**DESIGN, MANUFACTURE AND EVALUATION OF A HYDRAULICALLY
INSTALLED, MULTI-SAMPLING LYSIMETER**

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By

**Joseph A. Scroppo and Gail L. Scroppo
Bladon International, Inc.
25 Sheffield Lane, Oak Brook, IL 60521**

**Dr. Ronald H. Carty and Dr. Mark Chaimberg
Institute of Gas Technology
3424 South State Street, Chicago, IL 60616
Subcontractor**

**Robert D. Timmons and Mark O'Donnell
Timco Manufacturing, Inc.
P.O. Box 8, 851 Fifteenth Street, Prairie du Sac, WI 53578
Subcontractor**

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**Office of Research and Development
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**Research and Development Program Coordination Office
Waste Management and Technology Development, Chicago Field Office
U.S. Department of Energy
9800 S. Cass Avenue
Argonne, IL 60439**

**Research and Development Program Coordination Office
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PREFACE

Currently available technology is not adequate to assess environmental contamination at Department of Energy (DOE) sites, take permanent remedial action, and eliminate or minimize the environmental impact of future operations. Technical resources to address these shortcomings exist within the DOE community and the private sector, but the involvement of the private sector in attaining permanent and cost-effective solutions has been limited.

During 1990, on behalf of DOE's Office of Technology Development, Argonne National Laboratory (ANL) conducted a competitive procurement of research and development projects addressing soil remediation, groundwater remediation, site characterization, and contaminant containment. Fifteen contracts were negotiated in these areas.

This report documents work performed as part of the Private Sector Research and Development Program sponsored by the DOE's Office of Technology Development within the Environmental Restoration and Waste Management Program. The research and development work described herein was conducted under contract to ANL.

On behalf of DOE and ANL, I wish to thank the performing contractor and especially the report authors for their cooperation and their contribution to development of new processes for characterization and remediation of DOE's environmental problems. We anticipate that the R&D investment described here will be repaid many-fold in the application of better, faster, safer, and cheaper technologies.

Details of the procurement process and status reports for all 15 of the contractors performing under this program can be found in "Applied Research and Development Private Sector Accomplishments - Interim Report" (Report No. DOE/CH-9216) by Nicholas J. Beskid, Jas S. Devgun, Mitchell D. Erickson and Margaret M. Zielke.

Mitchell D. Erickson
Contract Technical Representative
Research and Development
Program Coordination Office
Chemical Technology Division
Argonne National Laboratory
Argonne, IL 60439-4837

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ABSTRACT

There is a need for a quick, simple, reliable, and inexpensive on-site method for sampling soil pollutants before they reach the groundwater. Vadose zone monitoring is an important aspect of sound groundwater management. In the vadose zone, where water moves via percolation, this water medium possesses the ability to transfer hazardous wastes to the nation's groundwater system. Obtaining samples of moisture and contaminants from the vadose zone is necessary if potential problems are to be identified before they reach the water table. Accurate determination of spatial distribution, movement, and concentrations of contaminants is essential to the selection of remediation technologies. There is a need for three-dimensional subsurface characterization technologies to identify the location of hazardous plumes and their migration.

Current subsurface characterization methods for dispersed contaminants primarily involve a time consuming, expensive process for drilling wells and taking samples. With no major water flow in the vadose zone, conventional monitoring wells will not function as designed. Drilling creates conduits for contamination to spread. Sampling often disturbs the environment to such an extent that results may be invalid. Any perturbation of the geologic media by drilling or equivalent intrusive mechanisms has the potential for spread of contamination. The multi-sampling lysimeter can be readily linked with physical and chemical sensors for on-site screening.

The hydraulically-installed suction lysimeter was capable of extracting soil pore liquid samples from unsaturated test soils without the need to predrill a well. More than 150 mls of soil pore liquid was extracted within a 24-hour period from test soils having less than 15 percent moisture content. Test results verified that the lysimeters installed with a hydraulic or mechanical ram were able to collect soil pore liquid samples in excess of the amount typically required for monitoring and analysis on a daily basis. Multiple sampling ports may be installed in an instrument to retrieve samples from multiple depths without sample contamination.

Modifications to the prototype design eliminated moving parts and the need for inflatable packers. The elimination of the packer system and the use of porous nickel contributed to increased system ruggedness.

EXECUTIVE SUMMARY

Technology Description

Chemical spills, underground storage tank leaks, and improper burial of contaminants have the potential to cause extensive groundwater contamination. Determining the extent of underground pollution and the potential for groundwater contamination requires monitoring in the vadose zone, the section between ground level and the groundwater table. Vadose zone monitoring can be accomplished using a suction lysimeter a long tube with a porous section through which liquid is extracted from the soil. The existing technology for obtaining liquid from the vadose zone involves drilling a well (usually four inches in diameter), injecting a silica slurry packing into the bottom of the hole, inserting a lysimeter sampling device, and backfilling and plugging the hole. This procedure is expensive due to the high cost of drilling and backfilling the well. Furthermore, the potential for cross-contamination is exacerbated by drilling a conduit through potentially contaminated soil.

The primary objective of this experimental program was to develop a suction lysimeter that can be inserted into the area of interest in the vadose zone without using a predrilled hole. In this program the effect of hydraulically inserting the lysimeter was investigated by comparing the operation of a specially designed and constructed lysimeter that has been manually driven into the soil with that of an identical lysimeter that has been installed using standard procedures including a silica four packing. In the project, the prototype of a new lysimeter design, approximately one inch in diameter and capable of being hydraulically installed at desired depth without drilling, was constructed and evaluated. Based on tests performed on the prototype lysimeter design, a modified lysimeter was designed, constructed, and evaluated. Currently no lysimeter is available that can be installed hydraulically. The Bladon instrument represents a practical means of profiling soil contamination at reasonable cost. The system can be readily customized to meet the needs of a particular site.

The hydraulically-installed suction lysimeter was evaluated by a series of tests including: visual inspection, bubble pressure, pore plugging, and soil moisture operating range. Visual inspections were conducted throughout the project to identify gross defects such as cracks, nonuniformity, and incorrect assembly. The inspection was an integral component of the quality assurance and quality control program. The bubble pressure tests were used to identify uniformity of pore size, air entry pressure, cracks, and leaks in the lysimeter. Bubble pressure measurements ensured that the pore size of each lysimeter was within a specific tolerance, and that minimum specifications for operation were achieved. The pore plugging tests were designed to measure the degree of plugging that would occur during field operation of the lysimeter. These tests were intended to determine the consequence of eliminating the silica slurry packing, and whether it altered the extent of pore plugging. The soil moisture operating range tests were used to determine the effect of soil desiccation on the operation of the lysimeter. These tests endeavored to discern the effects of eliminating the silica slurry packing, such as the ability to obtain samples from unsaturated soils.

Chemical reactions which promote precipitation of compounds on the lysimeter frit were not included in the experiments. In field applications, the effective porosity of the porous ceramic material may be constantly reduced over the time the lysimeter is in the geologic media.

Principle of Operation

The main component of lysimeter technology is the suction principle behind the porous sampler. Water is drawn through a porous sampler by capillary action. By establishing a pressure gradient, the water seeks a lower concentration under osmotic principles and thereupon effectively migrates to the porous sampler. Suction lysimeters typically will not function over a negative pressure of approximately 500 cm of water (49 kPa).

A stainless steel ram point is used for hydraulic or mechanical installation, thus eliminating the need to drill a well which can lead to cross contamination between soil horizons. Ram installation reduces the prospects for cross contamination. The prospects for cross contamination are, however, not eliminated. The instrument can be used to retrieve liquid and gas samples from the unsaturated zone and liquids from the saturated zone. A single instrument can have more than ten sampling ports without cross contamination.

Prototype Lysimeter Technology Performance

Bubble pressure tests were performed on all lysimeters which passed visual inspection. The porous section of the lysimeter was initially saturated by extracting a copious amount of water through the lysimeter via an extraction tube. Compressed nitrogen was then connected to the extraction tube and the pressure was slowly increased. The bubble pressure was identified as the pressure at which bubbles began to form on the outside of the porous section. The bubble pressure tests facilitated the detection of hairline cracks and leaks in the lysimeter, and were used to corroborate the pore size distribution data obtained from mercury porosimetry analysis. In addition, the quality control component of these tests identified a group of sixteen lysimeters which possessed bubble pressures with a $\pm 5\%$ tolerance range to be used in subsequent testing.

The pore plugging tests with the prototype lysimeters conformed to the following protocol: into each of three saturated test soils (medium sand, silty clay, 75% clayey topsoil-25% medium sand blend) two lysimeters were hydraulically installed and two lysimeters were inserted using the silica slurry packing method. Pore plugging tests were performed by applying a vacuum to the four lysimeters in each test chamber for a five-hour period, measuring the volume of liquid collected by each lysimeter, and returning the liquid to the test chamber. The procedure was repeated until the degree of plugging reached a plateau value, as determined by measuring equivalent volumes of collected water for a period of three consecutive days.

The pore plugging tests for the prototype lysimeters required approximately twenty days to complete. The results of the pore plugging tests demonstrated that all lysimeters plugged to some extent, and the degree of plugging was affected by the type of soil and the presence of a silica slurry packing. In the medium sand test soil, the volume

collected with the hydraulically installed lysimeters was significantly greater than with the lysimeters installed using the silica slurry packing. The large particle size of the soil relative to the pores of the lysimeter limited the plugging of the hydraulically installed lysimeters, while the lysimeters with the silica slurry packing experienced plugging from the soil as well as from the smaller particle diameter silica used in the slurry. The pore plugging tests in the silty clay test soil demonstrated the effect of obtaining liquid from a soil in which the particle size is comparable to the pore size of the lysimeter. The silty clay particles can easily enter the porous structure of the hydraulically installed lysimeter, while the silica slurry packing insulates the lysimeter from the soil. As a result, the hydraulically installed lysimeters plugged to a greater degree than did those installed with the silica slurry. The pore plugging tests in the clayey topsoil-medium sand blend were similar to those of the silty clay test soil in that the relatively small clayey topsoil particles could easily enter the porous structure of the hydraulically installed lysimeter. At the completion of the plugging test, the hydraulically installed lysimeters collected liquid at a rate of 14.7, 1.2, and 0.5 liters per day for the sand, clay, and topsoil-sand test soils, respectively. These volumes are far in excess of the amount required for monitoring and analysis on a daily basis. For comparison, the lysimeters installed with the silica slurry collected liquid at a rate of 4.0, 4.4, and 1.2 liters per day.

The soil moisture operating range tests for the prototype lysimeters were conducted in accordance with the following protocol: two each of the hydraulically installed and silica slurry packing lysimeters were inserted into a large test chamber filled with the clayey topsoil-medium sand blend. The moisture content of the soil was lowered by removing water through a series of extraction plates and tubes. Water was collected for a one-hour period at various degrees of dryness, as measured by the soil suction pressure of five tensiometers installed in the test soil. The results of the operating range tests indicate that the hydraulically installed lysimeters ceased to collect liquid when the soil suction pressure reached approximately 10 kPa. The lysimeters installed with the silica slurry packing continued to collect liquid up to a soil suction pressure of approximately 17 kPa. It was suggested that the limited capacity of the hydraulically installed lysimeters is a result of a possible break in contact of the porous ceramic section with the soil as the soil gets progressively drier, as well as a decrease in the efficiency of the porous section due to pore plugging. A break in continuity between the hydraulically installed lysimeters and the soil may only be a problem when the soil moisture decreases dramatically after installation of the lysimeter. If the lysimeter were installed hydraulically in a soil of low moisture content, it is possible that contact would be maintained and samples obtained at higher soil moisture pressures than those obtained in these tests.

Modified Lysimeter Technology Performance

In preparing the modified lysimeters, the objectives were to obtain a porous section with a narrow pore size distribution which would perform well in dry soils, and to increase the structural strength of the material. Three different porous sections were obtained for the modified lysimeter. One was of the same material as that used in the prototype lysimeter, with the exception being a different pore size distribution. One porous section was of a higher structural strength and larger porosity ceramic material. The final porous section was produced from a thin slab of porous nickel. Visual inspection and bubble pressure tests were performed on all modified lysimeters.

The experimental protocol for testing the modified lysimeters was altered from that of the prototype lysimeters. The pore plugging tests for the modified lysimeters were only performed in the test soil that produced the highest degree of plugging, the clayey topsoil-medium sand blend. Testing in the medium sand was deleted because the large particle size of the sand did not result in significant pore plugging with respect to the other two test soils. Correspondingly, testing in the silty clay was excluded because the degree of pore plugging was nearly equal to that in the clayey topsoil-medium sand blend. Furthermore, since pore plugging tests with the prototype lysimeters demonstrated that an adequate volume of liquid was obtained from the hydraulically installed and the silica slurry packing lysimeters, it was decided that it would be best to compare the modified porous sections with each other and that no silica slurry packing would be used with the modified lysimeters. This enabled the testing and comparison of four different porous sections at the same time. Due to the large diameter of certain modified porous sections it was decided that in lieu of hydraulic installation the modified lysimeters would be placed into the test chamber, and the test chambers would be subsequently filled with the test soil. This installation technique should not invalidate the test because the soil was thoroughly saturated with water prior to testing. The saturated soil becomes settled and compacted, simulating the effect of hydraulic installation.

To better simulate the performance of the lysimeters under field conditions, suction was continuously applied to the lysimeters. At the end of each twenty-four hour period the volumes collected by the lysimeters were measured and the liquid returned to the test chamber. The results of the pore plugging tests demonstrated the effect of pore size and porosity on the liquid volume collected by each lysimeter. At the completion of the ten-day plugging test the modified lysimeters installed into the saturated clayey topsoil-medium sand blend collected liquid at rates of 0.5 to 5.5 liters per day, far in excess of the amount required for monitoring and analysis. Furthermore, these rates are greater than those obtained by the prototype lysimeters.

The results of the soil moisture operating range test with the prototype lysimeters indicated a need to obtain a porous section which would allow collection in dry conditions. To separate the effects of pore plugging and soil dryness it was determined that the operating range tests be performed with lysimeters that had undergone pore plugging. Therefore, the operating range tests were carried out with the same set of modified lysimeters and in the same test chamber used for the pore plugging tests. This eliminated the impact of pore plugging on the operating range tests because pore plugging had already transpired. To better simulate the performance of the lysimeters under field conditions, suction was continuously applied to the lysimeters. At the end of each twenty-four hour period the volumes of liquid collected by the lysimeters were measured, the liquid was discarded, and the soil suction pressure was determined. The results of the soil moisture operating range test demonstrated that the modified lysimeters continued to collect liquid up to soil suction pressures of 24 kPa. Furthermore, several lysimeters were able to collect volumes of 0.1 liters per twenty-four hour period, far in excess of the amount required for monitoring and analysis on a daily basis, at soil suction pressure of 16 kPa. These results were significantly better than the prototype lysimeter, and verified that the modified lysimeters were able to collect an adequate volume of liquid from unsaturated soil conditions.

1.0 INTRODUCTION

1.1 Technology Scope

The vadose zone can be defined as the geological profile from the ground surface to the upper surface of the principal water bearing strata (16). Three primary regions, the soil zone, the intermediate vadose zone, and the capillary fringe, comprise the vadose zone. In this area, water movement generally occurs in the unsaturated state, the state in which soil water exists under less than atmospheric pressures. The vadose zone is characterized by the presence of solid, liquid, and vapor phases. Liquids are transported downward through the soil by percolation through gravitation forces, and upward and laterally as a result of capillary action. Vapors move through the soil in response to concentration and temperature gradients. The transport of liquids and vapors is facilitated by the presence of fractures or channels.

Chemical spills, underground storage tank leaks, and improper burial of contaminants have the potential to cause extensive groundwater contamination. To ascertain the extent of underground pollution and the potential for groundwater contamination requires monitoring in the vadose zone. Samples of the vapor phase are usually collected by a vapor probe, essentially a long tube which is installed vertically to a particular soil depth (32). Suction lysimeters are used to collect liquid samples from the vadose zone. The lysimeter sampling apparatus consists of a hollow porous section that is maintained at vacuum. Liquid is transported into the lysimeter due to the pressure differential across the porous section. Liquid flow through the porous section is sustained by maintaining a pressure differential which is finite yet below the air entry capillary pressure. The performance of suction lysimeters is restricted by the physical and chemical properties of the porous section. The porous section may be categorized by the type material, pore size distribution (or permeability), surface area, degree of hydrophilicity, and surface absorption characteristics.

The existing technology for obtaining liquid from the vadose zone involves drilling a well (usually four inches in diameter), injecting a silica slurry packing into the bottom of the hole, inserting a sampling device, and backfilling and plugging the hole. This procedure is expensive due to the high cost of drilling and backfilling the well. Furthermore, the potential for cross-contamination is exacerbated by drilling a conduit through potentially contaminated soil. In this project, a new lysimeter design, having multiple sampling zones and capable of being hydraulically-installed at desired depth without drilling, was evaluated. Based on tests performed on a prototype lysimeter design, a modified lysimeter was designed, constructed, and evaluated. It is intended to use the results of this study to improve the operation and lower the cost of sample collection in the vadose zone by suction lysimeters.

2.0 METHODOLOGY AND APPROACH

2.1 Facilities and Equipment

2.1.1 Suction Lysimeter

The Bladon modular suction lysimeter was designed to be installed into the vadose zone with a hydraulic ram. This design eliminates the need to drill and backfill a bore hole. A schematic diagram of the hydraulically-installed suction lysimeter is shown in Figure 2.1. The lysimeter, is comprised of a stainless steel ram point and body, one or more ceramic porous sections, and one or more extraction tubes. The stainless steel ram point was designed to promote the installation of the lysimeter into the test soils by a hydraulic ram. Liquid present in the vadose zone may be drawn into the lysimeter through the porous section by application of vacuum on the extraction tubes. The liquid samples are also transported to collection vessels at the surface by way of the extraction tubes.

The suction lysimeter will cease to draw liquid from the vadose zone if soil vapor infiltrates the pores of the ceramic section. The pressure at which vapor will enter the pores is known as the bubble pressure or capillary entry pressure, P_E , and may be described by the following equation for a porous medium of uniform pore size (1)

$$P_E = \frac{4\gamma \cos \theta}{D_t} \quad (2.1)$$

where γ is the surface tension of the liquid, θ is the angle of contact between the liquid and the surface of the solid porous material, and D_t is the pore diameter. The capillary entry pressure limits the operating range of the suction lysimeter by establishing a maximum suction pressure for a particular pore diameter. To obtain an aqueous sample at 20°C ($\gamma=72.8$ dynes/cm) from relatively dry soil by a hydrophilic porous section ($\theta = 0^\circ$) it is essential that the maximum pore diameter of the porous section be less than 2.87 μm .

2.1.2 Vadose Zone Testing Facility

The Vadose Zone Testing Facility, located at the Institute of Gas Technology's Energy Development Center, was designed to accommodate the pore plugging and operating range testing of suction lysimeters in an environment representative of field monitoring sites. Three 200 L polyethylene (PE) drums, each filled with a different test soil, were used for evaluating pore plugging in the suction lysimeters. The system configuration consisted of a large capacity vacuum pump connected to each of four collection flasks fabricated from translucent, 10 cm diameter, polyvinylchloride (PVC) pipes with sealed PVC end caps. The four 12 L collection flasks, graduated in 1 L intervals to facilitate volume measurement, were connected to the four suction lysimeters installed into one of the test chambers (Figure 2.2). The moisture content of the test soil was measured by a tensiometer (Model 2725 Jet Fill, Soilmaster Equipment Corp., Santa Barbara, CA) inserted into the center of the test chamber.

Figure 2.1 Schematic Diagram of Suction Lysimeter

Figure 2.2 Schematic Diagram of Pore Plugging Test Chamber

The soil moisture operating range test chamber consisted of a PE drum (1,100 L) filled with test soil. The configuration of the vacuum and collection apparatus was similar to that of the pore plugging flasks. The operating range apparatus included a series of extraction plates (Model 1950, Soilmaster Equipment Corp.) and extraction tubes (Model 1900, Soilmaster Equipment Corp.) used to reduce the moisture content of the test soil (Figure 2.3).

2.2 Reagents and Supplies

2.2.1 Test Soils

Three different soils were obtained for use in the pore plugging and soil moisture operating range tests. STS Consultants Ltd. (Northbrook, IL) performed a combined sieve hydrometer analysis following ASTM D-422 procedures and an organic content test following ASTM D-2974 for the three soils described as medium sand, silty clay, and clayey topsoil. A summary of the median grain size, specific gravity, and organic content are shown in Table 2.1, and the grain size distribution is in Appendix A (Figure A.1). Upon consultation with soil scientists at the U.S. Department of Agriculture (USDA), it was recommended that a blend of 75% clayey topsoil with 25% medium sand would yield a soil with intermediate permeability representative of "typical" topsoil. Therefore, based on the soil analyses and USDA recommendation, the composition of the test soils were: (1) 100% medium sand; (2) 100% silty clay; and (3) a 75% clayey topsoil - 25% medium sand blend.

Table 2.1 Soil Characteristics

Soil Type	Median Particle Size (μm)	Specific Gravity	Organic Content (%)
Medium Sand	500	2.65	0.0
Silty Clay	6	2.72	6.1
Clayey Topsoil	4	2.70	6.3

2.2.2 Silica Slurry

The silica slurry was produced by thoroughly mixing 500 g of a 200 mesh silica flour (Soilmaster Equipment Corp.) with approximately 0.15 L of distilled water. The silica slurry acquired the consistency of cement. Standard installation of the suction lysimeters was conducted by inserting a suction lysimeter into the center of a 10 cm PVC casing partially filled with the silica slurry packing.

2.2.3 Organic Compounds

Analytical grade ethanol and phenol were used in tests to determine the representativeness of samples collected by the suction lysimeter.

2.2.4 Porous Sections

All porous sections used in the prototype lysimeters were aluminum oxide (Al_2O_3) ceramic obtained from Timco Manufacturing, Inc. Additional Al_2O_3 porous sections for the modified lysimeters were procured from Timco Manufacturing, Inc. In addition, a modified Al_2O_3 porous section, with a higher structural strength was obtained from Ferro Corp. Finally, several porous nickel sections, with distinct thickness and pore size, were manufactured by the Institute of Gas Technology Fuel Cell Group.

2.3 Experimental

Experimental testing of the suction lysimeters, including bubble pressure, pore plugging, operating range, and representative sampling tests, were performed at the Institute of Gas Technology's Vadose Zone Testing Facility.

2.3.1 Bubble Pressure Tests

Bubble pressure tests were performed on each lysimeter to determine the capillary entry pressure of the porous section. The lysimeter was submerged in a transparent container filled with distilled water and was pressurized with nitrogen gas to test for leaks. Suction was applied to the extraction tubes and 0.5 L of water was drawn into the lysimeter. The suction was subsequently discontinued and the extraction tubes were gradually pressurized with nitrogen gas. The pressure at which bubbles began to form on the exterior surface of the porous section of the lysimeter, the bubble pressure, was recorded.

2.3.2 Pore Plugging Tests

The pore plugging tests were performed using three different saturated test soils in which four lysimeters were installed: two hydraulically and two using a standard silica slurry packing. The three 200 L pore plugging test chambers were prepared according to the following protocol. The soil was packed into each test chamber to a depth of 30 cm in intervals of 15 cm, and the soil was tamped down by hand after each interval. To accommodate the silica slurry packing, two 10 cm diameter PVC casings were placed on top of the soil at the desired location in the sample chamber (Figure 2.2). Soil was added to the sample chamber outside of the casings in 15 cm intervals and was tamped down by hand. The silica slurry, composed of 500 g of silica in 0.15 L distilled water, was poured into the PVC casing to a depth of approximately 10 cm. For the standard installation, each of two lysimeters was inserted into the silica slurry in the center of the PVC casing. Additional silica slurry to cover the porous section of the lysimeter was poured into the casing. The remainder of the soil was added to the test chamber to the same depth as the silica slurry at 15 cm intervals. The PVC casings were carefully removed and the sample chamber was completely filled with soil, tamping down by hand

every 15 cm. Two additional lysimeters were installed using a hydraulic ram into the test soil at the same depth as the standard lysimeters. To measure the soil suction, a tensiometer was installed at the center of the test chamber at the same depth as the lysimeters. The test soil was thoroughly saturated with water and allowed to equilibrate overnight.

The pore plugging tests were performed by applying suction on a vacuum line connected to a set of four 12 L graduated, translucent collection flasks, each of which was connected to a lysimeter. The flasks were used to collect and measure the volume of water which was drawn by the lysimeters from the test soils. At the end of each daily test, the suction was disconnected and the amount of water collected by each lysimeter was measured. The daily tests were repeated until the amount of water obtained from each lysimeter reached a plateau value.

2.3.3 Soil Moisture Operating Range Tests

The soil moisture operating range tests were performed using the clayey topsoil-medium sand test soil in which four lysimeters were installed: two hydraulically and two with a standard silica slurry packing. The 1,100 L test chamber was packed with soil in intervals of 15 cm, and the soil was tamped down by hand after each interval. To control the suction pressure in the test soil, two extraction plates were buried near the bottom of the test chamber (Figure 2.3). Two lysimeters were installed using the standard technique of a silica slurry packing, and two lysimeters (23) were hydraulically-installed. To measure the soil suction, a series of five tensiometers were installed in the test chamber at the same depth as the lysimeters. In addition to the extraction plates, five extraction tubes were inserted into the test soil. The test soil was thoroughly saturated with water and allowed to equilibrate for two weeks with the periodic addition of water.

The operating range tests were performed by applying suction on a vacuum line connected to a set of four 12 L graduated, translucent collection flasks, which were connected to the lysimeters. The flasks were used to collect and measure the volume of water which was withdrawn by the lysimeters from the test soils. At the end of the test period, the suction was disconnected and the amount of water collected by each lysimeter was measured. The soil moisture content was decreased by the removal of water through the extraction plates and tubes. The operating range test was repeated for progressively higher readings of the soil suction pressure (lower soil moisture content).

2.3.4 Representative Sampling Tests

The representativeness of samples obtained by the suction lysimeter was determined for aqueous solutions of ethanol and phenol. Standard solutions of concentrations ranging from 0.5 to 10 g/L were prepared in a glass beaker. A suction lysimeter was inserted into each standard solution and was used to transfer a sample of approximately 0.5 L to a collection flask. The concentration of the extracted sample was compared to that of the original solution by total organic carbon (TOC) analysis. The TOC concentrations measured for the standard hydrocarbon solutions at 2.5 g/L were used to standardize the TOC data from the extracted samples.

Figure 2.3 Schematic Diagram of Soil Moisture Operating Range Test Chamber

2.4 Quality Assurance

The Quality Assurance/Quality Control (QA/QC) program encompasses all activities which affect the quality of design, fabrication, assembly of components and system testing. Such activities are in conformance with applicable codes, standards, drawings, specifications, and contract requirements. The program includes procedures, instructions, etc. to fulfill QA requirements. Bladon International has the primary responsibility for the QA/QC Program. The QA/QC Program is administered by the project manager who is responsible for assuring compliance with QA/QC procedures and has the authority to ensure that the procedures are followed. The project manager has the responsibility to (a) identify QA/QC problems, (b) initiate action which results in solution, and (c) verify implementation of solutions to those problems. Quality Assurance encompasses all phases of project activities which affect the quality of lysimeter products and system evaluation. It is applicable to any item such as mechanical design, subsystem design, component manufacture/assembly/testing, raw materials, system test equipment, and system testing that is essential to the satisfactory performance of the suction lysimeter. The QA Program consists of procedures, instructions, and other documents which are used to fulfill designated QA requirements.

2.4.1 Test Program Quality Assurance

The overall Quality Assurance objectives for the test program are to ensure that the data generated are of high quality, are representative of the process being developed, and the results can be made applicable to a broad range of soils found at various monitoring sites. The QA objectives relate to (1) the proper measurement of the conditions during which the testing of the lysimeters are conducted, (2) the testing procedures used, including instrument calibration, and (3) the data reduction and interpretation.

The objectives were accomplished by assuring that the critical measurements were of high quality. The critical measurements made during the course of the experimental work are those without which the success of the overall project would be jeopardized. For example, during the soil moisture operating range tests for the prototype lysimeters, the soil suction pressure was measured by five tensiometers at the same depth as the lysimeters. To ensure accurate readings, the tensiometers were calibrated prior to installation in the test soil. Installation of the tensiometers was performed according to the standard operating procedures developed by the manufacturer. Finally, the soil suction pressure was measured only after a sufficient amount of time to allow the tensiometers to equilibrate with the test soil.

All of the lysimeter parameters measured in the test program were functions of both the design and materials of construction of the lysimeter, as well as the nature of the test soil. Variations due to the heterogeneous nature of the soil used, as well as the degree of compaction, were minimized by soil characterization and standard soil compaction techniques. In each test chamber, two of the prototype lysimeters were installed in the standard method using the silica slurry packing and served as internal standards for comparison of the hydraulically-installed prototype lysimeters. Replicates of all tests were performed whenever applicable.

2.4.2 Lysimeter Manufacturing/Assembly Quality Assurance

The lysimeter component manufacture/assembly/testing Quality Assurance program objectives are to ensure that all design data, materials used, manufacturing and unit assembly/testing are completed according to established procedures and specifications. The QA objectives relate to procurement of suitable raw materials, manufacturing in accordance with design specifications, component manufacture, assembly and unit testing prior to shipment for testing in the Institute of Gas Technology vadose zone laboratory. Procurement documentation, storage and handling were performed to provide traceability and to preclude damage or degradation.

All raw materials and components were identified by the source. Identification included composition and as applicable, lot number or other significant identification. Materials and services were subject to receiving (incoming) or source inspection.

In-process inspection and surveillance during component manufacturing, subsystem assembly and lysimeter testing was performed by Timco Manufacturing, Inc. In-process measurements were made to ensure that components were manufactured in accordance with design specifications. After assembly, the lysimeter was tested for leaks and bubble pressure tests were performed. Test data was compiled and transmitted to IGT where bubble pressure data was verified prior to lysimeter system testing.

3.0 RESULTS AND DISCUSSION

3.1 Prototype Suction Lysimeter

3.1.1 Bubble Pressure Tests

Bubble pressure tests, performed on each prototype suction lysimeter which passed visual inspection, were used to identify uniformity of pore size, air entry pressure, cracks, and leaks in the lysimeter. The bubble pressure is defined as the pressure at which bubbles begin to form on the outside of a porous section saturated with liquid. Preliminary testing yielded bubble pressures from 90 to 117 kPa. The QA/QC program mandated that the range of bubble pressure values be within a 10% tolerance for the complete set of prototype lysimeters. Accordingly, a number of porous sections were replaced. As shown in Table 3.1, the bubble pressures of the final set of prototype lysimeters were equal to 117 ± 10 kPa. By employing the relationship between capillary entry pressure and pore diameter (eqn 2.1) it is possible to equate a bubble pressure of 117 kPa to a maximum pore diameter of $2.5 \mu\text{m}$. The maximum pore diameter derived from the bubble pressure tests corresponds to the maximum (cumulative pore volume greater than 95%) pore diameter of approximately $2.4 \mu\text{m}$ derived from mercury porosimetry of the porous ceramic section (see Appendix A, Figure A.2).

3.1.2 Pore Plugging Tests

Pore plugging experiments were carried out in three different saturated test soils: medium sand, silty clay, and 75% clayey topsoil-25% medium sand blend. The volume of liquid collected during each 5-hour test over the complete test period is shown in Figure 3.1 for the medium sand test soil. At the start of the experiment, the volume of water collected by the hydraulically-installed lysimeters was approximately 10 times that of the lysimeters installed by the standard method using the silica slurry packing. Pore plugging in the porous ceramic section of the lysimeters resulted in a decrease in the volume of water collected during the 5-hour test period. At the end of the 21-day test period, the volume of water collected by the lysimeters had attained a plateau value, with the exception of lysimeter *B* which exhibited anomalous results. For the hydraulically-installed lysimeters *C* and *D*, the volume of water was reduced by an average of 65% over the complete test period. Lysimeter *A* was installed with the silica slurry packing showed a decrease of 55% over the same time period. The larger sample volumes collected by lysimeters *C* and *D* demonstrated the advantage of hydraulic installation for soils similar to the medium sand test soil.

The results of the pore plugging experiments in the silty clay test soil are shown in Figure 3.2. Contrary to the results in the medium sand test soil, the hydraulically-installed lysimeters collected a significantly smaller liquid volume than the lysimeters installed using the standard silica slurry packing. It is suggested that the smaller uptake of sample by the hydraulically-installed lysimeters is a consequence of the relatively small particle size of the silty clay test soil and thus, its increased ability to plug the pores of the ceramic section. The silica slurry packing shields the porous ceramic section from intimate contact with the soil and therefore, these lysimeters operate at a higher

Table 3.1 Prototype Lysimeter Bubble Pressures

Lysimeter ID Code	Manufacturer	Material	Bubble Pressure (kPa)
A	Timco	Al ₂ O ₃	117
B	Timco	Al ₂ O ₃	117
C	Timco	Al ₂ O ₃	117
D	Timco	Al ₂ O ₃	117
E	Timco	Al ₂ O ₃	117
F	Timco	Al ₂ O ₃	117
G	Timco	Al ₂ O ₃	117
H	Timco	Al ₂ O ₃	117
I	Timco	Al ₂ O ₃	117
J	Timco	Al ₂ O ₃	117
K	Timco	Al ₂ O ₃	117
L	Timco	Al ₂ O ₃	117
M	Timco	Al ₂ O ₃	117
N	Timco	Al ₂ O ₃	110
P	Timco	Al ₂ O ₃	117
Q	Timco	Al ₂ O ₃	117
R	Timco	Al ₂ O ₃	117

LITERS/5-HOUR TEST

STANDARD A

HYDRAULIC C

STANDARD B

HYDRAULIC D

Figure 3.1 Results of Pore Plugging Test for Prototype Lysimeters in Medium Sand Test Soil

LITERS/5-HOUR TEST

Figure 3.2 Results of Pore Plugging Test for Prototype Lysimeters in Silty Clay
Test Soil

efficiency. All four of the lysimeters, however, exhibited a marked decrease in the sample volume collected over the period of the test.

Results similar to the pore plugging in the silty clay test soil were obtained using the clayey topsoil-medium sand test soil (Figure 3.3). The relatively small particle size of the topsoil produced a larger degree of pore plugging in the ceramic section of the hydraulically-installed lysimeters. Furthermore, the volume of water collected in the clayey topsoil-medium sand was significantly less than the volume collected in the clay. This data further corroborates the concept that the particle size of the soil strongly influences the degree of pore plugging. A complete set of pore plugging data for the prototype lysimeters is given in Appendix A (Tables A.1, A.2, and A.3).

A comparison of the collection rate at the start and completion of the pore plugging test in the three test soils is shown in Figure 3.4. The differences observed at the start of the test clearly demonstrate the immediate effect of pore plugging. The rates of collection at the completion of the test illustrate the differences in the sample volume which could be obtained from different soils over a prolonged sampling period. In terms of a 24-hour daily collection rate at the completion of the plugging test, the hydraulically-installed lysimeters collected liquid at a rate of 14.7, 1.2, and 0.5 liters per day for the medium sand, silty clay and clayey topsoil-medium sand test soils, respectively. These volumes are far in excess of the amount required for monitoring and analysis on a daily basis (approximately 0.05 L). For comparison, the lysimeters installed with the silica slurry collected liquid at a rate of 4.0, 4.4, and 1.2 liters per day.

3.1.3 Soil Moisture Operating Range Tests

Soil moisture operating range experiments were performed in the clayey topsoil-medium sand test soil to determine the extent of any restrictions in the function of the lysimeters in unsaturated soils. The volume of water collected by the prototype lysimeters during the one-hour test, as a function of the soil suction pressure, is shown in Figure 3.5. The soil suction pressure is the conventional mode of indicating the degree of soil dryness. A soil suction pressure of 0 kPa corresponds to a completely saturated soil. Unfortunately, the soil suction pressure is not linearly proportional to the moisture content in the soil. Furthermore, the relationship between the soil suction pressure and soil moisture content varies depending upon the composition of the soil. Moisture analysis of the completely saturated clayey topsoil-medium sand blend by weighing and drying yielded a soil water content of 27.0%. The data indicate that the hydraulically-installed lysimeters collect a negligible volume of liquid when the soil suction pressure is greater than 5 kPa. The lysimeters installed with the standard silica slurry packing continue to obtain liquid samples at a soil suction pressure of 17 kPa (17.7% moisture). It is suggested that the limited capacity of the hydraulically-installed lysimeters is a result of a possible break in contact of the porous section with the soil as the soil gets progressively drier (5), as well as a decrease in the efficiency of the porous section due to pore plugging. The design of the modified lysimeter and incorporation of porous nickel were based upon these observations. It is important that the modification of the suction lysimeters emphasizes the ability of the lysimeters to obtain liquid from soils in which the suction pressure is at least 17 kPa. A break in continuity between the hydraulically-installed lysimeters and the soil may only be a

Figure 3.3 Results of Pore Plugging Test for Prototype Lysimeters in Clayey Topsoil-Medium Sand Test Soil

Figure 3.4 Comparison of Pore Plugging Tests for Prototype Lysimeters in Three Test Soils

Figure 3.5 Results of Soil Moisture Operating Range Test for Prototype Lysimeters in Clayey Topsoil-Medium Sand Test Soil

problem when the soil moisture decreases dramatically after installation of the lysimeter. If the lysimeter were installed hydraulically in a soil of low moisture content, it is possible that contact would be maintained and samples obtained at higher soil moisture pressures than those obtained in these tests.

3.1.4 Representative Sampling Tests

Representative sampling tests were performed to determine whether the concentration of organic compounds extracted by the suction lysimeter was representative of the organic concentration in the original solution. In particular, it is important to assess the degree of absorption onto the porous ceramic, as well as the possibility of loss through the vacuum system. The results of the representative sampling test for single extractions of aqueous ethanol and phenol solutions are given in Table 3.2. The data indicate that for the compounds and their concentration range used in this study, the lysimeter collects a representative sample of the solution.

Table 3.2 Lysimeter Sampling of Aqueous Solutions

Compound	Solution Concentration (g/L)		Percent of Original
	Original	Extracted	
Ethanol	10.00	9.14	91
	5.00	4.84	97
	2.50	2.47	99
	1.00	0.97	97
	0.50	0.59	118
Phenol	10.00	8.97	90
	5.00	3.53	71
	2.50	2.65	106
	1.00	1.06	106
	0.50	0.44	88

3.2 Modified Suction Lysimeter

In preparing the modified lysimeters, the objectives were to obtain a porous section with a narrow pore size distribution which would perform well in dry soils, and to increase the structural strength of the material. Three different porous sections were obtained from the modified lysimeter. One was of the same aluminum oxide (Al_2O_3) material as that used in the prototype lysimeter, with the exception being a different

pore size distribution. One porous section was of a higher structural strength and larger porosity modified Al_2O_3 ceramic material. The final porous section was produced from a thin slab of porous nickel rolled to produce different pore size distributions. Visual inspection tests were performed on all modified lysimeters.

3.2.1 Bubble Pressure Tests

Bubble pressure tests were performed on each modified suction lysimeter which passed visual inspection. As shown in Table 3.3, the modified lysimeters displayed a diverse range of bubble pressures. In addition, it was possible to identify hairline cracks in the porous section which were not detected by visual inspection.

3.2.2 Pore Plugging Tests

The experimental protocol for testing the modified lysimeters was altered from that of the prototype lysimeters. The pore plugging tests for the modified lysimeters were performed in the test soil that produced that highest degree of plugging, the clayey topsoil-medium sand blend. Testing in the medium sand was deleted because the large particle size of the soil did not result in significant pore plugging with respect to the other two test soils. Correspondingly, testing in the silty clay was excluded because the degree of pore plugging was nearly equal to that in the clayey topsoil-medium sand blend. Furthermore, since pore plugging tests with the prototype lysimeters demonstrated that an adequate volume of liquid was obtained from the hydraulically-installed and the silica slurry packing lysimeters, it was decided that it would be best to compare the modified porous sections with each other and that no silica slurry packing would be used with the modified lysimeters. This enabled the testing and comparison of four different porous sections at the same time. Due to the large diameter of certain modified porous sections it was decided that in lieu of hydraulic installation the modified lysimeters would be placed into the test chamber, and the test chambers would be subsequently filled with the test soil. This installation technique should not invalidate the test because the soil was thoroughly saturated with water prior to testing. The saturated soil becomes settled and compacted, simulating the effect of hydraulic installation.

To better simulate the performance of the lysimeters in field conditions, suction was continuously applied to the lysimeters. At the end of each twenty-four hour period the volumes collected by the lysimeters were measured and the liquid was returned to the test chamber. The results of the pore plugging tests, shown in Figure 3.6 (and Appendix A, Table A.4), demonstrate the effect of pore size and porosity on the liquid volume collected by each lysimeter. Pore plugging in the porous section resulted in a rapid initial decrease in the volume of water collected by each lysimeter. At the completion of the eleven-day pore plugging test the *N4* lysimeter collected water at a rate approximately 3.5 times that of the *FO* and *N1* lysimeters, and approximately 11 times that of the *A5* lysimeter. In terms of daily collection rate, the modified lysimeters installed into the saturated clayey topsoil-medium sand blend collected liquid at rates of 0.5 and 5.5 liters per day, far in excess of the amount required for monitoring and analysis. Furthermore, these rates are greater than those obtained by the prototype lysimeters.

Table 3.3 Modified Lysimeter Bubble Pressures

Lysimeter ID Code	Manufacturer	Material	Bubble Pressure (kPa)
A1	Timco	Al ₂ O ₃	55
A2	Timco	Al ₂ O ₃	62
A3	Timco	Al ₂ O ₃	55
A4	Timco	Al ₂ O ₃	*41
A5	Timco	Al ₂ O ₃	55
A6	Timco	Al ₂ O ₃	55
B1	Timco	Al ₂ O ₃	131
B2	Timco	Al ₂ O ₃	117
B3	Timco	Al ₂ O ₃	145
C1	Timco	Al ₂ O ₃	62
C2	Timco	Al ₂ O ₃	62
C3	Timco	Al ₂ O ₃	62
C4	Timco	Al ₂ O ₃	62
F0	Ferro	Al ₂ O ₃	55
N0	IGT	Porous Ni	34
N1	IGT	Porous Ni	62
N4	IGT	Porous Ni	55

* hairline crack

Figure 3.6 Results of Pore Plugging Test for Modified Lysimeters in Clayey Topsoil-Medium Sand Test Soil

The pore plugging test data can be compared to the baseline flow rate, the rate at which liquid is collected from a vessel containing water and no soil. The percent of baseline flow is defined as the flow rate at the completion of the pore plugging test in the test soil, divided by the baseline flow rate in water, multiplied by 100%. As shown in Table 3.4, pore plugging results in a significant decrease in the flow rate as compared to tests performed solely using water. The percent of baseline flow ranged from a low of 0.17% for the A5 lysimeter to a high of 1.13% for the N4 lysimeter.

Table 3.4 Baseline Flow Rate and Pore Plugging Test Data

(MILLILITERS PER MINUTE)					
	TEST	TIMCO A5	FERRO F0	NICKEL N1	NICKEL N4
A	BASELINE	198.6	164.2	303.1	335.7
B	PORE PLUGGING (DAY 11)	0.33	1.06	0.99	3.80
	% FLOW (B/A x 100%)	0.17	0.65	0.33	1.13

3.2.3 Soil Moisture Operating Range Tests

The results of the soil moisture operating range test with the prototype lysimeters indicated a need to obtain a porous section which would allow collection in dry conditions. To separate the effects of pore plugging and soil dryness it was determined that the operating range tests be performed with lysimeters which have undergone pore plugging. Therefore, the operating range tests were carried out with the same set of modified lysimeters and the same test chamber used for the pore plugging tests. This eliminated the impact of pore plugging on the operating range tests because pore plugging had already transpired. In order to better simulate the performance of the lysimeters in field conditions, suction was continuously applied to the lysimeters. At the end of each twenty-four hour period the volumes of liquid collected by the lysimeters were measured, the liquid was discarded, and the soil suction pressure was determined. The operating range tests began with a completely saturated clayey topsoil-medium sand blend with a moisture content of 27%. The results of the operating range test, shown in Figure 3.7, demonstrate that the modified lysimeters continued to collect liquid up to soil suction pressures of 28 kPa (16.0% moisture). Furthermore, several lysimeters were able to collect volumes of 0.1 liters per twenty-four hour period at a soil suction pressure of 16 kPa, far in excess of the amount required for monitoring and analysis on a daily basis. These results were significantly better than the prototype lysimeter, and verified that the modified lysimeters were able to collect an adequate volume of liquid from unsaturated soil conditions.

Figure 3.7 Results of Soil Moisture Operating Range Test for Modified Lysimeters in Clayey Topsoil-Medium Sand Test Soil

3.2.4 Comparison of Hydraulic and Standard Installation

Based on the results of the previous pore plugging and soil moisture operating range tests, the modified lysimeters with the Timco porous ceramic section were selected for further testing. The bubble pressure values for the modified lysimeters used to compare the hydraulic and standard methods of installation are given in Table 3.3.

Pore plugging experiments were carried out in the 75% clayey topsoil-25% medium sand blend saturated test soils using two hydraulically installed and two standard installed lysimeters. The volume of liquid collected during each 24-hour test over the complete test period is shown in Figure 3.8 (and Appendix A, Tables 4 and 5). Pore plugging in the porous section resulted in a rapid initial decrease in the volume of water collected by each lysimeter. At the completion of the twelve-day plugging test the standard installed lysimeters collected water at a rate approximately 1.5 to 3 times that of the hydraulically installed lysimeters. In terms of daily collection rate, the hydraulically installed modified lysimeters collected liquid at a rate of approximately 0.8 liters per day, far in excess of the amount required for monitoring and analysis. These flow rates are far superior to those of the prototype lysimeters.

The soil moisture operating range tests were carried out with the same set of modified lysimeters and the same test chamber used for the pore plugging tests. At the end of each twenty-four hour period the volumes of liquid collected by the lysimeters were measured, the liquid was discarded, and the soil suction pressure was determined. The results of the operating range test, shown in Figure 3.9, demonstrated that the hydraulically installed modified lysimeters continued to collect liquid up to soil suction pressures of 24 kPa, and the standard lysimeters up to a suction pressure of 36 kPa. Furthermore, the hydraulically installed lysimeters were able to collect volumes of approximately 0.1 liters per twenty-four hour period at a soil suction pressure of 18 kPa, far in excess of the amount required for monitoring and analysis on a daily basis. These results were significantly better than the prototype lysimeter, and verified that the modified lysimeters were able to collect an adequate volume of liquid from unsaturated soil conditions.

Figure 3.8 Results of Pore Plugging Test of Modified Lysimeters in Clayey Topsoil-Medium Sand Test Soil

Figure 3.9 Results of Soil Moisture Operating Range Test of Modified Lysimeters in Clayey Topsoil-Medium Sand Test Soil

4.0 TECHNOLOGY STATUS

4.1 Technology Development Evaluation

The hydraulically-installed suction lysimeter was capable of extracting liquid samples from unsaturated test soils without the need to drill a well. This is a significant advantage over the exiting technique due to the high cost attributed to drilling, backfilling a test well, and disposal of drill wastes at hazardous sites.

Because soil is not removed, risks to personnel and the environment will be significantly reduced. The technology is considered to be ready for demonstration. The instrument can be left in the ground for long-term monitoring or can be removed from the soil and reused. Having no moving parts, cleaning is simplified.

The results of the testing demonstrate that the degree of plugging and the soil moisture operating range were dependent upon the pore size distribution of the porous section, as determined by the bubble pressure. It was found that the smaller diameter pores limited the flow rate but increased the operating range as compared to the larger diameter pores. Furthermore, the relative size of the soil particles compared to the diameter of the pores was the mitigating factor in determining the degree of plugging.

An important characteristic of any lysimeter, but in particular one which will be installed hydraulically, is the strength and integrity of the porous section. The modified lysimeters which incorporated both the Timco and Ferro porous ceramic sections performed well in the pore plugging and soil moisture operating tests. However, while the Timco product was very brittle and highly susceptible to cracking, the Ferro material was able to withstand severe impact without cracking. The use of the hydraulically-installed multi-sampling lysimeter will be limited by the ability of hydraulic installation as is the case with the cone penetrometer.

The lysimeter system can be constructed on a modular basis using five-foot (or other size) sections containing the lysimeters that can be joined by threaded fittings. With normal vacuum systems the depth of insertion of the lysimeters is limited to 20 feet. However, by using a transfer vessel, samples from depths of greater than 100 feet can be achieved. Laboratory experiments have proven that a hydraulic installation coupled with the new design eliminates the need for a silica flour packing or filling the hole with packed dirt.

Commercially available lysimeters require the drilling of a well, insertion of a silica slurry, reintroduction of soil, and bentonite plugging. A ceramic cup lysimeter costs approximately \$250 and a stainless steel lysimeter costs about \$450. The innovative hydraulically installed multi-sampling lysimeter will cost approximately \$400 per unit when commercial, but will not require well drilling and associated activities as is the current practice. A survey of costs to drill a 4-inch diameter well, not in bedrock, but including soil sampling and well development revealed average cost per well to be approximately \$8,700 for 20 ft. to 40 ft. depth. These costs are based on a truck/ATV rig and crew costing \$176/hour on standard time, and an air ROT rig \$203/hour. The cost of a

workover rig and crew is estimated at \$141/hour on standard time. A grout plant is estimated to cost \$5/hour. Estimated costs on a per foot basis are as follows:

<u>Description of Per Ft. Costs</u>	<u>20 ft.</u>	<u>30 ft.</u>	<u>40 ft.</u>
Equipment and crew costs	369.25	246.17	184.63
Materials costs	51.97	40.72	35.09
Total estimated cost per ft.	421.22	288.89	219.72
Total estimated cost per well	\$8,424.00	\$8,607.00	\$8,789.00

A hydraulically installed multi-sampling lysimeter is expected to cost less than 20% of the cost to install a conventional cup lysimeter.

Van Sciver (35) demonstrated the time savings realized by using the drive-probe method. Forty-eight man-hours were expended for construction and placement of 32 soil gas probes. The work requirements for sampling and analysis were reduced by 89 percent. The costs to install the hydraulically installed multi-sampling lysimeter would be similar to those for installing gas probes.

4.2 Technology Integration Evaluation

Future development work will focus on improving the pore size distribution and strength of the porous ceramic sections. In addition, the overall diameter of the lysimeter will be decreased to ease insertion and to conform to the standard size currently used in the cone penetrometer. Physical and chemical sensors can be readily integrated into the device. The hydraulically installed lysimeter is easier to install than standard cup lysimeters and is more rugged. Because negative pressure systems enhance volatilization, a trap system is required for volatile contaminate sampling.

Applied Research Associates, Inc. (ARA) has developed technology to join site surface and subsurface exploration into a coherent program using the electric cone penetrometer (ECPT). A 1.40 5-in diameter instrumented rod is hydraulically pushed into the ground whereby physical and geophysical measurements are made. ARA claims that the instrument can also retrieve soil, soil water, and soil gas samples. The sampling port from the Bladon multi-sampling lysimeter can be readily incorporated in the ECPT developed by ARA.

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APPENDIX A

Table A-1 Prototype Lysimeter Pore Plugging Test Data for Sand

TEST DAY	(LITERS PER 5-HOUR TEST)			
	Standard Installation		Hydraulic Installation	
	A	B	C	D
1	0.88	1.14	10.00	7.43
2	0.80	1.14	9.63	7.41
3	0.83	1.13	9.04	7.23
4	0.87	1.31	7.80	6.63
5	0.83	1.17	5.58	5.54
6	0.87	1.10	5.47	5.30
7	0.84	0.91	4.46	4.05
8	0.89	0.95	4.06	3.44
9	0.82	0.82	4.39	3.43
10	0.71	0.75	3.93	3.09
11	0.68	0.77	3.79	2.99
12	0.65	1.06	3.70	2.97
13	0.59	1.13	3.43	2.80
14	0.58	1.02	3.73	2.92
15	0.51	0.89	3.47	2.76
16	0.52	1.05	3.16	2.64
17	0.49	0.95	3.03	2.61
18	0.45	1.03	2.99	2.61
19	0.45	1.05	3.44	2.93
20	0.44	1.29	3.18	2.88
21	0.45	1.30	3.19	2.84
22	0.38	1.29	3.20	2.91
Total Sample (Liters)	14.53	23.25	104.67	87.41

Table A-2 Prototype Lysimeter Pore Plugging Test Data for Topsoil-Sand

TEST DAY	(LITERS PER 5-HOUR TEST)			
	Standard Installation		Hydraulic Installation	
	E	F	G	H
1	1.38	0.78	0.39	0.66
2	0.74	0.72	0.23	0.32
3	0.51	0.90	0.16	0.22
4	0.35	0.77	0.13	0.17
5	0.36	0.70	0.15	0.14
6	0.45	0.56	0.14	0.13
7	0.40	0.51	0.13	0.13
8	0.38	0.45	0.10	0.10
9	0.38	0.40	0.08	0.10
10	0.34	0.38	0.07	0.09
11	0.33	0.30	0.08	0.09
12	0.29	0.33	0.08	0.09
13	0.27	0.34	0.10	0.09
14	0.27	0.34	0.08	0.08
15	0.28	0.32	0.08	0.08
16	0.24	0.28	0.06	0.07
17	0.23	0.28	0.07	0.09
18	0.22	0.27	0.09	0.10
Total Sample (Liters)	7.42	8.63	2.22	2.75

Table A-3 Prototype Lysimeter Pore Plugging Test Data for Clay

TEST DAY	(LITERS PER 5-HOUR TEST)			
	Standard Installation		Hydraulic Installation	
	I	J	K	L
1	3.87	3.54	1.93	0.72
2	3.22	3.11	0.84	0.53
3	2.92	2.84	0.57	0.40
4	2.48	2.59	0.64	0.27
5	2.17	2.47	0.54	0.27
6	1.91	2.29	0.48	0.28
7	1.65	2.18	0.40	0.24
8	1.63	1.73	0.32	0.42
9	1.41	1.61	0.33	0.43
10	1.30	1.65	0.28	0.38
11	1.14	1.54	0.26	0.35
12	1.09	1.43	0.30	0.34
13	1.11	1.38	0.23	0.33
14	1.00	1.30	0.25	0.30
15	0.95	1.26	0.26	0.27
16	0.84	1.20	0.22	0.26
17	0.88	1.15	0.25	0.29
18	0.85	1.07	0.18	0.25
19	0.81	1.07	0.23	0.25
20	0.83	1.12	0.22	0.22
21	0.79	1.05	0.23	0.29
Total Sample (Liters)	32.85	37.58	8.96	7.09

Table A-4 Modified Lysimeter Pore Plugging Test Data for Topsoil-Sand

TEST DAY	(LITERS PER 24-HOUR TEST)			
	TIMCO A5	FERRO FO	NICKEL N1	NICKEL N4
1	1.54	3.38	2.96	8.12
2	0.92	2.13	1.66	5.22
3	0.83	2.09	1.64	4.05
4	0.73	1.98	1.71	5.21
5	0.64	1.88	1.70	5.64
6	0.68	1.99	1.75	6.06
7	0.72	2.12	1.83	6.06
8	0.64	1.86	1.66	5.62
9	0.51	1.80	1.62	5.54
10	0.51	1.66	1.42	5.65
11	0.48	1.53	1.42	5.47
Total Sample (Liters)	8.20	22.42	19.37	62.64

Table A-5 Modified Lysimeter Pore Plugging Test Data for Topsoil-Sand

(LITERS PER 24-HOUR TEST)				
TEST DAY	Hydraulic Installation		Standard Installation	
	C1	C3	C2	C4
1	1.69	1.68	6.50	6.06
2	1.50	1.14	5.15	3.87
3	1.30	1.25	4.86	2.76
4	1.17	1.09	3.87	2.00
5	1.14	0.96	3.91	1.70
6	1.01	0.96	3.57	1.79
7	0.98	0.96	3.57	1.75
8	0.89	0.92	3.09	1.53
9	0.88	0.90	2.78	1.49
10	0.88	0.86	2.67	1.34
11	0.86	0.89	2.48	1.30
12	0.83	0.80	2.32	1.29
Total Sample (Liters)	14.13	15.41	46.77	30.88

Figure A.1 Grain Size Distribution for Test Soils

Figure A.2 Pore Size Distribution for Porous Ceramic Section

Distribution for DOE/CH-9203

Internal:

J. E. Battles
N. J. Beskid
S. K. Bhattacharyya
A. S. Boparai
S. S. Borys
D. E. Bugielski
J. Burton
D. J. Chaiko
S. M. Cross
J. C. Cunnane

J. S. Devgun
J. D. Ditmars
D. E. Edgar
M. D. Erickson
N. L. Goetz
J. E. Helt
D. O. Johnson
R. Kolpa
T. R. Krause

J. Laidler
R. Murtello
N. K. Meshkov
PCO Office (50)
A. D. Pflug
G. T. Reedy
N. F. Suther
M. Zielke
TIS Files

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J. C. Haugen, DOE-CH
S. L. Webster, DOE-CH
A. H. Aitken, Nuclear Diagnostic Systems, Inc., Springfield, VA
D. H. Alexander, USDOE, Office of Technology Development, Washington, DC
J. Allison, USDOE, Office of Waste Operations, Washington, DC
T. D. Anderson, USDOE, Office of Technology Development, Washington, DC
M. S. Anderson, Ames Laboratory, Iowa State University, Ames, IA
G. Andrews, EG&G Idaho, Idaho Falls, ID
R. W. Baker, Membrane Technology & Research, Inc., Menlo Park, CA
D. H. Bundy, USDOE, Albuquerque Operations Office, Albuquerque, NM
M. J. Barainca, USDOE, Office of Technology Development, Washington, DC
S. Bath, Westinghouse Hanford Company, Richland, WA
S. A. Buttermann, University of Michigan, Ann Arbor, MI
J. Baublitz, USDOE, Office of Environmental Restoration, Washington, DC
J. Bauer, USDOE, Office of Environmental Restoration, Washington, DC
B. G. Beck, Coleman Research Corporation, Fairfax, VA
R. C. Bedick, USDOE, Morgantown Energy Technology Center, Morgantown, WV
M. Berger, Los Alamos National Laboratory, Los Alamos, NM (5)
J. D. Berger, Westinghouse Hanford Company, Richland, WA (5)
D. Berry, Sandia National Laboratories, Albuquerque, NM (5)
D. Biancosino, USDOE, Office of Technology Development, Washington, DC
J. Bickel, USDOE, Albuquerque Operations Office, Albuquerque, NM
T. Blayden, STC Library, Westinghouse Electric Corp., Pittsburgh, PA
W. Bliss, Reynolds Electric & Engineering Co., Las Vegas, NV (5)
L. C. Borduin, Los Alamos National Laboratory, Los Alamos, NM
W. D. Bostick, Martin Marietta Energy Systems, Oak Ridge, TN
D. Bottrell, USDOE, Office of Technology Development, Washington, DC
G. G. Boyd, USDOE, Office of Technology Development, Washington, DC
J. L. Brutton, Applied Research Associates, Inc., Albuquerque, NM

J. Buelt, Battelle Pacific Northwest Laboratory, Richland, WA
J. Bursell, EIC Laboratories, Norwood, MA
W. Buttner, Transducer Research, Naperville, IL
J. W. Cammann, Westinghouse Hanford Company, Richland, WA
M. M. Carrabba, EIC Laboratories, Inc., Norwood, MA
R. A. Carrington, Mountain States Energy, Inc., Butte, MT (5)
M. Carter, USDOE, Laboratory Management Division, Germantown, MD
R. H. Carty, Institute of Gas Technology, Chicago, IL
K. A. Chucey, USDOE, Office of Waste Operations, Washington, DC
M. Chaimberg, Institute of Gas Technology, Chicago, IL
J. C. Clark, Bay Geophysical Assoc., Traverse City, MI
J. Collins, Coleman Research Corporation, Columbia, MD
P. Colombo, Brookhaven National Laboratories, Upton, NY (5)
D. Constant, South/Southwest HSRC, Louisiana State University, Baton Rouge, LA
S. Conway, Colorado Center for Environmental Management, Golden, CO (5)
J. Coronas, Ames Laboratory, Iowa State University, Ames, IA (5)
S. P. Cowan, USDOE, Office of Waste Operations, Washington, DC
R. B. Craig, Hazardous Waste Remedial Actions Program, Oak Ridge, TN
D. Daffern, Reynolds Electrical & Engineering Company, Las Vegas, NV
W. Daily, Lawrence Livermore National Laboratory, Livermore, CA
R. C. Doyle, IIT Research Institute, Virginia Tech. Center, Newington, VA
L. P. Duffy, USDOE, Environmental Restoration and Waste Management, Washington, DC
H. Dugger, Kaiser Engineers Hanford Company, Richland, WA (5)
A. J. Eirich, Kaiser Engineers Hanford Company, Richland, WA
D. Emilia, Chem-Nuclear Geotech, Grand Junction, CO (5)
B. D. Ensley, Envirogen, Inc., Princeton Research Center, Lawrenceville, NJ
L. Erickson, Center for HSR, Kansas State University, Manhattan, KS
L. Feder, Institute of Gas Technology, Chicago, IL
H. D. Feiler, Science Applications International Corp., Oak Ridge, TN
H. Feiner, Science Applications International Corp., Oak Ridge, TN
J. J. Fiore, USDOE, Office of Environmental Restoration, Washington, DC
W. Fitch, USDOE, Idaho Field Office, Idaho Falls, ID
J. Ford, Hazardous Waste Remedial Action Program, Oak Ridge, TN (5)
A. J. Francis, Brookhaven National Laboratory, Upton, NY
C. Frank, USDOE, Office of Technology Development, Washington, DC
R. B. Gammage, Oak Ridge National Laboratory, Oak Ridge, TN
C. Gehrs, Oak Ridge National Laboratory, Oak Ridge, TN
J. F. Gibbons, Applied Research Associates, Albuquerque, NM
R. Gilchrist, Westinghouse Hanford Company, Richland, WA (5)
B. Gillies, Energy Technology Engineering Center, Canoga Park, CA (5)
G. Glatzmaier, Solar Energy Research Institute, Golden, CO
S. Goforth, Westinghouse Savannah River Company, Aiken, SC
S. R. Grace, USDOE, Rocky Flats Office, Golden, CO
D. C. Grant, Westinghouse STC, Pittsburgh, PA
S. Grant, Center for HSR, Kansas State University, Manhattan, KS
T. C. Greengard, Rocky Flats Plant, Golden, CO
W. Greenman, GTS Duratek, Columbia, MD
Y. Guo, GTS Duratek, Columbia, MD
B. Gupta, National Renewable Energy Laboratory, Golden, CO (5)
K. Hain, USDOE, Office of Technology Development, Washington, DC

J. Hall, USDOE, Nevada Field Office, Las Vegas, NV
M. S. Hanson, Battelle Pacific Northwest Laboratories, Richland, WA
L. H. Harmon, USDOE, Office of Waste Operations, Washington, DC
K. A. Hayes, USDOE, Office of Environmental Restoration, Washington, DC
E. L. Helminski, Weapons Complex Monitor, Washington, DC
J. M. Hennig, USDOE, Richland Operations Office, Richland, WA
R. Hill, U.S. Environmental Protection Agency, Cincinnati, OH
J. Holm, USDOE, Office of Technology Development, Washington, DC
W. Holman, USDOE, San Francisco Operations Office, Oakland, CA
J. P. Hopper, Westinghouse Materials Company of Ohio, Cincinnati, OH (5)
D. Huff, Martin Marietta Energy Systems, Inc., Oak Ridge, TN
J. Hyde, USDOE, Office of Technology Development, Washington, DC
S. James, U.S. Environmental Protection Agency, Cincinnati, OH
S. Janikowski, EG&G Idaho, Idaho Falls, ID
W. J. Johnson, Paul C. Rizzo Associates, Inc., Monroeville, PA
D. W. Jones, Nuclear Diagnostics Systems, Inc., Brunswick, TN
D. Kabach, Westinghouse Savannah River Company, Aiken, SC
H. D. Kamaruddin, Membrane Technology & Research, Inc., Menlo Park, CA
J. Kaschemekat, Membrane Technology & Research, Inc., Menlo Park, CA
C. Keller, Science and Engineering Associates, Inc., Santa Fe, NM
D. Kelsh, USDOE, Office of Technology Development, Washington, DC
J. Kitchens, KBB, Inc., Sterling, VA
J. Koger, Martin Marietta Energy Systems, Oak Ridge, TN (5)
E. Koglin, U.S. Environmental Protection Agency, Las Vegas, NV
K. Koller, EG&G Idaho, Idaho Falls, ID (5)
G. Kosinski, Technics Development Corporation, Oak Ridge, TN
D. R. Kozlowski, USDOE, Office of Environmental Restoration, Washington, DC
R. Kuhl, EG&G Idaho, Idaho Falls, ID
E. J. Lahoda, GTS Duratek, Columbia, MD
S.-T. Lai, GTS Duratek, Columbia, MD
J. Lankford, USDOE, Office of Technology Development, Washington, DC
J. C. Lehr, USDOE, Office of Environmental Restoration, Washington, DC
R. Levine, USDOE, Office of Technology Development, Washington, DC
S. C. Lien, USDOE, Office of Technology Development, Washington, DC
R. G. Lightner, USDOE, Office of Environmental Restoration, Washington, DC
D. Lillian, USDOE, Office of Technology Development, Washington, DC
E. Lindgren, Sandia National Laboratory, Albuquerque, NM
B. Looney, Westinghouse Savannah River Company, Aiken, SC
W. Lowry, Science and Engineering Associates, Inc., Santa Fe, NM
P. Lurk, USDOE, Office of Technology Development, Washington, DC
R. W. Lynch, Sandia National Laboratories, Albuquerque, NM (5)
J. E. Lytle, USDOE, Office of Waste Management, Washington, DC
R. S. Magee, New Jersey Inst. Technol., Hazardous Substance Research Center, Newark, NJ
K. Magrini, Solar Energy Research Institute, Golden, CO
A. Malinauskas, Oak Ridge National Laboratory, Oak Ridge, TN (5)
S. A. Mann, USDOE, Office of Environmental Restoration, Washington, DC
D. Manty, Exploratory Research, U.S. Environ. Protection Agency, Washington, DC
J. Marchetti, USDOE, Defense Programs, Washington, DC
R. G. McCain, Westinghouse Hanford Company, Richland, WA
P. L. McCarty, Hazardous Substance Research Center, Stanford University, Stanford, CA

L. W. McClure, Westinghouse Idaho Nuclear Company, Inc., Idaho Falls, ID (5)
 T. McEvelly, Lawrence Berkeley Laboratory, Berkeley, CA (5)
 C. P. McGinnis, Oak Ridge National Laboratory, Oak Ridge, TN
 K. Merrill, EG&G Idaho, Idaho Falls, ID (5)
 D. J. Moak, Westinghouse Hanford Company, Richland, WA
 J. Moore, USDOE, Oak Ridge Field Office, Oak Ridge, TN
 K. Morehouse, Exploratory Research, U.S. Environ. Protection Agency, Washington, DC
 I. S. Muller, GTS Duratek, Columbia, MD
 H. D. Murphy, Los Alamos National Laboratory, Los Alamos, NM (5)
 C. Myler, West Point Chemistry Department, West Point, NY
 B. Nielsen, Tyndall Air Force Base, Tyndall Air Force Base, FL
 R. Nimmo, IIT Research Institute, Newington, VA
 K. Nuhfer, Westinghouse Materials Company of Ohio, Cincinnati, OH (5)
 M. O'Donnell, Timco Manufacturing, Inc., Prairie du Sac, WI
 M. O'Rear, USDOE, Savannah River Field Office, Aiken, SC
 R. Olexsi, U.S. Environmental Protection Agency, Cincinnati, OH
 R. P. Olsen, Membrane Technology & Research, Inc., Menlo Park, CA
 T. Oppelt, U.S. Environmental Protection Agency, Cincinnati, OH
 D. F. Oren, Geotech, Inc., Grand Junction, CO
 V. M. Oversby, Lawrence Livermore National Laboratory, Livermore, CA
 J. Paladino, USDOE, Office of Technology Development, Washington, DC
 S. Pamukcu, Lehigh University, Bethlehem, PA
 G. S. Patton, USDOE, Office of Technology Development, Washington, DC
 I. L. Pegg, GTS Duratek, Columbia, MD
 C. Peters, Nuclear Diagnostics Systems, Inc., Springfield, VA
 M. Peterson, Battelle Pacific Northwest Laboratory, Richland, WA
 J. Poppiti, USDOE, Office of Technology Development, Washington, DC
 E. J. Poziomek, University of Nevada, Las Vegas, NV
 S. Prestwich, USDOE, Office of Technology Development, Washington, DC
 R. E. Prince, GTS Duratek, Columbia, MD
 R. F. Probst, Massachusetts Institute of Technology, Cambridge, MA
 C. Purdy, USDOE, Office of Technology Development, Washington, DC
 R. S. Ramsey, Oak Ridge National Laboratory, Oak Ridge, TN
 N. Rankin, Savannah River Technology Center, Aiken, SC
 C. Rivard, Solar Energy Research Institute, Golden, CO
 R. Rizzo, Paul C. Rizzo Associates, Inc., Monroeville, PA
 A. Robbat, Tufts University, Medford, MA
 W. Robson, Lawrence Livermore National Laboratory, Livermore, CA
 L. Rogers, EG&G Energy Measurements, Inc., Las Vegas, NV (5)
 V. J. Rohey, Westinghouse Hanford Co., Richland, WA
 M. E. Rose, Membrane Technology & Research, Inc., Menlo Park, CA
 B. Ross, Science and Engineering Associates, Albuquerque, NM
 N. E. Rothermich, Hazardous Waste Remedial Actions Program, Oak Ridge, TN
 J. Ruller, GTS Duratek, Columbia, MD
 G. Sandness, Pacific Northwest Laboratory, Richland, WA
 G. Sandquist, University of Utah, Salt Lake City, UT
 P. A. Saxman, USDOE, Albuquerque Operations Office, Albuquerque, NM
 W. C. Schutte, USDOE, Office of Technology Development, Washington, DC
 K. Schwitzgebel, Sizemore Technical Services, Round Rock, TX
 G. L. Scropo, Bladon International, Inc., Oak Brook, IL

J. A. Scropo, Bladon International, Inc., Oak Brook, IL (10)
S. V. Segelke, Membrane Technology & Research, Inc., Menlo Park, CA
M. W. Shupe, USDOE, Office of Technology Development, Washington, DC
J. Simpson, USDOE, Office of Technology Development, Washington, DC
C. Sink, USDOE, Office of Technology Development, Washington, DC
S. C. Slate, Battelle Pacific Northwest Laboratories, Richland, WA (5)
R. Snipes, Hazardous Waste Remedial Actions Program, Oak Ridge, TN
J. L. Steele, Westinghouse Savannah River Company, Aiken, SC (5)
S. Stein, Environmental Management Organization, Seattle, WA (5)
K. Stevenson, USDOE, New York, NY (5)
D. Stoner, EG&G Idaho, Idaho Falls, ID
A. Tardiff, USDOE, Office of Technology Development, Washington, DC
L. Taylor, USDOE, Office of Environmental Restoration, Washington, DC
L. J. Thibodeaux, South/Southwest HSRC, Louisiana State University, Baton Rouge, LA
R. D. Timmons, Timco Manufacturing, Inc., Prairie du Sac, WI
J. Tipton, Remote Sensing Laboratory, Las Vegas, NV (5)
E. S. Tucker, Clemson Technical Center, Inc., Anderson, SC
J. A. Turi, USDOE, Office of Waste Operations, Washington, DC
G. P. Turi, USDOE, Office of Environmental Restoration, Washington, DC
R. Tyler, USDOE, Rocky Flats Office, Golden, CO
L. D. Tyler, Sandia National Laboratories, Albuquerque, NM (5)
C. L. Valle, Allied Signal Aerospace, Kansas City, MO (5)
G. E. Voelker, USDOE, Office of Technology Development, Washington, DC
J. W. Wagoner, USDOE, Office of Environmental Restoration, Washington, DC
J. Walker, USDOE, Office of Technology Development, Washington, DC
H. Wang, University of Wisconsin, Madison, WI
R. D. Warner, USDOE, Fernald Field Office, Cincinnati, OH
S. Weber, USDOE, Office of Technology Development, Washington, DC
W. J. Weber, Hazardous Substance Research Center, University of Michigan, Ann Arbor, MI
E. Weiss, Membrane Technology and Research, Inc., Menlo Park, CA
T. Wheelis, Sandia National Laboratories, Albuquerque, NM (5)
M. Whitbeck, University of Nevada, Desert Research Institute, Reno, NV
R. P. Whitfield, USDOE, Office of Environmental Restoration, Washington, DC
P. Wichlacz, EG&G Idaho, Idaho Falls, ID (5)
C. L. Widrig, Battelle Pacific Northwest Laboratories, Richland, WA
H. Wijmans, Membrane Technology & Research, Inc., Menlo Park, CA
J. G. Wijmans, Membrane Technology & Research, Inc., Menlo Park, CA
J. Wilson, Oak Ridge National Laboratory, Oak Ridge, TN
W. Wisenbaker, USDOE, Office of Environmental Restoration, Washington, DC
J. K. Wittle, Electro-Petroleum, Inc., Wayne, PA
S. Wolf, USDOE, Office of Technology Development, Washington, DC
T. Wood, EG&G Idaho, Idaho Falls, ID
J. L. Yow, Livermore, CA (5)
C. Zeh, USDOE, Morgantown Energy Technology Center, Morgantown, WV
L. P. Buckley, Atomic Energy of Canada Limited, Ontario, CANADA
D. R. W. Killey, Atomic Energy of Canada Limited, Ontario, CANADA
L. A. Moschuk, Atomic Energy of Canada Limited, Ontario, CANADA
T. M. Thompson, Atomic Energy of Canada Limited, Ontario, CANADA
S. Vijayan, Atomic Energy of Canada Limited, Ontario, CANADA
P. C. F. Wong, Atomic Energy of Canada Limited, Ontario, CANADA

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