Design and Construction of In-situ Moisture Sensors For a Solid Waste Landfill

Philip T. McCreanor and Debra R. Reinhart

Mercer University / University of Central Florida

Abstract

Undergraduate students at the Mercer University School of Engineering (MUSE) were employed to work on a cooperative project with graduate students at the University of Central Florida (UCF) to design a moisture sensor which could survive in the landfill environment and produce reliable data. Students from the mechanical, industrial, biomedical, and environmental engineering programs at MUSE worked under the close supervision of a professor in the environmental engineering program at MUSE to design and construct prototype sensors. Graduate students at UCF evaluated these sensors. As the evaluation process was performed, recommendations were made and the sensor design was modified.

Once the sensor design was finalized, undergraduate engineering students at MUSE were hired to construct sensors for installation in a bioreactor landfill in Florida. Approximately 180 sensors were produced over a six-week time period. Roughly two dozen students were employed by the project during this time period. In addition to physically constructing the sensors, students helped to define the assembly process, design templates and tools to help with the assembly process, and modify the basic sensor design for ease of assembly without compromising function.

This paper will present the theory behind the sensor design, a chronology of the sensor design process, and the sensor assembly process.

Finally, working with and motivating undergraduate students is much more challenging than working with graduate students. Lessons learned from this project and suggestions for managing undergraduate researchers will be presented.

1.0 Introduction

Since the authorization of RCRA subtitle-D in 1986, municipal solid waste (MSW) landfills have been designed and operated with the intent of minimizing the amount of precipitation contacting the waste mass and thereby producing leachate. MSW landfills have also been required to have a leachate collection system that allows for the collection and removal of leachate which has precipitated through the waste mass. While these regulatory constraints have been successful at minimizing the impact of landfills on groundwater they may not be the best long-term landfill management plan. Microorganisms cannot operate in a dry environment and therefore the waste mass will not degrade. Moreover, the containment structures that isolate the waste mass from the environment will eventually deteriorate, moisture may then enter the waste mass, and the landfill may become biologically active and a variety of gas and liquid phase chemicals may be produced and/or mobilized.

Bioreactor landfills have been proposed as a better long-term landfill management plan. In this operational paradigm, leachate collected from the landfill is reintroduced into the waste mass in a controlled fashion with the intent of controlling and enhancing the degradation of the waste mass into an inert material. In some cases, supplemental liquids in addition to the leachate are added to the waste mass to further enhance degradation. This technology has been successfully demonstrated in lab and pilot scale studies however, full-scale implementation has been challenging. Monitoring the impact and routing of the leachate reintroduction system in full-scale landfills has been particularly difficult.

Undergraduate students at the Mercer University School of Engineering (MUSE) were employed to work on a cooperative project with graduate students at the University of Central Florida (UCF) to design a moisture sensor which could survive in the landfill environment and produce reliable data. Students from the mechanical, industrial, biomedical, and environmental engineering programs at MUSE worked under the close supervision of a professor in the environmental engineering program at MUSE to design and construct prototype sensors. Graduate students at UCF evaluated these sensors. As the evaluation process was performed, recommendations were made and the sensor design was modified.

Once the sensor design was finalized, undergraduate engineering students at MUSE were hired to construct sensors for installation in a bioreactor landfill in Florida. Approximately 180 sensors were produced over a six-week time period. Roughly two dozen students were employed by the project during this time period. In addition to physically constructing the sensors, students helped to define the assembly process, design templates and tools to help with the assembly process, and modify the basic sensor design for ease of assembly without compromising function.

This paper will present the theory behind the sensor design, a chronology of the sensor design process, and the sensor assembly process.

Finally, working with and motivating undergraduate students is much more challenging than working with graduate students. Lessons learned from this project and suggestions for managing undergraduate researchers will be presented.

2.0 Theory

Three moisture-sensing technologies were found to be compatible with the monitoring requirements for and operation of a bioreactor landfill. These technologies were Time Domain Reflectometry (TDR), Time Domain Transmission (TDT), and resistance measurement sensors. TDR and TDT sensors are based on troubleshooting techniques developed by the co-axial cable industry. In a TDR measurement, a rapid rise voltage spike is applied to the sensor. The measurement instrumentation then analyzes the reflection of the voltage wave. The shape and characteristics of the reflected voltage wave can be used to determine a variety of material properties including moisture content. In a TDT measurement, a rapid rise voltage spike is applied to one end of the sensor. The measurement instrumentation then evaluates the time required for the voltage spike to arrive at the other end of the sensor. This arrival time may be correlated with the moisture content of the medium the sensor has been placed in. Resistance sensors measure moisture based on the resistance between two electrodes. A completely dry soil has a very high resistance to electron flow. As the soil is moistened, water in the pore spaces provides a conductive medium for electron flow and resistance decreases. Calibration curves for determining moisture content from resistance measurements can be developed. TDR and TDT sensors are much more costly on a per sensor basis than resistance sensors and require a special measurement and excitation device and co-axial cable multiplexers. Therefore, resistance sensors were pursued for use in this project.

The use of resistance sensors was pioneered by the irrigation industry. Sensors consisting of two concentric electrodes embedded in a block of gypsum were used to monitor moisture content in the root-zone to determine irrigation requirements. Soil water typically has a very low-conductance. Therefore, a gypsum matrix was used to provide a consistent liquid conductivity. These sensors have been used in landfills but were found to have the following shortcomings:

- The sensor was fairly fragile and susceptible to damage during handling and installation.
- In low pH, high moisture movement scenarios, the gypsum matrix dissolved completely.
- Once wet, the sensors seldom dried out even in cases where the surrounding area was known to be dry.

The Yolo County Controlled Landfill Demonstration Project[1] attempted to mitigate some of these issues by using a resistance sensor consisting of a slotted PVC-pipe filled with pea-gravel. Two bolts were place in the gravel to act as the electrodes. While these sensors addressed several of the shortcomings of the gypsum sensors, new problems were encountered. The pea-gravel was much more permeable than the waste matrix so it was impossible to see the movement of moisture in the landfill unless the sensor was being monitored while a moisture front was passing through the sensor or the sensor was in a completely saturated waste matrix.

3.0 Sensor Design Evolution

This project focused on identifying a sensor matrix that eliminated the shortcomings of the gypsum sensor while still providing reliable, high-quality moisture data. Two parameters were evaluated, the grain size of the sensing matrix and the impact of liquid conductivity on the sensor readings. The sensors constructed for evaluation purposes utilized a 6-in. long, 2-in. inside diameter (ID) slotted PVC-pipe for the bodies. The bottom and top of the body were sealed using 2-in. diameter, 0.5-in. thick PVC-discs. The wiring connections were made adjacent to the top disc. The wiring connections were then packed with electrician's duct-seal and a 2-in. PVC cap was glued to the top of the sensor. The sensors were constructed at Mercer University and then sent to the University of Central Florida for testing and evaluation

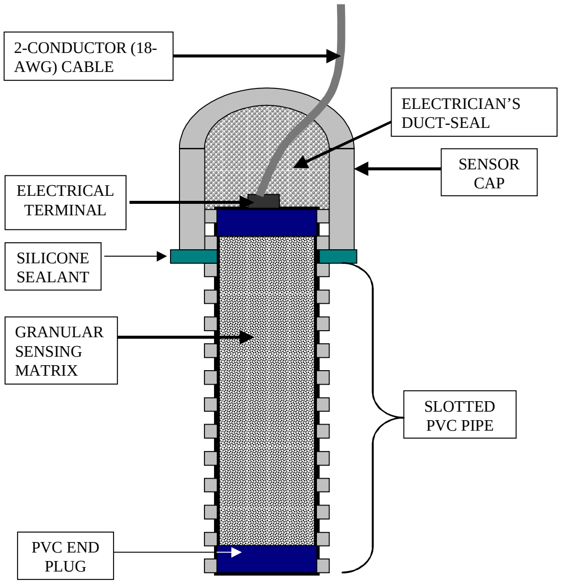

Figure 1. Sensor configuration used for evaluation of sensing matrix.

The first sensor design utilized a pea-gravel with particle sizes ranging from ~0.125 in. to ~0.375 in. for the sensing matrix. Two vertical electrodes constructed from #6 threaded stainless steel (SS) rods were used to make the resistance measurement. These sensors had the same problems encountered by the Yolo County group. The sensor essentially provided only two readings, completely wet and completely dry.

The second sensor design utilized filter-gravel as the sensing matrix with two vertical electrodes as in the first design. Media with effective particle size ranges of 0.063 to 0.188 in. and 0.063 to 0.125 in. were evaluated. While these materials performed better than the pea-gravel, they still drained very quickly and were obviously much more permeable than the waste matrix would be.

The third sensor design utilized filter-sand as the sensing matrix. Media with effective particle size ranges of 0.022 to 0.026 in., 0.024 to 0.032 in., 0.032 to 0.047 in., and 0.039 to 0.055 in. were evaluated. The slot-sizes in the PVC-pipe required to retain these particles were so small that it would have been impossible for the sensing matrix to contact the waste materials. Therefore, the electrode configuration was adapted to account for this. Market grade stainless-steel mesh was used as the outer electrode. The mesh size was selected based on the particle size used for the sensing matrix, Table 1. The center electrode was constructed from #6 threaded SS rod. A

Table 1. Filter sand sizes and mesh size used for outer electrode.

Filter sand effective size range (in.)	Mesh number	Mesh opening size (in.)
0.022 - 0.026	30	0.0203
0.024 - 0.032	30	0.0203
0.032 - 0.047	24	0.0277
0.039 - 0.055	18	0.0386

slot width of 0.20 in. was used in the sensor bodies. These sensors were found to perform much better than the previous two sensor designs. The sensors drained fairly rapidly from a saturated condition to a field capacity fractional saturation of approximately 0.4. Air-drying of the sensor from field capacity to completely dry then required up to several days depending on the filter sand used and the drying conditions employed. The filter sand with an effective size of 0.022 to 0.026 in. was determined to be the most promising media. This sensor was then evaluated using liquids with conductivities of 6.6, 13.9, and 22.7 mS/cm. Results from these experiments are shown in Figure 2. Leachate at the landfill these sensors were to be installed in had a conductivity of approximately 13.9 mS/cm. These results suggest that shifts in the conductivity will not greatly impact the sensor behavior. The slight hump in the 22.7 mS/cm curve was most likely due to an experimental error since the curve is similar to the 6.6 and 13.9 mS/cm curves at all other times.

Following these lab tests, the sensors were installed in a variety of different media (potting soil, compost, and shredded paper) with known moisture contents to evaluate the sensor behavior in-situ. These tests were rather disappointing. It was found that it took the sensors an extremely long time to reach equilibrium with the adjacent media. In some cases, the sensor reading never changed. It was theorized that the SS mesh was acting as a barrier to the movement of liquid between the media of interest and granular sensing matrix.

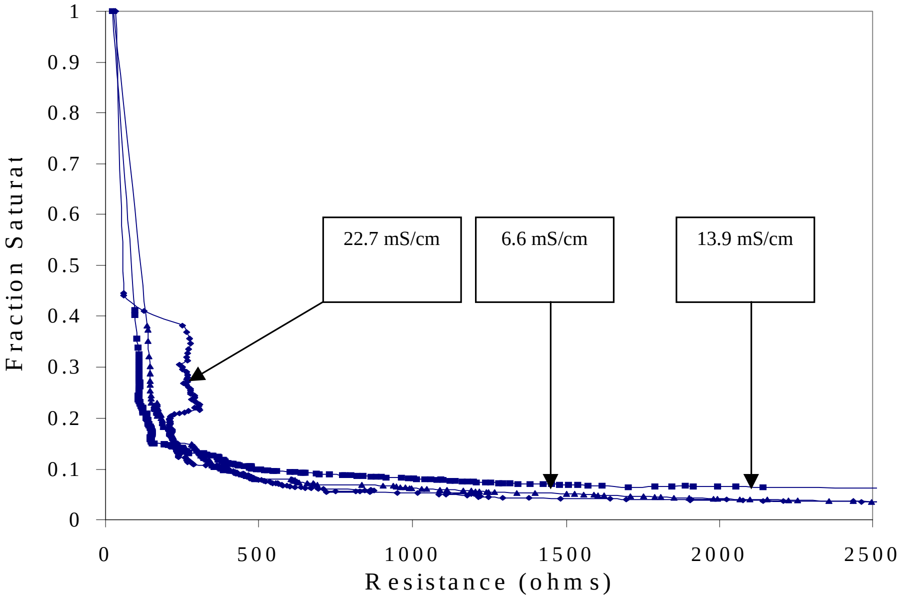

Figure 2. Resistance measured as function of saturation and liquid conductivity.

The fourth sensor design focused on addressing the moisture movement problem. While the 0.022 to 0.026 in. filter sand was a good sensing matrix, something had to be done to link the sensing matrix to the waste matrix. Liquid had to be exchanged between the sensing matrix and the waste matrix such that when the waste was wetter than the sensor, liquid would move into the sensor and when the sensor was wetter than the waste, liquid would move out of the sensor. Three fiberglass wicks ~8 in. in length were installed laterally through the sensor at four different levels in the sensor. When evaluated in the lab, these sensors were found to dry much more quickly than the previous sensor designs. When installed in a media of known moisture content, the sensors were found to equilibrate with the adjacent media fairly quickly. Scenarios where the sensor was installed both wetter and drier than the adjacent media were investigated. The sensor performed well in both of these scenarios.

Once the sensing matrix had been finalized, the sensor was re-configured to simplify installation of the sensor, allow for the measurement of temperature via a type-T thermocouple, and provide a tube for obtaining gas samples.

4.0 Sensor Construction

The moisture sensors were constructed using the following procedure.

- A 7.5-in. long, 2-in. diameter length of slotted (0.2-in slot width) schedule-40 PVC of pipe was cut.
- A 6-in. by 6.4-in. rectangle of #30 market-grade SS mesh was cut. A short piece of 18-AWG copper wire was soldered onto the long edge of the mesh near the middle.
- A 2-in. diameter circle of #30 market-grade SS mesh was cut.
- A 0.375-in. by 0.375-in. square of #30 market-grade SS mesh was cut.
- A 7.75-in. piece of #6 SS threaded rod was cut.
- Two 0.75-in. thick by 2-in. diameter PVC discs were cut for the top and bottom of the sensor.
- In the bottom plug a 0.125-in. diameter hole was centered and drilled 0.25 in. deep. Four, fully penetrating, 0.25-in. diameter holes were drilled between the edge of the disk and the centered 0.125-in. diameter hole. These 0.25-diameter holes were evenly spaced around the centered 0.125-in. diameter hole.
- In the top plug, a 0.125-in. diameter, fully penetrating hole was centered and drilled. A 0.25 in. hole was drilled close to the edge of the plug and tapped for a ¼” NPT fitting. A 0.25-in. NPT fitting for quick connect to a 0.375 in. outside diameter (OD) tube was glued and then threaded into the plug. A small indentation was filed in one of the edges of the top plug to allow access for the mesh connection wire. The 0.375-in. by 0.375-in. square of mesh was glued into the bottom of the 0.25-in. NPT fitting to retain the sand.
- A 0.25-in. diameter hole was drilled through the nose of a 2-in. diameter well point.
- The circle of SS mesh was glued onto the bottom plug on the opposite side of the partially penetrating 1/8” hole.
- The bottom plug was glued into one end of the slotted PVC-pipe such that the SS mesh was to the outside.
- The well tip was glued into the same end as the bottom plug such that the SS mesh was sandwiched between the plug and the well tip. The holes in the well point and bottom plug allowed the sand matrix to drain. The 2-in. circle of SS mesh was used to retain the sand.
- The bottom plug and well tip were clamped together and allowed to set.
- The 6-in. by 6.4-in. rectangle of SS mesh was inserted into the slotted pipe with the 6-in edge running parallel to the pipe axis and with the copper wire at the top.

- Three 8”-long fiberglass wicks were threaded through the SS mesh at four different levels. A total of twelve wicks were used in each sensor. Tatting needles were used to thread the wicks through the mesh.
- One end of the #6 SS rod was dipped in PVC cement and then lightly tapped into the hole in the bottom plug.
- The rod was centered and the sensor then filled with sand to a height just exceeding that of the mesh.
- The upper plug was glued and inserted into the top of the sensor with the quick connect tube fitting to the outside of the sensor body. The sensor was clamped lengthwise and allowed to set.
- The wire to the SS mesh and # 6 SS rod (sensor electrodes) were fitted with crimp style electrical connectors.

Once the moisture sensor had been constructed, the type-T thermocouple, gas sampling tube, and moisture sensor cable could be attached and the electrical connections sealed. This was done using the following procedure.

- Appropriate lengths of thermocouple, 0.375in.-OD sampling tube, and shielded, 2-conductor (18-AWG) cable were cut. Lengths were determined based on the depth at which the specific sensor was to be installed in the landfill.
- One end of the thermocouple was stripped, the exposed wires were twisted together to form a mechanical connection, the twist was soldered, and then sealed with an epoxy.
- One end of the shielded, 2-conductor cable was stripped so that ~0.25 in. of each conductor was exposed.
- The thermocouple, sampling tube, and 2-conductor cable were taped together and bundled to simplify handling.
- A groove approximately 0.063-in. deep, 0.125-in. wide, and 2-in. long was routed lengthwise on the outside of the sensor body. This slot was located at the top of the sensor body.
- A fully penetrating slot 0.625-in. wide and 1.5-in. long was milled lengthwise into a standard 2-in. PVC pipe deep socket coupling. The slot started 0.625 in. from the top edge of the coupling. Sharp corners were removed from the upper edge of the slot using a round file.
- The stripped ends of the thermocouple and 2-conductor cable and the sampling tube were fed through the slot in the deep socket coupling.
- The sampling tube was inserted into the quick connect fitting and the fitting was tightened.
- One conductor from the 2-conductor cable was connected to the inner electrode and the other conductor was connected to the outer electrode of the moisture sensor via the crimp connectors.
- The thermocouple was placed in the slot along the outside of the sensor body.
- Glue was applied to the upper 1 in. of the sensor body and the inner edge of the deep socket coupling. The coupling was slid onto the sensor body. Care was taken to assure that the tip of the thermocouple was exposed. The glue was then allowed to set.

- A 2.375-in. diameter, 0.25-in thick PVC disc was cut. A 1-in. forstner bit was used to create a slot at the edge of the disk.
- Electrician's duct seal was packed around the electrical connections. Enough duct seal was used to fill slightly higher than the lip at the midpoint of the deep socket coupling.
- The 2.375-in diameter PVC disc was glued into the socket and pressed firmly onto the lip at the center of the coupling . The thermocouple, sampling tube, and cable were routed through the slot in the disk and this slot was aligned with the slot in the deep socket coupling.
- Chico A3® sealant was poured into the wiring termination area to prevent liquids from entering the wiring connection area.
- A 0.25-in. thick layer of DryLok® FastPlug® was poured into the deep socket coupling to further protect the electrical connections.

A completed sensor is shown in Figure 3.

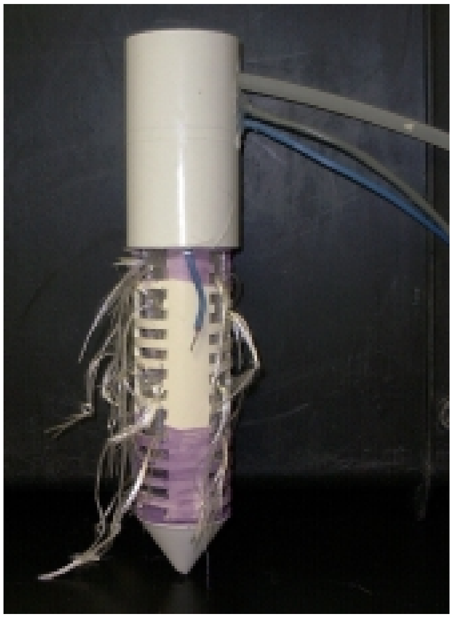

Figure 3. Finished sensor for monitoring moisture content and temperature and obtaining a gas sample.

5.0 Managing Undergraduate Students

Undergraduate students are much different than graduate students from a variety of perspectives. They carry a larger course load than graduate students and therefore have a much higher class room time obligation than graduate students. Typically, an undergraduate student will be in a classroom setting 18+ hours per week as compared to ~9 hours per week for a graduate student. Thus, they have significantly fewer hours to dedicate to working on a research project during the normal business day. Furthermore, undergraduate students typically require a significant amount of supervision particularly when they first become involved with a project. Unless the supervising researcher plans to be on call at all hours, they should be mindful of when the student will be available to work on the project. Requiring the students to have specified working hours also helps with this issue.

The graduation of an undergraduate student is generally not directly linked to successful completion of the research project at hand. Therefore, undergraduate students do not see breaks and holidays as an opportunity to work on a research project. They are unlikely to stay for breaks if they have the ability to travel. Spring break occurred during the major sensor construction effort. The majority of the students that had been working on the project prior to spring break had been doing so at least in part to have travelling money. An almost entirely new work force had to be hired and trained in order to continue sensor construction over the break.

Senior engineering students are the most attractive to hire for true undergraduate research positions. They generally have a large enough knowledge base to contribute to the project with a minimum of supervision. However, senior engineering students generally have a fairly intense course load that typically includes several design projects. They may not have enough time available to work productively on a research project. Identifying promising sophomores and grooming them to work extensively on the project during their junior year and then having them work in an advisory capacity in their senior year is an approach that has been found to work well at MUSE.

Two fairly unique student types were encountered while working on this project. The first was the student that works on project to the point of neglecting their required scholastic activities. This type of student can put a professor in a fairly awkward situation with other faculty members. Students working on a research project should be informed that their classroom studies are to be their priority. The second type of student completed all of the paper work required to work on the project, never showed up to work, and (fortunately) never submitted any time cards. Six to eight students of this type were encountered during this project. If a researcher needs a large work force to complete a project, they should hire 25% more students than they actually anticipate needing.

6.0 Future Work

Observations made during the sensor development process and manufacture of the sensors suggest that the following items should be considered for further investigation.

- The impact of electrode configuration and spacing on sensor performance should be studied.
- The hydraulic properties of the fiberglass wicks should be investigated.
- The concentric electrode configuration is compatible with TDR technologies. The sensor should be evaluated for operation in a TDR mode.
- The manufacturing process should be streamlined and evaluated for quality control. In particular, problems were encountered with the sand settling after sensor assembly.

Acknowledgements

The authors would like to acknowledge the Florida Bioreactor Landfill Demonstration Project (www.bioreactor.org) and Ricci Bros. Sand Co., Inc. (www.riccisand.com). The Florida Bioreactor Landfill Demonstration Project provided funding for this project. Ricci Bros. Sand Co., Inc. provided the filter gravel and filter sand used in the development and construction of the sensors.

References

1 – Augenstein, Don, Yazdani, Ramin, Moore, Rick, Dahl, Karina, "Yolo County Controlled Landfill Demonstration Project," Solid Waste Technologies, May/June 1998.

Biographical Information

PHILIP T. MCCREANOR
Philip T. McCreanor is an Assistant Professor in the Environmental Engineering Program at Mercer University in Macon, GA. Dr. McCreanor possesses a Ph.D. in Environmental Engineering and a M.S. in Environmental Science from the University of Central Florida and a B.S. in Mechanical Engineering from the University of Miami. His research interests include bioreactor landfills, remote sensing, instrumentation, and unsaturated groundwater flow.

DEBRA R. REINHART
Dr. Reinhart is Associate Dean for the College of Engineering and a Professor with the Univeristy of Central Florida's Civil and Environmental Engineering Department. She has over eighteen years in the environmental engineering field and has been conducting research and teaching in the solid waste management field for the last ten years. She has authored over 50 publications and presentations.