FINAL TOPICAL REPORT
LONG-TERM MONITORING SENSOR NETWORK

Contract # DE-AC26-01NT41303

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DISCLAIMER

PUBLIC ABSTRACT

Long-term monitoring (LTM) associated with subsurface contamination sites is a key element of Long Term Stewardship and Legacy Management across the Department of Energy (DOE) complex. However, both within the DOE and elsewhere, LTM is an expensive endeavor, often exceeding the costs of the remediation phase of a clean-up project. The primary contributors to LTM costs are associated with labor. Sample collection, storage, preparation, analysis, and reporting can add a significant financial burden to project expense when extended over many years. Development of unattended, in situ monitoring networks capable of providing quantitative data satisfactory to regulatory concerns has the potential to significantly reduce LTM costs. But survival and dependable operation in a difficult environment is a common obstacle to widespread use across the DOE complex or elsewhere. Deploying almost any sensor in the subsurface for extended periods of time will expose it to chemical and microbial degradation. Over the time-scales required for in situ LTM, even the most advanced sensor systems may be rendered useless. Frequent replacement or servicing (cleaning) of sensors is expensive and labor intensive, offsetting most, if not all, of the cost savings realized with unattended, in situ sensors.

To enable facile, remote monitoring of contaminants and other subsurface parameters over prolonged periods, Applied Research Associates, Inc has been working to develop an advanced LTM sensor network consisting of three key elements: (1) an anti-fouling sensor chamber that can accommodate a variety of chemical and physical measurement devices based on electrochemical, optical and other techniques; (2) two rapid, cost effective, and gentle means of emplacing sensor packages either at precise locations directly in the subsurface or in pre-existing monitoring wells; and (3) a web browser-based data acquisition and control system (WebDACS) utilizing field-networked microprocessor-controlled smart sensors housed in anti-fouling sensor chambers. The monitoring network is highly versatile and can be applied to a variety of subsurface sensing scenarios in different media. However, the current project focused on monitoring water quality parameters of pH, oxidation-reduction potential, conductivity, and temperature in groundwater.

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1. Background

Long-term monitoring (LTM) associated with subsurface contamination sites is an expensive endeavor across the Department of Energy (DOE) complex and elsewhere, often exceeding the costs of the remediation phase of a clean-up project. The primary contributors to LTM costs are associated with labor. Sample collection, storage, preparation, analysis, and reporting can add a significant financial burden to project expense when extended over many years. Development of unattended, *in situ* monitoring networks capable of providing quantitative data satisfactory to regulatory concerns has the potential to significantly reduce LTM costs. However, survival and dependable operation in a difficult environment is a common obstacle to widespread use across the DOE complex or elsewhere.

Deploying almost any sensor in the subsurface for extended periods of time will expose it to chemical and microbial degradation. Over the time-scales required for *in situ* LTM, even the most advanced sensor systems may be rendered useless. Frequent replacement or servicing (cleaning) of sensors is expensive and labor intensive, offsetting most, if not all, of the cost savings realized with unattended, *in situ* sensors.

Under contract # DE-AC26-01NT41303 to the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), Applied Research Associates, Inc. (ARA) is working to enable facile, remote monitoring of contaminants and other subsurface parameters over prolonged periods through the development of an advanced long-term monitoring sensor network.

2. Technology Description

To meet this objective, we are developing, integrating, and field testing three key elements:

1. A unique, anti-fouling sensor chamber that can accommodate a variety of chemical and physical measurement devices based on electrochemical, optical, and other techniques. The chamber will be self-cleaning, *in situ*, yet removable from the subsurface so that the sensors can be exchanged in cases where their longevity is insufficient to meet extreme LTM requirements (e.g., 30 years or longer).
2. Two rapid, cost effective, and gentle means of emplacing sensor packages either at precise locations directly in the subsurface or in pre-existing monitoring wells. Wireline Cone Penetrometer Technology (WirelineCPT) will be utilized for direct emplacement, whereas a packer-based chassis configuration will be used for emplacement within pre-existing monitoring wells. This technology will allow for continuous assessment of groundwater conditions at precisely placed, isolated depths along existing screened intervals. In addition, multiple-level installations will be enabled, allowing vertical profiling of groundwater quality over multiple strata, as may be spanned by relatively long (e.g., 10-20 feet) existing well screens.
3. A web browser-based data acquisition and control system (WebDACS) utilizing field-networked microprocessor-controlled smart sensors housed in anti-fouling

sensor chambers. The WebDACS will employ multi-drop RS-485 serial communications and cable-based or wireless transmission to a central host computer to provide long-term, automated, and unattended operations with data available to users via the web in near real-time.

Once completed, the monitoring network will be highly versatile and can be applied to a variety of subsurface sensing scenarios in different media. However, this project is focussing on monitoring water quality parameters of pH, oxidation-reduction potential, conductivity, and temperature in groundwater. An option to the base contract, if approved, will allow us to demonstrate the system beneath a coal pile run-off basin at the Savannah River Site (SRS).

3. Benefits

The sensor chamber with integrated acoustic cleaning capability offers to reduce substantially or eliminate the expenses associated with retrieving the sensors for cleaning as well as the labor costs associated with sample collection, storage, preparation, analysis, and reporting in the baseline LTM approach.

Utilization of the WirelineCPT system permits minimal disruption of the subsurface environment, minimal generation of investigation-derived waste (IDW), enhanced worker protection, increased speed, and lower cost.

Use of the inflatable well packers will enable precise control of sensor positioning and allow for continuous assessment of groundwater conditions at precisely placed, isolated depths along existing screened intervals. In addition, multiple-level installations will be enabled.

Automated, unattended data acquisition and logging of sensor data using WebDACS will eliminate the delays, data handling costs, and transcription errors that have always been associated with paper-based analytical reporting and manual data handling. In addition, worker safety will be improved by eliminating the need to handle contaminated samples and IDW.

4. Statement of Work

A. SCOPE OF WORK

The objective of this project is to enable facile, remote monitoring of contaminants and other subsurface parameters over prolonged periods through the development of an advanced LTM sensor network.

To meet this objective, three key elements will be developed, integrated together, and field-tested under this program:

1. A unique, anti-fouling sensor chamber that can accommodate a variety of chemical and physical measurement devices based on electrochemical, optical and other techniques. The chamber will be self-cleaning, *in situ*, yet removable from the subsurface so that the sensors can be exchanged in cases

where their longevity is insufficient to meet extreme LTM requirements (e.g., 30 years or longer).

2. Two rapid, cost effective, and gentle means of emplacing sensor packages either at precise locations directly in the subsurface or in pre-existing monitoring wells. Wireline Cone Penetrometer (WirelineCPT) technology will be utilized for direct emplacement, whereas a packer-based chassis configuration will be used for emplacement within pre-existing monitoring wells.
3. A web browser-based data acquisition and control system (WebDACS) utilizing field-networked microprocessor-controlled smart sensors housed in anti-fouling sensor chambers. The WebDACS will employ multi-drop RS-485 serial communications and cable-based or wireless transmission to a central host computer to provide long-term, automated, and unattended operations with data available to users via the web in near real-time.

The project will be accomplished in two stages. The Base Contract consists of laboratory research culminating in the fabrication of prototypes of the four main components of the LTM network: (1) antifouling sensor chamber, (2) WirelineCPT chassis, (3) inflatable packer-based chassis, and (4) WebDACS. Option 1 involves integration and preliminary testing of the prototype network through a practical demonstration at a DOE site where a more limited LTM program will already be in progress.

B. TASKS TO BE PERFORMED

BASE CONTRACT – DEVELOPMENT OF LTM NETWORK ELEMENTS

Until the National Environmental Policy Act Review and approval process is completed and notification is provided, the Contractor shall take no action that would have an adverse impact on the environment or limit the choice of reasonable alternatives to the proposed action.

Task 1.1 – Ultrasonic Sensor Chamber Development

The Contractor shall perform laboratory experiments to evaluate the effectiveness of ultrasonics for *in situ* cleaning of sensor packages (sensor + chamber) under accelerated bio-fouling conditions. Ultrasonic parameters shall be varied to establish optimum conditions for *in situ* cleaning of sensors and chamber surfaces when emplaced in soil and groundwater. The system shall also be tested to ensure that the chemical composition of the sample to be measured is not altered by the cleaning system. Upon completion of the laboratory tests, a prototype chamber designed to be compatible with the deployment systems developed under Task 1.2 shall be fabricated and tested.

Task 1.2 – Deployment Systems and Procedures Development

The Contractor shall design, fabricate, and test chassis systems utilizing inflatable well packers and WirelineCPT tools. The chassis systems shall be tested for compatibility with the ultrasonic chamber developed in Task 1.1 and functionality (mechanical performance, ability to protect against infiltration of flowing sands, etc.). Upon completion of the laboratory tests, one or more chassis prototypes shall be designed, fabricated and tested with a sensor chamber for WirelineCPT and groundwater well emplacement.

Task 1.3 – Sensor Field Networking Development

The Contractor shall assemble a system for low power, wireless field networking of sensors. The system shall be tested with a minimum of five sensors utilizing a microcontroller hardware interface. Microcontroller firmware shall be developed as necessary. A solar power source shall be integrated into the network hardware.

Task 1.4 – LTM WebDACS

The Contractor shall modify ARA's existing WebDACS system to increase security, allow for user control of all sensor acquisition parameters via a web browser interface, and provide compatibility with other data acquisition systems through development of a device driver-object interface. Modifications to WebDACS shall be tested to ensure complete functionality.

Task 1.5 – Topical Report

The Contractor shall prepare a draft topical report at least 60 days prior to completion of the Base Contract on the technical results achieved during the Base Contract. This report shall be prepared in accordance with provisions J.16 and J.17 and shall include discussion on topics including, but not limited to, results of any analyses, numerical simulations, and/or laboratory or field validations. The results shall be documented to allow validation. The report shall also include a discussion of other pertinent aspects of the project effort, including, but not limited to: description of work performed, product/method inputs and outputs, product/method operating conditions, product efficiency, product/method longevity, product/method maintenance, and discussion detailing steps necessary to develop the technology into a marketable product. After review and comment by the appropriate DOE representatives, the Contractor shall modify the report to become the Final Topical Report on the Base Contract. If the government elects not to continue with the remaining effort, the Topical Report will become the Final Report.

NOTE: In accordance with provision B.1, the Contractor shall not proceed with Option 1 until written Contracting Officer approval to proceed has been received by modification of the contract.

<u>OPTION 1 – LTM NETWORK PROTOTYPE FIELD DEMONSTRATION</u>

Until the National Environmental Policy Act Review and approval process is completed and notification is provided, the Contractor shall take no action that would have an adverse impact on the environment or limit the choice of reasonable alternatives to the proposed action.

Task 2.1 – Develop Test Plan

The Contractor shall develop a test plan for system integration and field testing of the LTM network prototype. At a minimum, the test plan shall include objectives of testing; description of equipment, setup, design and procedures, and duration of tests; data analyses and reporting; and criteria for determining the success of testing. The test plan shall also include an Environmental, Safety, and Health (ES&H) plan. The test plan shall be submitted within 20 days after receipt of approval to proceed with Option 1, to the DOE COR for review and approval.

Task 2.2 – System Integration and Field Testing

The Contractor shall integrate and demonstrate the overall LTM network prototype at the Savannah River Site or other DOE site. Tests shall be performed to allow for evaluation of the functional performance of the LTM network and its major components. The Contractor shall conduct system integration and testing in accordance with the approved test plan.

Task 2.3 – Final Report

The Contractor shall prepare a draft final report on the technical progress of the project. This report shall follow guidelines set forth in the agreement and shall include discussion on topics including, but not limited to, results of any analyses, numerical simulations, and/or laboratory or field validations. The results shall be documented to allow validation. The report shall also include a discussion of other pertinent aspects of the project effort, including, but not limited to: description of work performed, product/method inputs and outputs, product/method operating conditions, product efficiency, product/method longevity, product/method maintenance, and discussion detailing steps necessary to develop the technology into a marketable product. After review and comment by the appropriate DOE representatives, the Contractor shall modify the report to become the Final Report on the project activities to date. The Contractor shall prepare an Integrated Technology Summary Report (ITSR) in consultation with the COR.

C. DELIVERABLES

The periodic, topical, and final reports shall be submitted in accordance with the attached "Reporting Requirements Checklist" and the instructions accompanying the checklist. In addition to the periodic, topical, and final reports, the Contractor shall provide the following:

1. Topical Report after completion of the Base Contract and Option 1
2. Final Report on completion of the contract
3. Test plan for Option 1
4. Written responses to comments made at Peer and Gate Reviews
5. ITSR
6. Integrated LTM network prototype

D. BRIEFINGS/TECHNICAL PRESENTATIONS

1. The Contractor shall prepare detailed briefings for presentation to the COR at Pittsburgh, PA or Morgantown, WV. Briefings shall be given by the Contractor to explain the plans, progress, and results of the technical effort. The first briefing shall be presented within 60 days after award. The Contractor shall present a briefing at least 45 days before completion of the

Base Contract and a final briefing at least 45 days before the completion of Option 1.

2. The Contractor shall provide and present a technical paper(s) at the DOE/NETL Annual Contractors Review Meeting to be held at a location to be determined by DOE.
3. The Contractor shall prepare detailed briefings for presentation at the annual SCFA Mid-Year Meeting generally held in Atlanta, GA (or other selected site that will be determined later). This briefing will present the progress made during the 12-month period and the status of the project.
4. The Contractor shall attend Peer and Gate Reviews and provide written response to comments made at that review.

5. Technical Progress

The general success criterion for the project is to develop and deploy a prototype LTM network in the field. Specific criteria, as presented in the project management plan, are listed below, accompanied by a discussion of progress achieved to date toward meeting each criterion.

5.1 Self-Cleaning Sensor Chamber

Criterion (1): Fabrication and successful laboratory demonstration of a sensor chamber that can be cleaned in situ using ultrasonic technology. *This criterion will be met if the cumulative degradation of the sensor response over several fouling and cleaning cycles remains within or asymptotically approaches a value not to exceed either five percent of the full-scale signal to noise ratio or twice the factory rated precision of the sensor.*

Laboratory Survivability Tests

The laboratory testing program began with a preliminary system assessment of the Orion Pentrode™ performance under sonic irradiance.

Several experiments with the Orion Combination ISFET electrode were conducted to develop an understanding of the relationship between sonication and analytical measurement performance. Three primary conditions have been studied. These conditions are: undisturbed (no sonication), intermittent sonication and continuous sonication. Intermittent sonication was experimentally defined as short (2-second) pulses separated by long (5-minute) intervals. Continuous sonication was experimentally defined as a long (5-minute) sonication event.

An important initial consideration was to determine what power levels the electrode could withstand before failure. The primary variables that affect the energy experienced at the electrode are sonication power from the power supply, geometry of the sonication horn, distance from the sonication probe to the electrode sensing surface, orientation of the sonication horn to the electrode sensing surface, and the fluid transferring the sonic energy. The criterion for failure was an inability to return measurements of pH, ORP, conductivity and temperature for a laboratory standard solution.

Numerous experiments were conducted with no apparent failure of the measurement electrode. The most aggressive conditions involved an experiment with the following parameters: sonication power supply at 100% (measured 52 Watts), sonication duration at 1.0 minute, sonication probe at 1.5 cm from electrode sensing surface, sonication probe diameter at 6.0 mm, sonication orientation head-on and, a sonication fluid of laboratory tap water.

A standard configuration was used for over 30 sonication events where no failure or degradation of the electrode system was observed. This configuration was as follows: sonication power supply at 50% (measured 22 Watts), sonication duration of 5.0 minutes, sonication probe at 1.5 cm from electrode sensing surface, sonication probe diameter at 6.0 mm, sonication orientation head on and sonication fluid laboratory tap water.

The analytical performance of the electrode was primarily studied with laboratory tap water composed of untreated well water. Under undisturbed conditions the electrode exhibited an initial time to equilibrium followed by longer-term stability. Values of pH for the electrode immersed in fresh test solution rose approximately 0.20 pH units with an equilibration time around 20 minutes. Conductivity values increased 20 μS/cm over 10 minutes. Electrode drift over 17 hours was observed at 8.57 to 8.51 (standard units) and 346.8 to 360.1 (μS/cm) for pH and conductivity, respectively.

Continuous power experiments were initially conducted to observe the potential failure of the electrode. These experiments also initiated a study of the measurement properties of the analytical system during and after a sonication event. In general terms, during a sonic event the measured pH of the test solution decreased on the order of 0.50 pH units while the conductivity exhibited a slight increase on the order of 10 to 20 μS/cm

The behavior of conductivity and pH are considerably different after completion of the sonication event. The conductivity exhibits a substantial increase to values 100 to 200 uS/cm greater than the original conductivity. This increase initiates after three to four minutes of stable measurements and then begins with a maximum rate 10 uS/cm per minute. The rate of increase then slows with the measured value finally stabilizing. In some experiments, the conductivity then began a slow decrease to an intermediate level. This behavior was not observed universally. Once the conductivity had stabilized it could be quickly returned to the initial, pre-sonication value by either manually stirring the solution with a stainless steel spatula or by applying a short pulse from the sonicator (2 seconds at 30% power). With either the manual or sonic stirring the conductivity would then continue to increase and could achieve values as high as the first post-sonication increase. The new increase could also be reduced to the original value by either manual or sonic stirring. pH values after sonication rapidly increased to values approaching pre-sonication conditions. Our interpretation of the observed phenomenon is that sonication produced bubbles via cavitation that remained on the sensor surface. These bubbles continued to slightly affect sensor performance until they were reabsorbed slowly into the solution or were dispersed via stirring.

We considered two approaches to maintaining electrode performance. One approach is to clean the electrode only after its performance has been degraded to a certain level; the other approach is to quasi-continuously clean the electrode so that its performance is maintained at all times. The first idea implies infrequent and perhaps intense cleaning regimen, while the second implies frequent and perhaps more gentle conditions.

To investigate the analytical behavior in the quasi-continuous case the electrode parameters were monitored in 30- to 60-second intervals, while the sonicator was pulsed for 2 seconds at 50% power in five-minute intervals. The duration of the experiments generally exceeded one hour. Conductivity and pH measurements under these conditions exhibited good long-term stability although data points close in time to sonication pulses were somewhat noisier.

We chose quasi-continuous sonication, similar to that described above, for the initial bio-fouling experiments as we anticipated that analytical performance would be best maintained under conditions in which the electrode/sensing chamber is prevented from fouling.

Oxidation Reduction Potential (ORP) measurements were examined under various experimental conditions and somewhat distinctly from pH and conductivity (primarily the result of the meter's data logging capability; where only two parameters can be recorded simultaneously). The electrode was calibrated with an electrode calibration solution obtained from Thermo Orion. The signal observed on the meter, $E_{h,}$ is referenced to the internal KCl (saturated) Ag/AgCl electrode where the value displayed is corrected to the Standard Hydrogen Electrode. An external reference solution of saturated quinhydrone exhibited a response within the expected range.

ORP measurements in laboratory tap water produced data that were noisy and difficult to interpret. One of the more striking effects was the difference in ORP depending on whether the sonication probe was in contact with the test solution. When in contact with the solution and connected to the power supply, large negative ORP changes were observed (200 mV). This behavior was not exhibited when the test solution was changed to either the primary or reference calibration standards. The reason for this behavior is that the tap water had very low buffering capacity for electron exchange, and was therefore a difficult solution in which to obtain meaningful ORP measurements. In other words, the tap water exhibited little or no oxidation or reduction potential, so the signal-to-noise ratio of the measurement in this solution was inherently low.

Laboratory Biofouling and Recovery Tests

Several tests of ultrasonic probe maintenance in an aggressively biofouling environment were completed. In each test, the outputs of three identical Orion pHuture multi-probes were recorded on a regular basis. Three laboratory prototype sensor housings of a single design were fabricated and integrated into a bioprocessing apparatus that exposed the sensor to an aggressive biofouling environment. We permanently emplaced two probes in the biofouling regime. One probe was installed in a sonicated flow-through chamber, and the other was installed in an unsonicated flow-through chamber. A third probe was only periodically inserted into the third flow-flow chamber to obtain reference measurements for evaluating the response of the other two probes. Water from a bioreactor passed continuously through the flow-through chambers, using a three-head peristaltic pump to assure all flow rates remained equal.

A photograph of the apparatus is depicted in Figure 1. The flow-through chambers and bioreactor are transparent to allow rapid visual confirmation of advanced biological growth. As the photograph shows, the water in the system appears black due to the high concentration of microorganisms.

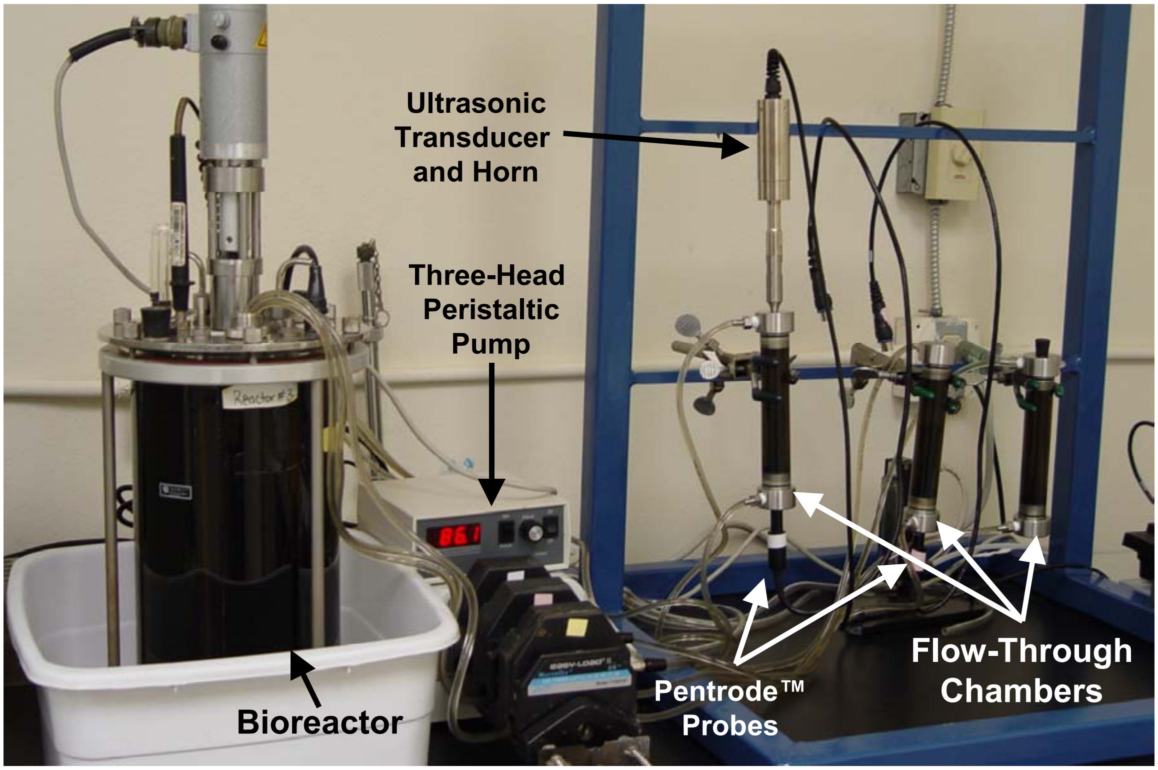

Figure 1. Photograph of laboratory testing apparatus for biofouling experiments.

The relative biological activity among tests was compared on the basis of heterotrophic plate counts (HPCs) performed on samples from this environment. Typically these samples yielded concentrations in the 10^7 count range.

In each experiment, the sonication regimen was distinctly different. Table 1 summarizes the controlled parameters of each test and the HPCs.

Table 1. Summary of ultrasonic cleaning tests in a biofouling environment.

Test	Start Date	Pulse Duration	Minimum Period Between Pulses	Power Level (% of 135W)	Heterotropic Plate Count
1	9 Dec 2002	2 sec	1 hr	50%	$>10^7$
2	18 Dec 2002	4 sec	24 hr	50%	$>10^7$
3	12 Feb 2003	2 sec	4 hr	50%	$>10^7$
4	18 Feb 2003	2 sec.	4 hr	25%	$>10^7$

In all tests to date, the pH response of both the control and test probes was found to be stable, while conductivity was conclusively degraded in the control probe, but maintained in the (sonicated) test probe. As anticipated, the fouling had no discernable effect on temperature, and ORP was found to be too sporadically variable (e.g., noisy) in this extreme environment to support comparisons. The tests have verified, that for conductivity, temperature, and pH, the subject probe type can be maintained against biofouling or periodically restored using long-term power levels that are easily achievable in a remote installation. Results with respect to ORP are inconclusive, but not negative.

Detailed conductivity results are provided in the figures below. In each figure, *relative conductivity* versus time is plotted for the duration of the test. *Relative conductivity* is a quantity we devised to facilitate comparison of the sonicated (test) and non-sonicated (control) probes by relating to the probe (reference) that was not subject to the fouling environment, but only inserted periodically. It is the ratio of the probe response to that of the reference probe. A *relative conductivity* of 1.0 would therefore indicate perfect agreement with the reference probe.

The vertical green lines in the figures indicate times when a sonication event was initiated (e.g., the probe was pulsed with ultrasonic energy). The symbols and lines in black represent the test probe (sonicated) and those in red represent the control probe (unsonicated).

During the test depicted in Figure 2, the test probe was sonicated for a duration of 2 seconds every hour at 50% power. As the plot shows, the control probe exhibited continual degradation over the first 80 hours while the test probe remained in consistently good agreement with the reference probe (e.g., within about 5%) over the duration of the test.

In the second test, the sonication schedule was altered, delivering to the test probe one-twelfth the ultrasonic energy it had received in the first test. As Figure 3 indicates, again the deviation between the control probe and the reference probe increased steadily. However, the deviation of the test probe varied as a function of the time following sonication. This pattern implied a periodic restorative effect of the sonication, which the third and fourth experiments were designed to characterize more closely. In Figures 4 and 5, there are three plots for two probes. As in the earlier figures, symbols and lines in red represent the control probe, but to highlight the effects of sonication, there are now two plots for the test probe; one in blue, signifying data acquired just prior to sonication events, and one in black, signifying data acquired just after sonication events.

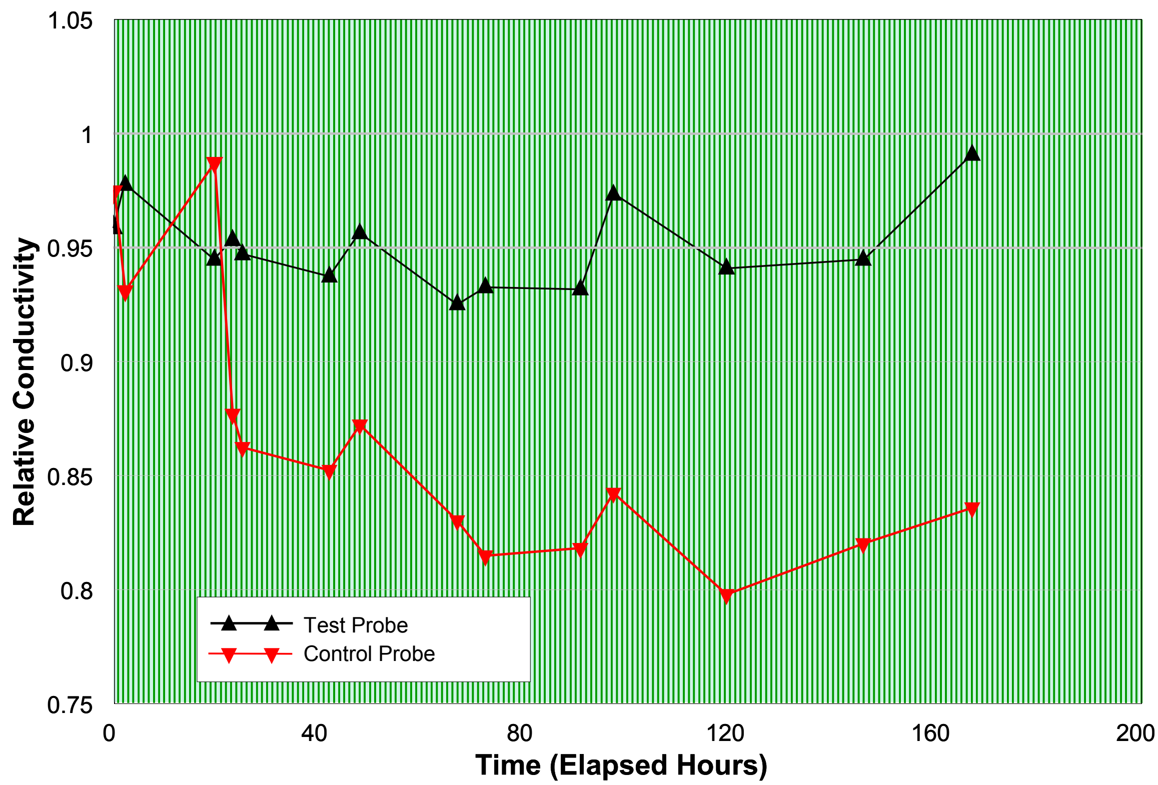

Figure 2. Results of biofouling test conducted beginning December 9, 2002.

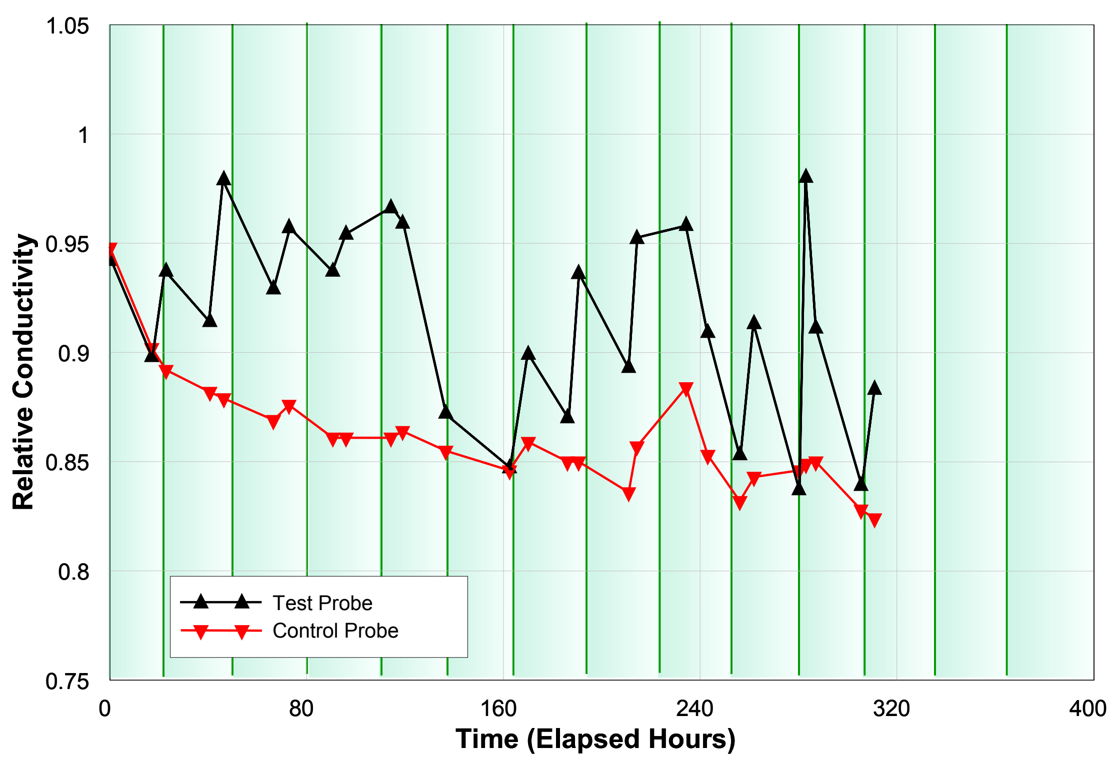

Figure 3. Results of biofouling test conducted beginning December 18, 2002.

Figure 4 and Figure 5 show the result of sonication three times per day with regard to the performance of the conductivity measurement. In both cases, a 4-second pulse was applied. The test depicted in Figure 4 was at 50% power, whereas that in Figure 5 was at 25% power. Comparing the figures, it is evident that in both cases, the sonication had a restorative effect on the probe performance, but the 50% power level was generally more effective than the 25% power level at maintaining probe function. Also notable is that the control probe degraded almost identically in both situations, indicating similar degrees of biofouling-induced stress. It appears likely from these results that a regimen of sonication every 4 hours, without overnight interruption, would have resulted in adequately maintained probe function in both instances. The performance of the test probe shown in Figure 4 satisfies the success criteria for this task, maintaining the response of the sonicated probe within 5% of the reference probe (which is within full scale).

A highly favorable result of these experiments is the low electrical power required to keep the sensors clean. The equivalent continuous power required to maintain probe function via sonication is less than 0.1 Watts, which is a small fraction of the capability of typical low-cost solar charging systems to provide. Therefore, no difficulty is anticipated in meeting the sonication power requirements for unattended long-term operation.

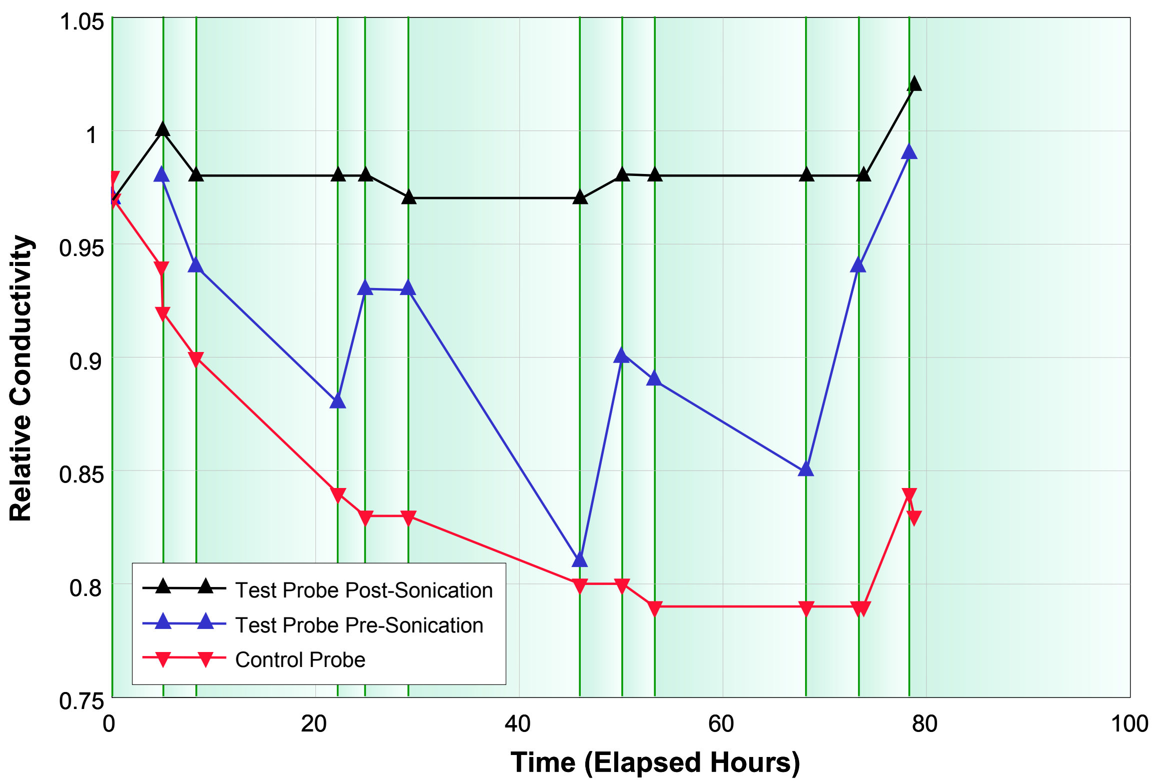

Figure 4. Results of biofouling test conducted beginning February 12, 2003.

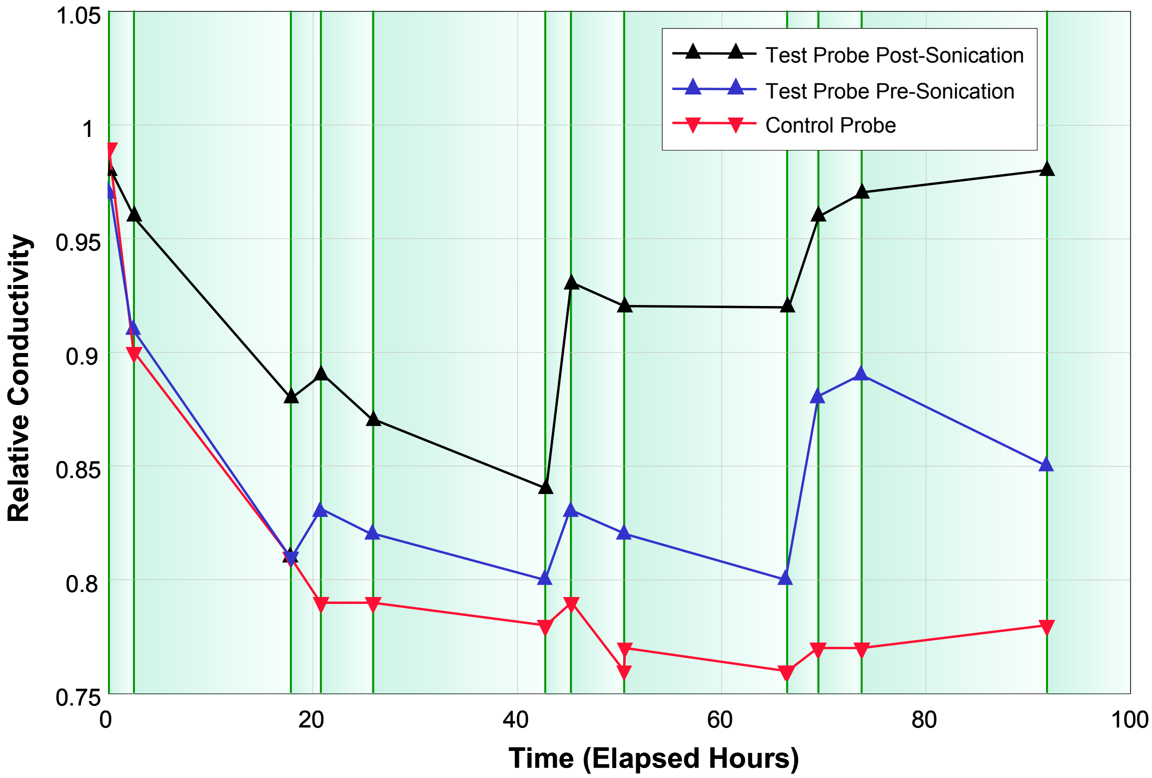

Figure 5. Results of biofouling test conducted beginning February 18, 2003.

Optical Fouling Experiments

The biofouling tests involving the Orion Pentrode™ were followed by a series of three tests to determine the effectiveness of ultrasonic irradiance in maintaining transparency through optical flats for optically-based sensors in dense bacterial solutions. For this test series, we mounted 12-mm diameter fused silica optical flats (see Figure 6) in stainless steel pedestals. The pedestals' shape factor matches that of the Pentrode™ so they are readily mountable in the laboratory test apparatus. Continuing with the same experimental approach as previously, one flat is allowed to foul unimpeded while the other is periodically sonicated. The flats will be inspected visually for the formation of bio-film that may interfere with optical sensing devices. In addition, they will be tested with an active source spectrophotometer, to evaluate their transmission of light over a wide range of wavelengths, including the ultraviolet (UV) range. UV light is important for many optical chemical measurements, but its impedance would not be apparent visually.

Figure 6. Photograph of optical flats, as used in optical biofouling tests.

In the first experiment, two optical flats were fouled in the standard innoculum for seven days. One optical flat served as the control while the other was sonicated twice daily for two seconds at 50% power. A 3.0mm diameter sonication horn was used. Visual inspection of the optical flats, after the fouling period, indicated nearly equal, heavy bacterial film growth on both flats. The laboratory noticed that the sound emanating from the test chamber was unusually muffled and did not indicate the normal degree of agitation observed during the sonication events of previous experiments. It is highly possible that cavitation, necessary for effect biofilm cleaning, did not occur.

The biofilm in this experiment was estimated to be 100-300 microns thick and was lightly attached to the optical flats. The biofilm was dense and would render the flats unsuitable for optical measurements. No actual transmission measurements were made due to the apparent lack of ultrasonic cleaning.

A second biofouling experiment was performed on two new optical flats. Given the dense growth of the preceding experiment, we reduced the exposure time to the bacterial solution to two days. The standard 6.0-mm horn was employed for sonication. Visual inspection of these flats indicated a slight difference between the sonicated and unsonicated flats. Unfortunately, the sonicated flat in this experiment was damaged during shipping and no precise optical measurement could be made to evaluate the effectiveness of sonication.

The final experiment was conducted with a two-day exposure period. The 6.0-mm sonication horn was utilized with sonication parameters as in the first experiment. Both a microscope objective lens and visual inspection of these flats indicated a difference in clarity between the control and sonicated flat. Optical absorbance was measured at 550 nm in a Spectronic Genesys spectrophotometer. The results are presented in Table 2.

Table 2. Optical Absorbance Results

Sample	Absorbance	Transmission
Blank (Air)	0.0000	1.000
Sonicated Flat	0.0330	0.925
Control Flat	0.0625	0.865

Absorbance measurements have been converted to transmission for discussion purposes. The transmission difference between the sonicated and control flat indicates at least partial cleaning by the applied ultrasonic irradiance. The difference between the blank and the sonicated flat is primarily due to surface reflectivity. This experiment shows good potential for ultrasonic cleaning of optical surfaces in dense bacterial environments.

Sensor Chamber Design

We designed a fieldable prototype sensor chamber that utilizes PVC for all parts in contact with the groundwater, except the piezoelectric horn, which must be made of stainless steel. PVC was selected for its record of acceptance by environmental regulators in subsurface monitoring applications (e.g., monitoring well material). In addition, it is inexpensive to acquire and behaves relatively will when machined.

A specialty vendor (Piezo Technologies, Inc., Indianapolis) was selected to provide the prototype down-hole piezoelectric ultrasonic transducers and matching power supply. Work was carefully coordinated between ARA and the transducer designers to ensure compatibility and proper interfacing of the components. The layout of the transducer assembly is shown in Figure 7.

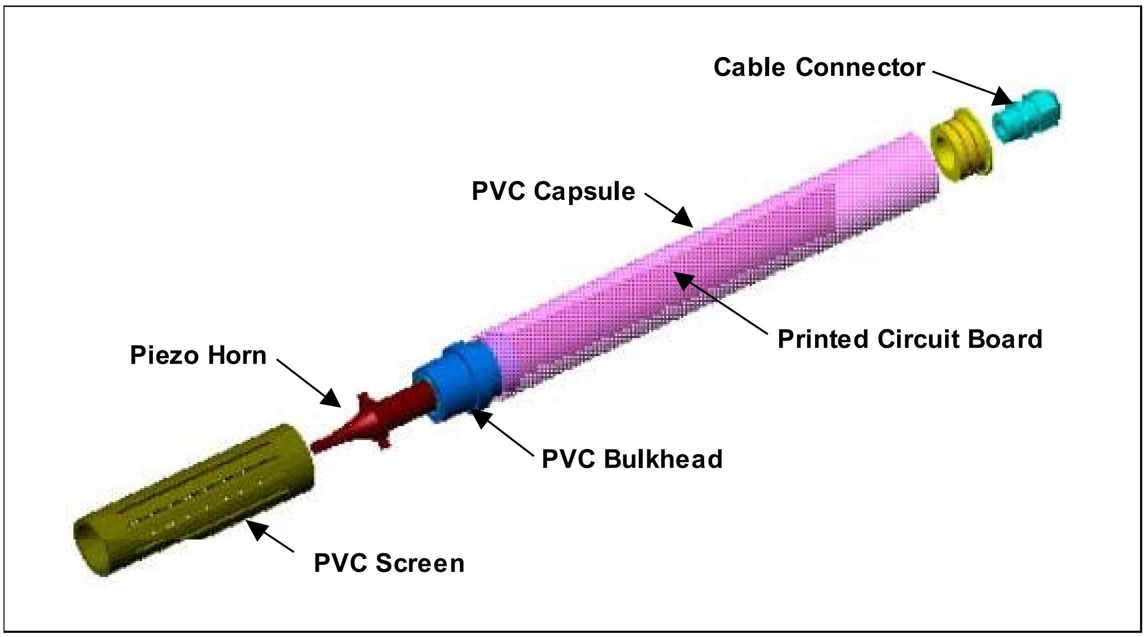

Figure 7. Ultrasonic transducer assembly.

The ultrasonic transducer assembly mates to sensor assembly shown in Figure 8. This assembly accommodates the multi-parameter water quality probe chosen for demonstrating the self-cleaning sensor chamber. The probe is controlled and its output recorded using a down-hole microcontroller and circuitry encapsulated in the lower end of the sensor chamber. This circuitry is connected to the printed circuit board (PCB) in the transducer assembly by a four-conductor ribbon cable carrying power, ground, and serial communications signals from above ground. At the transducer PCB, these four conductors are passed to the cable connector via four independent, passive traces. This cable also conveys DC power to the ultrasonic transducer assembly from the solar source at the surface. Sonication and measurement do not occur simultaneously, so crosstalk or interference along this cable is not an issue.

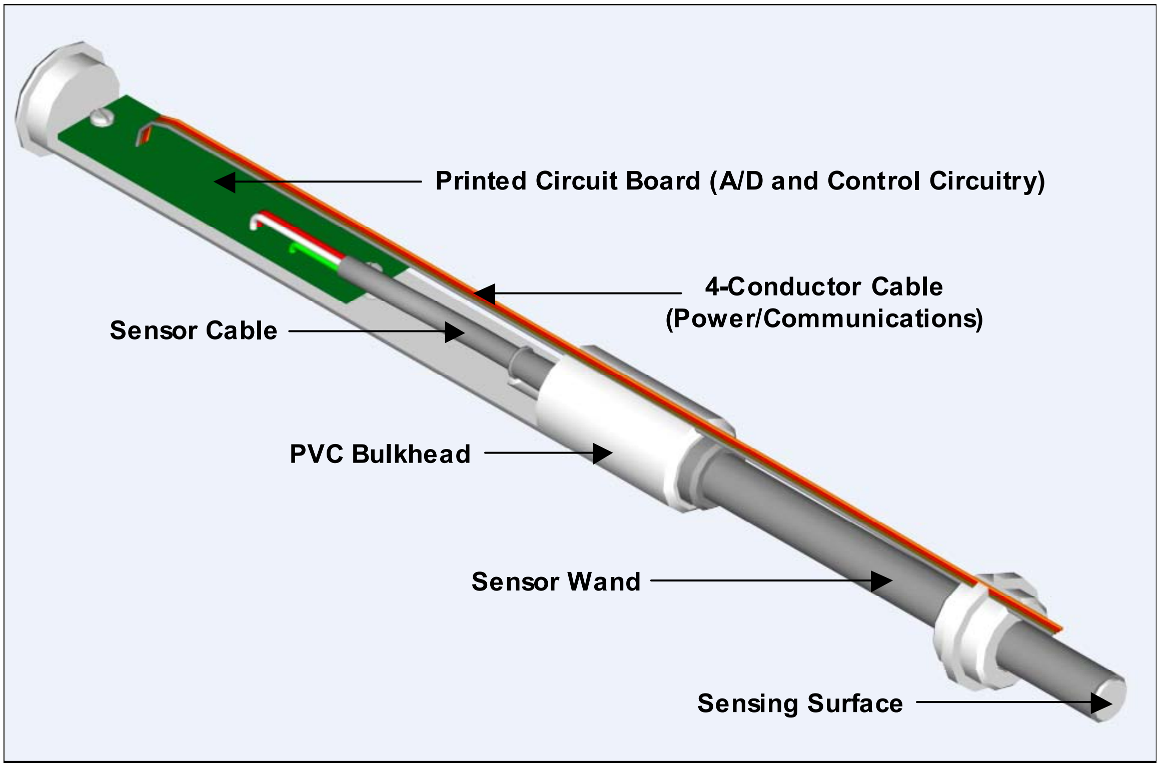

Figure 8. Sensor assembly.

5.2 Deployment Systems

Criterion (2) Fabrication and successful field deployment of Wireline CPT and inflatable packer-based chassis for subsurface emplacement of sensor packages. *To meet this criterion, the emplantable Wireline CPT sensor package must survive a deployment to refusal depth (e.g., to the maximum push capacity of the CPT rig), and the inflatable packer-based chassis must create a competent seal within an existing well casing, as verified by tracer testing.*

In-Well Deployment

To date, substantial progress has been made toward deploying self-cleaning sensor packages within an existing well casing. Due to the difficulty of maintaining fluid pressure within an inflatable packer for durations up to several years, we have opted to utilize a mechanical sealing approach for this deployment method. The system isolates a section of well screen by mechanically compressing a pliable, ring-shaped seal in the longitudinal direction such that it dilates against the well body in the lateral direction. The packer is constructed principally of PVC. Several seal materials will be available to choose from to ensure contaminant compatibility. Learned Technologies of North Chatham, MA assisted us on this task, designing a variation of their Well-Off™ (patent pending) well sampling system that accommodates our sensor chamber. A photograph of the mechanical well packer appears in Figure 9. During emplacement, a pneumatically controlled installation tool holds the collar wedge back towards the flange, relieving pressure on the gasket. In this state, the gasket is relaxed and the packer slides freely within the well. Upon removal of the installation tool, the compression spring pushes the collar wedge against the gasket, forcing a seal against the interior of the monitoring well.

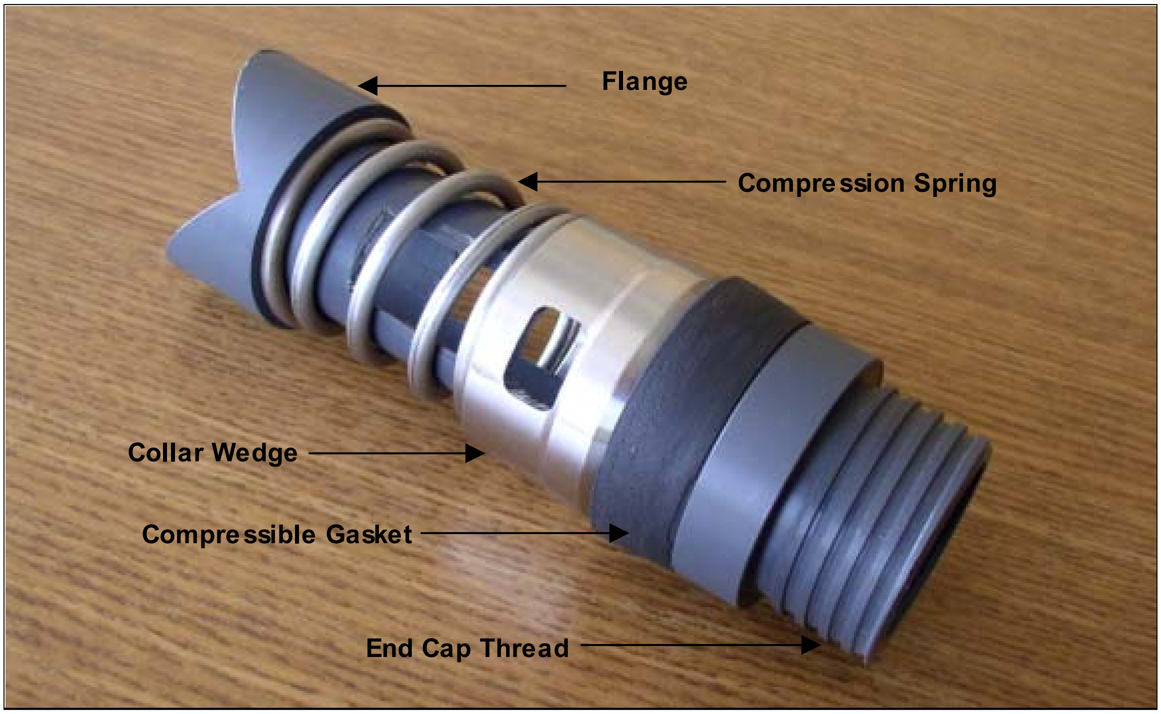

Figure 9. Photograph of mechanical well packer.

Two such packers are used to isolate a section of well and hold the sensor chamber in place. An end cap can be threaded onto the lower packer in the well, to support the sensor chamber and keep water out from screened regions below.

Emplantable WirelineCPT Deployment

Design of the WirelineCPT deployment tool is complete. As part of this effort, we investigated numerous possible materials for creating an effective porous filter or membrane between the sensor chamber and the geologic formation. The most effective filtering options all require pressure gradients greater then what would be available under ambient groundwater conditions to drive flux through the filter. We finally selected slotted PVC well screen for the job of allowing water, but not sediment, to permeate the sensor chamber. PVC is advantageous due to its widespread regulatory acceptance for groundwater monitoring applications. We have designed an implantation tool that utilizes a removable shield to protect the slotted filter during penetration. A new double-acting Wireline CPT lock mechanism keeps a hollow, blank CPT tip in place while the CPT rod penetrates to the desired sensor deployment depth. The locking mechanism also provides structural strength and rigidity during penetration. Once at the desired depth, the locking mechanism is removed, leaving the rods free to be withdrawn from the embedded hollow tip. Before withdrawing the rods, the sensor chamber is lowered down through the embedded rod string, coming to rest partially inside the hollow CPT tip and partially protruding above it. The rods are then withdrawn, exposing the PVC well screen, sensors, and ultrasonic horn to the native groundwater, and all that remains in the ground are the blank CPT tip, the PVC sensor housing, and the cable to the surface.

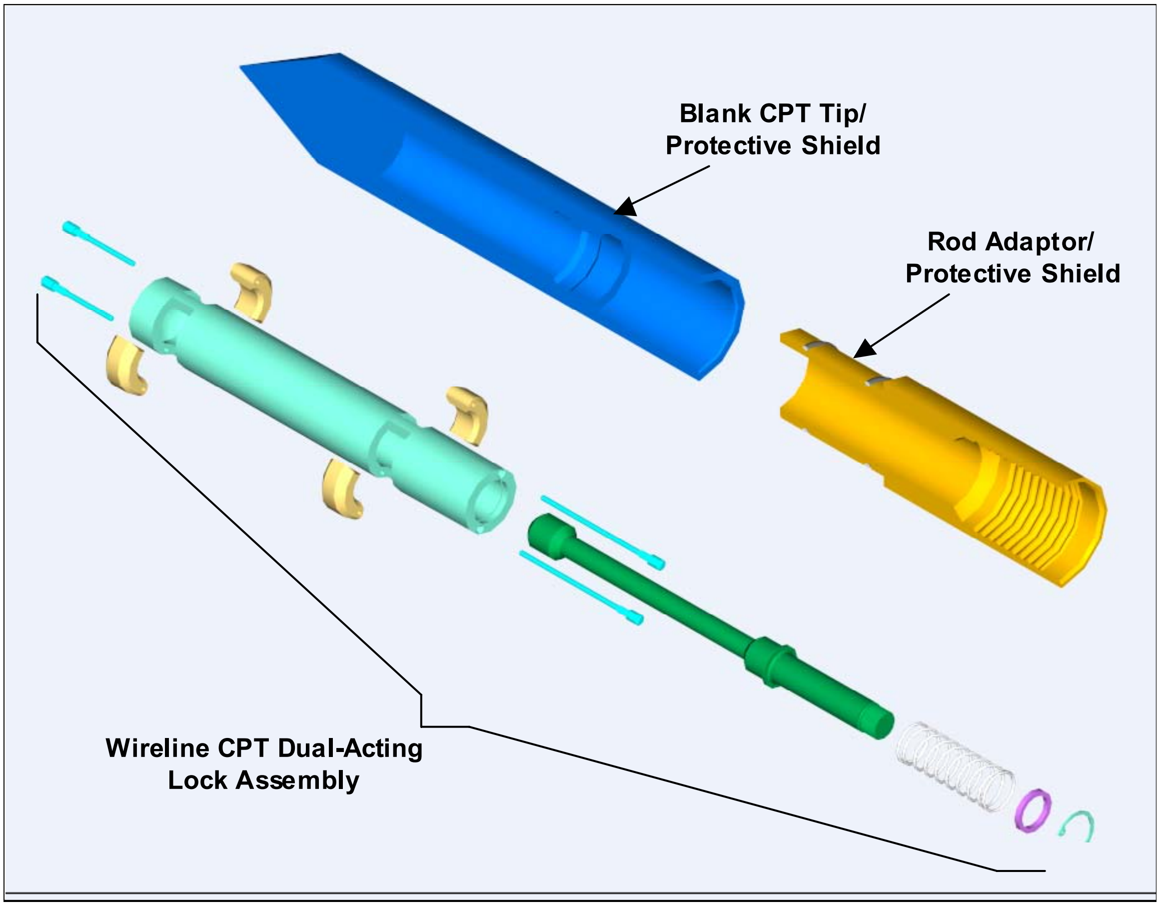

Figure 10. WirelineCPT tool for implanting subsurface sensors.

5.3 Field Networking

Criterion (3): Assembly and successful demonstration of a wireless, solar powered transceiver system for the prototype LTM network. *This success criterion will be measured by the ability of the system to communicate reliably over distances of greater than two miles line-of-sight and to maintain a back-up battery charge with no discernable decrease in battery voltage over the duration of the field demonstration.*

Hardware Improvements Protocol

Success criterion (3) is at least partially dependent on the outcome of a contract option that has not been funded. However, progress on this task has, to date, included:

1. Re-design of our RS-232 to RS-485 serial protocol converters for long-range, multi-drop, cable-based field communications;
2. Fabrication, bench testing, and long-term field testing of the re-designed protocol converters;

3. Identification of two point-to-point radio telemetry systems, and extensive testing of one; and
4. Discussions with an OEM supplier of low-cost, low-bandwidth data telemetry using global pager networking.

Under the first achievement, we developed a new electronics design that offers several advantages over, and expands the applicability of, the previous design. The new design allows the use of multiple protocols on the master data collection device, including RS-232, TTL, and inverted TTL logic. In addition, the hardware handshaking pins are exploited in the new design to allow hardware-controlled cycling of power to the interfaced instrumentation (for energy management and remote re-boot capability). The support of TTL as the master protocol now allows measurements from emplantable sensors to be logged on industry standard data logging equipment. The new converters were bench tested in December 2001, and two prototypes were installed in a long-term field monitoring test in January of 2002. In this test, the converters are enabling communication between ARA "smart" sensors and Campbell Scientific CR10X data loggers. The CR10X is a de facto industry standard. The prototype devices have operated continuously without failure for over two years, collecting data once per hour from seven devices each. This long-term field testing continues as of this writing.

Wireless Communication

In addition to enabling more reliable cable-based field communications, the new protocol converters will easily interface to commercial off-the-shelf radio telemetry equipment. We have thoroughly tested the operation of one radio telemetry option, and begun investigation of another. The first option, Freewave™, is a spread spectrum serial communications system. Its operating characteristics are listed in Table 3. We have tested the Freewave™ system up to two miles line-of sight with moderate data rate communications in real-time data acquisition and control applications, and found that it meets all the performance requirements of the success criteria for the wireless field communications. Freewave™ also includes a sleep mode to conserve power during non-active periods between polling of the sensor network, and is operable in a point-to-multi-point mode, so a single WebDACS acquisition agent can acquire wireless data from multiple sensors at a field site.

Table 3. Operating characteristics of FreeWave radio telemetry system.

Radio link:	
Frequency Range	902-928 MHz
Method	Frequency hopping spread spectrum
Hopping Patterns	15 per band, 105 total, user selectable
Hopping Channels	50 to 112, user selectable
Hopping bands	7, user selectable
Range, Line-of-sight	60 miles
Occupied Bandwidth	230 KHz
Modulation	GFSK, 144 ~ 188 Kbps
RF Connector	MCX female
System Gain	140 dB
Transmitter:	
Output Power	100 mW to 1 Watt (+30 dBm)
Receiver:	
Sensitivity	-106 dBm for 10^{-6} BER -108 dBm for 10^{-4} BER
Selectivity	20 dB at fc ± 115 KHz 60 dB at fc ± 145 KHz
Data Transmission:	
Error Detection	32 bit CRC, retransmit on error
Data Encryption	Substitution, dynamic key
Link Throughput**	115.2 Kbps standard speed, 38.4 Kbps low speed
** Uncompressed , measured assuming 75% frequency availability	
Data Interface:	
Protocol	Either RS-232/RS-422/RS485, or TTL,1200 Baud to 115.2 KBaud, DCE
Connector	10-pin PCB male header
Diagnostics Interface:	
Connector	Separate 3-pin PCB header
Power Requirements:	
Voltage	6 to 30 Vdc
Current	mA at 12 Vdc
Transmit	500
Receive	60
Idle	16
Sleep	5
Environment and Mechanical:	
Operating temperature	-40 °C to +75 °C
Dimensions	73 L x 62 W x 15 H (mm) 2.86 L x 2.44 W x 0.59 H (in)
Weight	70 g 2.5 oz

Although the FreeWave option has been shown to satisfy the success criteria, even longer-range point-to-multi-point wireless communications appear achievable using a digital packet transmission (e.g., Ethernet protocol) system. At the close of the project, we were still investigating a cost-effective packet radio system for this application. The packet transmission paradigm has several advantages over straight serial communication, including better fault tolerance and superior security capability, as well as benefits for internet connectivity to the WebDACS.

Solar Power

Solar power supplies, voltage regulators, and rechargeable batteries appropriate to the application are readily available commercially from a number of vendors. We have experience on other projects with solar-powered, unattended data logging, and we have identified several suitable solar power systems for this application. We utilized COTS solar power equipment in our possession to conduct field testing of wireless remote data collection by WebDACS from existing ARA smart sensors. Battery charge was maintained and no problems were noted over a period of approximately three months. As well, this long-term demonstration of solar-powered, wireless operation continues. Full demonstration of the success criterion associated with the solar systems relies on the field demonstration planned under the contract option (not yet executed).

5.4 Web-Based Data Acquisition

Criterion (4): Successful communication and data acquisition from a network of five or more microprocessor-controlled sensors via the World Wide Web. *The criterion will be met if the server, under the direction of a user, can successfully transmit every command in the control protocol to each node in the network and receive a valid response via the web and wireless link.*

All success criteria of WebDACS have been met. During development, the following tasks were accomplished:

- Redefined the application architecture to consist of 3-tiers: a MySQL data storage tier, a PHP application management tier (server side), and a Flash MX based client user interface tier;
- Completed PHP base classes for WebDACS application management tier;
- Added user/group permissions tables to SQL data structure for WebDACS;
- Defined SQL data structure for calibration management, acquisition agent session management, and virtual sensor implementation;
- Completed programming of software base classes in PHP to support server-side functionality for WebDACS user interface;
- Re-designed and programmed the server-side data acquisition agent process broker, to include security functions, and client-server synchronization management; and
- Programmed the Flash MX client user interface for reporting and data download.

- Re-programmed the data acquisition agent in Visual Basic 6, to run on Windows-based desktop, notebook, or tablet PCs, and include management of modem communications with sensors and server synchronization bookkeeping; and
- Tested components and tiers separately and together.

Object oriented design and programming practices were employed throughout the effort, and all code modules underwent rigorous testing, both alone and in conjunction with other modules. The results of benchmarking tests indicate in excess of three million sensors measurements per day can be posted to the central data server via the World Wide Web. These results are scale well with available server capacity, which is currently limited to an inexpensive shared server platform.

A live demonstration site for WebDACS is on-line and operating at http://webdacs.ara.com/. Visitors may log in and view data collected wirelessly from solar-powered soil moisture, resistivity, and temperature sensors deployed at ARA's New England Division facilities using the username "guest" and password "guest." A video introduction to using WebDACS is also available upon request.

5.5 Field Demonstration

Criterion (5): Successful installation, integration, and extended operation of a prototype LTM network at a DOE site (SRS).

This is a criterion of success intended exclusively for the demonstration contract option. This success criterion will not be demonstrated under the base contract.

6. Conclusions

Several of the success criteria of the base contract either have been demonstrated or will have been demonstrated by the end of the contract period. Accomplishments to date are detailed below:

- The ability to maintain and/or restore the function of a solid state multi-parameter water quality probe via periodic irradiation with ultrasonic energy has been demonstrated in the laboratory under extreme biofouling conditions.
- The ultrasonic energy required to maintain probe function has been observed to be well within the capacity of inexpensive unattended solar panels to provide, and there appear to be no practical barriers to applying the ultrasonic probe maintenance technique to sensors emplanted *in situ*.
- A self-cleaning sensor chamber and ultrasonic transducer assembly have been designed.
- A method of reliably securing a self-cleaning sensor chamber to the inside surface of an existing monitoring well has been developed and is in production.
- A method of emplanting self-cleaning sensor chambers directly in the subsurface using WirelineCPT has been developed. No devices have yet been fabricated for testing.

- The ability to cache sensor data locally and securely transfer data from a portable computer to a central database server via a full-time or on-demand internet connection has been established and tested at acquisition rates exceeding one million measurements per day.
- The ability to securely access, display, and download data logged in the WebDACS via a standard web browser has been demonstrated along with the ability of the user to control the time period and combination of sensor for which data are reported.
- The WebDACS web-based data acquisition and control system is currently operable and fully functional. It has the ability to collect data from existing emplantable sensors such as the soil moisture and resistivity, cache the data on a field computer, periodically upload the data via the internet to a central data server, and report data graphically or download it via any standard, Flash-enabled web browser. The system employs user/password protection and 128-bit encrypted communications to ensure data integrity. The ability to support additional sensor protocols is rapidly being added.

The project's accomplishments to date demonstrate significant progress toward meeting several of technological requirements for long-term site monitoring required under Long-Term Stewardship, supporting critical elements of both the Environmental Management and Legacy Management missions. We strongly recommend continued support of the project through the integration and demonstration phase.