signal from its true value. Small discontinuities in the

POLO Module cross section that are inherent to the sensor design can also degrade the output. In each of these cases, the overall performance is affected in small, yet predictable, ways. Rather than attempting to control each of these variables individually, the easier and more accurate method is to perform a mechanical calibration of the entire POLO System. A known stimulus is applied to the POLO transducer so that a direct comparison can be made between the raw POLO output and the true, or correct, output. Since the POLO output specifically includes the transducer, leadwires, data acquisition package, and computer, a powerful tool to lump together and eliminate systematic error is realized through POLO Module physical calibration. The ratio of the true output to the raw POLO output is a single calibration factor.

A calibration measurement for a single set of test conditions produces a factor that relates the POLO output to the correct output at a single point. Unfortunately, the single calibration value is not applicable over the entire operating range of the device. To fully minimize systematic error, calibration measurements are repeated over the expected operating range of the device. For the POLO Module, the calibration procedure includes a range of deflections, orientations, and ambient temperatures. The resulting one-to-one map of the POLO output to the true output accounts for most of the systematic error of the POLO System. A detailed description of the POLO calibration frame and how it is used is provided in Section 4.4.

4.0 EQUIPMENT INSTALLATION AND MOBILIZATION

Many pieces of specialized equipment were used for the POLO field demonstration. Although vertical penetrometer insertions are most common, a device that pushes the rods into the ground at a near horizontal angle was used to accommodate the unusual constraints of the current field application. Several tools more specific to POLO work were also used and evaluated. The data acquisition system, Initializer, calibration frame, and computer tracking program were developed during earlier phases of the project. Each component was designed for field use and evaluated in laboratory tests that simulated field conditions. Some were modified for the near horizontal insertions. These peripheral pieces of equipment were re-evaluated as an integral part of the field work. All modifications and calibration work on these components conformed to the quality assurance guidelines described in Appendix A - Quality Assurance/Quality Control. Safety equipment is an important topic that is discussed in UTD's Health and Safety Plan, included in Appendix D.

4.1 Penetrometer Equipment

The primary focus of this field research was to evaluate the path tracking performance of the POLO Module. A secondary goal was to adapt POLO for use with a penetrometer, a geotechnical instrument that thrusts small diameter (4.45 centimeter) hollow steel rods vertically into the ground. The vertical insertions were a problem for the POLO demonstration because access to the tip at the end of a run is required to verify POLO tracking. The possibility of pushing vertically from the top of a hillside and diverting the rods towards the base of the slope was considered, but it was found that a "hole-out" could not be achieved without putting an excessive bend in the rods. The 90 degree bend to go from vertical to horizontal over a 30 meter path is difficult for a string of rods to negotiate without breaking. To overcome this problem, a device called a rod pusher was selected for use during the field tests. A rod pusher is similar to a penetrometer except that it operates in a near horizontal orientation and can be used to achieve a "hole-out" of the string of penetrometer rods when used near a steep hillside.

Figure 9 shows the basic rod pusher mechanism consisting of a rigid steel frame, two hydraulic rams, and a cradle. The cradle is a semi-circular tube, 20 centimeters in diameter, that is closed at one end and holds a single penetrometer rod. When the hydraulic rams are activated, the entire cradle moves, forcing the rod forward. The device is approximately 12 feet long and 2 feet wide. Power for the hydraulic cylinders is supplied by an industrial hydraulic system. Pressure gages continuously monitor thrust and a pressure relief valve avoids overthrusting the device.

A rod pusher is typically mounted in a steel cage that is placed in an excavated trench. As a rod is advanced, a reaction force is obtained from the surrounding soil. To minimize environmental disturbance, this standard rod pusher apparatus was

Figure 9. The rod pusher is similar to a penetrometer except that it has a near horizontal orientation.

modified for surface anchoring. As shown in Figure 10, the front end of the rod pusher was mounted to a thick steel plate resting on the ground surface. The steel plate is held in place using an auger stake down system typically used for a large directional drill rig. The rear of the device was welded to 2 adjustable legs so that a variety of penetration angles between 0 and 20 degrees are achievable. The entire rod pusher apparatus weighs about 1 ton. In operation, the device is capable of 20 tons of thrust/pullback force and advances rods at a rate of up to 3 inches per second. No permanent construction or excavation is required to use the device and all equipment is removed upon completion of a test. A 60 horsepower diesel backhoe supplies hydraulic power. Alternately, a smaller and portable 25 horsepower diesel hydraulic power pack can be used.

Although the basic rod pusher apparatus is a field tested device, it is being used in a new and unique way. Namely, a rod pusher is not typically used as a surface mounted device. To help avoid equipment failures during the POLO field tests, a separate field trial was conducted with the rod pusher apparatus well in advance of any POLO field work. The photographs in Figures 9 and 10 were taken during this early test.

The rig was mobilized to a field site and the steel plate was anchored to the ground. For extra safety, 2 additional anchors were driven into the ground and attached to the front of the base plate with log chains. The extra anchors were intended to help hold the base plate in place, but the primary anchor system proved to be more than adequate. As a precaution, the safety anchors will continue to be used during the POLO field work. The anchoring process took approximately 1/2 hour.

Figure 10. The rod pusher apparatus will be mounted above ground to minimize environmental impacts.

On the first test, over 25 meters of standard penetrometer rod were pushed into the ground. Several zones of stiff clay were encountered, but the operator was able to thrust the rods past these difficult areas. After all the rods from the first test were successfully retrieved, the device was set up at a second neighboring test location. The work proceeded with similar success until an immovable underground obstacle (probably a boulder) was struck after pushing about 25 meters of rod into the ground. Primarily due to operator error, the rod pusher continued to force the rods ahead, causing two rods above the ground surface to buckle and break. The remaining rods were successfully retrieved without incident. There are 2 key points to note from this episode. First of all, even as the rods broke the equipment was operated safely. No one was hurt or in danger and no equipment, other than the rods, was damaged. Secondly, the surface anchor system held under an extreme load condition. It was found that the rod pusher apparatus operated with similar success for the POLO field tests.

4.2 Portable Data Acquisition System

During the field test POLO measurements were made away from the convenience of a wall outlet. The data acquisition apparatus used in previous laboratory work was modified to make electronic POLO measurements in the field. Figure 11 is a picture of this new portable version, consisting of a power supply, a portable computer, and strain measurement equipment. Figure 12 is a flow chart that identifies the primary components. The power supply was sourced from a deep cycle (marine-type) battery coupled with a high performance inverter. The sinusoidal AC output signal from the inverter provided a clean noise-free signal to power both the portable computer and strain measurement equipment. A 2 Kilowatt field generator was available to charge the batteries as needed. The laptop computer used was a reliable IBM compatible 286 central processing unit used to execute the POLO tracking algorithm, data sampling, graphics, and data storage. A protective cover was used to keep dust and moisture away from the computer components that are susceptible to this type of contamination. The strain measurement equipment made accurate field data directly available to POLO's computerized tracking algorithm. A strain indicator supplied power to, and samples output from, a single wheatstone bridge circuit. The strain indicator also performed electronic noise filtering and signal amplification functions. A switch and balance unit manually multiplexed the strain indicator through all 6 wheatstone bridge circuits of the POLO Module. An analog to digital converter transformed the raw strain information into a format that the computer could easily process. A 35 meter wireline linked this equipment to the subsurface POLO Module.

Figure 11. The data acquisition system enabled accurate and precise measurements in a field environment.

Figure 12. The data acquisition system used in the program consisted of a power supply, strain measurement equipment, and a portable computer.

The portable data acquisition system was evaluated in an outdoor environment prior to conducting full blown POLO tracking experiments. The purpose of these tests was to monitor equipment performance under hot, windy, and dusty conditions. All components, including the POLO Module, were placed in an outdoor test location during hot springtime weather. The computer and strain measurement equipment were shaded from direct sunlight. The strain gage output was continuously monitored, while a voltmeter was used to check the deep cycle battery voltage at regular intervals. Even after 4 hours of continuous use, strain readings fluctuated a negligible amount and the battery maintained the desired 12 Volt output. Two deep cycle batteries were available during field testing so that one was charged while the other was used to power the test equipment. None of the equipment was affected by exposure to wind or dust from the outdoor environment because of the protective covering that was placed over the critical components.

The preceding discussion describes how these electronic components were ruggedized and how they remained operable in a field environment. Calibration of this equipment is a separate and important topic. A general discussion of calibration is included in Section 3.3. As noted there, it is easier and more accurate to calibrate the portable data acquisition system as an integral part of the entire POLO System. The step by step process for POLO System calibration is described in Section 4.4.

In implementation of the strain measurement equipment used for the program there were three separate, but interconnected, boxes located at the surface with the computer. Several repetitive manual steps, such as depressing the "Enter" key on the computer once for each strain gage bridge measurement was necessary. Communication with the POLO Module was conducted via an analog signal carried over a wireline. While this was an appropriate and accurate way to evaluate prototype sensor

performance, it can be slow and cumbersome. An entirely new and custom built POLO strain measurement package developed independently by UTD, is nearly complete. This package speeds up and simplifies the measurement process and is intended for use after the POLO System is fully commercialized. The new device was not ready in time for the POLO field demonstration and will be evaluated in subsequent POLO field trials. This electronics development task is not sponsored by the Department of Energy, but is a separate internal research and development project entirely supported by UTD, Incorporated.

The upgraded POLO electronics will have numerous advantages over the existing POLO equipment. In fact, the new POLO electronics package is an advance over state of the art for measurements at the tip of ANY underground probe. The new unit locates all of the surface components identified in Figure 12 as "strain measurement equipment" down the hole with the POLO probe. Since all critical measurements and signal adjustments are made in close proximity to the strain gage circuits, the system is less susceptible to errors from long leadwires, unknown temperature differentials or background noise. Of even greater importance is signal transmission to the surface in digital format, which is virtually error-free for any length of leadwire. The current POLO apparatus has 24 leadwires, the new POLO implementation will be powered by and multiplex this same information over only 2 leadwires. The simplification from eliminating 22 of 24 leadwires is a significant improvement.

There are other benefits to having a data acquisition system dedicated to POLO measurements. Surprisingly, the new instrument will probably cost less than its predecessor. The upgrade was specifically designed and built to make a single type of strain measurement, while the original more expensive unit was purchased off the shelf and is capable of a wide variety of strain measurements, few of which are relevant to POLO work. On a different note, the size and shape of the downhole data acquisition package will function in harmony with numerous other sensors to be used in conjunction with POLO. The electronics are fully encapsulated against environmental or mechanical damage and take up a fraction of the space at the center of the POLO Module. Recall that a POLO Module is a hollow tube that has the same size and shape as a standard penetrometer rod. More specifically, the data acquisition package will fit inside a semicircular area that has a 1.9 centimeter diameter. The remaining semicircular area is totally open and can be used to route grout tubes, fiber optic cables, or additional strain gage wires past the POLO electronics and to the extreme tip of the probe for other penetrometer applications.

4.3 Initializer

The POLO System is a dead reckoning navigational tool that starts from a known position and references all subsequent positions back to the original starting point. To make the positioning information most useful, the location of the starting point should be known with respect to an external set of benchmarks. For a standard penetrometer

probe, this procedure is accomplished with the Initializer shown in Figure 13. The Initializer was designed, assembled, and tested in an earlier phase of POLO development. A simple measurement procedure, performed one time at the start of each test, provides all the necessary information. Before explaining the operation of the device, it is important to define a few key terms that are consistent with common surveying nomenclature and convention.

Figure 13. The Initializer measures the position and heading of the penetrometer probe at the start of a test.

As shown in Figure 14, the POLO Initializer makes three angular measurements, β , α and ϕ . By referencing the gravity vector, the vertical axial plane ABCD described by the axis of the penetrometer rods is initially defined. The elevation angle β , the module inclination with respect to vertical measured within plane ABCD, is the first angle measured. The azimuth angle α , which lies in a horizontal plane and is clockwise from project north to the vertical axial plane when looking downward, is measured second. After measuring the β and α compass coordinates, the module rotation angle ϕ is determined. ϕ is the initial angular orientation of a longitudinal reference line on the module measured from vertical in the cross section of the probe. Vertical is defined by the "high side" of the POLO Module that lies in vertical plane ABCD. By convention, the module rotation angle is measured counterclockwise from the axial plane to the reference line when viewed in the direction of penetrometer advance.

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Figure 14. The three angular Initializer measurements conform to standard surveying nomenclature.

Figure 15 is a sketch of the Initializer that identifies its primary components. First, the device is clamped with self-centering v-blocks directly onto a penetrometer rod at a suitable distance above ground level. The Initializer should be positioned so that it rests on the "low side" of the rod and lies roughly in the plane ABCD. It is important to check the cross axis clinometer at this point. If the Initializer is attached correctly, the cross axis clinometer should indicate a cross axis angle close to zero. The elevation adjustment screw is then retracted downward until the platform is firmly seated on the platform stops. Next, the cross axis adjustment knob is used to rotate the base until the axial clinometer reads its maximum value. At this point, the base is in close alignment with the axial plane and the axial clinometer displays the elevation angle. For highest accuracy, the cross axis knob is graduated in degrees and minutes for determining the small amount that the Initializer is clamped off the axial plane. If the error is significant, a correction factor can be applied.

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Figure 15. The Initializer components are ruggedized for field use.

The elevation handwheel is then used to raise the platform until the axial clinometer indicates that the platform is level. The elevation angle is the difference between 2 readings of the axial clinometer. One is taken with the platform seated on its stops, the other with the platform level. With the platform in its leveled position, the transit can then be used to measure the azimuth angle to an external reference point, such as true North. In the final step, the orientation ring is placed on the base and around the penetrometer rod. The protractor scale is equipped with a 5 minute vernier and can be used to measure the module rotation angle. The three measured angles: elevation, azimuth, and module rotation, can then be used by the POLO tracking algorithm to reference external coordinates for position tracking.

For the field demonstration, a penetrometer was used in a near horizontal orientation, rather than a standard vertical orientation. A minor addition to the Initializer transformed it for work in a near horizontal mode. As shown in Figure 16, a horizontal adjustment plate was added to the platform so that the transit remains in a level orientation. In other words, since the rod was shifted through 90 degrees, the Initializer was also shifted by 90 degrees so that the procedure to make the basic angular measurements remains unchanged.

After this modification was completed, the Initializer was re-calibrated. The horizontal Initializer was mounted on the test frame shown in Figure 16. A precision transit was used to survey the azimuth (α) and elevation (β) angles of the braced penetrometer rod. The Initializer was placed on the braced rod and similar measurements were made. A direct comparison of the angles measured by the transit with the angles measured by the Initializer showed them to be accurate and repeatable. The rotation angle (ϕ) was measured manually using a bubble level as a reference and measuring the angular displacement to a reference line scribed on the braced penetrometer rod. This information was compared with the value measured by the orientation ring on the Initializer and once again found to be accurate and repeatable. As reported in earlier phases of work, the Initializer accuracy is better than ± 0.20 degrees for the α , β , and ϕ angles.

Figure 16. The Initializer was adapted to make angular measurements in a near horizontal mode.

4.4 Calibration Frame

Although great care is taken during manufacture, assembly and field use, there is unavoidable error associated with POLO measurements. The same is true for any measurement system. The POLO output is expressed in terms of strain and represents the intensity and orientation of any bend encountered by the POLO Module. Numerous factors, such as misalignment of the strain gages, attenuation of the electronic signal, and the manufacturing tolerances of the metal components tend to shift the strain signals from their true value. These inconsistencies influence overall system performance in small, yet predictable ways. As fully described in Section 3.3, a mechanical calibration of the entire POLO System that specifically includes the POLO Module and electronic components is an accurate and convenient way to lump together and eliminate all these errors at one time. Figure 17 is a photograph of the frame used for calibration of POLO field modules. Figure 18 identifies the primary components of the frame.

Calibration tests on both field modules indicated that the natural bends of the two modules (out of straightness) were negligible. However, it was determined the reference line on the shield of the modules was slightly offset from the alignment with the reference gage. The shield reference line is used to set up the Initializer before the POLO Module is pushed into the ground and appropriate correction was made.

During a calibration test, the POLO Module was linked to the data acquisition system and placed in the calibration frame. The hydraulic jack was used to deflect the POLO Module. The dial gage measured the contour of the bend with respect to the stable base and the orientation ring/vernier measured the direction of the bend with respect to a vertical reference. With the POLO Module held in this stable position, the outputs of the strain circuits at the lag, mid, and lead measurement stations were monitored. The bend contour and direction were computed from this raw strain information using algorithms internal to the POLO computer program. If the contour and bend direction from the electronic measurements were different than the observed values, a single calibration point was attained. By varying the amount of deflection while rotating the POLO Module in the pillowblock bearings a full range of bends could be applied. Any discrepancies between the "observed" and "electronic" position of the POLO sensor over its full range of operation were factored into a calibration routine that was applied to each set of measurements.

4.5 POLO Computer Program

The POLO System is fundamentally different from traditional path mapping equipment. Guidance systems for oil well installations make use of the earth's gravitational or magnetic fields. Locators for the utility industry monitor the signal

Figure 17. Frame used for POLO calibration.

Figure 18. Primary components of calibration frame.

attenuation of a radio wave. Rather than referencing an external parameter that is subject to local anomalies, POLO achieves superior performance by directly measuring the path of the probe. The strain gage signal is not a comparative measurement, but a physical property of the POLO Module that uniquely and precisely describes its path.

The POLO tracking algorithm is based on a physical understanding of the path of the tip of an underground probe, which bends and deflects according to the fundamental equations for beams with transverse loads. A variety of beam loading conditions are possible for a penetrometer. During early advances, when the path is essentially straight, a purely axial load is applied and very little bending is observed. When the probe deflects off an underground obstruction, the loading is more like a "point load". In other instances, more complicated loading conditions may occur. For any of these cases, the three dimensional path of the tip of the probe containing the POLO Module is fully described by the strain measurements. The POLO tracking algorithm simply adds up the path followed by each advance of the penetrometer probe. The running summation for all advances determines the tip location.

Although a penetrometer does not manually rotate the entire push rod string like a drill, it is expected that some wind up will occur, particularly after travelling a circuitous route. In other words, an alignment mark on the POLO Module at the tip of the penetrometer may not correspond accurately with an alignment mark along the entire length of rod at the surface. To accommodate this occurrence, an algorithm to track the rotations of the POLO Module was developed. The bend orientation of the lead strain gage station and the lag strain gage station on the POLO Module are monitored for each advance of the POLO Module. Refer to Section 3.2 for a full description of the layout of the POLO Module and the definition of these terms. At the end of the subsequent advance the lag station is close to the position previously occupied by the lead station. A comparison of the lead and lag orientations at the same spot on the penetrometer path accounts for the rotation or windup of the push rod string.

The POLO tracking algorithm is one part of the much larger POLO computer program. The schematic of Figure 19 shows its overall structure. The top level POLO program controls the flow and accesses each of the lower programs. Internal initialization routines that are transparent to the user are carried out first, then a loop sequentially monitors the sub-programs for each penetrometer advance. The user interface program controls the inputs to the program. Data can be accessed in three ways. The data acquisition program can be used to automatically monitor the strains and distance traveled. In this instance an updated position location is available with a few keystrokes. This option is the most efficient and will be the most frequently used method of acquiring tracking information. The raw tracking information, namely strain and distance traveled, can also be entered manually at a computer terminal or read from a stored data file. The data file option will be most useful for reviewing the history of a penetrometer trajectory after its original insertion. Additionally, all tracking experiments are stored on diskette. Critical information that identifies the date, time, and location of

the penetrometer test are stored along with raw tracking information. With this approach, path tracking information gathered in real time in the field can be analyzed on a computer at a later date. As a side benefit, the deflection information can also be processed to monitor for imminent rod breakage due to excess deflection.

Figure 19. The POLO computer program has a modular structure and enhanced graphic display that makes it user friendly.

The display program shows penetrometer position using screen graphics. Figure 20 is a prototype display that shows the position of the tip as defined by a cartesian coordinate system whose origin is established at the point where the penetrometer enters the ground. The reference system described here is for a penetrometer operating in a near horizontal mode and is defined using the POLO Initializer. In general, vertical penetrometer insertions are much more common. A simple coordinate translation can

be made from the existing horizontal system to whatever system is most convenient for the user. The Y-axis coincides with the principal direction of travel. For a near horizontal insertion, the Y-axis is defined in a horizontal plane as defined by a bubble level and offset a specified azimuth angle from project north. The X-axis is also defined in a horizontal plane as defined by a bubble level, but is orthogonal to the Y-axis. The Z-axis coincides with vertical as defined by a plumb bob.

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Figure 20. The POLO graphic display is a user friendly way to visualize a penetrometer path.

The graphic display of Figure 20 has two parts that provide accurate information on the probe location in a format that is easy to visualize. The left portion of the screen is the deflection circle. The center indicates a straight path that coincides with the horizontal Y-axis defined above. The outer circle represents the maximum deviation from a straight and horizontal penetrometer path over the entire distance traveled. The final version of the deflection circle will be labeled with appropriate units of length such as meters. The cross indicates the tip position of the penetrometer that has deviated from a straight horizontal path. For initial advances, when the path is nearly straight and horizontal, the cross appears near the center of the deflection circle. However, once a deviation occurs the rate of deviation should increase with each advance and the cross will rapidly move away from the center of the deflection circle.

The long narrow rectangle on the right of the computer screen shown in Figure 20 is the distance bar. The entire rectangle represents the maximum horizontal distance to be traveled by the penetrometer. The final version of the distance bar will be labeled with appropriate units of length such as meters. The portion of the distance bar that is black is the current horizontal distance traversed by the penetrometer. The example shown in Figure 20 indicates that the penetrometer has reached approximately half of the total expected horizontal distance. For initial advances the distance bar nearly matches the total length of the penetrometer rod in the ground. As the distance traveled at a non-horizontal angle increases, less of the total rod length contributes to the horizontal distance and the distance bar increases more slowly.

The numbers at the bottom of the screen indicate the exact position of the penetrometer tip in XYZ coordinates. Some of the space at the bottom of the screen is also reserved for the computer to display prompts to obtain more positioning information. For example, after each advance the computer updates the XYZ coordinates and asks if there is more strain information to be processed. The POLO computer program has been compiled in a stand alone system that is easily transferrable to any MS-DOS based computer. The entire program requires less than 150 kilobytes of computer memory. The time required to process the strain information for a single advance is a fraction of a second and will not slow the other penetrometer operations.

5.0 FULL-SCALE FIELD DEMONSTRATION

This chapter describes the field evaluation of the POLO System, inclusive of the final field demonstration on July 20, 1994 at the Savannah River Site. Prior to that event, five weeks of component testing and integrated system testing were conducted. The first tests of the POLO equipment were conducted in Virginia, near the UTD home office. Subsequent tests were conducted at the Savannah River Site. Thus, the first set of field trials encompassed at least two different geologic zones. The detailed Test Plan, submitted to DOE in May 1994, is included as Appendix B. This document describes procedures that were followed during the test and establishes a protocol for the evaluation of the POLO System in terms of its success criterion. The success criterion for the POLO System that was established prior to the Phase I effort and carried through for all subsequent work was to locate tip position to within 0.50% of the distance traveled for distances less than 70 meters.

5.1 Fort Belvoir Field Trial

During early debugging and component testing, angled pushes were planned for a test site on the Fort Belvoir Army Post. Fort Belvoir is located in Northern Virginia along the Potomac River. The test site was a vacant and lightly wooded lot with a steep hillside running along its southern perimeter. It was planned to perform an angled push in the direction of the slope so that the tip of the POLO probe would "hole-out" on the hillside surface. Once access to the tip was gained, standard survey equipment could be used to verify POLO's ability to track position.

Even though several site visits and a geologic investigation were carried out prior to testing, unforeseen and extremely challenging geologic conditions were encountered. About 1 foot below the ground surface a thick layer of pebbles/boulders was encountered. In more than a dozen trials, the penetrometer probe was not able to pierce this layer. The layer also prevented the augers and pins for anchoring the pusher device from being fully engaged. Nearly horizontal pushes were also tried in an attempt to remain above the dense pebble/boulder layer. However, at these more shallow depths, the penetrometer tip got hung up on embedded tree roots. After pushing the machine to the point of breaking the penetrometer rods and working with little success to get the pusher machine adequately anchored at the ground surface, the decision was made to relocate to an alternate site. While a survey of available field sites was conducted, the field work at Fort Belvoir continued.

Although fully integrated POLO tests were not conducted, useful information on individual components was gained. The work at Fort Belvoir was the first time that POLO equipment had been used outside the laboratory. The week of extremely rugged testing included pushing with the full 20 ton thrust of a penetrometer insertion system, breaking neighboring penetrometer rods due to excessive bending, and ambient temperatures in excess of 100° F with high humidity. Even in these worst case

conditions, the POLO strain gage circuits correctly measured bending. Calibration tests performed in the laboratory after this field work confirmed that the POLO Module was not bent or damaged in any way. In addition, the field data acquisition system, more fully described in Section 4.2 of this report, was found to operate reliably. The hot, humid field conditions did not affect this equipment, although extra care was taken to keep dirt away from the critical components. The deep cycle marine battery was able to provide a reliable power supply to the portable computer, strain indicator, and inverter during a long work day.

The POLO Initializer described in Section 4.3 of this report also performed well. The measurement of elevation, azimuth, and rotation were successfully made after the POLO Module was first placed in the ground. In most cases, these critical measurements that establish the starting heading of the POLO probe were monitored with an accuracy of ± 0.1 degrees, which keeps the error due to Initialization a relatively small component of overall system error. As expected with any prototype, the first field use of the Initializer pointed out several areas where refinements could be made. In future versions, the weight of the device will be reduced by using smaller and lighter weight components. Additional ease of use will be provided by designing a mounting bracket to elevate the Initializer for more convenient viewing through the transit.

The rod pusher apparatus described in Section 4.1 operated as planned. The device performed the same function as a traditional vertical insertion system, yet the angled pushes allowed for POLO verification work. The surface anchoring system, used to minimize subsurface environmental disturbance, held the pusher in place when high thrust loads were applied. As with all the other equipment used during the initial POLO testing, the rod pusher served its intended purpose.

5.2 Kingstowne Field Trial

Gravel pits, sand pits, and stone quarries were all evaluated as potential alternate POLO test sites. These sites were either unsuitable for POLO testing or were located too great a distance from the UTD home office. With the assistance of the Halle Company of Silver Spring, Maryland, a nearby vacant field slated for future development was located. The site included a ridge with sandy clay soil that was ideal for POLO tests. After having the site inspected by Miss Utility, the POLO equipment was mobilized to the top of this ridge for the second week of POLO testing.

Over the next week, four fully instrumented POLO pushes were completed. The same procedure was used for each test. While the rod pusher was set up and anchored to the ground surface, the POLO electronics were set up. This work included pre-threading 130 feet of leadwire through the penetrometer rods and connecting it to the POLO Module. At the start of a test, the POLO Module was placed into the cradle of the rod pusher and thrust into the ground. The Initializer was placed directly on the POLO Module and used to determine the initial heading of the device by measurement of the

azimuth, elevation, and rotation angles. The initialization procedure was extended to provide information for the independent survey. Using the transit mounted on the Initializer, the azimuth heading of the probe was laid out with survey stakes. With this approach, the azimuth heading was local to the current test. Any deviation from this straight heading when the tip "holed-out" was measured by survey and used for POLO verification. When the survey work was completed, the Initializer was removed and the first set of POLO tracking measurements was made. Six full bridge strain circuits on the POLO Module were directly acquired by the computer in less than 10 seconds. This information was processed by the computer and used to instantaneously update the location of the tip. The string of penetrometer rods was then advanced one meter into the ground. The circuits of the POLO Module, located at the tip of the penetrometer rod string, were monitored as another section of rod was added at the surface. The process of signal measurement and rod advancement was repeated until the tip of the string "holed-out" on the slope of the hillside.

While the rods were still in the ground, the survey for POLO verification was conducted. The "X" coordinate was measured by tape and is the left or right distance from the tip to the azimuth line that was laid out earlier. The "Y" coordinate was also measured by tape and is the horizontal distance along the azimuth line from the starting point to the tip. The "Z" coordinate was measured using a stadia rod and a tripod-mounted transit and is the difference in vertical height from the start point to the finish point. The error for the POLO run was found from the difference between the X, Y, and Z from POLO and the X, Y, and Z from the survey using the common root mean square method and taking account of the uncertainty in the survey values.

On the basis of the four Kingstowne tests, it was found that the POLO Module behaved differently than originally anticipated. It was originally thought that the POLO probe would conform to a single path due to the lateral confining pressure of the soil. However, it was found that when a penetrometer follows a curved path, (and they almost always do!), the transverse components of the end forces must be counterbalanced by interaction with the soil shown in Figure 21. These counterbalancing forces between the penetrometer rod and the soil place compressive forces on the soil which give rise to two phenomena affecting the accuracy of the POLO system.

The first phenomenon is soil compression. If the forces are very light, the pressures may remain in the elastic region so that the rod deflects outward momentarily when loaded but returns to its original path position when the thrusting load is removed. Heavier forces result in heavier deformations which remain after the load is removed.

The second phenomenon might be called soil scrubbing. This is caused by a combination of the counterbalancing forces with relative motion between the penetrometer rod and the soil as the penetrometer advances. Particles of soil are loosened and moved toward the inner side of the curve, causing the centerline of the penetrometer rod to move outward away from the original center of curvature.

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Figure 21. Interaction between penetrometer rod and the soil.

Both of these phenomena cause the hole cross section to become elongated. This allows the penetrometer rod to lie in the hole in a different configuration from that seen by the POLO unit when it traversed the original path. Although this effect is small, it becomes important when one is seeking to maintain a locational error smaller than 0.5%. The effects have been analyzed on an empirical basis in the following way.

The magnitude of the pressure of the rod on the soil is determined by two factors. The first is the severity of the bend. As shown in Figure 21, the lateral components of the forces at the ends of the penetrometer rod increase with decreasing bend radii, and these determine how large the counterbalancing forces must be. The second is the strength of the soil. A stronger soil will require increased thrust forces, resulting in larger lateral pressures. However, stronger soils will have a proportionally greater ability to support pressures from the penetrometer rod, so we shall assume that the net effects of strength on deflection are neutralized.

The amount of scrubbing taking place is assumed to be related to three factors. One is the strength of the soil, e.g., its ability to resist scrubbing action and the dislodgment of particles. The second is the magnitude of the pressure exerted by the penetrometer rod on the soil. As mentioned above, this is a function of the severity of the bend. The third is the amount of relative motion. This means that if 50 feet of rod are pushed past a point on the curve, we would expect the soil removed by scrubbing to be double the amount removed when only 25 feet of rod pass that point.

The above reasoning was developed into an operational framework and used to correct each of the four data sets collected at Kingstowne. Table 2 summarizes the output of the tracking experiments at Kingstowne. The first column identifies the test and

the second column identifies the total length of rod in the ground. The next 3 columns of data are the X, Y, and Z coordinates of the survey data. The last column is the total error, expressed in terms of the distance traveled. The error term was computed by computing the difference between the POLO coordinates and the survey coordinates and combining them using the root mean square method. In one case, Test No. 4, allowance was made for the ± 0.5 inches uncertainty in the survey coordinates. It can be seen that after the soil conditions are accounted for, the POLO System met the success criterion of tracking with less than 0.50% error.

5.3 Savannah River Field Demonstration.

After the Virginia tests were successfully completed, preparations for the demonstration at Savannah River were initiated. Prior to any field work, an 8 hour training session was attended by all field personnel. This included the UTD field staff as well as the penetrometer subcontractor, Ditch Witch of Georgia. With the assistance of the Environmental Sciences Group of the Savannah River Technology Center, all equipment was mobilized to a site near the railroad tie disposal site in area F. As shown previously in Figure 4, the area includes a steep ravine that was thought to be ideal for angled pushes. Tests over the next week proved otherwise.

Table 2. POLO tests at Kingstowne, Virginia.

Test No. ---	Total Distance inches	Survey Coordinates			System Error %
		X	Y	Z	
1	276	-11.9"	272.0"	-33.8"	0.22
2	552	-85.7	529.3	-98.5	0.25
3	413	-43.9	401.3	-72.6	0.13
4	394	-20.3	386.5	-66.3	0.48 ⁽¹⁾

⁽¹⁾Survey coordinates are estimated to have errors of ± 0.5 inches to ± 1.0 inches based on an independent check.

The tests were laid out similar to the work in Virginia. The only significant difference was that extreme caution and safety gear were used for work near the ravine. The shear walls were always viewed as a potential cave-in hazard. Several angled

pushes were attempted in this area, but met with limited success. A hard layer approximately 3 feet below ground surface consistently stopped forward advance. When the "brute force" method was attempted, the first significant damage to the POLO Module took place. The end adapter that joins the sensor portion of the POLO Module to the trailing penetrometer rod broke free, leaving the expensive sensor stranded below the ground surface. With approval for limited backhoe excavation, a shallow pit was dug. During this process, the backhoe blade inadvertently struck the POLO Module and broke the protective shield. Interestingly enough, even after the POLO Module was in two pieces, the strain gage circuits continued to function properly. This mishap could not be repaired quickly in the field, thus ending the first week of testing at the Savannah River Site. Repairs to the damaged POLO Module were conducted at the UTD home office prior to further testing.

The week prior to the field demonstration, tests resumed at the Savannah River Site with the second POLO Module. Rather than attempting to push through the tough virgin soil next to the ravine, pushes were made through a large man-made mound adjacent to the ravine as shown in Figure 22. The less consolidated soil proved easier to push through. Over the course of three days leading up to the public field demonstration, three successful POLO pushes were made through the mound. Once a suitable amount of data for the site was available, the emphasis shifted away from field research and toward preparations for the public demonstration.

The public demonstration was made to an audience of fifteen people which included government and industry representatives. Prior to visiting the site, the representatives were given a briefing which explained the purposes and principles of operation of POLO. In a question and answer period which followed, a consensus was expressed that POLO should be useful in a number of applications. Several participants urged the DOE to continue its involvement in any way possible to assure having POLO available at the earliest possible date and support its integration into other applications.

Following the discussion, the group moved to the field demonstration site. See Figure 23. There, the POLO system was operated, and the group was given an opportunity to observe and ask questions. One technical problem occurred which was attributable to field testing from the previous day's run. During that previous run, human error led to severing the umbilical cable. This required major repairs and a reworking of the computer program, all of which were done by the crew working throughout the night prior to the public demonstration. In the confusion which followed, the computer program was altered to accommodate some changes in module circuitry. The resulting program did not include all necessary steps and, as a result, provided incomplete trajectory information. Project personnel, utilizing hand calculation, were able to work with the primary data to develop a prediction of the "hole-out" position of the penetrometer. This was found to agree with coordinates surveyed in by Savannah River Company (SRC) personnel and by the UTD survey team to within 0.36%. (Survey results agreed with each other to approximately 0.25%.) Thus, the results of the public

demonstration were within accuracy expectations, despite the technical difficulties. This event demonstrated the value of maintaining a file of primary data, which the system was designed to do on all runs.

Figure 22. Penetration through a man-made mound.

Table 3 presents a summary of the results obtained during the four Savannah River tests mentioned above. It is laid out in the same format as Table 2 (Kingstowne results). The computed error may be seen to fall within the $\pm 0.5\%$ goal established at the beginning of the project.

Figure 23. POLO public demonstration.

Table 3. POLO tests at Savannah River.

Test No.	Total Distance inches	Survey Coordinates X Y Z			System Error %
1	589.0 est	3.4"	588.0"	1.2"	0.45
2	616.2	33.9	608.4	-5.6	0.46
3	557.6	-39.3	553.2	-18.6	0.48
4	413.7	5.7	412.9	-23.7	0.36 ⁽¹⁾

⁽¹⁾Based on SRC survey data.

5.4 Discussion

Tables 2 and 3 summarize the results of the error analyses for field tests and the final demonstration test at two test sites. The results indicate that POLO met the success criterion of accuracy to 0.50% distance traveled. The Virginia site was a natural deposit with normally consolidated clay whereas the Savannah River tests were performed in a non-compacted man-made mound of sand to cobble size particles. Thus, POLO has been shown to perform in two significantly different types of soil.

One of the requirements for the field tests performed on POLO has been the ability to survey the penetrometer tip when it "holes-out". This allows the POLO predictions to be compared with the survey data. The only way possible for "hole-out" at the surface or on the side of a slope is to perform near horizontal pushes. Because conventional penetrometer trucks cannot push rods at shallow angles, a rod pusher was used in the field tests. However, no modifications in the POLO system are required for conventional penetrometer usage.

POLO test results from the use of a rod pusher are less accurate because the rod pusher and its anchorage to the ground are more flexible than a penetrometer truck. This allows variations in insertion angles as POLO is being pushed into the ground. A slight variation in the elevation angle for the first couple of pushes can significantly affect POLO predictions. In conventional penetrometer applications this effect will be minimal and the errors are expected to be smaller.

Another difference in POLO performance using a rod pusher compared to conventional penetrometer trucks is that with the rod pusher most of the path is at a relatively shallow depth with small confining pressures. This allows the POLO module to translate laterally more freely in the hole as it is being pushed forward, which results in larger errors. In conventional penetrometer applications the path gets deeper with each push, resulting in larger confining pressures. This in turn keeps POLO from translating laterally in the hole and is expected to result in more accurate mapping of the hole.

At the end of the Phase II laboratory testing of this contract an error analysis was performed to determine the contribution of the error from individual components of the POLO system to the overall system error. In addition, predictions were made regarding the field based errors. The results of this analysis are shown in Table 4. Based on the field tests and observation of the individual components during the Phase III effort, the field based predictions shown in Table 4 are considered to be accurate and remain unchanged.

Table 4. POLO meets or exceeds the success criteria.

Components	Error	
	Laboratory based	Field based
Module	$\pm 0.10\%$	$\pm 0.25\%$
Signal Conditioning	0.10%	0.20%
Computation	0.20%	0.25%
Initializer	0.10%	0.25%
Predicted System Error	$\pm 0.26\%$	$\pm 0.48\%$

5.5 Conclusions

The main conclusion drawn based on the field tests performed in Phase III is that the POLO system can map the path of a penetrometer with an accuracy of 0.50% of distance traveled. The ability to know the position of the penetrometer is a significant advance in the current state of the art and will make penetrometers useful in more diverse applications.

A secondary conclusion is that the POLO system has been shown to be robust and fully useable under field conditions.

6.0 COMMERCIALIZATION

The Department of Energy's Environmental Restoration and Waste Management program and the existing Program Research and Development Announcement (PRDA) are designed to accomplish, in addition to other goals, the development of tools and methods for the characterization, remediation, and monitoring of underground environmental conditions. This mission will lead to the development of new technologies that provide faster, better, and safer solutions. UTD has maintained direct contact with field sites of the Department of Energy and other federal agencies as system needs are continuously refined. This discussion focuses on problems that cannot be solved with current technology, and highlights the role of a fully commercialized POLO System for environmental restoration. Representatives from these organizations attended the field demonstration. The following list is not exhaustive and is a small part of the larger discussions that have been underway for several years.

At the Savannah River site, the characterization of waste and contamination beneath buildings is a concern, but the recognized need for accurate position location adjacent to steel reinforced concrete has not been met. Penetrometers for expedited site characterizations, enhanced by the POLO System, could be a cost effective way to accomplish these inspections. To provide a first-hand look at the new POLO technology, the Environmental Sciences Division of the Savannah River Technology Center agreed to host the full-scale POLO field demonstration.

The characterization and remediation of deep soil contamination at Savannah River is also a concern. Directionally drilled parallel horizontal wells have been used to extract waste by the injection and extraction of methane and other nutrients in gaseous form, but the cost of oil well directional drilling techniques is very high. Penetrometers enhanced by the POLO System could perform position specific sampling and dramatically cut characterization costs while improving the quality of data collection.

The Idaho National Engineering Laboratory (INEL) has numerous poorly defined pits in alluvium which have been filled with mixed wastes. The potential for leaching of contaminants is high and must be carefully monitored. When leaks are identified and prior to full-scale remediation, a site characterization must take place. INEL researchers are performing a needs analysis for a new sensor delivery system to conduct these types of remote underground evaluations. Since a key element of this system is the ability to precisely determine underground position, UTD was contacted about using the POLO System to provide real-time path tracking information. Informal discussions have been maintained with reciprocal visits between INEL and the UTD home office.

The Hanford site has over 150 underground storage tanks where the surrounding soil and substrata must be characterized before attempts are made to remove or treat the waste. The site also requires the characterization of underground conditions beneath several buildings. Penetrometers have been successfully utilized to help the

environmental restoration efforts. However, the POLO System will significantly improve the time of characterization as well as safety by pinpointing the sampling location beneath tanks and buildings. A specific interest by Hanford personnel in having POLO integrated into directional drilling equipment for other applications has also been expressed.

A tri-service effort, along with DOE support through the Department of the Army is actively developing new sensors and equipment for the Site Characterization and Analysis Penetrometer System (SCAPS). The SCAPS systems are being assembled by the Army Corps of Engineers (COE) for use by the Army Environmental Center (AEC). In briefings to both the COE and AEC, the significant increase in capability that could be made by incorporation of the POLO System into its penetrometer operation has been recognized.

While the research for the Department of Energy has focused on the development of POLO for use with penetrometers, the true market is much broader. Virtually every underground probe could benefit from the locational capabilities that the POLO System makes available. Discussions are underway for the development of the POLO System for several other technologies. The five major commercialization areas for POLO being pursued include:

- * Environmental Characterization (This DOE PRDA Application)
- * Utility Contractor Directional Drilling
- * Micro Tunneling
- * Oil and Gas Slim-hole Directional Drilling
- * Mineral Exploration Borehole Surveys

To reach the broadest audience, numerous presentations have been delivered at national conferences. Most recently, a paper entitled "POLO: An Entirely New System For Directional Boring Tracking" was presented at the annual No-Dig Conference sponsored by the North American Society for Trenchless Technology (NASTT) in Dallas, Texas in April of 1994. NASTT is the national society for directional utility contractors, another area where POLO is expected to have wide application. The paper and presentation highlighted some of the key features of POLO, namely that it is not influenced by either magnetic materials or overlying structures. Subsequently, new partnering discussions were held with several interested parties.

APPENDIX A
QUALITY ASSURANCE/QUALITY CONTROL

INTRODUCTION

This Quality Assurance/Quality Control program has been established to ensure that the level of accuracy, precision, and reproducibility of data is adequate to fulfill the objectives of the work to be performed. Given the nature of the research to be conducted, brand new technology may be developed and experiments heretofore not conducted will be performed. As a result, standards for use of newly developed equipment inclusive of techniques necessary to ensure optimal conformance with objectives A and B will be developed and reported on within the appropriate program documentation. It is recognized, however, that most experiments can be broken down into several basic components regardless of the subject of the experiment. The remainder of this QA/QC program document addresses these elements which are grouped as follows.

- 1) A procedure to control experimental conditions using technical standards, instructions, and other appropriate means commensurate with the complexity and risk of the work;
- 2) A procedure to identify, control, and maintain components, equipment, facilities, hardware, and material;
- 3) A procedure to control handling, storage, shipping, cleaning, and preservation to prevent damage, loss, or deterioration;
- 4) A procedure to control calibration, maintenance, accountability, and use of measuring and testing equipment used for monitoring and data collection;
- 5) A method(s) to ensure that designs use sound engineering/scientific principles and current appropriate standards;
- 6) A procedure to ensure that purchased items and services meet requirements established for them by the performing organization;
- 7) A procedure to specify when and what type of inspections are required;
- 8) A procedure to demonstrate that equipment and processes perform as intended; and
- 9) Procedures to continually improve the quality of the work done through the improvement of work practices guided by internal performance assessment.

Each of the foregoing program elements is dealt with separately in the following sections (by number).

1) EXPERIMENTAL CONTROL

In keeping with standard scientific and engineering practice, a plan for each experiment to be performed will be developed. The plan will include a statement of the scientific objective of the experiment, the procedures to be used during the experiment, the variables to be controlled, and variables to be measured will be described inclusive of level of accuracy. Careful consideration of contract success criteria will be made when identifying the level of accuracy required in making measurements. The experimental plan may be in the form of internal handwritten memos, engineering notes, and/or performing engineer/scientist diary entries (with foreknowledge that disclosure of individual experimental plans to UTD management and contract sponsor is required upon demand).

2) COMPONENTS, EQUIPMENT, FACILITY, HARDWARE, ETC.

All components, equipment, facilities, hardware, etc., identified as required for the conduct of research will be treated with care and in accordance with standard UTD, Incorporated inventory practice (where appropriate). Manufacturer recommended maintenance practices will be followed where applicable. All facilities will be kept neat and orderly to facilitate a safe work place for all employees.

3) PREVENTION OF DAMAGE, LOSS, DETERIORATION

Equipment will be handled, stored, shipped, and cleaned in accordance with manufacturer supplied instructions. Practices will be defined which will optimize the utilization of the equipment while providing for prevention of damage, loss and/or deterioration.

4) MEASURING AND TESTING EQUIPMENT CONTROL

As equipment and facilities are required for use in conduct of an experiment, the individual responsible for development of the experiment plan will determine the status of all necessary equipment. Calibration and maintenance issues pertaining to the equipment will be carried out as required within the context of manufacturer recommendations and complied with prior to experiment performance.

5) SOUNDNESS OF APPROACH

All experiment plans will be reviewed and discussed with the project Principal Investigator, Program Manager, project QA/QC Officer, and UTD's Vice President of Operations prior to experiment execution. The experiment will be scrutinized in the context of relevance to overall contract objectives, success criteria, required accuracy, and for compliance with UTD's corporate philosophy of approach which stresses the observance and role of fundamental physical laws.

6) PROCUREMENT ACCEPTANCE AND PERFORMANCE STANDARDS

As equipment, services or supplies are purchased for performance of the subject contract, acceptance of such will be subject to the qualifications identified within individual purchase orders. Product conformance to purchase order qualifications will be made solely on the judgment of the engineer or scientist ordering the equipment, service or supplies. Performance standards commensurate with the success criteria identified within the program will be used.

7) INSPECTIONS

All purchased equipment, supplies, and materials which are modified by subcontractors will be inspected upon shipment and prior to acceptance of delivery for conformance with purchase order specifications. Given that the volume of such purchases is anticipated to be relatively low, all such items will be inspected in light of conformance as opposed to the standard large volume practice of sample inspections.

8) EQUIPMENT AND PROCESS PERFORMANCE

Prior to performance of experiments, the required equipment will be evaluated and tested to ensure that it is working within manufacturer specifications. All experimental results will be compared against predicted experimental performance, and identification of potential sources of differences will be postulated and tested to verify source of error where possible. In this manner the influence of equipment or processes not performing per expectation will be specifically identified and quantified.

9) QUALITY IMPROVEMENT THROUGH PERFORMANCE ASSESSMENT

Post experiment review of all experiments will be performed by the performing scientist/engineer, Principal Investigator, Program Manager, project QA/QC Officer, and UTD, Incorporated Manager of Operations. Experimental results and experimental procedures used will be reviewed and evaluated in light of "hind sight" to determine if

lessons learned can be used in future experiments. Identification of such opportunities will be documented and included within the appropriate program documentation.

Any questions and/or unusual circumstances may be discussed with UTD's QA/QC officer (Mr. John Hill) or Vice President of Operations (Mr. Ali Amini).

APPENDIX B

TEST PLAN

INNOVATIVE DIRECTIONAL AND POSITION SPECIFIC SAMPLING TECHNIQUE

Test Plan For POLO Field Demonstration

May 1994

B.1.0 PURPOSE

This document describes, in a narrative format, the equipment and procedures that shall be followed during the field test of the POLO System, a new technology to locate the tip of a probe as it moves underground. The report establishes a framework from which safe and successful field research can be conducted. It also clearly documents how the POLO demonstration shall meet all the guidelines specific for drilling work at the Savannah River Site. Section B.11.0 establishes a more rigid set of protocols, presented in an experimental format that documents how POLO performance will be evaluated with respect to the pre-established success criterion. The project is sponsored in part by The Department of Energy's Environmental Restoration and Waste Management Division, whose mission, in addition to other goals, is the development of tools and methods for the characterization, remediation, and monitoring of underground environmental conditions. The POLO System will help provide faster, better, and safer solutions to these environmental restoration problems.

B.2.0 SCOPE OF WORK

It has long been recognized that new and innovative solutions are needed to increase the accuracy and efficiency of equipment for environmental restoration. Subsurface exploration is one critical area where technology lags behind the demand. Traditionally, expensive monitoring wells have been used for finding contamination, identifying extent of contamination, remediating, and finally monitoring sites. Recently, underground probes delivered by a penetrometer system have been used as cost effective alternatives to monitoring wells. Penetrometers achieve higher rates of advance by pushing small diameter rods into the ground and avoiding the rotary motion of a drill. With any of these methods, the path of the well or the penetrometer probe is known with only broad approximations. As a result, the location of the sampling point is uncertain, when in fact small errors can have a significant impact on the interpretation of plume origins and other characteristics.

The POLO System for the field demonstration has been configured for use with penetrometer systems. POLO locates the tip position of a penetrometer as it is placed underground while meeting the rigid constraints of environmental restoration applications. POLO is applicable to small diameter probes, does not obstruct the center of the probe, is rugged, is unaffected by the presence of steel or other magnetic material, and is capable of remote operation beneath steel tanks or foundations. Other than displacing a small amount of soil as it moves underground, the penetrometer based POLO Module is a passive device that does not interact with the subsurface environment in any way.

B.3.0 PERMITS AND CLEARANCES

Before any field work is initiated, the required forms will be submitted and approvals obtained. The initiating document for any field research project is the Test Plan. This report is developed by the Project Manager, reviewed by UTD Management, and submitted to the personnel in charge of the field site. It contains relevant information on the scope of work and the materials to be used. A Project Health and Safety Plan will be submitted with the Test Plan. The Health and Safety Plan defines potential hazards to the field crew and specifies protective measures that will be taken to guard against injuries or exposure to health hazards.

Beyond the Test and Health and Safety Plans, additional permits and clearances are site specific. The documentation described here is required at the Department of Energy's Savannah River Site in South Carolina, but is representative of the level of documentation at other locations. A Site Clearance Permit will be obtained to prevent subsurface work in an area where various interferences exist or in areas scheduled for construction. A Work Clearance Permit (WCP) will be obtained after the project's health and safety documentation is reviewed and approved. All field personnel will sign and date the WCP to indicate that they are aware of all job requirements at the worksite.

B.4.0 TEST PREPARATION

Almost 2 years have been devoted to the design, manufacture and testing of the POLO System components. Each piece was designed for field use and evaluated in a laboratory environment that simulated field conditions. In this way, many of the problems encountered in scaling up from the laboratory to the real world can be avoided. For example, the laboratory prototype POLO Module, intended for use at the tip of the penetrometer probe, was designed, assembled, and tested with the full size and shape of a penetrometer rod. Rigorous testing of the POLO Module, its associated data acquisition system, and the POLO Initializer that locates the starting position of a penetrometer test demonstrated the feasibility of the POLO concept. Laboratory scale tracking experiments that specifically tested all components as an integrated system had similar success. The success criterion used to evaluate all testing was tracking to within 0.50% of the distance traveled. All work to date has met or exceeded this requirement. On this basis, the POLO System was deemed ready for a full scale field demonstration.

In preparation for the field work, final modifications to the POLO equipment were made. Small modifications were required for most components. For example, a portable power supply for the data acquisition system was developed and tested so that POLO measurements can be made in the field, away from the convenience of a wall outlet. The power supply consists of a 12 Volt deep cycle marine battery and a high performance inverter that produces a clean sinusoidal AC signal. In addition, environmental protective coverings were installed to shield electronic components that are susceptible to moisture and dirt.

B.5.0 EQUIPMENT AND MATERIALS

UTD, Incorporated and the penetrometer subcontractor will furnish all equipment, materials, and labor to conduct the POLO field tests. The primary piece of field equipment is a penetrometer device which has been modified for angled insertions. This unique device is shown in Figure B-1 and is fully described here to highlight its simple and rugged construction, as well as its capability for safe operation. The penetrometer rig consists of a rigid steel frame, two hydraulic rams, and a cradle. The cradle is a semi-circular tube, 8 inches in diameter, that is closed at one end and holds a single push rod. The hydraulic rams push against the rigid steel frame to force the cradle forward. This action thrusts a rod into the ground. The entire device is approximately 12 feet long and 2 feet wide. Power for the hydraulic cylinders is supplied by an industrial backhoe. Pressure gages continuously monitor thrust and a pressure relief valve avoids overloading the push rods. The entire apparatus is mounted to a thick steel plate that is anchored to the ground surface. The penetrometer rig weighs about 1 ton, is capable of 20 tons of thrust/pullback force, and advances rods at a rate of up to 3 inches per second.

The penetrometer rig was successfully field tested. The device was anchored to the ground and used to thrust over 80 feet of rod into the ground at a shallow angle. The push rods are 1 3/4 inches in diameter and 40 inches in length. The sandy clay soil was similar to what will be encountered at the Savannah River Site. As noted earlier,

Figure B-1. The penetrometer rig is capable of near horizontal insertions.

an industrial backhoe was used, not for excavation, but to supply hydraulic power. Even after striking several underground obstructions, including one immovable obstacle, the penetrometer rig remained undamaged and anchored securely to the ground. At all times the device was operated in a safe manner. No permanent construction or excavation was required to use the device and all equipment was removed upon completion of the test. Similar performance is expected for the work at the Savannah River Site.

Additional equipment is required for test support and routine maintenance. All equipment will be maintained in good mechanical condition and used within its operational limits. At least two one-ton service trucks and one utility trailer will be on site to supply materials, tools, and spare parts during the field test. Grouting equipment, to include grout pumps, hoses, tremie pipe, and mixing equipment will also be on site. A steam cleaner will be available as necessary for cleaning the equipment.

The list of safety equipment is extensive and is fully documented in the Health and Safety Plan. Standard safety equipment includes hardhats, safety glass, steel-toed workboots, and safety glasses. Plastic sheeting with a minimum 4 mil thickness will be on hand for placing under leaking equipment.

POLO equipment will be relatively unobtrusive compared to the larger equipment for performing the test. Nevertheless, it is among the most important equipment at the worksite. The only downhole device is a steel POLO Module, which has the same shape as a penetrometer rod but is twice as long. Data logging instrumentation for the POLO Module includes a data acquisition system and a personal computer, both powered by battery. Customized surveying equipment for locating the starting point of a penetrometer insertion completes the POLO package.

B.6.0 FORT BELVOIR FIELD TRIAL

A preliminary field trial will focus on evaluating individual POLO components close to home and before mobilizing to a distant field site. The work will take place near the Hydrology and Soil Testing Activity at Fort Belvoir on or about June 13, 1994 and conclude two weeks later on June 24. In some cases, it will be the first time that the equipment has been used in an actual outdoor environment. A key part of this work is gaining familiarity with how the equipment can be most effectively used. Some debugging and refinement work in this area is expected. For example, the Initializer is a surveying tool that has been customized to determine the penetrometer insertion point. Its measurements define the starting penetrometer heading for use by the POLO tracking algorithm. Actual field trials will determine where it is most convenient to clamp this device onto the push rods for an accurate and precise reading while avoiding obstructions on the penetrometer rig. After all the equipment is up and running, test pushes will be performed at the top of a steep hillside and directed toward the slope.

When the penetrometer tip emerges somewhere on the slope, a survey will determine the start and end points. Tests that specifically include all POLO components will provide the greatest insight into where improvements should be made.

B.7.0 SAVANNAH RIVER DEMONSTRATION

The POLO field demonstration will allow for further refinements and provides a forum for the display of the new locator technology. This narrative discussion gives an overview of the field work and highlights how the guidelines specific to work at the Savannah River Site will be met. Attachment A establishes the detailed experimental procedure that will be followed to evaluate the POLO System with respect to the pre-established success criterion. The work at Savannah River will commence on or about June 27, 1994 and conclude three weeks later on July 15. The pushes will be performed in an area adjacent to the railroad tie disposal pit near the F-area. The exact location of the test site is summarized in Table B-1, which contains the Savannah River Company (SRC) grid coordinates for two neighboring test areas.

Table B-1. The SRC coordinates identify the size and location of the two test areas at the Savannah River Site.

TEST AREA	EASTING COORDINATE (feet)	NORTHING COORDINATE (feet)
1	50100	80100
	50300	80100
	50100	79900
	50300	79900
2	50450	80000
	50950	80300
	50950	79850
	50450	79850

B.7.1 Equipment Inspection

All equipment shall be available for inspection upon arrival to the worksite. As required, an inspection sticker with an expiration date will be maintained on equipment upon completion of a successful inspection. The Project Manager is responsible for the equipment re-inspection before the expiration date.

B.7.2 Personnel

The worksite will be run by a Project Manager who is supported by a team of experienced field engineers. The field engineers will monitor the POLO tracking equipment. In the absence of the Project Manager, the Senior Field Engineer will manage the worksite.

The penetrometer rig will be operated and maintained by a two-man team of skilled field technicians. The equipment operator has extensive experience in the utility drilling industry, where work is performed close to the surface and well above the water table. All work for the POLO demonstration will be conducted above the water table, without drilling mud, and without bringing spoil to the surface. In addition, the work will be performed at uncontaminated locations. The usual requirement of a licensed driller in the State of South Carolina is not applicable in this case. This near surface operation does not constitute a "drilling" activity.

All personnel shall be instructed in the operation of the penetrometer rig and safe working practices before mobilizing to the worksite. In addition, all personnel shall attend an orientation session on safety, security, and environmental concerns given by the Savannah River Site Supervisor when they arrive at the worksite.

B.7.3 Worksite Setup

All work will follow the procedures documented in the Health and Safety Plan. The worksite will be clearly marked with a rope barricade. All work in or around this area will be closely monitored by at least one field engineer.

B.7.4 Test Procedure

This section gives an overview of the POLO work. Refer to Attachment A for an experimental plan for the evaluation of POLO with respect to a pre-established success criterion.

The penetrometer rig described in Chapter B.5.0 will perform the tests. The POLO tool will be added to the cone penetrometer tip and angled pushes will be performed. All penetrometer work will be conducted in a near horizontal orientation and above the water table. It is expected that one, and possibly two, subsurface

penetrometer paths will be traversed during each work day. The diameter of the probe is 1 3/4 inches. It may be possible to use the same penetrometer hole more than once. All holes will be backfilled with grout as described in the subsequent detailed discussion.

The goal of this work is to demonstrate path tracking performance, so access to the tip is required at the end of a run. This will be accomplished by directing the angled push from the top of a hill towards a steep slope. Both test areas have an exposed face due to erosion which will allow a push from the horizontal surface to the near-vertical face. The entry and exit holes will be surveyed to determine the accuracy and precision of the POLO tool.

During the first week at Savannah River, work will continue as at the Fort Belvoir field trials. Individual components will be tested, specifically including any modifications made during preliminary field trial. Additional debugging and refinement work is expected. Although the soil types at both test sites are roughly classified as sandy clay, it will be particularly interesting to evaluate POLO performance at different field sites. By the start of the second week, the focus will shift towards completing repeatable and accurate integrated system tests that include all POLO components. Over time, insight will be gained into more subtle aspects of POLO operation. For example, the POLO Module is calibrated before being used downhole. What is an appropriate calibration interval?. Should the device be calibrated on a daily or weekly basis? A portion of the third and final week of research will be a demonstration that is open to DOE field personnel as well as invited guests from industry.

B.7.5 Hole Documentation

Each penetrometer hole will be clearly documented after its completion. The documentation will include the date of the work, the Savannah River Company grid coordinates of the starting point, the total depth achieved during the near horizontal penetration, the total hole length, and the hole diameter. The abandonment procedure for each hole will also be noted.

B.7.6 Hole Abandonment

After a test, each penetrometer hole will be open to the soil and not cased in any way. To complete the abandonment process, a tremie pipe will be placed to the end of the hole in preparation for grouting. Cement grout free of lumps will then be pumped through the tremie pipe, pulling the tremie pipe up periodically until grout returns to the ground surface. The remaining tremie pipe will then be removed from the hole and the hole will be topped off with standard grout mix, bringing the cement level to ground surface. The site will then be cleaned and restored to its original condition. The grout will then be allowed to cure.

A standard grout mix shall be used for each hole. The mix includes one sack of Class A Portland cement (94-lb sacks), two pounds of dry sodium bentonite, and approximately 7 gallons of potable water. This mix will produce approximately 1.4 cubic feet of grout, which will fill a 100 foot penetrometer hole. The grout as pumped shall weigh between 13.2 and 15.0 pounds per gallon. The mixing of grout will be done in such a manner that the bentonite is distributed evenly throughout the grout with no lumps present in the mix being pumped into the well. Measures to dispose of excess grout in case the hole caves in during the hole abandonment procedure have been considered. The work is greatly simplified because of the small volume of grout to be used. As noted above, the grout will be mixed in 1.4 cubic foot units, or approximately 10 gallons at a time. When one penetrometer hole is full, the equipment will be quickly mobilized to a neighboring hole to continue the abandonment efforts. If no other holes are available, the grout will be pumped onto the ground or a large plastic sheet and allowed to harden. If necessary, the waste grout will be removed from the worksite. Water will then be flushed through the pump and tremie pipe to remove all excess grout to avoid damaging the equipment.

B.8.0 ENVIRONMENTAL PROTECTION

The POLO project has been reviewed from an environmental perspective and has been granted a "Categorical Exclusion" under the guidelines set forth by the National Environmental Policy Act. The field research does not pose a threat to any aspect of the environment. However, safeguards shall be in place to avoid accidents. For example, the environment at the worksite will be protected from accidental contamination by a sheet of 4 mil plastic placed beneath the full length and width of the penetrometer rig and any other equipment that leaks or has a potential to leak. Accumulations of oil or fuel on the sheet of plastic will be absorbed with acceptable absorbent materials. The absorbent and contaminants will be removed and disposed of as directed by the Savannah River Site Supervisor. Contaminants will not be allowed to run or wash off the plastic onto the ground. As necessary throughout the penetrometer operations and upon completion of work at the worksite, the plastic will be rolled up without spilling the contaminants, and disposed of as directed by the Savannah River Site Supervisor.

B.9.0 SAFETY

The UTD Health and Safety Program, submitted under separate cover, establishes rules and procedures that are designed to ensure that each job will be as free as possible from hazards. The company's safety policy is stated here for the record. No person shall be required to work in surroundings that are unsafe or dangerous to his/her health. The safety and protection of employees is first priority on the job site. Work will stop before a job is done unsafely.

Field research, and drilling activities in particular, are normally confined to a relatively small worksite within any project area. The term "drilling" is applied loosely here to include penetrometers, which use thrust but not rotary motion. A worksite is defined as that area around the field equipment which is enclosed by a rope barricade. Equipment found on a drilling worksite can include a drill rig, backhoe, service trucks, and support tools.

UTD, Incorporated has the primary responsibility for establishing and maintaining safe working conditions at the worksite. UTD will comply with the applicable safety requirements at all times when work is in progress. Although the Project Manager takes the lead in maintaining compliance, the field engineers and equipment operators will also help to monitor the worksite. Basic safety equipment includes hardhats, safety glasses, and safety shoes.

B.10.0 QUALITY ASSURANCE

The POLO project includes the development and evaluation of several new pieces of equipment and will involve the collection of a large volume of experimental data. The following sections establish the quality assurance framework from which all experimental planning, testing, and analysis will be performed.

B.10.1 Planning

Planning will precede each experiment as an essential first step in order to identify all critical components that could influence the results. In this way, appropriate sensing instrumentation will be selected to meet the experimental goals. For each instrument or element, the quality assurance process will evaluate: 1) accuracy and precision; 2) compatibility with other system components; 3) cost factors; and 4) signal conditioning considerations such as response time and fidelity. Calibration and maintenance concerns that impact experimentation and testing will also be addressed at this time.

Planning will continue as an integral part of any ongoing test procedure. Frequent meetings will be held to identify critical components or elements that require quality assurance action. This procedure will facilitate continued refinement of the measurement requirements and help bring about reliable results.

B.10.2 Testing

Numerous instruments will be used to collect a large volume of experimental data. To guarantee the reliability of the data and the validity of the results of this work, several procedures have been established. Each procedure is consistent with standard research practice.

B.10.2.1 Sampling

All sampling will be statistically significant. This includes the concern that there be a sufficient number of readings (data points) for one test trial and that there be conducted a sufficient number of trials to establish repeatability. Where applicable, data collection will conform to classical sampling theory so that experimentally desirable standard deviation values and confidence intervals can be achieved.

B.10.2.2 Precision and Accuracy

The requirements for precision and accuracy are set forth as the experiment is planned and maintained by following the procedures established for each measurement. Precision refers to the agreement between repeated measurements of the same quantity. The achievable precision will largely be determined before the test, when the selection of appropriate instrumentation and sensors for the experimental measurements is carried out. Accuracy measures the agreement between a reported value and the known accepted value. The accuracy will be tracked by the use of properly calibrated auxiliary equipment. For example, surveying equipment will be used to verify the position information recorded by the POLO System. The Project Manager will monitor the individual sub-system performance to insure that the overall POLO precision and accuracy is capable of meeting the success criterion for accuracy.

B.10.2.3 Data Handling and Management

Test data will be gathered both manually (by hand) and by computer. In both cases, it will be necessary to note the significant digits of the instruments monitored and to insure that units of measurement are consistent throughout the test. For computer-derived data, the use of double precision will be maintained where applicable. Additionally, effective data handling must consider the sensitivity achievable by data acquisition equipment.

B.10.2.4 Identification of Other Significant Test Conditions

Any factors which could influence the resultant data stream will be noted. Peripheral conditions such as temperature or time of day will be noted during each test. Documentation for each test will be maintained with enough detail so that any experiment could be replicated at a later date.

B.10.2.5 Manufacturer's Specifications

All manufacturer's suggestions will be followed for proper use of any test equipment. This includes the operation and maintenance procedures, as well as all calibration requirements. In so doing, equipment performance can be optimized and the precision and accuracy of the data can be enhanced.

B.10.3 Analysis

The soundness and legitimacy of the data will be evaluated in a rough way as it is collected. An understanding of the expected results, developed during the planning stage, will help to identify and isolate problematic measurements as they occur. Later, as a first step of the full analysis stage, statistics will be implemented to identify any "outliers" in the data set. The goal of this work is the elimination of experimental error, which occurs when mistakes are made in the measurement process.

Once a reliable data set has been developed, the adequacy of the measurements can begin to be evaluated. Systematic errors, or those which affect all measurements alike and are usually due to imperfections and improper instrument adjustment, can often be corrected as part of this process. This information will be refined and developed into calibration routines for the equipment. In this way, the ultimate accuracy and precision values for each critical element of the POLO System can be identified. As more measurements are repeated over time, insight into the frequency of equipment calibration will be gained.

After minimizing all sources of error by first gaining familiarity with the instruments, then fine tuning the measurements, a realistic estimate of the total system error can be made. On a theoretical basis, one way to estimate the total system error is by summing the absolute value of the individual sources for error (POLO Module, tracking algorithm, initializer, etc.). However, the root mean square error, which is obtained by summing the squared errors and taking the square root, is generally accepted as a more realistic estimator. In the final analysis, system performance is more important than the behavior of individual components. It is extremely difficult, if not impossible, to include all factors that can influence system behavior.

The most accurate and direct way to evaluate system performance is to fully integrate all components into the measurement loop and check the output against an independent benchmark measurement. This procedure inherently includes all sources of error. When evaluated with respect to a pre-established success criterion, a true measurement of total system error is achieved. In the case of POLO, the final output is location. During the field demonstration, the benchmark measurement will be an independent survey of the endpoint with respect to the starting point. The pre-established success criterion is positioning to within 0.50% of the distance traveled. In real terms, the success criterion specifies that after traveling a distance of 100 meters, the POLO System must be able to locate the true tip position within a sphere of error that has a diameter of 1 meter.

The ultimate success of the POLO System rests on the need to minimize all sources of error. To accomplish this, and to promote an efficient development process, there may be some need to invoke an iterative approach as an intermediate quality

assurance measure. The iteration would consist of sub-system testing, followed by some error analysis and then re-testing to analyze the effect of a particular adjustment. The need for this approach will be evaluated by the quality assurance team.

B.11.0 DETAILED TEST PLAN

Purpose

To evaluate the path tracking performance of the POLO System with respect to the success criterion, which is position location to within 0.50% of the distance traveled for distances less than 70 meters.

Apparatus

POLO Module, data acquisition system, Initializer, survey equipment, penetrometer system modified for near horizontal pushes, backhoe for hydraulic power, push rods, and miscellaneous hand tools.

Procedure

After taking the necessary safety precautions, the penetrometer rig will be set up at the top of a hill so that the push rods are directed toward the slope. The inclination of the device will be adjusted so that a "hole-out" of the tip will be achieved somewhere on the slope. The POLO module will be calibrated and attached in the penetrometer string immediately behind the tip. Hydraulic thrust will then be used to advance the rods into the ground. When the POLO Module is seated approximately 1 meter into the ground, the penetrometer advance will be temporarily halted while the POLO initialization procedure is conducted. The POLO Initializer is a customized survey tool that will be clamped directly onto the portion of the POLO Module that is sticking out of the ground. Three angular measurements (elevation, azimuth, and module rotation) will be made to clearly define the location and heading of the penetrometer rod insertion. When the initialization procedure is complete, the rods will be advanced until the POLO Module is fully seated in the ground. At this time, the POLO tracking measurements will be made via an umbilical that is pre-threaded through the center of the penetrometer rods and connects the POLO Module to the surface computer. Six strain readings will be made by an automated data acquisition package in approximately 10 seconds. The length of rod in the ground will be determined by subtracting the amount of rod sticking out of the ground from the total length to the tip and will be entered at the computer keyboard. This information will be instantaneously processed by the computer tracking algorithm and used to update the screen display of tip position. While the tracking information is being acquired, a penetrometer rod can be added directly behind the POLO Module by a standard threaded connection. The new string of penetrometer rods will then be advanced one full penetrometer rod length into the ground, a distance of approximately 40 inches. No measurements will be made as the rods are advanced. At the end of the

advance, a second set of strain and distance measurements will be made. As before, the computer screen will display the updated tip position. Note that it is not possible to verify tip position while it is located underground. This process will be repeated until approximately 30 meters of rod is in the ground and a "hole-out" of the tip is achieved somewhere on the slope.

Once a "hole-out" is achieved, no additional rods will be pushed into the ground. The penetrometer equipment will be turned off and the POLO prediction of the final tip position on the slope will be recorded. With the rods still in the ground, an independent survey of the point of exit with respect to the starting point will be conducted. All survey work will be performed by qualified individuals and in accordance with standard procedure and nomenclature. The measurements will be referenced to a cartesian coordinate system established with respect to project north, vertical as measured by a plumb bob, and horizontal as measured by a bubble level. A surveyor's transit will be set up and leveled for this work. Elevation angle, azimuth angle, and required distance measurements will be made to establish the end point with respect to the start point in the project's coordinate system. The measurements will be checked from a second vantage point to guarantee the validity of the survey results. With the survey completed, the rods will be pulled back out of the ground. All measurements and data analysis will conform to the quality assurance guidelines that have been established. In addition, all work will conform to the requirements for work at the Savannah River Site, including grouting the hole left by the penetrometer rods as part of the hole abandonment procedure.

Data

An example of the type of raw data to be collected during a field test is shown in Table B-2 and expressed in the same format as the data files generated by the field computer. The data are NOT based on field measurements, but are intended as an illustrative example. Closer to 100 data points will be collected during a real field test. The first row represents the X, Y, and Z coordinates of the starting point in meters and is expressed with respect to the project coordinate system. For standard operation the X, Y, and Z coordinates at the start are equal to 0. The second row contains the azimuth, elevation, and rotation angle, measured in degrees, that will establish the initial heading of the POLO Module. The three angles will be determined by the Initializer device during a one time measurement at the start of a penetration. Both the starting coordinates and the Initializer angles are manually entered into the computer.

The remaining rows of data shown in Table B-2 will be generated as the POLO Module traverses its underground path. The first column of data is the number of the advance. The second column of data is the length of the advance in meters which will be measured by counting each one meter segment of push rod as it enters the ground. The remaining columns of data are the strain measurements made at three gage stations (lag, mid, and lead, respectively) and expressed in microstrain. The three gage

stations are placed at increments along the length of the POLO Module. Six strain measurements are made in all because each gage station has two circuits. One complete set of strain measurements will be made before the start of each advance, while the POLO Module is stationary. The shove and strain data are processed by the POLO algorithm and the new tip position is instantaneously displayed on the computer screen. The last point along the path, where there is access to the tip at ground surface, will be available for independent verification.

Table B-2. A POLO data file defines the penetrometer starting point and angle of insertion, then uses distance and strain measurements to map the path (sample data only).

X = 0.00 METERS		Y = 0.00 METERS		Z = 0.00 METERS			
AZIMUTH = -1.2 DEGREES		ELEVATION = 1.1 DEGREES		ROTATION = -10.5 DEGREES			
ADVANCE #	LENGTH OF ADVANCE METERS	STRAIN MEASUREMENTS MICROMETERS/METER					
		LAG		MID		LEAD	
		1	2	1	2	1	2
1	1.00	-1390	-1790	-1054	-1357	278	-1604
2	1.00	-954	-2081	-914	-1477	388	-1489
3	1.00	-710	-1936	-309	-1266	585	-990
4	1.00	-120	-1555	-118	-1150	539	-882
5	1.00	-40	-1382	-53	-936	511	-725
6	1.00	35	-1180	83	-751	534	-576
7	1.00	162	-1097	65	-778	439	-431
8	1.00	168	-807	183	-478	425	-243
9	1.00	249	-574	91	-153	182	-171
10	1.00	10	-327	35	73	0	-1

Results

The position of the tip is defined by a cartesian coordinate system whose origin is established at the point where the penetrometer enters the ground. The reference system described here is for a penetrometer operating in a near horizontal mode and is defined using the POLO Initializer. In general, vertical penetrometer insertions are much more common. A simple coordinate translation can be made from the existing horizontal system to whatever system is most convenient for the user. The Y-axis coincides with the principal direction of travel. For a near horizontal insertion, the Y-axis is defined in a horizontal plane as defined by a bubble level and offset a specified azimuth angle from project north. The X axis is also defined in a horizontal plane as defined by a bubble level, but is orthogonal to the Y-axis. The Z-axis coincides with vertical as defined by a plumb bob.

Figure B-2 is an example of a POLO tracking sequence as it is displayed on the screen of the field computer. The graphic display has two parts that provide accurate information on the probe location in a format that is easy to visualize. The left portion of the screen is the deflection circle. The center indicates a straight path that coincides with the horizontal Y-axis defined above. The outer circle represents the maximum deviation from a straight and horizontal penetrometer path that is expected over the entire distance traveled. The final version of the deflection circle will be labeled with appropriate units of length such as meters. The cross indicates the tip position of the penetrometer that has deviated from a straight horizontal path. For initial advances, when the path is nearly straight and horizontal, the cross appears near the center of the deflection circle. However, once a deviation occurs the rate of deviation should increase with each advance and the cross will rapidly move away from the center of the deflection circle.

The long narrow rectangle on the right of the computer screen shown in Figure B-2 is the distance bar. The entire rectangle represents the maximum horizontal distance that is expected by the penetrometer. The final version of the distance bar will be labeled with appropriate units of length such as meters. The portion of the distance bar that is black is the current horizontal distance traversed by the penetrometer. The example shown in Figure B-2 indicates that the penetrometer has reached approximately half of the total expected horizontal distance. For initial advances the distance bar nearly matches the total length of the penetrometer rod in the ground. As the distance traveled at a non-horizontal angle increases, less of the total rod length contributes to the horizontal distance and the distance bar increases more slowly.

While the graphic display at the top of Figure B-2 is easiest to visualize, the numbers at the bottom of the computer screen are more accurate and precise. They indicate the exact POLO prediction of the location of the penetrometer tip in X, Y, and Z cartesian coordinates. An independent survey for POLO validation will generate the same X, Y, and Z information. The survey will be conducted using a transit, stadia rod,

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Figure B-2. The POLO graphic display is a user friendly way to visualize a penetrometer path.

and tape measure. The same coordinate system will be established by referencing the vertical gravity vector as defined by a plumb bob and the direction established for project north. Elevation, azimuth and distance measurements will be made and transformed into cartesian coordinates that represent the tip position with respect to the starting point. With this approach, the POLO output and the survey output are directly comparable. Additionally, the positioning information uses standard convention and nomenclature and will be consistent with other survey information at the Savannah River Site.

Table B-3 demonstrates how the total system error will be computed. The data shown is NOT based on an experiment, but is illustrative of the calculation procedure. Note that the total system error will be computed at only one point, where the tip of the penetrometer probe is accessible at the ground surface. The X, Y, and Z coordinates that define the tip position and are expressed in meters. Each coordinate has a survey value and a POLO prediction. The X and Z coordinates roughly indicate the amount of deviation from a straight path. The Y coordinate is the horizontal distance along the primary direction of travel, but roughly corresponds to the total distance traveled. The term "roughly" is used here because when the push is at an angle, most, but not all, of the travel is in the direction of horizontal the Y-axis. The error for each axis was

obtained by comparing the surveyed coordinate with its neighboring POLO coordinate. For example, the surveyed X coordinate -0.43 meters (shown in Table B-3) in the first row of the first column is directly comparable with -0.40 in the next column. The total system error was calculated by combining the error from the X, Y, and Z coordinates using the square root of the sum of the squares and dividing by the travel distance.

Table B-3. The total system error is expressed as a % of the distance traveled and was computed by comparing the surveyed X, Y, and Z coordinates with the predictions of the POLO algorithm (sample data only).

TRAVEL DIST METERS	TIP POSITION - CENTIMETERS						TOTAL SYSTE M ERROR %
	X COORDINATE METERS		Y COORDINATE METERS		Z COORDINATE METERS		
	SURVEY	POLO	SURVEY	POLO	SURVE Y	POLO	
20	-0.43	-0.40	18.58	18.50	2.00	2.00	0.43
50	-0.60	-0.60	48.20	48.00	2.40	2.30	0.45
100	-0.80	-0.80	99.50	99.10	3.90	3.70	0.45

Discussion

Any measurement system is subject to a combination of accidental error, experimental error, and systematic error. Accidental errors occur due to human error. One common occurrence is following an incorrect experimental procedure. Mistakes of this sort are normally avoidable when familiarity with the equipment is gained. One of the primary reasons for the extended five week POLO field test is to gain expertise with the equipment and to learn where accidental errors specific to POLO measurements can occur. Once sources of accidental error are identified they can be avoided.

Experimental error is unavoidable and occurs due to the limitations of the measuring device. An acceptable level of experimental error can be identified based on the required end use of the device and is a key element of the system design process. The only way to reduce experimental error is to use new instrumentation with higher precision and accuracy. Experimental error occurs on a more or less random basis. For example, the output of the strain gage bridge can be measured to an accuracy of plus or minus two microstrain. Any one reading can fall anywhere within this error band, and there is no way of knowing which value is correct. If several readings were taken and

averaged, the random error would be reduced, but never eliminated. The error will be plus as often as minus and to be distributed more or less uniformly. One set of readings may err on the "high" side. If a subsequent set occurs a short time later and is on the "low" side, it will cancel some or all of the previous error. By continued variation and compensation for each other, random experimental errors will produce a net error that is well within overall requirements.

The single source of error that a designer can most easily influence, without changing the instrumentation, is systematic error. Systematic error occurs when a piece of equipment produces an incorrect result, but the mistake occurs in a measurable and repeatable way. This type of error can be minimized with calibration procedures. The POLO Module provides a good example of systematic error and how it may be minimized. The POLO Module has a grooved tubular body which carries the strain gages and has a unilateral tolerance of 0.001 inches on the radial distance from its centerline to the base of the strain gage grooves. Because of this, some strain gages will be located at a different distance from the centerline than others. This problem is compounded by the fact that the adhesive used to attach the strain gages may not be of uniform thickness for all gages. In this example, there is an error band caused by manufacturing tolerances which cannot be precisely defined. However, it will be systematic, that is, any particular gage will remain at the same distance once the manufacture is complete. The solution is to bend the POLO Module into known configurations and record gage readings for various orientations about its axis, in effect, to calibrate. Thus, systematic errors can be identified and eliminated or reduced to acceptable levels by calibration.

One tries, in designing a good system, to do an analysis which describes how each component reacts to inputs and how components' behaviors combine to produce systematic error. Fortunately, the POLO System is fully amenable to this type of performance analysis. During prototype development this enabled a preliminary evaluation of each individual component in its "as built" condition to identify errors. Error terms were combined to obtain a realistic estimate of the total system error before any tracking experiments were conducted. The error analysis was reviewed a second time based on the results of integrated tests that were conducted in a laboratory environment. The laboratory investigation did not change the original error estimates.

The primary components of the POLO System will be re-evaluated on an individual basis during the field tests. Each POLO component is identified in Table B-4 with a current estimate of its contribution to total system error. In each case, the error band for a particular component was transformed into the error in final location of the penetrometer point based on the distance traveled. Table B-4 lists two error values for each principal component. One value, labeled "Laboratory Based" was derived from final laboratory testing with the fully calibrated equipment and is the best estimate available to date. The "Field Based" error will be determined during the upcoming investigation.

Table B-4. POLO meets or exceeds the success criteria.

Components	Error	
	Laboratory based	Field based
Module	$\pm 0.10\%$	$\pm 0.25\%$
Signal Conditioning	0.10%	0.20%
Computation	0.20%	0.25%
Initializer	0.10%	0.25%
Predicted System Error	$\pm 0.26\%$	$\pm 0.48\%$

The current estimates shown in the box are from field experience and the understanding that field measurements are more difficult to make and are subject to somewhat larger error bands. The goal of the field based error estimate was not to give an exact error range, but to be sure that the influence of uncertainties has been carefully considered in preparation for the full-scale field demonstration.

As noted earlier, much of the error with the POLO Module can be eliminated through calibration. A frame for these benchmark measurements has been developed and used for this purpose. After calibrating for systematic errors and on the basis of laboratory work, the POLO Module contributes less than 0.10% to the total system error.

Signal conditioning includes all of the equipment used to measure a strain value and make it available to the computer in a digital format. To achieve highest resolution, careful consideration was given to minimizing the systematic errors from system noise, environmental noise, and signal attenuation. System noise is an error inherent to the data acquisition system and was minimized by using a high quality instrument that was calibrated and designed specifically for strain gage measurements. Environmental noise comes from an external source, such as a large temperature fluctuation, and was reduced by adhering to procedures for compensating and isolating the electrical circuits. Signal attenuation is a problem for longer leadwires and can be accommodated by adjusting the transducer output to a known value based on a known stimulus. On the basis of the best estimate currently available, the bending strain can be measured to an accuracy of approximately plus or minus 2 microstrain and this contributes 0.10% to the total system error.

The computation portion of the POLO System transforms the raw strain data into useful tracking coordinates. The primary unavoidable error component for computation is from modeling a complex natural phenomenon. There are no accidental errors associated with faulty coding in the POLO computer program. Error was minimized by the development of a sophisticated algorithm that takes into account how the POLO Module bends and deflects as a beam. The unavoidable error due specifically to the new beam algorithm was tested by tracking theoretical beam-type paths and found to be less than 0.10%. In addition, a rotation algorithm was developed to automatically monitor the rotational position of the POLO Module. While a penetrometer does not manually rotate the drill string some wind up is expected to occur after traveling a circuitous route. To model this effect during testing, the POLO Module was allowed to rotate freely during laboratory tracking experiments. The best estimate of total system error due to computation, which includes both deflection and rotation, is 0.20%.

The Initializer is the instrument used to determine the starting point of a POLO penetration. Three angular measurements, the azimuth, elevation, and rotation, are made with the initializer. Like the POLO Module, the initializer is a piece of equipment that is subject to systematic error because of its manufacturing tolerances. Also like the POLO Module, the error was minimized once a calibration had been performed. The calibrated accuracy of the initializer is 0.10 degree for all three angular measurements and this contributes 0.10% to the total system error.

In summary, the effect of systematic errors on the POLO System has been minimized by design and calibration. Experimental errors are random in nature and will tend to cancel out over a series of measurements. Accidental error will be avoided once full familiarity with the equipment is gained in the field. At the bottom of each column in Table B-4 is given the total system error, based on the error bands shown in that column. The standard method of taking the root mean square error was used to calculate total system error. Root mean square error is computed by taking the square root of the sum of the squared error terms. The reader will note that in both cases the error falls within the success criterion of 0.50% of the distance traveled as set forth in the contract.

There is no particular significance attached to the success criterion of 0.50% error with respect to the distance traveled for distances less than 70 meters. It is not a value that was targeted for a particular penetrometer application. The value was estimated based on the accuracy believed to be achievable by the strain gage technology. Although the POLO System has no competitors for equipment similar to penetrometers, POLO shows a good probability of achieving accuracies equal to or better than those achievable with guidance systems used for other underground locator systems, namely directional drills. It is also important to note that the 70 meter travel distance is not currently feasible for most penetrometer systems in most geologic conditions due to

thrust limitations. Several penetrometer users and manufacturers have advised that the limit of present technology for a 4.45 centimeter (1 3/4 inch) diameter sampling rod is closer to 30 meters. Thus, POLO should give position location to within 0.15 meters.

APPENDIX C
DOCUMENTATION FOR NATIONAL ENVIRONMENTAL POLICY ACT

**INNOVATIVE DIRECTIONAL AND
POSITION SPECIFIC SAMPLING
TECHNIQUE**

Documentation for National Environmental Policy Act

September 1994

C.1.0 PROJECT OVERVIEW

The Phase III field research evaluated the ability of the new POLO Sensor to track the path of a small diameter probe as it moves underground. It was completed in two distinct stages. In the first stage, a Preliminary Field Trial was conducted for two weeks near Fort Belvoir, Virginia, located adjacent to the UTD, Incorporated home office in Newington, Virginia. The goal of this early work was to debug and refine the POLO system close to home and before mobilizing to a distant field site. The NEPA documentation presented here focuses on this two week Preliminary Field Trial at Fort Belvoir.

In the second stage of the Phase III field research, a Final Field Demonstration was conducted at an uncontaminated location of the Savannah River Site in Aiken, South Carolina. The work was similar to the Preliminary Field Trial at Fort Belvoir, except that POLO was also put on display for DOE personnel and invited guests from industry. With the assistance of the Environmental Sciences Group of the Savannah River Technology Center, UTD submitted a separate set of NEPA documentation for the Final Field Demonstration directly to DOE Savannah River. Based on similar work previously performed at the same test location, the POLO research for the Final Field Demonstration was found to qualify as a categorical exclusion under the NEPA guidelines.

C.2.0 DESCRIPTION OF POLO EQUIPMENT

The POLO System is a major enhancement to existing equipment for environmental restoration. Traditionally, expensive monitoring wells have been used for finding contamination, identifying extent of contamination, remediating, and finally monitoring sites. Recently, penetrometers and lysimeters have been used as cost effective alternatives to monitoring wells. With all of these methods, however, the alignment of the well or the penetrometer probe is known with only broad approximations. As a result, the location of the sampling point is uncertain, when in fact small errors can have a significant impact on the interpretation of plume origins and other characteristics. The POLO System locates the tip position of these probes as they are placed underground, while meeting the rigid constraints of environmental restoration applications. POLO is applicable to small diameter probes, does not obstruct the center of the probe, is rugged, is unaffected by the presence of steel or other magnetic material, and is capable of remote operation beneath steel tanks or foundations.

Figure C-1 shows that the POLO Sensor uses 3 sets of strain gages mounted on an internal body to monitor bend orientation and intensity. An outer shield protects the gages and electronics. Thread adapters on either end attach directly to standard penetrometer rods. The entire device is made of stainless steel, and is 1.75 inches in outer diameter and 60 inches long. Bundled signal wires at the center of the probe

transport the strain gage output to the surface. Other than displacing a small amount of soil as it moves underground, the POLO sensor is a passive device that does not interact with the subsurface environment.

Figure C-1. The POLO Sensor does not disturb the environment.

C.3.0 DESCRIPTION OF FIELD TEST

The field research focuses on the path tracking performance of the POLO sensor adapted for use with penetrometers. A penetrometer is a geotechnical instrument that operates in a vertical orientation and uses exclusively hydraulic thrust to advance small diameter (1 3/4 inch) steel hollow rod into the ground. After reviewing the available field sites, it was found that a vertical insertion could not achieve a "hole-out" without putting an excessive bend in the rods. To overcome this problem, a penetrometer-type device called a rod pusher was used to advance the rods in a near horizontal orientation.

Figure C-2 shows a nine foot rod pusher that consists of a rigid steel frame, two hydraulic rams, and a pusher plate. To minimize environmental disturbance, the rod pusher is mounted to a thick steel plate resting on the ground surface. The steel plate is held in place using an auger stake down system typically used for a large directional drill rig. The rod pusher apparatus weighs about 1 ton, is capable of 20 tons of thrust/pullback force, and advances rods at a rate of 1 inch per second. No permanent construction or excavation is required to use the device and all equipment can be removed upon completion of a test.

Figure C-2. The rod pusher apparatus is mounted above ground to minimize environmental impacts.

Figure C-3 illustrates that the basic test plan is to set up the rod pusher a distance back from the top of a steep hillside and pointed toward the slope. The POLO Sensor is thrust into the ground, followed by an initialization procedure to establish the angular heading at the start of the penetration. A hollow steel penetrometer rod that is 1.75 inches in outer diameter and 40 inches long will be attached behind the POLO sensor and the entire string will be advanced further into the ground. An umbilical at the center of the rods brings the strain gage signals back to the surface, where a computer is used to measure the tip position. The process of rod attachment, rod advancement, and signal measurement is repeated throughout a test.

Other than displacing a small amount of soil, the string of rods will not interact with the subsurface in any way. During its travel, the POLO Sensor will travel above the water table at depths of less than 20 feet and parallel to the ground surface. After pushing 20 to 50 feet of rod, a "hole-out" is achieved somewhere on the slope. A survey is conducted to determine the start and end positions of the tip, and survey results are compared with the output from the POLO computer program. The POLO sensor and penetrometer rods are then pulled back from the ground. With time it is expected that the soil will cave in around the hole that has been left by the probe.

Figure C-3. The rod pusher apparatus is used to insert, then retract, a small diameter rod into the soil.

Several soil penetrations can be made from a single stake down position. In addition, several stake down positions for the rod pusher apparatus can be used at each field site. For example, if a large underground boulder is encountered midway through a push, it may be necessary to retract the rods and mobilize to another nearby field location, say 5 ft away. At the end of the field test, demobilization includes removal of all equipment and material from the test site. Minimal environmental disruption is expected.

The POLO equipment is monitored by a two man team of experienced field engineers who also manage the job site. In addition to the POLO Sensor and Initializer that were described earlier, support equipment includes a computer with a field power supply, a small calibration rig, and hand tools. The equipment is stored in a one ton service truck.

The rod pusher apparatus is maintained by a full-time two-man team of skilled operators. The support equipment includes a portable hydraulic power pack for the rod pusher apparatus and a one ton service truck for the rod pusher hand tools. Welding and cutting equipment is also available to make modifications in the field. A backhoe is provided for excavation purposes, and to move the heavy rod pusher and power pack from point to point. The equipment is transported to the site with a Kenworth tractor and a Lo Boy trailer.

C.4.0 DESCRIPTION OF AFFECTED ENVIRONMENT

Fort Belvoir is a large army post located along the Potomac River in Fairfax County, Virginia. The test site is away from the river in an uncontaminated, vacant, and lightly wooded location. Minimal surface disturbance occurred in the immediate area of the rod pusher apparatus. The ground surface is nearly level, but is adjacent to a hill that is used to achieve a "hole-out" of the probe tip. The slope of the hill is about 20 degrees with respect to horizontal. It is leaf covered or vegetated and shows no signs of significant erosion.

A paved roadway runs within 50 feet of the test site. Ample parking for support vehicles is within walking distance. The location of a small underground water line was clearly identified and avoided. Power lines and trees were also avoided. The underground work took place within 20 feet of ground surface and above the water table in sandy clay soil. It is expected that the soil displaced by the probe will cave back into the hole with time and will not cause any surface or subsurface hazard. The entire test section is above the groundwater table.

C.5.0 ENVIRONMENTAL IMPACTS

The field work was not in violation of applicable statutory, regulatory, or permit requirements for environment, safety, and health. In addition, there were no siting, construction, or expansion of waste storage, disposal recovery, or treatment facilities. There were also no uncontrolled or unpermitted releases of hazardous substances. The field test will not put anything into the ground that is not removed later. The following documentation describes all environmental aspects of the field test.

C.5.1 Land Use

The test site is located in a lightly wooded two acre lot that is part of a research facility on Fort Belvoir, Virginia. Permanent construction or excavations were not required and no hazardous wastes were produced. The field test did not affect land use or physically change the site.

C.5.2 Air Quality

A small amount of exhaust came from the 60 horsepower diesel engine of the backhoe that supplied hydraulic power to the rod pusher apparatus. The unit was used four hours per day for the duration of the ten day field test. This equipment was in compliance with emissions regulations.

C.5.3 Water Quality

The equipment did not use water and the underground probe remained above the water table. The field test did not cause erosion or alter a floodplain or wetland.

C.5.4 Impact on Vegetation and Animals

The field test did not permanently alter or destroy the habitat of any plant or animal species. Localized and temporary disruptions occurred in the immediate vicinity of the test equipment.

C.5.5 Visual Resources

The field test did not require any permanent construction that will contrast with the present landscape or alter scenic views.

C.5.6 Historic/Cultural Resources

The test site is not listed on the National Register of Historic Places.

C.5.7 Open-Space/Recreation

The field test did not have a permanent effect on existing or future recreational opportunities in the area. The test site is located adjacent to a regional park that will not be affected.

C.5.8 Transportation

There is a private and paved access road within 50 feet of the test site. The work did not influence traffic patterns.

C.5.9 Energy Requirements

The field test did not impact energy usage in the municipality in which it is located.

C.5.10 Noise Level

In the immediate area of the test site the hydraulic power pack was louder than ambient noise levels, but below acceptable limits set by OSHA. The decibel level did not exceed 88 dB. Hearing protection was available and required for all workers at the test site.

C.5.11 Environmental Restoration

The field test was not an environmental restoration activity and as such does not involve siting, construction, operation, or decommissioning of waste management facilities.

C.5.12 Solid Waste and Hazardous Materials

The field test did not use or produce hazardous waste materials.

C.5.13 Worker Health and Safety

The field test did not expose workers to hazardous chemicals, hazardous wastes, or extreme temperatures. Hearing protection and protective clothing such as hard hats, steel-toed boots, and work gloves were required for all workers. A worker safety program is in place and additional training was provided by an experienced field engineer who is familiar with OSHA safety requirements at field sites.

The physical hazards at the job site were those that are encountered at any field site and can be avoided by following established safety procedures. A safety zone was established around the perimeter of the work site. Workers followed safety procedures when operating machinery or lifting heavy equipment. In addition, the routing of all known utilities was documented in advance and avoided during the field test. The probe and its attached equipment were grounded.

C.5.14 Public Controversy

The field test did not generate public controversy.

C.6.0 SUMMARY

The Field Trial for Phase III of the DOE Contract for an "Innovative Directional and Position Specific Sampling Technique" did not pose a threat to any aspect of the environment. The work qualifies as a categorical exclusion under CFR 1021.410, Appendix B to Subpart D.

APPENDIX D

HEALTH AND SAFETY PLAN FOR POLO FIELD DEMONSTRATION

INNOVATIVE DIRECTIONAL AND POSITION SPECIFIC SAMPLING TECHNIQUE

Health and Safety Plan For POLO Field Demonstration

September 1994

D.1.0 PROJECT OVERVIEW

The Department of Energy's Environmental Restoration and Waste Management program and the existing Program Research and Development Announcement (PRDA) are designed to accomplish, in addition to other goals, the development of tools and methods for the characterization, remediation, and monitoring of underground environmental conditions. The POLO System is one of these new technologies and will help provide faster, better, and safer solutions to environmental restoration problems. This Health and Safety Plan documents equipment and procedures that will be followed during the POLO field demonstration.

D.1.1 Purpose

The purpose of the field research is to demonstrate the accuracy and utility of the POLO System, a new locator technology that will enhance the performance of penetrometers and other types of drilling equipment for environmental restoration. Traditionally, expensive monitoring wells have been used for finding contamination, identifying extent of contamination, remediating, and finally, monitoring sites. Recently, penetrometers have been used as cost effective alternatives to monitoring wells. With all of these methods, however, the alignment of the well or the penetrometer probe is known with only broad approximations. As a result, the location of the sampling point is uncertain, when in fact small errors can have a significant impact on the interpretation of plume origins and other characteristics.

The POLO System locates the tip position of these probes as they are placed underground, while meeting the rigid constraints of environmental restoration applications. POLO is applicable to small diameter probes, does not obstruct the center of the probe, is rugged, is unaffected by the presence of steel or other magnetic material, and is capable of remote operation beneath steel tanks or foundations. Other than displacing a small amount of soil as it moves underground, the POLO sensor is a passive device that does not interact with the subsurface environment.

D.1.2 Test Procedure

The POLO field test will demonstrate an innovative technology for determining the subsurface position of a cone penetrometer tip or a directional drilling head. UTD, Incorporated will contract for a penetrometer, modified for near horizontal insertions, to perform the tests. The POLO tool will be added to the cone penetrometer tip and angled pushes will be performed. All penetrometer work will be conducted in a near horizontal orientation and above the water table.

The pushes will be performed in an area adjacent to the railroad tie disposal pit near the F-area. The exact location of the test site is summarized in Table D-1, which contains the Savannah River Company (SRC) coordinates for two neighboring test

areas. Both areas have an exposed face due to erosion which will allow a push from the horizontal surface to the near-vertical face. The entry and exit holes will be surveyed to determine the accuracy and precision of the positioning tool.

Table D-1. The SRC coordinates identify the size and location of the two test areas at the Savannah River Site.

TEST AREA	EASTING COORDINATE (feet)	NORTHING COORDINATE (feet)
1	50100	80100
	50300	80100
	50100	79900
	50300	79900
2	50450	80000
	50950	80300
	50950	79850
	50450	79850

D.1.3 Safety Policy

The UTD Health and Safety Program rules and procedures are designed to ensure that each job will be as free as possible from hazards. No person shall be required to work in surroundings that are unsafe or dangerous to his/her health. The safety and protection of employees is first priority on the job site. Work will stop before a job is done unsafely.

D.1.4 Worksite Responsibility

Field research, and drilling activities in particular, are normally confined to a relatively small worksite within any project area. The term "drilling" is applied loosely here to include penetrometers, which use thrust but not rotary motion. A worksite is defined as that area around the field equipment which is enclosed by a rope barricade. Equipment found on a drilling worksite can include a drill rig, backhoe, service trucks, and support tools.

UTD, Incorporated has the primary responsibility for establishing and maintaining safe working conditions at the worksite. UTD will comply with the applicable safety requirements at all times when work is in progress. Although the Project Manager takes the lead in maintaining compliance, the field engineers and equipment operators also will help to monitor the worksite.

D.2.0 PERMITS AND CLEARANCES

Before any field work is initiated, the required forms will be submitted and approvals obtained. The initiating document for any field research project is the Program Plan. This report is developed by the Project Manager, reviewed by UTD Management, and submitted to the personnel in charge of the field site. It contains relevant information on the scope of work and the materials to be used. A Project Health and Safety Plan will be submitted with the Program Plan. The Health and Safety Plan defines potential hazards to the field crew and specifies protective measures that will be taken to guard against injuries or exposure to health hazards.

Beyond the Program and Health and Safety Plans, additional permits and clearances are site specific. The documentation described here is required at the Department of Energy's Savannah River Site in South Carolina, but is representative of the level of documentation at other locations. A Site Clearance Permit will be obtained to prevent subsurface work in an area where various interferences exist or in areas scheduled for construction. A Work Clearance Permit (WCP) will be obtained after the project's health and safety documentation is reviewed and approved. All field personnel will sign and date the WCP to indicate that they are aware of all job requirements at the worksite.

D.3.0 ENVIRONMENTAL REQUIREMENTS

Prior to arrival at the field site, a detailed evaluation of the environmental impacts of the proposed work will be conducted to meet the requirements of the National Environmental Policy Act (NEPA). The work for the POLO field demonstration has already qualified as a "Categorical Exclusion" because it will take place at an uncontaminated location and will not harm the environment. The POLO Sensor is a passive device that attaches to the tip of a push rod string and, other than displacing a small amount of soil, does not interact with the subsurface environment in any way.

Although the POLO field work is loosely termed "drilling" for convenience, this is technically not the case. A penetrometer-type device that uses only thrust, without the rotary motion of a drill, will be used for all tests. This distinction is important because a penetrometer avoids the surface and subsurface disturbance associated with rotary excavation, drilling mud, etc. The following discussion describes the environmental safeguards that will be in place during the field work.

D.3.1 Protection of the Environment

The environment at the worksite will be protected from accidental contamination. A sheet of 4 mil plastic will be placed beneath the full length and width of the penetrometer rig and any other equipment that leaks or has a potential to leak. Accumulations of oil or fuel on the sheet of plastic will be absorbed with acceptable absorbent materials. The absorbent and contaminants will be removed and disposed of as directed by the Savannah River Site Supervisor. Contaminants will not be allowed to run or wash off the plastic onto the ground. As necessary throughout the penetrometer operations and upon completion of work at the worksite, the plastic will be rolled up without spilling the contaminants, and disposed of as directed by the Savannah River Site Supervisor.

D.3.2 Oil and Fuel Spills

Any spills of oil or fuel which are not completely contained on the plastic sheet will be reported to the Savannah River Site Supervisor.

D.3.3 Site Housekeeping

The worksite shall be kept clean and free of trash and other debris. All trash shall be placed in a garbage can or plastic bag and disposed of as directed by the Savannah River Site Supervisor. In addition, tools that are not in use shall be kept in their appropriate storage container.

D.4.0 FIELD TEST EQUIPMENT

The POLO field demonstration will be conducted using a penetrometer-type device whose hydraulic power is supplied by a diesel backhoe. At least two one-ton service trucks and one utility trailer will also be on site to supply tools, spare parts, and safety equipment during the field test.

D.4.1 Equipment Inspection

All equipment shall be available for inspection upon arrival to the worksite. As required, an inspection sticker with an expiration date will be maintained on equipment upon completion of a successful inspection. The Project Manager is responsible for the equipment re-inspection before the expiration date.

D.4.1.1 Penetrometer Rig

The penetrometer rig used for the POLO field demonstration consists of a rod pusher modified for angled insertions and anchored at the ground surface. This unique device is described here fully, to highlight its simple and rugged construction, as well as

its capability for safe operation. Figure D-1 shows that the penetrometer rig consists of a rigid steel frame, two hydraulic rams, and a cradle. The cradle is a semi-circular tube, 8 inches in diameter, that is closed at one end and holds a single push rod. When the hydraulic rams are activated the entire cradle moves, forcing the rod forward. The device is approximately 12 feet long and 2 feet wide. Power for the hydraulic cylinders is supplied by an industrial backhoe. Pressure gages continuously monitor thrust and a pressure relief valve avoids overloading the push rods.

Figure D-1. The penetrometer rig thrusts a small steel rod into the ground.

The side view in Figure D-2 shows that the penetrometer rig is mounted to a thick steel plate resting on the ground surface. The steel plate is held in place using an auger stake down system typically used for a large directional drill rig. The penetrometer rig weighs about 1 ton, is capable of 20 tons of thrust/pullback force, and advances rods at a rate of about 3 inches per second. No permanent construction or excavation is required to use the device, and all equipment will be removed upon completion of a test. As shown in the background of Figure D-2, a 60 horsepower diesel backhoe supplies hydraulic power to the device.

Figure D-2. The penetrometer rig will be anchored to the ground and perform angled insertions.

The rig shall be of adequate size to complete the POLO demonstration without placing undue strain on its frame and without endangering any person at the worksite. All components of the rig shall be maintained in good condition and protective guards will be in place where appropriate. Excessive noise or exhaust fumes coming from the penetrometer rig shall not be allowed. In any event, hearing protection shall be available. All operating controls shall function properly. The penetrometer rig shall be equipped with an emergency kill switch that is accessible to all field personnel.

D.4.1.2 Steam Cleaners

Steam cleaners may be used to clean the penetrometer rig and downhole equipment. If trailer mounted, the trailer load rating shall be adequate to support both the cleaner/heating mechanism and a tank full of water. All rotating shafts, belts, and

pulleys shall be covered with protective guards. The tongue of the trailer on which a steam cleaner is mounted shall have a swing-down or crank-down support. The trailer shall have operating tail and brake lights and safety chains, which shall be used when being towed.

D.4.1.3 Utility Trailers

All utility trailers shall be maintained in good condition for hauling loads. The tires on utility trailers shall be heavy-duty and adequate for the maximum rated trailer load weight. Tires shall be free of cuts or other damage. Any load carried on a trailer shall be held down securely so that no movement will occur. The trailer load limit shall not be exceeded. Utility trailers shall have working tail and brake lights and safety chains which shall be used when being towed.

When parked at a worksite, any equipment that has a tendency to roll shall be held in place on the trailer with either chocks or metal stakes set inside pockets. Equipment shall not be left unsecured so that it could roll off the side of the trailer.

D.4.1.4 Portable Generators and Arc Welders

Portable generators and arc welding machines at the worksite will be grounded while in use. When not operating, generators or welders need not be grounded, but shall be chocked and secured from rolling. If the generator or welder is mounted on a trailer, the trailer shall have a tongue support stand, operating tail and brake lights, and safety chains. For the POLO field demonstration, this equipment will probably be secured on the back of a one-ton service truck.

D.5.0 PERSONNEL

The worksite will be run by a Project Manager who is supported by a team of experienced field engineers. The field engineers will monitor the POLO tracking equipment. In the absence of the Project Manager, the Senior Field Engineer will manage the worksite.

The penetrometer rig will be operated and maintained by a two-man team of skilled field technicians. The equipment operator has extensive experience in utility drilling, where work is performed close to the ground surface. A South Carolina Driller's license should not be required because all work will be conducted well above the water table. In addition, penetrometer work does not technically constitute a "drilling" activity.

All personnel shall be instructed in the operation of the penetrometer rig and safe working practices before mobilizing to the worksite. In addition, all personnel shall attend a safety orientation given by the Savannah River Site Supervisor when they arrive at the worksite.

D.6.0 SAFETY PRACTICES

The safety and protection of employees is first priority on the job site. Work will stop before a job is done unsafely.

D.6.1 Use of Safety Equipment

The selection of safety equipment depends upon the equipment and surroundings at the worksite. Fortunately, the POLO demonstration will be conducted in areas with no known hazards, using standard penetrometer components modified for an angled push. For this situation, the required safety equipment is typical of any construction site. Minimal skin protection is necessary, and no respiratory protection other than a dust mask for mixing cement is required.

D.6.1.1 Hardhats

All persons shall wear an approved hardhat which complies with ANSI Standard Z89.1-1968 when inside the rope barricade around the penetrometer worksite.

D.6.1.2 Safety Glasses

All persons inside the rope barricade around the penetrometer worksite shall wear safety glasses with side shields that meet ANSI standard Z87.1-1979. Safety glasses shall be worn to protect the eyes at all times. They shall not be worn in such a position that they provide little or no eye protection, such as down on the wearer's nose. They shall be kept clean and free of mud and scratches as best as possible under existing working conditions.

D.6.1.3 Steel-Toed Boots

The use of steel-toed boots that meet ANSI standard 241.1-1972 is required for all field engineers and equipment operators. Visitors to the penetrometer site shall wear sturdy leather shoes.

D.6.1.4 Safety Belt

A safety belt that meets ANSI Standard A10.14 shall be worn by personnel operating more than four feet above ground surface. In addition, a safety belt shall be worn for all work near the edge of a cliff or ravine. The safety line shall limit any fall to a maximum distance of 4 feet. There will not be a drill rig present at the POLO field demonstration and hence no elevated work from the mast of a drill rig.

D.6.1.5 Hearing Protection

The use of hearing protection devices that meet ANSI standard S2.19-1974 is required whenever the noise level of any piece of equipment exceeds 90 decibels within 4 feet of the noise source. Any person who is within 4 feet of a noise source shall have hearing protection in place as long as the noise persists. If the noise level exceeds 90 decibels throughout the entire work area, then all persons in the work area shall wear hearing protection as long as the noise is present. The ambient noise levels at the POLO field demonstration are expected to be significantly less than the 90 decibel threshold. The major source of noise is an idling backhoe that is used to supply hydraulic power to the penetrometer device.

D.6.1.6 Dust Filters

Dust filters shall be worn by all personnel who could breathe dust from sacks of bentonite and/or cement that are opened and mixed on site. The POLO field demonstration will generate very little dust. One sack of cement and a small amount of bentonite will be enough to fill the small opening left after retrieval of the penetrometer rods.

D.6.1.7 Gloves

The use of gloves for hand and finger protection is generally required for all penetrometer operations. However, there are some circumstances in which wearing gloves could actually be more hazardous, such as when working around hoses or chain. Field personnel are therefore allowed the discretion of not wearing gloves for certain tasks if they believe that such tasks can be accomplished more safely without gloves. For other routine tasks or operation of equipment, gloves shall be worn by all drill crew personnel at all times.

The preferred gloves for routine penetrometer operations is the cotton work glove with plastic "non-slip" beads or grips. The use of leather gloves, which may become slippery when wet, is discouraged. Leather gloves with wrist and forearm coverage shall always be worn when using an oxygen/acetylene cutting torch at a worksite in order to prevent burns. Rubber gloves shall be worn by field personnel if it becomes necessary to stick hands and arms in wet cement mix.

D.6.2 Worksite Safety Requirements

The POLO safety requirements are typical of any well run construction site.

D.6.2.1 Worksite Rope Barricades

As soon as the angled push penetrometer is driven onto a worksite, a rope barricade shall be erected around the entire site. The barricade shall extend outward from the rig far enough to contain any peripheral equipment, including push rods or grouting equipment. The rope barricade shall extend around the entire worksite perimeter at waist height. It shall be posted with a sign stating that hardhats and safety glasses with side shields are required for entry. No person is to go inside this rope barricade without wearing a hardhat and safety glasses with side shields. The rope barricade shall be maintained in position as long as equipment is at the site. Should it become necessary to lower the barricade, such as for a service truck to enter or leave, it shall be put back up immediately.

D.6.2.2 Penetrometer Rig Setup

Once a rope barricade has been erected around the worksite, the penetrometer can be anchored in place. As a safety precaution, the anchor plate will be chained to the ground with long pins driven in front of the penetrometer. All required equipment and materials shall then be placed around the worksite in a neat and orderly manner. Particular attention shall be given at this time to potential safety hazards from objects which could fall from the frame of the penetrometer or roll off of a utility trailer. Rod pushing shall not commence until all equipment is in place and the crew is ready to devote full attention to the assigned task.

D.6.2.3 Push Rod

Push rods shall be transported to the worksite in a rack designed to hold such equipment, and securely attached to the penetrometer rig, service truck, or utility trailer. If transported on a utility trailer, the push rods shall be held securely in place so that they will not roll from side to side. In addition, metal stakes shall be in place on the sides of the trailer to prevent any loose rods from falling off.

At a worksite, push rods shall be set out so that they can be picked up and laid down in a safe manner. They may be laid on crossties on the ground, on steel support racks, or left on the utility trailer. They shall be secure from rolling and/or falling. Any support racks used to hold push rods shall have adequate strength to hold this equipment without collapsing. Push rods placed directly on the ground shall be chocked to prevent rolling. No special lifting equipment is required to lift or move push rods, which weigh less than 30 pounds apiece.

D.6.2.4 Chains and Wire Cables

Unlike a drill rig, the penetrometer rig for the POLO demonstration does not utilize wire cables. However, safety specifications for wire cables are included in the unlikely event that one is used. All wire cables are to be inspected by a field technician before the start of work each day. Cables shall be free of broken strands or weak spots. Any wire cable that has broken strands shall be replaced immediately unless the cable will not be used.

Wire cable that is badly kinked, mashed, or otherwise damaged shall be taken out of service. Heavy loads shall not be placed on a damaged cable. If it is anticipated that a heavy load will be placed on a cable, then damaged cables shall be replaced before work progresses to that point.

All cable clamps shall be installed with the U-bolt placed on the short end of the cable. At least two cable clamps are to be installed on each loop. Field technicians shall inspect cable clamps daily to ensure that the clamp nuts have not worked loose. The cable shall be cut clean, free of any projecting strands, and wrapped with tape.

Under no circumstances shall a cable be loaded above its rated strength. In the event a push rod string becomes stuck in the hole, the field crew shall attempt to work the equipment loose without endangering anyone by breaking a wire cable.

Log chains may be used to help anchor the penetrometer rig in place. All chains are to be inspected by field technicians before start of work each day. Any chain that is damaged or has weak spots shall be replaced immediately, unless the chain will not be used. All chain connections will be made through a hook of the correct size, and capable of withstanding the applied loads. Under no circumstances shall a chain or hook be loaded above its rated strength.

D.6.2.5 Fire Extinguisher

At least one fully charged fire extinguisher shall be present at the worksite where it shall be quickly and easily accessible in the event of a fire. The minimum acceptable extinguisher rating is 10 pound ABC. During a penetrometer push, the extinguisher shall be mounted in a visible location, such as the side of the rig. A fire extinguisher will also be placed in close proximity to a portable generator while it is in use. The fire extinguisher shall not be placed in a location where it interferes with work or is likely to be knocked over.

The fire extinguisher must be maintained in a fully charged condition at all times. Should the fire extinguisher become partially or fully discharged, it must be recharged or replaced with a fully charged extinguisher immediately.

A fire extinguisher shall be readily accessible whenever any equipment is being refueled at a worksite. The extinguisher shall be located within 30 feet of any source of flame, which includes welding equipment, cutting torches, and free-standing heaters.

D.6.2.6 Wheel Chocks

With some exceptions, all vehicles and wheeled equipment brought to the worksite shall have chocks placed under the wheels to prevent rolling. Service trucks and other vehicles used primarily for transportation of personnel to the site are not required to be chocked. Acceptable wheel chocks are those constructed of reinforced rubber. Wooden chocks may be used if none of the rubber chocks are available.

Utility trailers and similar equipment shall have chocks placed under the wheels when parked at a worksite. Vehicles which come to a worksite for short periods of time shall have chocks under the wheels anytime the driver is not at the controls in the cab of the vehicle. Vehicles equipped with hydraulic jacks are not required to be chocked when fully supported by the jacks. When the jacks are not in use, chocks shall be in place. Tractors that are equipped with a backhoe and/or buckets need not be chocked when parked, provided the backhoe and/or bucket is lowered to the ground.

D.6.2.7 Flammable and Combustible Materials

Flammable and combustible materials such as gasoline or diesel fuel may be brought onto the worksite by either of two methods: (1) in bulk containers, or (2) in UL-approved safety cans.

If a flammable or combustible liquid is brought onto a drilling site in a bulk container, the container shall be permanently mounted onto the transporting vehicle. Fuel cannot be transported in unsecured 55-gallon drums. Bulk containers shall be clearly marked as to the contents. Bulk fuel delivery trucks shall be grounded whenever equipment is being re-fueled.

Flammable and combustible fuels also may be brought on the worksite in UL-approved 5-gallon metal cans. Such cans shall have explosion resistant (flap-type) lids, and shall be clearly marked as to the contents. These cans will not be stored or left in the back of a pickup truck, but shall be kept at a location at least 30 feet away from the drill rig. If fuel cans are stored, the area shall be roped off and posted with a "No Smoking" sign. Containers of hydraulic oil, motor oil, and other combustible materials needed at the worksite also shall be stored at this location.

D.6.2.8 Oxygen and Acetylene Bottles

Bottles of oxygen and acetylene shall be secured from falling or rolling during transport to the site. When left at the worksite, oxygen and acetylene bottles shall be stored in an upright position and secured with a rope or chain to a rigid support. These bottles shall be secured from falling at all times, including when they are in use.

If the pressure regulators and hoses are not attached to the bottles, then the bottle caps shall be in place, screwed down all the way. Regulators and hoses shall not be attached to the bottle if they will not be used during the course of work that day. Bottle caps shall always be in place on the bottles during transport.

Any time an oxygen/acetylene torch is used to cut metal or for other purposes, a face shield and leather gloves with wrist and forearm protection shall be worn by the person operating the torch. If other persons are required to be in the vicinity of the torch while the metal is being cut, they shall wear safety glasses with side shields and leather gloves as necessary to protect against burns.

D.6.2.9 Cement Grout

Where abandonment procedures exist, cement grout shall be used to fill the small hole produced by the penetrometer probe. Cement may be brought to a worksite ready mixed, or mixed in tubs at the site, depending upon the quantities required. If mixed on site, those persons doing the mixing shall wear dust filters to avoid breathing the cement dust. In addition, should a helper have to insert his hand or arm into the liquid mix for any reason, he shall wear rubber gloves that extend far enough up the arm to prevent any contact of the cement with the bare skin.

All persons in the vicinity of a penetrometer rig must wear safety glasses with side shields when cement grout is being pumped under pressure. Care should be taken by the rig operator and crew to ensure that the cement does not come into contact with anyone's face and eyes. Should anyone get cement in their eyes, they should flush their eyes with clean water and then be taken for emergency treatment. Cement that comes in contact with bare skin should be washed off immediately.

D.6.2.10 Power Lines

Power lines, both underground and above ground, can present significant hazards to penetrometer crews. It is the responsibility of the Savannah River Site Supervisor to identify all potential underground power line hazards in an area where subsurface work is to be done. If there is any question regarding the presence or location of underground power lines, the area shall be searched for buried cables and cleared before any subsurface work can begin. In areas where underground power lines are present, no holes are to be drilled without prior knowledge of exact hole locations.

The POLO penetrometer equipment, which has been modified for near horizontal operation, is only about 5 feet high. However, when work proceeds in the vicinity of overhead power lines, at least 20 feet of clearance will be maintained. When setting up close to an overhead power line, the rig shall be parked parallel to the line, whenever possible. Wheel chocks shall be placed under all wheeled equipment parked in the vicinity of an overhead power line. When working near overhead power lines, care should be exercised to avoid breaking wire cables which could come in contact with the line.

D.6.2.11 Other Underground Lines

Other types of lines, such as communication lines, water pipelines, and drain lines, are commonly buried. It is the responsibility of the Savannah River Site Supervisor to verify that no buried lines of any type are present at areas where subsurface penetrometer work is to be performed.

D.6.2.12 Severe Weather

Penetrometer activities routinely continue through hot weather, cold weather, and light rain. During these conditions, the Project Manager shall watch the crew for signs of heat exhaustion in the summer and hypothermia in the winter. The Project Manager shall take any steps necessary to bring the crew members back to full working potential so that accidents can be avoided.

Work will stop when rain interferes with drilling operations to the point of causing a safety hazard. Such hazards exist when vision is impaired, when workers are more concerned with staying dry than with the work being done, or when footing becomes slippery and difficult. When icy conditions exist, most equipment will be covered with ice and work shall not be attempted until the ice has been cleared.

Whenever a thunderstorm with lightning approaches a worksite, all work shall stop. The crew shall move away from the equipment and take cover either in vehicles or shelter. No one shall remain on or anywhere near the equipment while a thunderstorm with lightning is in the area. The crew may return to the equipment and resume work only when the thunderstorm has moved on, away from the area. No exceptions to this policy are allowed, regardless of problems that could occur as a result of stopping work.

D.6.2.13 Cliff Face

The POLO field demonstration involves setting up a penetrometer rig at the top of a heavily eroded area with a near vertical face. During a test, an angled push will be directed toward the cliff face so as to achieve a "hole-out" of the tip. Extra precautions

will be taken to avoid accidents during work in this area. A rope barricade will be set up an appropriate distance (typically 10 - 15 feet) from the embankment. All work in front of the barricade will be conducted with a safety belt.

D.7.0 ACCIDENTS AND INJURIES

The top priority is aiding any injured parties. After the fact, any event that causes physical harm to an individual or damages equipment will be fully investigated.

D.7.1 Accidents With No Injuries

When an accident with damage to equipment occurs, but with no injuries, the event will be reported to the Project Manager, who will in turn immediately notify the Savannah River Site Supervisor. The event will be investigated, and the cause of the damage ascertained prior to re-commencement of work. Repairs to the equipment will be made so that the problem is avoided in subsequent work.

D.7.2 Accidents With Injuries

An individual who is properly trained in first aid and cardio pulmonary resuscitation (CPR) shall be at the site full time. In addition, a first aid station that has a first aid kit, soap and water, drinking water, etc. will be designated at the worksite. A sign will be used to identify its location.

In the event an accident occurs in which there is an injury, or an employee becomes seriously ill while on the job, the following procedures shall be followed:

1. Do not move the victim unless there is danger of further injury if the victim is not moved.
2. Administer emergency first aid as required. First aid shall be given by someone who has had proper training. A first aid kit will be maintained at the worksite at all times.
3. Contact the nearest emergency room. At the Savannah River Site, contact the Emergency Operating Center at 3-3911. Request immediate medical assistance. Give the following information:
 - Your name and the telephone number from which you are calling.
 - The nature of the injury or illness.

- The location of the person needing assistance or a location where the paramedic team can meet you.
 - The name of the person needing assistance.
4. The paramedic team will provide first aid assistance and will transport the victim to the nearest medical facility or hospital.
 5. Field personnel shall not attempt to transport the victim to a medical facility unless the injury or illness is not serious, or unless all attempts to obtain assistance have been unsuccessful. In the event of a minor injury or illness, such as a cut that requires stitches, a small broken bone, or a sprain, the victim can be driven to the nearest medical facility for treatment.
 6. Any injury to field personnel shall be reported immediately to the Project Manager, who will in turn notify the Savannah River Site Supervisor.