In Situ Permeable Flow Sensor

Subsurface Contaminants Focus Area

Prepared for
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Office of Science and Technology

February 1998

INNOVATIVE TECHNOLOGY
Summary Report

In Situ Permeable Flow Sensor

OST Reference # 99

Subsurface Contaminants
Focus Area

Demonstrated at
U. S. Department of Energy
Savannah River Site
Aiken, South Carolina
Hanford Site
Richland, Washington
Weeks Island Strategic Petroleum Reserve Site
Weeks Island, Louisiana
Other Federal and Commercial Sites

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available online at http://em-50.em.doe.gov.

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SECTION 1

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Technology Summary

Problem

Ground-water flow through the subsurface is perhaps the most important mechanism for dispersing most types of toxic waste disposed of in the ground. Therefore, accurate information on ground-water movement is critical in locating and designing waste disposal sites and for monitoring the postclosure performance of remediated waste sites. An understanding of ground-water flow is also essential to optimize the effectiveness of waste remediation processes, such as air sparging, in well vapor stripping, and bioremediation.

How it Works

The In Situ Permeable Flow Sensor (ISPFS) directly measures the direction and velocity of ground-water flow at essentially a single point in unconsolidated, saturated soil sediments. After the ISPFS is permanently installed in the ground, the 30 calibrated temperature sensors on its surface are activated, establishing a temporally and spatially uniform heat flux around the probe. Ground-water flow past the ISPFS is indicated by the change in the temperature distribution around the surface of the tool as some of the heat emanating from the probe is moved around the tool by the ground water moving past the ISPFS. The downstream side of the probe will be relatively warm compared to the upstream side. The direction and magnitude of the flow is calculated from the measured temperature distribution on the surface of the probe.

Figure 1. A flow sensor being installed through a hollow-stem auger.

- The ISPFS provides unique information, specifically a point estimate of ground-water flow direction and velocity at a scale of approximately one cubic meter. ISPFSs can be used to accurately measure ground-water velocities in the range from 0.01 to 1 ft/day (3 X 10^{-6} to 3 X 10^{-7} cm/s). Measurement resolution is 0.001 ft/day (3 X 10^{-7} cm/s).

- The ISPFS’s ability to measure ground-water flow has implications for improving characterization, restoration strategies, landfill designs, monitoring, and risk and performance assessments. The technology is ideally suited to
  - establish and document the zone of capture for recovery used in pump and treat systems,
  - measure the zone of effectiveness or capture for remediation systems such as in situ bioremediation and air sparging systems (flow of injected fluids),
  - measure the nature of ground-water and surface-water interactions, and
  - monitor permeable and impermeable subsurface barrier performance.

Advantages Over the Baseline

The unique information provided by the ISPFS cannot be measured using standard hydrologic methods. Although the scale of measurement is quite different, a baseline technique that yields similar information is a standard pump or slug test to provide information on hydraulic conductivity and measurements of the ground-water elevation in three wells to determine gradient. These data can be combined to provide an estimate of ground-water velocity. (Hydraulic conductivity is the rate at which fluids move through geologic materials.)

The advantages of ISPFS over the baseline method include the following:

- The scale measured with the baseline method depends on the spacing of the three wells so the measurement is at the scale of tens of meters to hundreds of meters. The ISPFS measures the subsurface at a scale of one cubic meter.
- Because one borehole can be used to calculate the three components of flow direction, ISPFS minimizes the number of boreholes necessary for monitoring.
- Because fewer boreholes are required and smaller-diameter bores can be used, ISPFS minimizes the risk of creating pathways for contaminant migration.
- Because neither wells nor pump tests are needed, ISPFS minimizes the amount of investigation-derived waste.
- Because data can be collected remotely and a large number of observations through time are recorded with minimal effort, ISPFS minimizes the costs of data collection and reduces the risks of worker exposure.
- The ISPFS minimizes subsurface disturbance of remediation systems.

Technology Status

ISPFS parts and service are commercially available from HydroTechnics. Software is copyrighted by Sandia National Laboratories and is licensed to HydroTechnics. There is no patent on the technology; it is public information. As a service provider of ISPFS, HydroTechnics will install the flow sensors, collect data, and provide periodic reports. If the user wishes to install the ISPFS equipment, HydroTechnics will provide technical support.

Demonstration Summary

ISPFS was developed at Sandia National Laboratories (SNL) with support from the U.S. Department of Energy’s (DOE) Office of Science and Technology (OST). The technology has been demonstrated at DOE’s Savannah River Site (SRS) near Aiken, South Carolina; the Hanford Site near Richland, Washington; Weeks Island Strategic Petroleum Reserve Site in Louisiana; at the U.S. Department of Defense’s (DOD) Edwards Air Force Base in California; and at commercial sites.

Key Results

The ISPFS successfully provided unique information (point estimates of ground-water flow vectors) at the above demonstration sites under both natural and perturbed (i.e. during remediation) conditions. Small-scale measurement of ground-water flow can be critical to optimizing remedial design or developing a site conceptual model. ISPFSs provide information over an extended period of time at an extremely low cost. After the sensors are installed, data collection is accomplished via an automated system.

- ISPFSs were used at SRS to monitor ground-water flow during in-situ air sparging and bioremediation demonstrations.
- ISPFSs were used to model the complex hydrologic interaction between ground water and river water at the Hanford Site.
- Results from ISPFSs were used to develop a conceptual model of hydrologic dynamics during in-well vapor stripping at Edwards AFB.
- ISPFSs were used to make critical decisions during characterization and subsequent remediation of an oil-storage facility at the Weeks Island Strategic Petroleum Reserve, Louisiana.

Contacts

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Licensing

Sandy Ballard, HydroTechnics Inc., (505) 797-2421

Web Site Location

http://www.hydrotechnics.com/flowsensors/.

Other

All published Innovative Technology Summary Reports are available online at http://em-50.em.doe.gov. The Technology Management System, also available through the EM50 Web site, provides information about OST programs, technologies, and problems. The OST Reference # for the In Situ Permeable Flow Sensor is 99.

SECTION 2

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Overall Process Definition

The ISPFS consists of a cylindrical heater 30 in long by 2 in diameter with an array of 30 calibrated temperature sensors on the surface. The probe is permanently installed in the ground to ascertain for years the direction and velocity of ground-water flow.

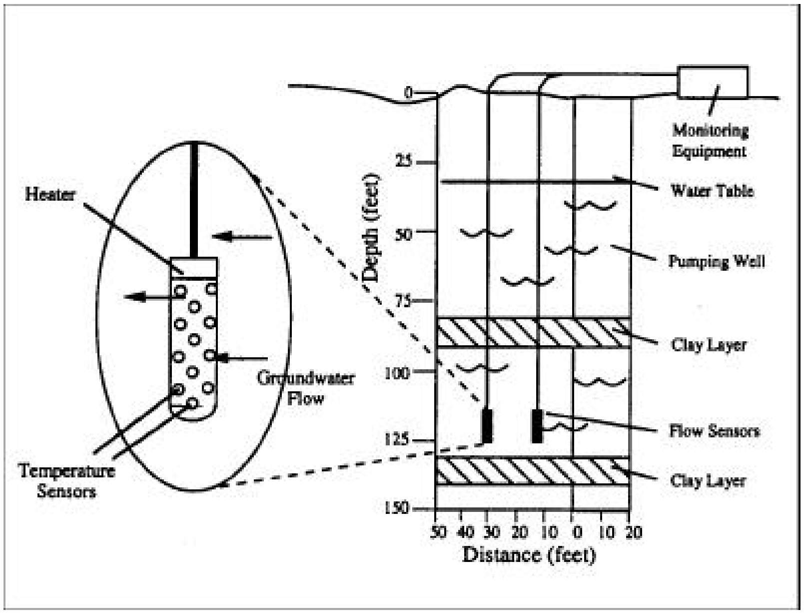

Figure 2. In Situ Permeable Flow Sensor Schematic Diagram showing installation of two flow sensors adjacent to a pumping well.

- Major elements of the technology and support equipment/systems

  — Flow sensors with cable that are permanently installed in the ground,
  — Data acquisition equipment, including data logger, personal computer, and modem,
  — HTFLOW^{C} software for data processing,
  — Continuous electric power,
  — Telephone service if remote communication is needed.

- Installation of the probe in the ground

  — The probe is installed to the desired depth with a standard hollow-stem auger drilling rig or any other drilling method that does not involve the use of drilling fluids.
  — The probe is installed through the casing, and the casing is retracted.
  — Saturated, unconsolidated sediments collapse around the probe providing good contact with the formation.
  — As the casing is retracted, bentonite or grout is added to seal critical zones.
  — Additional sensors and/or sampling devices can be installed in the annulus above the in situ flow sensor.

- Ground-water flow measurements

  — The heater in the flow sensor is activated, creating a characteristic temperature field around the probe.

— In the absence of flow, the temperature distribution on the surface of the probe is independent of azimuth position and is symmetric about the vertical midpoint of the probe.

— Flow past the probe is shown as cooler temperatures on the upstream side and warmer temperatures on the downstream side. (See Figure 3.)

— PC-based software, developed at Sandia National Laboratories, converts the temperature distribution measured around the probe into flow velocity. (See Figure 3.)

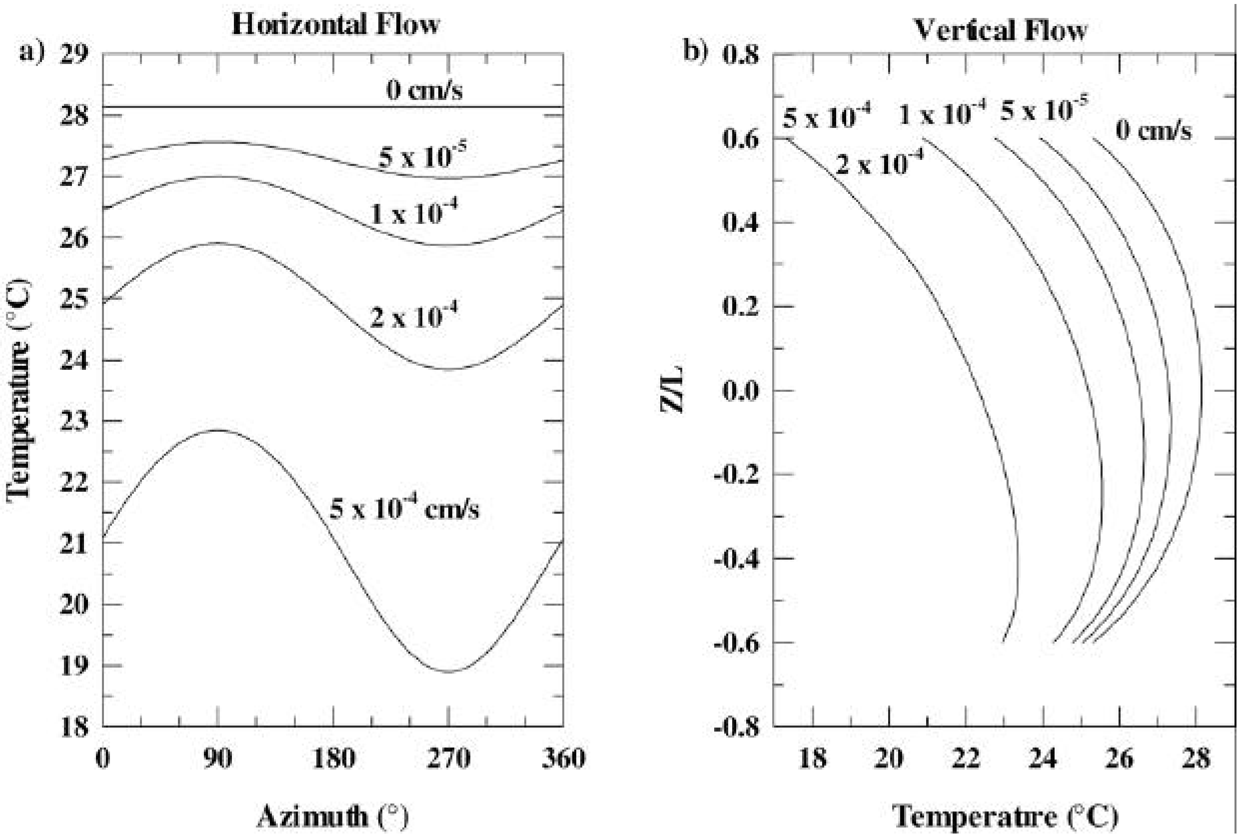

Figure 3. Theoretical temperature as a function of azimuth for a probe buried in a purely horizontal flow field (a), and as a function of vertical position for a probe buried in a purely vertical flow field (b).

System Operation

- Measurements are made by continuously applying approximately 80 watts of power to the heater.
- The sediments and ground water surrounding the probe are heated by 20 to 30°C.
- Measurements can be made in the field or remotely. Remote operation can significantly reduce operational costs.
- Output from software is flow velocity magnitude and 3-D direction of ground-water flow.
- Material energy requirements and other expendable items that will be used in the operation include continuous electrical power. A single 110 VAC, 15-amp circuit can power up to 10 flow sensors.
- Data collection and interpretation are automated.
- The system is simple to use and can be operated by a technician familiar with the use of personal computers. Training can be conducted during a single one-day session.
- Secondary waste is generated only during installation of sensors when a hole is drilled in the ground.

SECTION 3

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0Demonstration Plan

Savannah River Site Demonstration

Flow sensor probes were installed in the field at the Savannah River Site (SRS) near Aiken, South Carolina to monitor the effects of in situ air stripping (air sparging) and in situ bioremediation, which were being demonstrated to treat volatile organics (solvents) in soils and ground water at the M Area. The remediation technologies injected air into the ground below the water table at a depth of approximately 150 ft. The probes were installed to monitor the area of influence of the injected air.

A second demonstration was conducted at SRS at the TNX Area to provide information to validate flow sensor data. The ground-water velocity measured with the flow sensors was compared to that measured using standard hydrological methods. Flow sensors were installed in a confined aquifer at distances of 5 and 12 m from a monitoring well that contained a dedicated submersible pump.

Results

- The magnitude of the measured velocity was linearly related to the pumping rate, as predicted by theoretical considerations.
- The direction of the flow measured with the flow sensors was toward the pumping well.

The results are graphically presented in Figure 4.

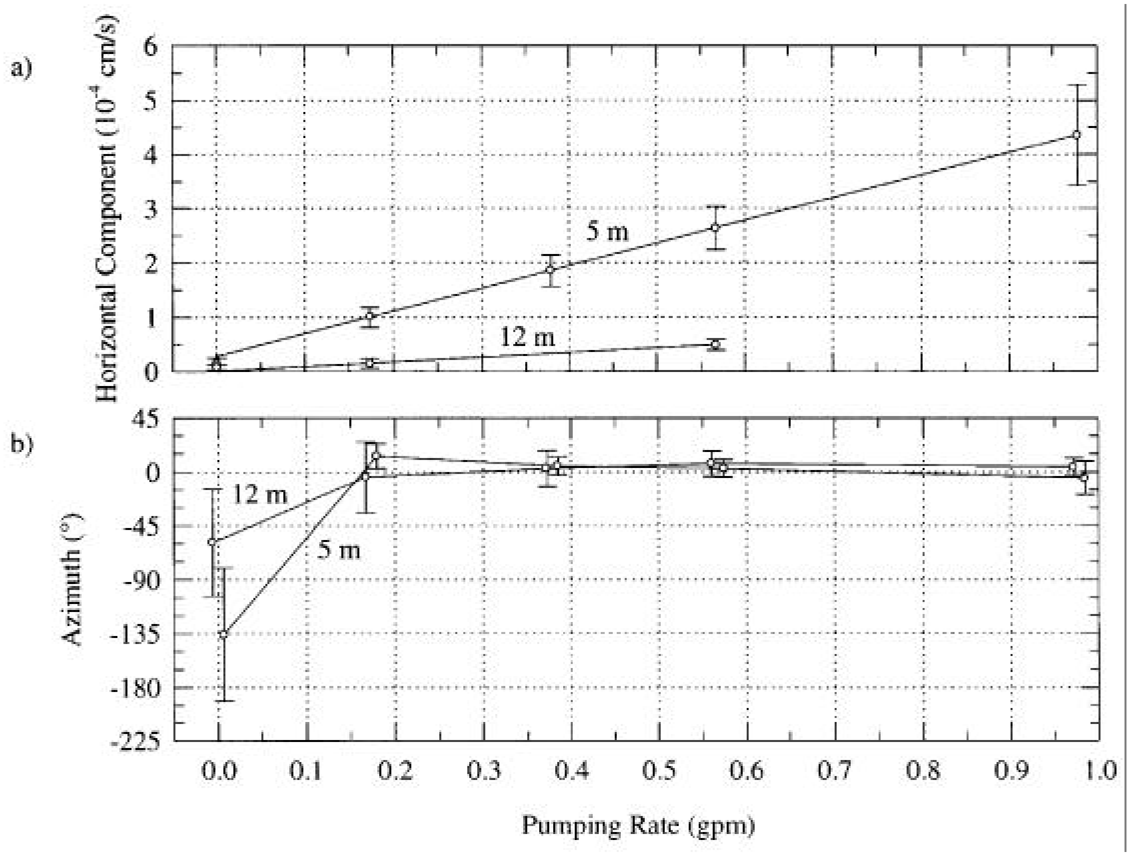

Figure 4. Magnitude (a) and direction (b) of the horizontal component of flow as a function of pumping rate.

Hanford Site Demonstration

ISPFSs were installed at the Hanford Site near Richland, Washington to study the interaction between ground water beneath the site and surface water in the Columbia River at the site boundary. The level of the Columbia River varies from 3 to 5 ft daily in response to variations in release from an upstream dam. The seasonal variance in river stage is 6 to 8 ft, lower in the fall and higher in the spring.

Results

- ISPFSs demonstrated relatively steady vertical and downstream components of flow that were essentially not correlated with river stage.

— During times of high-river stage, water flowed from the river into the bank.
— During times of low-river stage, ground water flowed toward the river.

- Ground-water/surface-water interactions showed a time lag of 5 h, as the river stage changes.
- Close to the river bank, three components of ground-water flow interact in a complex manner. (See Figure 5 below.)

— Relatively steady flow from the interior of the Hanford Site to the near-bank environment,
— Relatively steady flow downstream,
— Temporally variable flow in and out to the banks of the river in response to fluctuations in river stage.

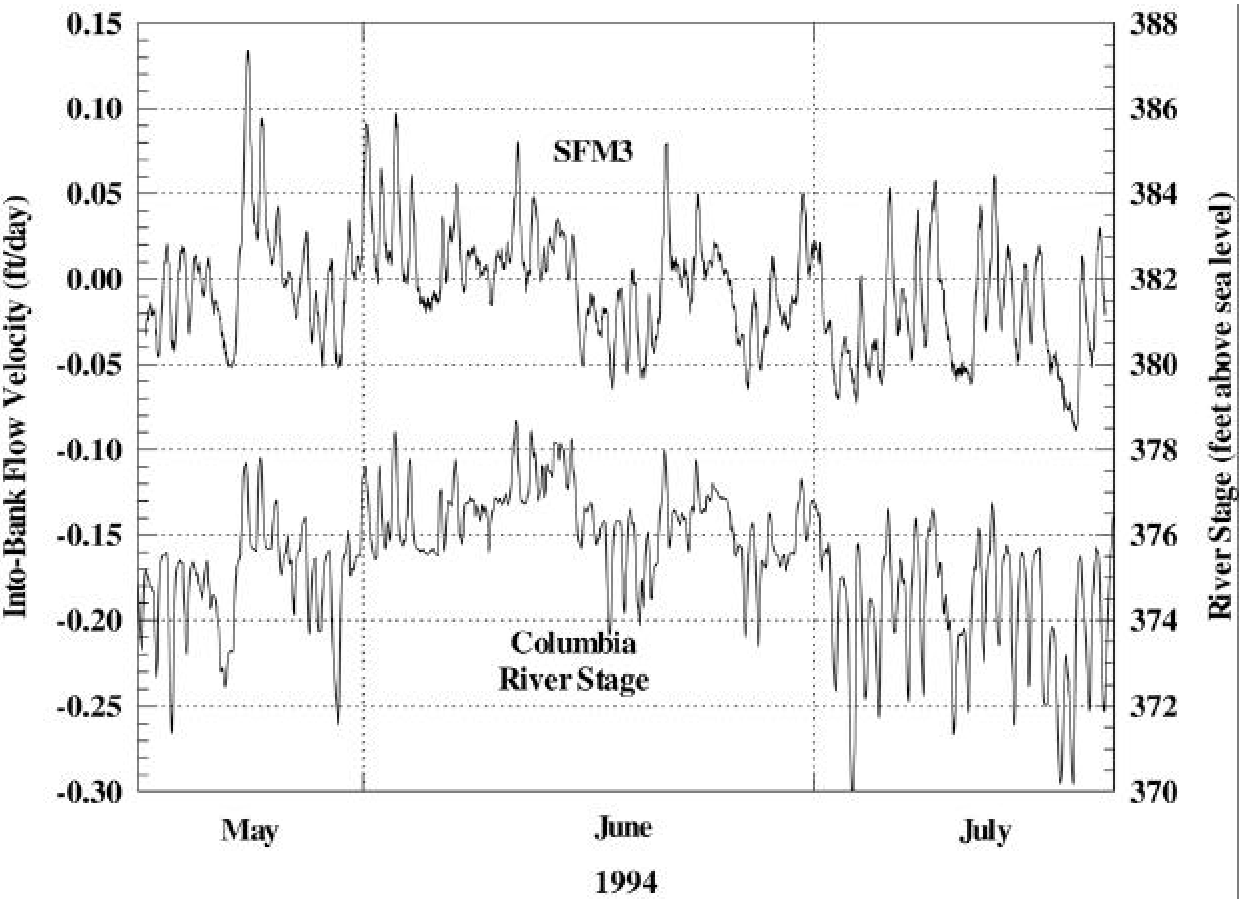

Figure 5. Columbia River stage (right vertical axis) and into-bank component of horizontal flow velocity (left axis) measured by flow sensor SFM3 during first data collection interval.

Edwards Air Force Base Demonstration

ISPFSs were deployed at Edwards Air Force Base in California to monitor the hydrologic regime during a demonstration of in-well vapor stripping to remediate trichloroethylene (TCE) in ground water.

In-well vapor stripping establishes a toroidal-shaped ground-water circulation system within an aquifer surrounding a well. In-well vapor stripping uses a well with two separate screens located at different positions vertically within the well casing to treat the ground water in situ. To initiate the circulation system, air is injected below the water table in the well.

Three ISPFSs were installed to characterize the ground-water flow field around the remediation well at distances of 17, 35, and 50 ft from the well.

Results

- The circulation system produced flow away from the well in the upper part of the aquifer (adjacent to the upper screen) and toward the well in the lower part of the aquifer (adjacent to the lower screen). The radial distance of the circulation cell is heavily dependent on the anisotropy in hydraulic conductivity in the formation.
- All three sensors measured horizontal flow, even 50 ft from the well, helping significantly to understand the dynamics of the remedial system. (See Figure 6.)
- All three sensors measured significant downward-directed flow. Downward flow was caused by the creation of conduits during the installation of the flow sensor. This occurrence emphasizes the need for careful installation of sensors using grout or bentonite to seal the annulus of the borehole above the probes in critical zones. This problem is not unique to ISPFSs but can result from any operation that accesses the subsurface, such as installation of monitoring wells.

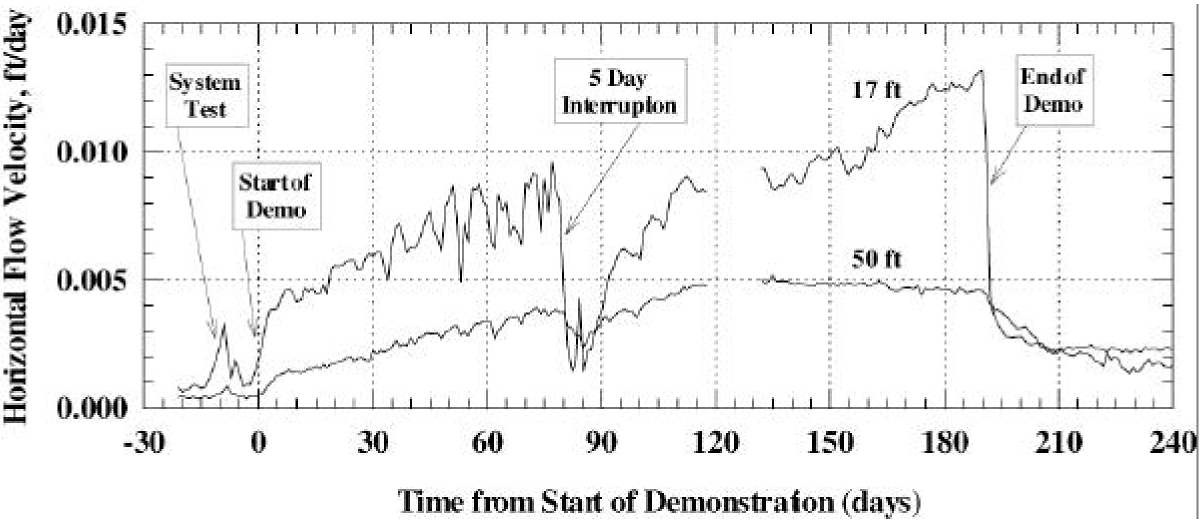

Figure 6. Horizontal flow velocity, relative to background, recorded by the near and far flow sensors during a demonstration at Edwards Air Force Base.

Weeks Island Strategic Petroleum Reserve Site

ISPFSs were used to monitor ground-water flow into a sinkhole that had formed over the edge of a former salt mine where DOE had stored 72 million barrels of crude oil. (See Figure 7.)

Characterization revealed that the sinkhole was the surface expression of a sand-filled conduit within the salt. Flow sensors were installed in the conduit to measure downward flow of ground water into the salt dome.

Results

- A downward flow of approximately 1 ft/day was measured.
- The velocity of flow measured by the ISPFSs convinced decision makers that the site was unsuitable for storage of crude oil. The oil was removed, and the facility was abandoned. During removal of the oil, flow sensors were used to monitor the flux of brine into the conduit.

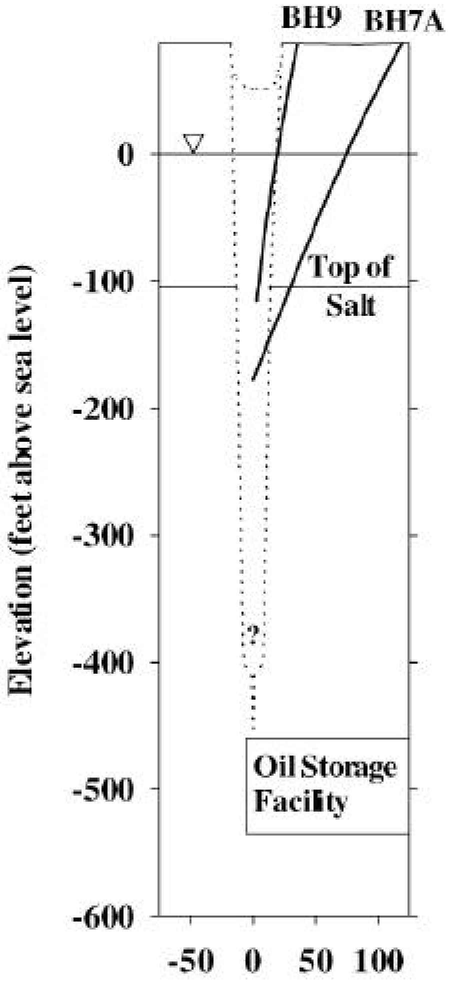

Figure 7. Cross section through the SPR Weeks Island sinkhole.

Other Demonstrations and Deployments

- Researchers from the Department of Agricultural Engineering at Texas A&M University used flow sensors to study the infiltration of pesticides from a corn field into the ground water and then into the Brazos River immediately adjacent to the site. During a pump test conducted on the site, flow-velocity data measured with the flow sensors matched the pumping-test data.
- On-going investigations involving flow sensors include the effects of air sparging/bioremediation on ground water, the interaction of ground water and sea water in a coastal environment, monitoring flow through an iron-wall funnel-and-gate remediation system, monitoring ground-water flow field in the vicinity of in situ permeable barriers used to remediate VOCs in ground water, and ground-water/surface-water interaction in a municipal ground-water resource investigation.

SECTION 4

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Competing Technologies

The baseline technology uses hydraulic-head measurements and pumping-test data from monitoring wells. Hydraulic-head measurements are made in a minimum of three screened boreholes to determine hydraulic gradient. Slug or pump testing determines hydraulic conductivity, which is combined with the gradient to calculate velocity.

The baseline method provides similar information but measurements are made over a larger scale. The baseline method may perturb the subsurface remediation system.

Disadvantages of Pump and Slug Tests

- Pump tests generate a large volume of ground water that must be treated and disposed of as hazardous waste.
- Slug tests require injection of a volume of water that can mobilize the contaminants away from the well. If small volumes of water are used, the hydraulic conductivity determined is only valid for the formation in close proximity to the well.

Disadvantages of Commercial Flow Meters (KV flow meter) and Colloidal Borescope

- These technologies are typically used to characterize ground-water flow in a borehole. The probe is lowered into a borehole and removed after the measurement is made.
- These technologies measure only the horizontal component of flow.
- These technologies can be deployed only in boreholes, raising a concern that the results may be unrepresentative of flow under natural conditions. The presence of a well filter pack and screens, etc. may influence flow data. ISPFS attempts to mimic natural conditions as closely as possible.
- Competing technologies are not automated. Hence, measurements at different times over a long period of time require a significant level of effort.

Technology Applicability

The ground-water flow information provided by the ISPFS has implications for improving characterization, restoration strategies, landfill designs, monitoring, and risk and performance assessments. The ISPFS is especially appropriate during long-term monitoring projects because it is permanently installed in the ground.

Flow sensors are best used during projects in which they supplement or replace a portion of the monitoring wells or where they are deployed in tandem in the same borehole with other sensors or monitoring devices.

Patents/Commercialization/Sponsor

ISPFS parts and service are commercially available from HydroTechnics. Software is copyrighted by Sandia National Laboratories and is licensed to HydroTechnics. There is no patent on the technology; it is public information. As a service provider for the ISPFS, HydroTechnics will install the flow sensors, collect data, and provide periodic reports. If the user wishes to install the ISPFS equipment, HydroTechnics will provide technical support.

SECTION 5

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Methodology

A cost comparison of ISPFS with the baseline technology is difficult because the two methods of calculating ground-water flow direction and velocity are different and the information provided by the two methods is used in different ways.

- The ISPFS provides unique information on ground-water velocity and direction and is especially valuable when these parameters need to be measured at a relatively small scale. The scale measured with the baseline method is a function of the spacing of the three wells, so the measurement is at the scale of tens of meters to hundreds of meters, whereas the ISPFS measures the subsurface at a scale of one cubic meter.
- In order to estimate flow, the baseline method measures the hydraulic conductivity of the formation with a pump test. The pump test requires three to five days of an engineer's time to perform and interpret and can be especially costly in a contaminated aquifer where thousands of gallons of ground water must be collected and treated. The information provided by the flow sensors, however, cannot replace the suite of information that can be collected from monitoring wells, i.e. water chemistry, etc.

The only baseline method that can be reasonably compared with the ISPFS technology is for an application where the baseline method would calculate gradient using monitoring wells in conjunction with a pumping test.

The cost scenario presented below is a hypothetical one that applies ISPFSs to monitor flow through a permeable gate of a passive barrier treatment system. This scenario was selected because none of the actual applications described in Section 3 would have conducted a pump test to collect velocity information. For example, at Edwards Air Force Base, ISPFSs were used to monitor an in-well vapor stripping demonstration. A pumping test could not have been conducted to collect velocity information for this application because it would have perturbed the remediation system. The hypothetical scenario provides the most reasonable cost analysis of ISPFS with the baseline.

Cost Analysis

Capital/Operating Costs for ISPFS Technology

Table 1. Price List from HydroTechnics, the vendor of ISFPS

Flow Sensor	\$2,500 + \$1/ft of cable
Installation Assistance	\$500/day + travel
HTFLOW© Software	\$1,000/license
Data Logger (up to 12 probes)	\$2,000/each or \$150/month
Power Supply	\$200/each

Most of the equipment can be purchased or rented from HydroTechnics, the vendor. If installation assistance is desired, HydroTechnics will assemble the probes in the field, assist with probe emplacement in the ground, measure the orientation of the probe so that the direction of the horizontal component can be properly referenced after installation, install all the cabling in electrical conduits, connect the cables to the data acquisition system, configure the data acquisition system (including remote data acquisition capabilities), and provide a written report on the configuration of the system.

HTFLOW© software is a PC-based program used to convert the measured temperature data from the flow sensors into flow velocity. It includes many capabilities for processing, graphically displaying and manipulating both the temperature data and the flow velocity information. A Windows 95 version will be available in summer 1997.

Permeable Wall Monitoring Scenario

Permeable treatment walls rely on the natural flow of water through a permeable granular treatment bed. Contaminants in the ground water are either destroyed or sorbed and clean water exits the system. Permeable treatment walls may be configured as a continuous treatment bed, or as a funnel-and-gate system.

A key factor in documenting the performance of permeable wall systems is the amount of water flow through the treatment bed and the quality of the water exiting the system. Because the chemistry in permeable treatment beds is dynamic, conditions in the wall can change over time. The hydraulic properties of the wall can change (e.g., precipitates can form and reduce permeability). As a result, the measured water levels on the two sides of the wall are no longer directly related to flow through the permeable bed. In many cases, water levels could be similar even if the wall were operating at its full initial capacity and if it were completely clogged. Concentrations measured on both sides of the treatment bed would also be similar if the wall was operating versus clogged.

Although several sensors could be installed along a treatment wall or near the ends of a funnel system to determine the amount of flow passing through the gate, a single flow sensor down-gradient of the gate would provide data on the treatment-bed hydraulics similar to an annual pump test. If the gate > 3 ft wide, install the sensor in the gate. If the gate < 3 ft wide, install the sensor down gradient of the gate.

Table 2 is a cost comparison between an In Situ Permeable Flow Sensor system and a simplified pump test for monitoring the performance of a permeable wall system.

Table 2. Cost Comparison of ISPFS with a Simplified Pump Test

Simplified Pump Test (baseline technology)	In Situ Permeable Flow Sensor
Description: Pump a well on the exit side of a permeable treatment bed and measure changes in pressure in a well upgradient of the treatment bed. Calculate permeability of the bed to allow estimate of water velocity (i.e., quantity of water treated) from measured pressures.	**Description:** Flow sensor installed in or near exit of permeable treatment bed.
Assumptions: No water disposal restrictions because the water has been treated by the wall. One test performed each year and included in documentation of treatment bed status. Each test requires one-person week for a hydrogeologist, materials, and for write-up. Ten years of operation (this is the current recommendation for operating period before wall refurbishment may be needed).	**Assumptions:** One probe, 50 ft of cable, two days for HydroTechnics installation with travel and other expenses, HTFLOW© software, and data collection and write-up each year. Ten years of operation. The flow sensor is assumed to be installed during the installation of the monitoring wells and has a lifetime of at least 10 years.
Estimated Initial Costs: None. Monitoring wells, pumps, and water level tape already exist for water quality monitoring. (Note: If pressure transducers were used, costs would be higher.) **Total Initial Cost:** $0	**Estimated Initial Costs:** Installation: $2,000 Monitoring probe: $2,500 Cable: $50 Data logger: $2,000 HTFLOW© Software: $1,000 **Total Initial Cost:** $7,550
Estimated Annual Costs: Hydrogeologist ($75/hour): $3,000 Materials: $1,000 Report: $1,000 **Total Annual Cost:** $5,000	**Estimated Annual Costs:** Collect data and write report: $1,000 **Total Annual Cost:** $I,000
Total Cost over 10 Years: $50,000	**Total Cost over 10 Years:** $17,550

Table 3 shows the payback period and return on investment for the purchase of an ISPFS system.

Table 3. Payback Period on Purchase of ISPFS

Payback	1.9 years
Net present Value @ 3.5%	$25,716
Net Present Value @ 10%	$17,028
Internal Rate of Return	52.2%

Cost Conclusions

- The cost analysis shows significant savings when using the ISPFS as compared to the baseline technology.
- The cost analysis is conservative and cost savings could be greater if pump test water was required to be treated.

Similar cost savings can be realized for other applications.

SECTION 6

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Regulatory Considerations

- Installation of the ISPFS eliminates the need for pump testing, which requires surface handling and treatment of large volumes of potentially contaminated ground water according to RCRA requirements.
- Effort should be made during sensor installation to reduce the potential for creation of pathways for contaminant migration. Sensors can be installed within a hollow-stem auger or by cone penetrometer. Grouting should be conducted to seal off zones of concern.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- The system is simple to operate and can be used safely by properly trained technicians.
- The potential exposure of workers to hazardous materials is significantly reduced because once the sensor is installed, ground water is not brought to the surface for monitoring purposes.

Community Safety

- Use of flow sensors for barrier monitoring can provide early detection of leaks and possible contamination of drinking water systems.

Environmental Impact

- The environmental impact is reduced because a smaller number of boreholes is required to characterize ground-water flow.
- The impact to the environment can be reduced further if additional sensors and samplers are installed in the annulus above the flow sensor.

Socioeconomic Impacts and Community Perception

- Use of the technology will have small impact on the labor force and the economy of the region.

SECTION 7

[redacted]

1Implementation Considerations

- The site manager must work with the regulator to assure acceptance of the data collected.
- ISPFSs at Edwards Air Force Base were monitored successfully for 18 months.
- When considering application of ISPFSs, flow should be estimated to determine if the sensors can measure the flow at an appropriate scale.
- If more than 12 sensors are deployed or if the distance between probes does not allow connection to a single data logger, additional equipment will be required.

Technology Limitations/Needs for Future Development

- ISPFSs are appropriate for use only in saturated, unconsolidated sediments.
- The installation depth is limited only by the ability of appropriate drilling techniques to access the desired depth.

Technology Selection

- Specific job requirements and site conditions will dictate the selection of the best technology for characterization of a particular site. ISPFSs should be considered as a tool within a toolbox of ground-water monitoring technologies. The flow sensors provide unique information on the direction and magnitude of ground-water flow velocity at a given site.
- Customers should consider installation of samplers and sensors in the annulus above the flow sensor.
- Flow sensors could be deployed below abandoned boreholes or wells by deepening an existing hole.

APPENDIX A

[redacted]

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