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7. Abstract

This integrated test plan describes the use of the in situ permeable flow sensor, developed by Sandia National Laboratory, to measure gas flow in unsaturated sediments. The ability of this technology to measure groundwater flow velocity in saturated sediments has already been successfully demonstrated.

To set up the test, the flow sensor will be emplaced in the subsurface surrounded by an array of four boreholes, and air will be pumped from the subsurface through at least one of the surrounding boreholes. This preliminary test will be considered successful if the flow meters measure a velocity vector which is pointed toward the air extraction well when air is being pumped from it, and measure a velocity magnitude which increases with increasing air extraction rate and decreases with horizontal distance from the air extraction well.

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## CONTENTS


1.0 INTRODUCTION . . . . . 1
1.1 PURPOSE AND SCOPE . . . . . 1
1.2 BACKGROUND . . . . . 3
1.3 SITE SETTING . . . . . 3

2.0 TECHNOLOGY DESCRIPTION . . . . . 3

3.0 DEMONSTRATION OBJECTIVES AND PARAMETERS . . . . . 6
3.1 OBJECTIVES . . . . . 6
3.2 PARAMETERS . . . . . 7

4.0 REGULATORY COMPLIANCE . . . . . 8
4.1 NEPA . . . . . 8
4.2 CERCLA . . . . . 9
4.3 RCRA . . . . . 9
4.4 WASHINGTON ADMINISTRATIVE CODE . . . . . 9
4.5 CULTURAL RESOURCES REVIEW AND ECOLOGICAL SURVEY . . . . . 10

5.0 HANFORD COMPLIANCE . . . . . 10
5.1 SAFETY . . . . . 10
5.2 QUALITY ASSURANCE . . . . . 10
5.3 TRAINING . . . . . 10

6.0 ORGANIZATION AND RESPONSIBILITIES . . . . . 11
6.1 DEMONSTRATION OPERATIONS . . . . . 11
6.2 PROJECT ENGINEER . . . . . 11
6.3 FIELD TEAM LEADER . . . . . 11
6.4 PRINCIPAL INVESTIGATOR . . . . . 11

7.0 DESCRIPTION OF TASKS AND PROCEDURES . . . . . 13

8.0 DEMONSTRATION SCHEDULE . . . . . 16

9.0 REFERENCES . . . . . 17


**FIGURES:**


1. Hanford Site Map and Location of the 200 West Area . . . . . 2
2. Location of the Proposed Environmental Restoration Disposal Facility . 4
3. Field Demonstration Organization . . . . . 12
4. Proposed Arrangement of the Test Holes . . . . . 14
5. Well Schematics for In Situ Permeable Flow Sensor Testing . . . . . 15

# 1.0 INTRODUCTION

## 1.1 PURPOSE AND SCOPE

This integrated test plan describes the demonstration of the in situ permeable flow sensor, developed by Sandia National Laboratory, to measure air flow in unsaturated sediments. The ability of this technology to measure groundwater flow velocity in saturated sediments has already been successfully demonstrated. This preliminary test of this device in the unsaturated zone will be considered successful if in fact the flowmeters are able to detect a gas flow velocity.

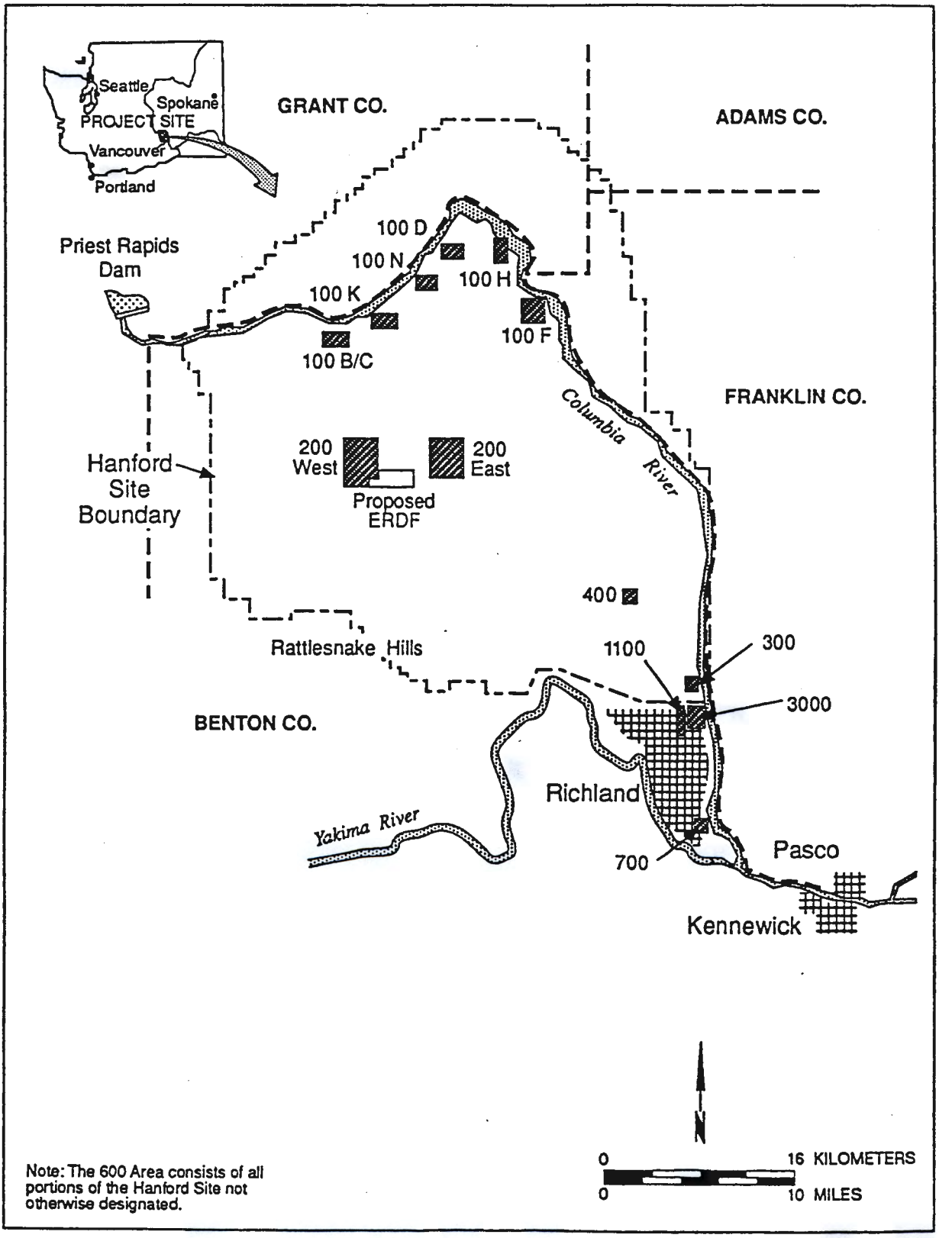
The field demonstration described in this integrated test plan is being conducted as part of the Volatile Organic Compounds-Arid Integrated Demonstration (VOC-Arid ID). The VOC-Arid ID is one of several U.S. Department of Energy (DOE) integrated demonstrations designed to support the testing of emerging environmental management and restoration technologies. The purpose of the VOC-Arid ID is to identify, develop, and demonstrate technologies that may be used to characterize, remediate, and/or monitor arid or semiarid sites containing VOCs (e.g., carbon tetrachloride) with or without associated metal and radionuclide contamination. Initially, the VOC-Arid ID activities are focusing primarily on the carbon tetrachloride and associated contamination found in the 200 West Area of the Hanford Site (Figure 1).

The 200 West Area Carbon Tetrachloride Expedited Response Action (ERA) is being conducted by the DOE at the direction of the U.S. Environmental Protection Agency (EPA) and Washington Department of Ecology (Ecology) to minimize contaminant migration within the unsaturated soils in the 200 West Area by removing the carbon tetrachloride. The ERA is a cleanup action under the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA), which allows expedited response to be taken where early remediation will abate imminent hazard or prevent significantly increased degradation that might occur if action was delayed until completion of a remedial investigation/feasibility study and record of decision. The ERA's current approach for removing the carbon tetrachloride is to use soil vapor extraction with aboveground treatment, using a vacuum system and a network of soil vapor extraction vadose wells.

The VOC-Arid ID and ERA programs have been closely integrated to better ensure that ongoing cleanup applications and needs will drive technology development and that potential users for those technologies will be readily identified. Development of a sensor for gas flow measurement in the unsaturated zone would be valuable to the ERA project because measurements of flow direction and magnitude in soils and in boreholes are needed to understand and control air flow in the subsurface. Controlling flow in the subsurface is critical for optimizing the vapor extraction process.

Testing of the in situ permeable flow sensor will be conducted at the location of the proposed Environmental Restoration Disposal Facility (ERDF) (Figure 1). The data regarding subsurface air flow rates and pathways collected during the flow sensor testing will be used in the ongoing characterization of the proposed ERDF.

Figure 1. Hanford Site Map and Location of the 200 West Area.

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### 1.2 BACKGROUND

The proposed technology is an extension of a technology for measuring groundwater flow velocity called the in situ permeable flow sensor, which was developed by the principal investigator with funding from the Office of Technology Development beginning in fiscal year 1990 (Ballard et al. 1994). It was field tested at Savannah River as part of the VOC-Non Arid Sites Integrated Demonstration and is currently being transferred to the private sector for commercialization. The gas flowmeter being proposed is based on the same operating principle as the in situ permeable flow sensor and will use identical hardware.

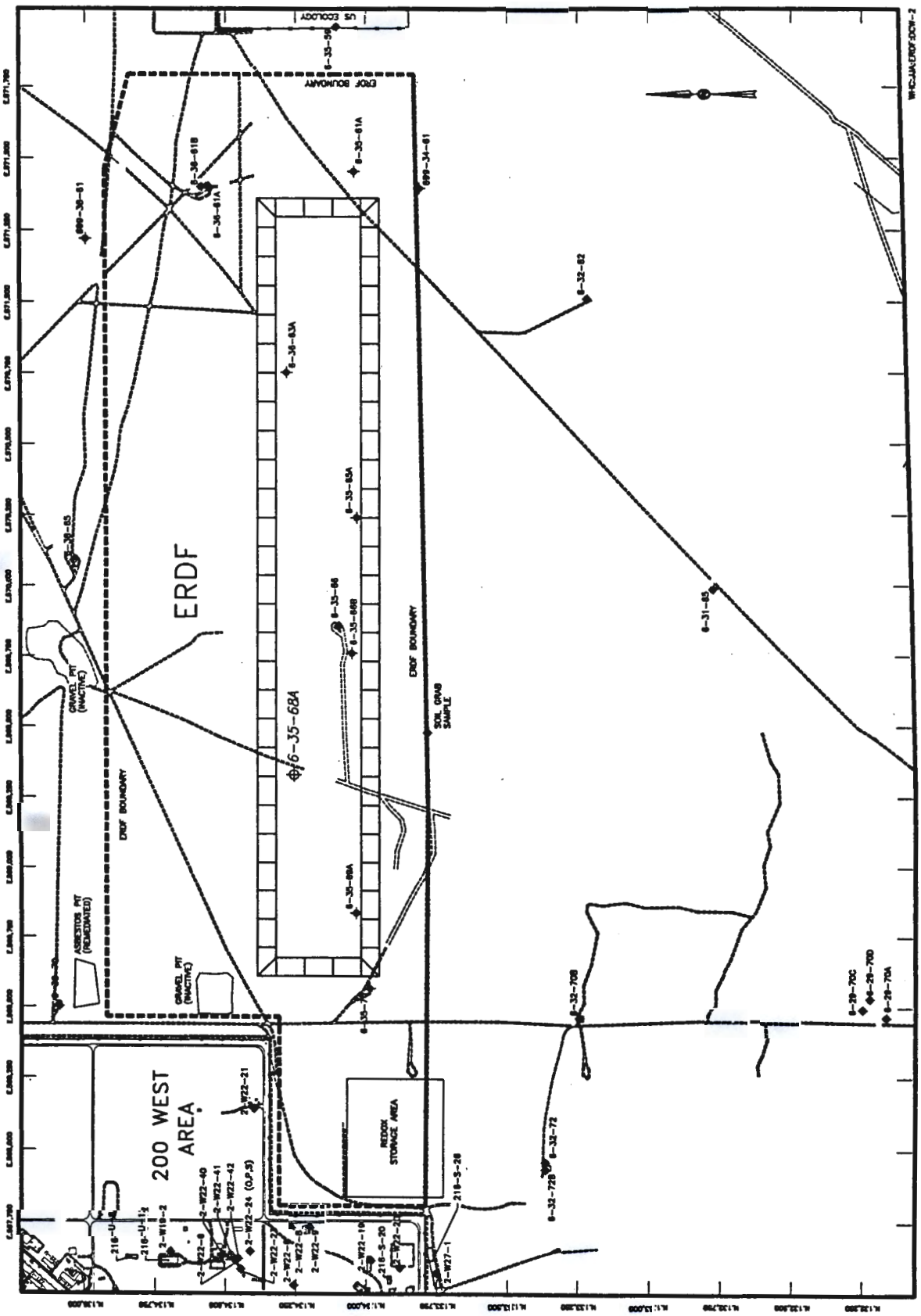
### 1.3 SITE SETTING

Preliminary field testing will be conducted at the site of the proposed ERDF, an uncontaminated site between the 200 West and 200 East Areas (Figure 1). The flow sensor will be emplaced to a depth of approximately 17 ft. The test will be conducted at the site of abandoned borehole 699-35-68A (Figure 2).

## 2.0 TECHNOLOGY DESCRIPTION

The gas flowmeter, like the in situ permeable flow sensor for groundwater, will use a thermal perturbation technique to measure the fluid flow velocity vector in permeable materials. The principle of operation is to emplace a long, thin, heated cylinder into the subsurface at the point where the flow velocity measurement is to be made. This cylinder consists of a rod 75 cm long and 5 cm in diameter made of very low thermal conductivity polyurethane foam. On the surface of the rod are deployed a thin-film, flex circuit style heater and an array of temperature-measuring thermistors. When the heater is activated, a nearly uniform heat flux is established across the surface of the rod. This heat flux warms the material surrounding the probe. In the absence of any flow past the probe, the temperature distribution on the surface of the probe, measured by the array of thermistors, is independent of azimuth and symmetric about the vertical midpoint of the probe. The ends of the probe are cooler than the midsection of the probe because heat transfer away from the ends of a finite-length heated cylinder is more efficient than from the midsection of the cylinder. If there is flow past the probe, the surface temperature distribution is perturbed as some of the heat emanating from the surface of the probe is advected around the instrument by the flowing fluid. Warmer temperatures are observed on the downstream side of the probe and cooler temperatures on the upstream side. The magnitude and direction of the full three-dimensional fluid flow velocity vector are determined by inverting an equation that describes the probe surface temperature distribution as a function of the flow velocity past the probe and the thermal properties of the fluid and the fluid-saturated sediments surrounding the probe (Romero, in press).

Figure 2. Location of the Proposed Environmental Restoration Disposal Facility.



The proposed gas flowmeter is based on the identical theoretical considerations and mathematical equations as the groundwater flow sensor. The only difference is that the thermal properties of air will be used instead of those of water. Because the heat-carrying capacity of a given volume of air is several orders of magnitude less than that of a similar volume of water, gas flow velocities measurable by the technology will be several orders of magnitude higher than detectable groundwater flow velocities. The gas flowmeter should be capable of measuring gas flow velocities as low as a few feet per day.

The proposed gas flowmeter could be used in two different modes. In the first mode of operation, the instrument will be hung in a packed-off, screened section of a borehole to measure the horizontal component of the gas flow velocity in the formation surrounding the hole. No technology for making this type of measurement is known to exist, so this would represent a valuable new capability. The position of the instrument will be maintained along the axis of the borehole with a centralizer, and packers will be used above and below the probe to minimize borehole effects. The diameter of the probe will be smaller than the inner diameter of the borehole so that an annulus of air will exist around the probe. If there is a significant horizontal flow in the section of the formation adjacent to the flowmeter, air will enter one side of the borehole, impinge on the side of the probe closest to where the air entered the hole, flow around the probe, and exit the hole 180° away from where it entered. As the air flows around the probe, heat emanating from the probe will be advected around the probe, perturbing the temperature on the surface of the probe. In this scenario, the direction of the air flow in the formation and relative changes in the magnitude of the formation flow velocity will be determined with considerable confidence, but the absolute magnitude of the air flow velocity in the formation surrounding the borehole will only be estimated with significant uncertainty because of the complex thermal and pneumatic processes occurring in the borehole, the borehole casing, and the surrounding gravel pack. The mathematical equation relating the probe surface temperature distribution to the flow velocity past the probe assumes the probe is buried in an infinite, homogeneous medium. Because these assumptions are grossly violated in the borehole environment, the magnitude of the flow velocity past a probe deployed in a borehole cannot be accurately determined. Laboratory tank experiments and numerical simulations will be required to calibrate the instrument. These calibration experiments are beyond the scope of this task.

In the second mode of operation, the instrument will be emplaced directly into the ground in contact with the formation to measure the full three-dimensional air flow velocity through unsaturated permeable geologic formations. In this mode, both the direction and magnitude of the flow velocity will be measured with maximum confidence since the perturbation to the pneumatic and thermal properties of the subsurface will be minimized. A number of emplacement techniques are possible. What has been done in the past with the in situ permeable flow sensor is to use a hollow stem auger to drill down to the depth where the measurement is to be made, lower the probe down the center of the auger and then retract the auger, leaving the flow sensor in place. In the saturated, unconsolidated sediments in which the groundwater flowmeter has been used, the formation quickly collapses around the instrument, leaving it permanently buried in a relatively undisturbed setting. With the gas flowmeter being proposed, it is likely that the borehole would stay open long enough that any drilling technique that does not involve the

use of drilling fluids could be used to drill the hole, the drill string removed from the hole, the probe lowered into the hole and then backfilled with the cuttings removed from the hole during drilling. It would be advisable to grout the hole for some distance above the position where the tool was emplaced to prevent enhanced air movement in the vertical conduit of disturbed material connecting the probe position and the ground surface. Another emplacement scheme that should be investigated is to push the sensor directly into the ground using a cone penetrometer technology. This emplacement strategy, which has not yet been attempted, would probably significantly reduce the disturbance to the formation and result in an even more defensible flux measurement.

There are a few limitations on use of the technology. First, the instruments cannot be deployed too close to the ground surface because other manifestations of surface weather such as surface temperature oscillations and rainfall events will influence the thermal behavior of the probe. Daily temperature oscillations typically penetrate to depths of about 10 ft and, while correction for their effects can be applied, they will complicate data interpretation. Longer period temperature oscillations, such as storm events and seasonal fluctuations, will also have an effect, but corrections will be easier to calculate. During rainfall events, surface water, which may be at a significantly different temperature than the soil around the probe, will be flushed past the probes, wiping out any temperature signal due to air flow past the tool. The depth to which these phenomena are important depends on the thermal and hydraulic properties of the medium above and surrounding the probe. While these effects will be investigated for the specific site where the probes are used, the probes should probably not be deployed at depths shallower than about 10 to 15 ft.

## 3.0 DEMONSTRATION OBJECTIVES AND PARAMETERS

### 3.1 OBJECTIVES

The test objectives for the preliminary field demonstration of the in situ permeable flow sensor for measuring air flow velocity in unsaturated sediments are presented below.

A. Evaluate whether the in situ permeable flowmeters are sensitive to air flow velocity in unsaturated sediments.

B. Compare and assess the flow measurements made in a screened interval of a test borehole with measurements obtained from a probe buried directly in the ground.

C. Determine the length of time required to operate the flowmeter to obtain valid flow data.

D. Determine the length of time to analyze the flowmeter data and the length of time between data collection and analysis.

E. Evaluate the ease of use of the in situ permeable flowmeters in the unsaturated zone.

F. Determine the versatility, or limits on operating conditions, of the in situ permeable flow sensor in the unsaturated zone.

G. Determine the infrastructural requirements for operation and data analysis using the in situ permeable flow sensor.

H. Determine the number of people required to operate the in situ permeable flow sensor.

## 3.2 PARAMETERS

The following parameters will be recorded or measured to demonstrate that the test objectives have been met.

A. Measure the temperatures of each of the 30 thermistors on the surface of each probe as a function of time to document the response of the flowmeters. Measure and record the magnitude, location, and duration of all pertinent operating conditions (e.g., applied vacuum, meteorological conditions, time, location of air extraction well and monitoring well). Vary system conditions (e.g., applied vacuum magnitude and location, sensor location) until sufficient characterization is obtained.

   The test will be considered successful if the flowmeters measure a velocity vector that is pointed toward the air extraction well when air is being pumped from it, and measure a velocity magnitude that increases with increasing air extraction rate and decreases with horizontal distance from the air extraction well. Because no independent measurements of the magnitude of the air flow velocity will be made, it will not be possible to determine whether the measured velocity magnitudes are "correct," only that they behave in an expected fashion, in a relative sense. It will be possible to make some qualitative assessment of the reasonableness of the velocity magnitudes based on assumptions of sediment homogeneity, isotropy, and the zone of influence of the air extraction system. If these objectives are achieved, a full proposal will be submitted to more fully characterize the validity of the velocity magnitudes and to more completely demonstrate the technology.

B. Measure thermistor temperatures and experimental conditions described above for each flowmeter simultaneously.

   It is anticipated that measurements obtained from a probe buried directly in the ground will be more sensitive and more reliable than those obtained from a probe deployed in a borehole. However, the obvious advantages associated with a reusable borehole device make it worth investigating the magnitude of the difference in measurement techniques.

C. Record the length of time to achieve stable flow measurements.

D. Record the length of time to analyze the flowmeter data and the length of time between data collection and analysis.

E. Record any problems associated with system transport to site and setup. Record the length of time to install and prepare the flowmeters for data collection. Record any problems with emplacing the flowmeters into the subsurface and in the boreholes. Record any problems associated with flowmeter operation.

F. Measure thermistor temperatures, meteorological and site conditions, and experimental setup and durations.

G. Record the need for and use of items such as power sources, materials, deployment platforms, heaters, generators, computers, vacuum pumps, and pressure transducers.

H. Record the number of people required to operate the in situ permeable flow sensor and to record the data.

## 4.0 REGULATORY COMPLIANCE

This section identifies the regulatory compliance requirements for this field demonstration. The major requirements for the demonstration are derived from the National Environmental Policy Act (NEPA), CERCLA, and the Washington Administrative Code (WAC). Because of the limited nature of residuals from this demonstration, no requirements under the Clean Air Act, Clean Water Act, or other federal or state environmental laws are specifically applicable.

### 4.1 NEPA

NEPA, 42 USC 4321 et seq., is the basic federal charter for protecting the nation's environment. NEPA's focus is to ensure that federal agencies such as DOE give appropriate consideration to environmental impacts in their decision-making. For NEPA compliance purposes, the activities described in this integrated test plan can be divided into two categories: testing of the permeable flow sensor and drilling the five 17-ft-deep boreholes at the test site needed to conduct the sensor testing.

On April 30, 1992, DOE determined that VOC-Arid ID sensor development and demonstration activities fit within a typical class of action currently available for a categorical exclusion listed in Subpart D of the DOE NEPA Implementing Procedures, 10 CFR 1021. The testing and demonstration of the flow sensor technology as described in this integrated test plan is within the scope of activities described in the Information Bulletin supporting that categorical exclusion approval, and the minimal environmental impacts that may be caused by these activities are clearly within the range of impacts assumed in DOE's categorical exclusion approval. Accordingly, no further NEPA compliance documentation is required for demonstration of the flow sensor technology.

On December 4, 1992, DOE determined that both intrusive and nonintrusive site characterization and environmental monitoring activities on and near the Hanford Site fit within a typical class of action currently available for a categorical exclusion listed in Subpart D of the DOE NEPA Implementing Procedures, 10 CFR 1021. While characterization of the proposed ERDF is not the central purpose of the permeable flow sensor testing described in this integrated test plan, the data produced during the testing regarding gas flow in the ERDF's subsurface will be used in the ongoing characterization of the proposed ERDF. The drilling of the five 17-ft-deep boreholes at the test site, and the expected resulting minimal environmental impacts, are within the scope of activities and impacts described in the Information Bulletin supporting the categorical exclusion granted for site characterization and environmental monitoring activities. Accordingly, no further NEPA compliance documentation is required for the drilling of these five boreholes.

### 4.2 CERCLA

CERCLA, 42 USC 9601 et seq., is designed to manage the unplanned, uncontrolled releases of hazardous substances. In particular, CERCLA is the governing framework for the ERA being conducted in the 200 West Area at Hanford to remove carbon tetrachloride from the soil vadose zone. CERCLA is also the governing framework for the construction of the ERDF.

The flow sensor field demonstration will be conducted at the ERDF site and in coordination with ERDF activities. Site characterization for the ERDF is described in Weekes and Borghese (1993).

### 4.3 RCRA

Subtitle C of the *Resource Conservation and Recovery Act* (RCRA), 42 USC 6921-6939b, establishes a comprehensive program to regulate newly generated hazardous waste. Administered by Ecology and EPA, RCRA Subtitle C requirements are contained in WAC, Chapter 173-303, and in 40 CFR Parts 260 through 272, and apply to the generation, accumulation, treatment, storage, and disposal of hazardous waste. No solid, hazardous, or mixed wastes are expected to be generated by this test. In the event such wastes are generated, they will be managed in accordance with applicable RCRA requirements, including Westinghouse Hanford Company (WHC) Environmental Investigations Instruction (EII) 4.2, "Interim Control of Unknown, Suspected Hazardous, and Mixed Waste," and EII 4.3, "Control of CERCLA and Other Past Practice Investigation Derived Waste" (WHC 1988a).

### 4.4 WASHINGTON ADMINISTRATIVE CODE

Drilling activities to be conducted in support of the demonstration of the flow sensor will be conducted in accordance with all applicable requirements of WAC 173-160. After the test is completed, the boreholes will be abandoned in accordance with WAC 173-160.

### 4.5 CULTURAL RESOURCES REVIEW AND ECOLOGICAL SURVEY

The test sites were determined to have no historic properties as discussed in Cultural Resources Review, #93-600-028. Ecological survey #93-600-9 has also determined that these demonstration activities would not endanger any ecological resources at the test site.

## 5.0 HANFORD COMPLIANCE

This section identifies Hanford Site compliance areas for this field demonstration.

### 5.1 SAFETY

Activities under this integrated test plan will be conducted according to the Job Safety Analysis for this work.

### 5.2 QUALITY ASSURANCE

All work on the Hanford Site is subject to the requirements of DOE Order 5700.6C, *Quality Assurance* (DOE 1991), which establishes broadly applicable quality assurance (QA) program requirements.

To ensure that the field demonstration activities are consistent with DOE Order 5700.6C, *Quality Assurance*, all work will be performed in compliance with WHC's QA manual, WHC-CM-4-2 (WHC 1988b), and with applicable procedures outlined in the QA program plan, WHC-EP-0383 (WHC 1990). This QA program plan describes the various plans, procedures, and instructions that will be used by WHC to implement the requirement of DOE Order 5700.6C (DOE 1991).

The objective of the test plan and the appendices is to ensure that the data obtained and the conclusions drawn are sufficiently accurate and reliable to support decisions associated with the evaluation of the demonstration.

### 5.3 TRAINING

No special health and safety considerations are expected. The proposed ERDF is not considered a hazardous waste site. No special training will be required; however, standard training including all relevant training required for Hanford Site employees and visitors will be required.

Safety training requirements are listed in the Job Safety Analysis. Security requirements are consistent with those needed for visitor access to the test site.

# 6.0 ORGANIZATION AND RESPONSIBILITIES

The field test will be performed by Demonstration Operations working with the principal investigator (Figure 3). General organization and responsibilities for the VOC-Arid ID, Demonstration Operations, and the ERA can be found in their respective project management plans. Organization for the field demonstration is shown in Figure 3. General responsibilities and specific responsibilities for the field demonstration follow.

## 6.1 DEMONSTRATION OPERATIONS

Demonstration Operations is responsible for site characterization, engineering, and conduct of field demonstrations. Demonstration Operations ensures regulatory and DOE/Hanford compliance for field demonstration activities.

## 6.2 PROJECT ENGINEER

The project engineer is responsible for coordinating with the principal investigators and the field team leaders and ensuring the availability of needed equipment and materials.

## 6.3 FIELD TEAM LEADER

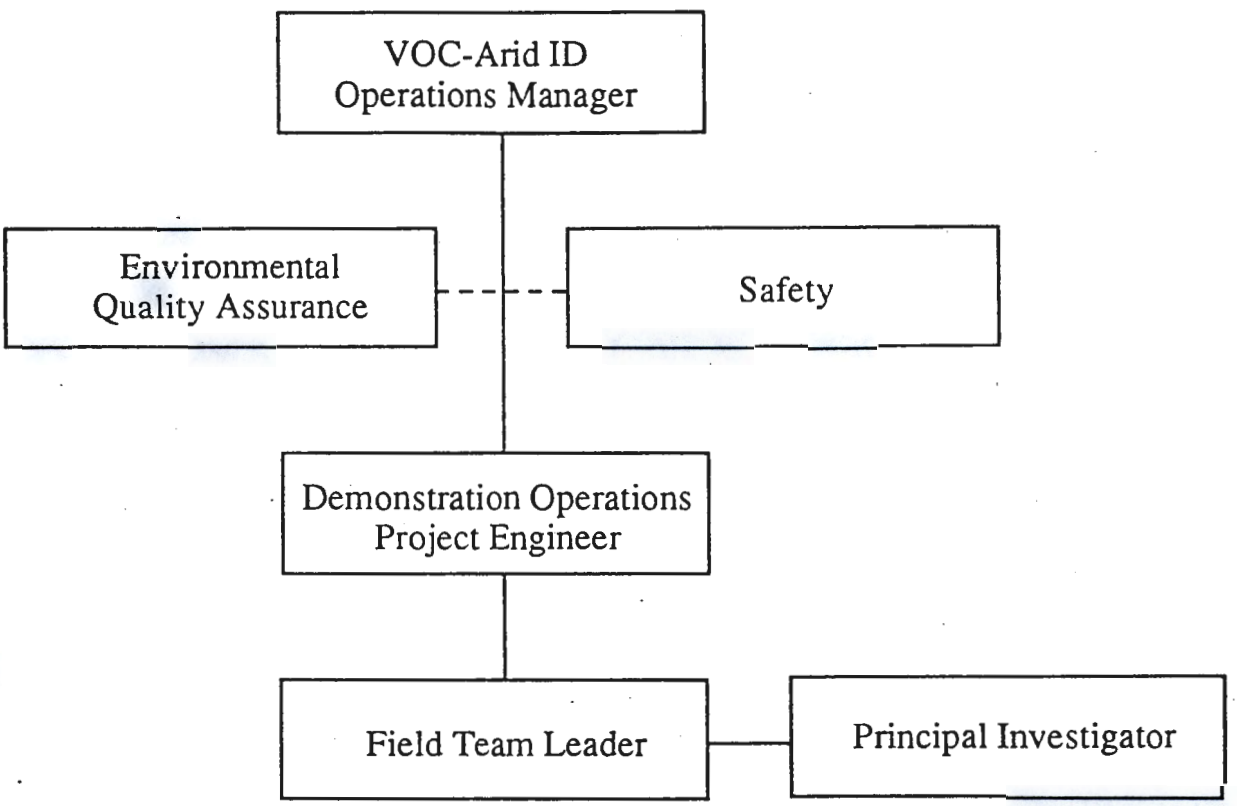
The field team leader is responsible for overall technical field management of the project and control of site access. All onsite personnel report through the onsite field team leader to accomplish their work.

## 6.4 PRINCIPAL INVESTIGATOR

The principal investigator will:

- Ensure that the test objectives are met
- Conduct the testing through coordination with the field team leader
- Provide all monitoring equipment to be tested
- Provide personnel to set up the equipment, perform the test, and analyze the results
- Prepare a performance evaluation report that reviews the results of the testing related to each objective.

Figure 3. Field Demonstration Organization.



## 7.0 DESCRIPTION OF TASKS AND PROCEDURES

A preliminary test of the in situ permeable flow sensor is proposed to determine if it can be used to measure gas flow velocity in unsaturated sediments. The ability of this technology to measure groundwater flow velocity in saturated sediments has already been demonstrated (Ballard et al. 1994). To investigate whether the technology can measure gas flow velocity as well, two flow sensors will be used. One flow sensor will be deployed directly into the ground while the other will be deployed in a screened interval of a borehole. Air will be pumped from the subsurface through other screened boreholes and air flow velocity in the subsurface monitored with both flowmeters.

Each probe consists of a rod of low thermal conductivity polyurethane foam surrounded by a thin film flex circuit style heater, another flex circuit on which an array of carefully calibrated thermistors is mounted, and a waterproof covering. The foam part of the rod is 30 in. long by 2 in. in diameter. The ends of the rod are capped with end pieces made of G10 epoxy laminate. The end pieces have a maximum diameter of 2.625 in. Sufficient 1-in.-diameter schedule 80 PVC pipe is connected to the top of the tool to reach the ground surface after emplacement. The reference direction of the probe is transferred to this PVC pipe so that the azimuthal orientation of the probe will be known after emplacement. Cables emanate from the top of the tool and extend through the interior of the PVC pipe to a data acquisition system at the surface.

These thermistors have been calibrated in the Sandia National Laboratory calibration facility, using the same instrumentation that will be used to make measurements in the field, to an accuracy of 0.01 °C. These temperatures will be input into a computer code called FLOW, which calculates flow velocity parameters from the temperature distribution on the surface of the probe and the thermal properties of the medium in which the probe is deployed.

The test will be conducted within the proposed ERDF. The site selected for this test consists of silty sand from 0 to 6 ft depth, underlain by gravelly sand from 6 to 17 ft depth. The gravelly sand is in turn underlain by sand. All of these formations are unconsolidated. The flow sensors will be deployed near the bottom of the relatively permeable gravelly sand unit at a depth of 16 ft. The resulting data will contribute to the ongoing characterization of the proposed ERDF.

Five 17-ft-deep boreholes will be drilled at the test site. Figure 4 illustrates the proposed arrangement of the holes in plan view. One flowmeter will be buried directly into the ground at the sensor borehole location at the center of the array shown in Figure 4. This will be accomplished by first drilling the hole to approximately 17-ft depth with a hollow-stem auger. After the hole is drilled, the probe will be lowered into the ground through the auger. The auger will then be retracted 3 ft, and the hole will be allowed to collapse around the probe, leaving it buried in the ground. If the hole does not collapse, it will be backfilled with filter pack to a depth of a few feet above the top of the probe, and then the remainder of the hole will be backfilled with bentonite pellets or some other relatively impermeable material (Figure 5).

Figure 4. Proposed Arrangement of the Test Holes.

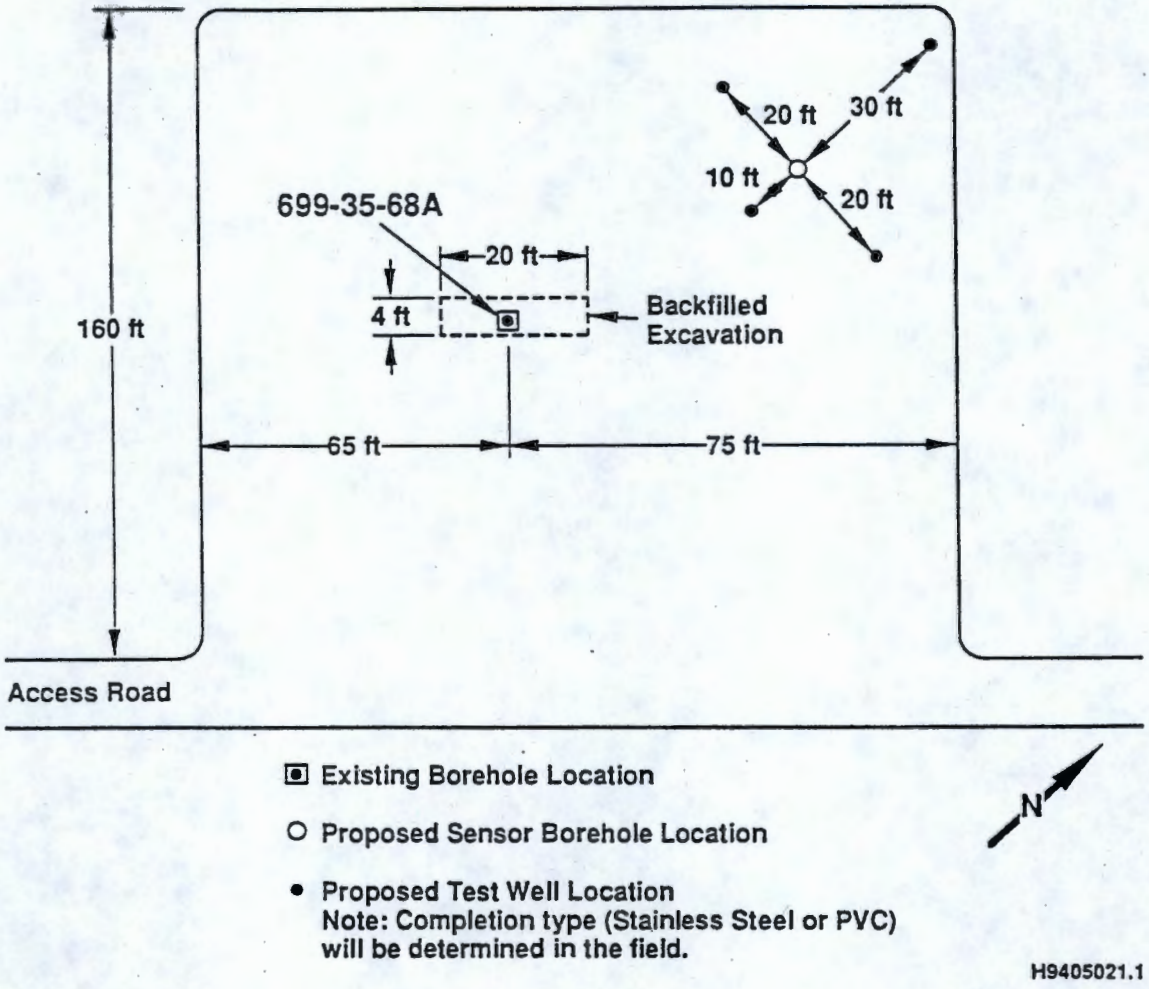
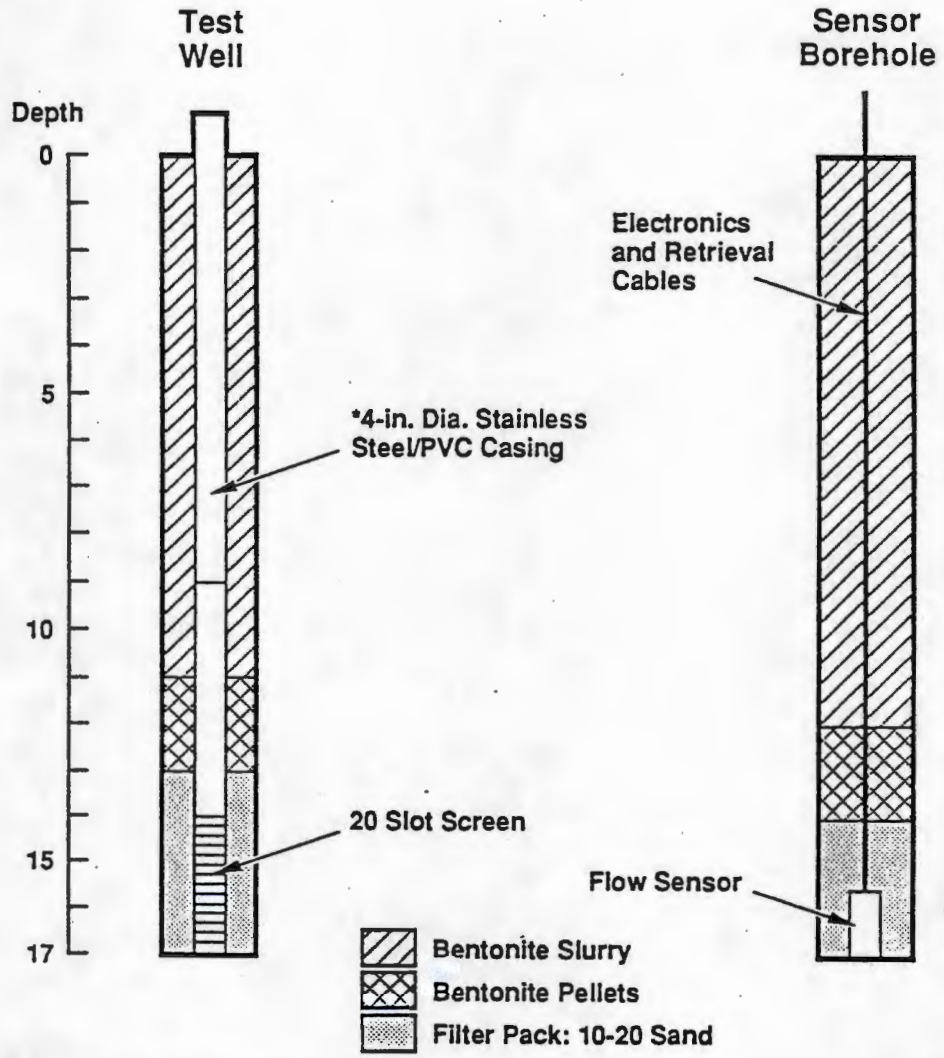


Figure 5. Well Schematics for In Situ Permeable Flow Sensor Testing.




*Note: Two to four test wells will be completed with stainless steel screen and casing. Two test wells may be completed with PVC screen and casing.

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Four test wells will be located within 10 to 30 ft of the sensor borehole (Figure 4). Each of these holes will also be drilled to 17 ft and completed with 4-in.-diameter steel or PVC casing (Figure 5). Each hole will have a 3-ft section of 20 slot wire wrap screen at the bottom. The section of the holes from the bottom of the hole to a depth of approximately 13 ft will be backfilled with material removed from the subsurface during drilling. The section from 13 to 11 ft depth will be completed with hydrated bentonite pellets and from 11 ft to the surface with bentonite slurry. The top of each hole should be fitted with a removable, air-tight cap. The second flow sensor will be deployed in the screened interval of at least one of these four wells.

A data acquisition system capable of recording the data obtained from the flow sensors will be used. This system consists of a Campbell Scientific CR10 data logger and AM416 multiplexer in a weatherproof box. One system will be required for each flowmeter. A laptop computer will be used to download and process the data. The electric heaters on the flowmeters require approximately 70 V of DC voltage to operate; therefore, a DC power supply capable of supplying the necessary power will be used. This power supply will require a single 110 VAC, 15-amp circuit to operate. Electric power can be supplied by either line power or a generator (diesel- or gasoline-powered). Power must be supplied to the flow sensors continuously (i.e., 24 h/day). If a generator is used, it should have the capacity to hold enough fuel to operate continuously for 15 h. A diesel generator, if available, could be refueled while running. The use of a gasoline generator would require that two generators be used, so that one is always running when the other is being refueled. The power supply that drives the heater on the flow sensor can be turned off for a short period of time, allowing the flow sensor to be moved from one generator to the other without adversely affecting the data.

Immediately after emplacement, the heaters on the flow sensors will be activated and the flow sensors monitored with the data acquisition system. After the flow sensors have warmed up, which should take about 24 h, a background reading will be obtained. Then air will be pumped from one of the screened wells and the effect on the flow sensor measurements observed. After measurements have stabilized, the vacuum pump will be moved to a different well and the air pumped from it until the flow sensor measurements have again stabilized. This procedure will be repeated until the flow sensor behavior has been adequately characterized. It will be important to monitor barometric pressure at the surface throughout the experiment to provide a basis for understanding any observed vertical components to the air flow velocity.

## 8.0 DEMONSTRATION SCHEDULE

Field setup will begin on approximately May 23, 1994, and is anticipated to continue for approximately 1 week.

## 9.0 REFERENCES

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