Development of an In-Situ Decommissioning Sensor Network Test Bed for Structural Condition Monitoring - 12156

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ABSTRACT

The Savannah River National Laboratory (SRNL) has established an *In Situ* Decommissioning (ISD) Sensor Network Test Bed, a unique, small scale, configurable environment, for the assessment of prospective sensors on actual ISD system material, at minimal cost. The Department of Energy (DOE) is presently implementing permanent entombment of contaminated, large nuclear structures via ISD. The ISD end state consists of a grout-filled concrete civil structure within the concrete frame of the original building. Validation of ISD system performance models and verification of actual system conditions can be achieved through the development a system of sensors to monitor the materials and condition of the structure. The ISD Sensor Network Test Bed has been designed and deployed to addresses the DOE-Environmental Management Technology Need to develop a remote monitoring system to determine and verify ISD system performance. Commercial off-the-shelf sensors have been installed on concrete blocks taken from walls of the P Reactor Building at the Savannah River Site. Deployment of this low-cost structural monitoring system provides hands-on experience with sensor networks. The initial sensor system consists of groutable thermistors for temperature and moisture monitoring, strain gauges for crack growth monitoring, tiltmeters for settlement monitoring, and a communication system for data collection. Baseline data and lessons learned from system design and installation and initial field testing will be utilized for future ISD sensor network development and deployment.

INTRODUCTION

The Department of Energy (DOE) is presently implementing permanent entombment of contaminated, large nuclear structures via *in situ* decommissioning (ISD) [1]. The ISD end state consists of a grout-filled concrete civil structure within the concrete frame of the original building. Validation of ISD system performance models and verification of actual system conditions can be achieved through the development a system of sensors to monitor the materials and condition of an ISD structure.

The Savannah River National Laboratory (SRNL) has established an ISD Sensor Network Test Bed, a unique, small scale, configurable environment, for the assessment of prospective sensors on actual ISD system material, at minimal cost. To evaluate the feasibility and utility of remote sensors to provide verification of ISD system conditions and performance characteristics, an ISD Sensor Network Test Bed has been designed and deployed. The test bed addresses the DOE-EM Technology Need to develop a remote monitoring system to determine and verify ISD system performance [2].

Designing a remote monitoring program for ISD structures requires an understanding of the likely changes over time in and around the ISD facility. Appropriate sensors must be deployed to detect those changes and to provide monitored data of sufficient type and quality to allow the DOE to assure its stakeholders that the ISD structure is performing in accordance with the protracted lifetime prediction of the concrete-degradation model, meaning the building is structurally sound and the entombed contaminants are not being released to the environment [3].

Remote sensor monitoring systems can also play critical roles not only in aging structures, but also in newly designed systems, for both civil structures that may have less stringent safety demands, as well as nuclear structures that typically must meet stringent safety performance requirements against both natural phenomena hazards and other events. Sensors for materials' conditions, and/or environmental conditions that impact material performance can provide a monitoring system that supports the demonstration of functional performance and structural integrity of a structure, system, or component (SSC) with time. Thus, the incorporation of sensors to provide real time, non-invasive monitoring for various structural and operating parameters can greatly improve reliability and safety envelope of the SSCs.

The ISD Sensor Network Test Bed at SRNL has been designed to provide an understanding of signal responses and subsequent data interpretation along with an on-site opportunity to investigate commercial off-the-shelf (COTS) and new technology sensors for ISD applications [4]. Concrete blocks obtained from the P-Reactor facility slated for ISD are being used to test COTS structural monitoring sensors. In an environment similar to conditions for the ISD structure, sensors, multiplexers, a corresponding data logger, and a power supply system have been assembled at the concrete blocks to monitor strain (cracks), temperature, and local tilt. Data recording and transmission to a data logger and then to a server have been optimized for data processing. The server and an output dashboard have been configured for storage and easy reporting of retrieved data.

Lessons learned from the SRNL ISD Sensor Network Test Bed have been incorporated into plans that were developed for a meso-scale concrete/grout test bed at Florida International University (FIU). Information and data obtained from the SRNL test-bed work and FIU meso-scale work will steer the selection of future instruments for ISD structures and will also provide monitoring protocols for evaluating the structural health of aging concrete in nuclear facilities and in containment structures such as concrete vaults and pads.

BACKGROUND

Concrete blocks (six 2 to 5 ton blocks) removed from the outer wall of the P Reactor Building have been transferred to SRNL, and concrete cores have been sectioned from the blocks for characterization of the materials and the effects of aging [5].

As a structure degrades, changes occur to the materials that make up the structure. If known in advance, these changes can be tracked, measured, and mitigated in order to prevent the release of radionuclide contaminants into the surrounding environment. Above-grade concrete degrades by a variety of mechanisms, including carbonation, rebar corrosion, freeze/thaw, growth of vegetation, and alkali-silica reactions. These mechanisms lead to volumetric change induced cracking and water ingress into the concrete structure. The end result is ultimately structural collapse, ponding of water, leaching, and infiltration of contaminants into the environment. Chemical analyses on samples taken along the longitudinal axes of the P-Reactor cores show that there is a 25 millimeter carbonation layer (i.e., no portlandite) present in the interior wall of the reactor building and a negligible carbonation layer in the exterior wall [5]. Once the carbonation layer reaches the rebar, which is approximately 50-75 millimeters into the concrete wall, the steel is susceptible to corrosion. Based on the growth rate of the carbonation layer and a numerical model for degradation, it is predicted that the carbonation layer will not reach the steel reinforcement for at least another 100 years. Structural insult due to reinforcement bar corrosion and concrete spallation is expected after that time, and a loss of ISD structural capacity may result with concomitant impact on overall ISD performance [5].

Detection of structural changes prior to collapse can be achieved by measuring and tracking a variety of sensor arrays. For example, temperature change is used to determine moisture ingress, and strain and tilt sensors are used to track movements of the structure due to cracking and uneven settlement. The use of these arrays in tandem can alert stewardship entities of degradation changes in initial stages when cost effective mitigation options may still be assessed and implemented. However, the long-term stability and behavior of these arrays should be demonstrated and characterized prior to implementation in a structure intended for ISD.

The above characterization and the initial data collected from the sensors installed on the P Reactor blocks constitute the baseline materials condition of the P Reactor ISD external concrete structure. Continued monitoring of the P Reactor Building blocks will enable evaluation of the effects of aging on the P Reactor ISD structure. The collected data will support validation of the material degradation model and the condition assessment of the ISD structure with time.

OBJECTIVES

The purpose of the Sensor Network Test Bed at SRNL is to expose sensors to conditions expected in ISD structures in order to identify potential issues with sensor installation, instrument functionality and response, data logging, and data communication.

The key objectives for deployment of sensors in the test bed for this part of the program include:

- Understand potential issues with installation
- Identify sensor network power needs as supplied by a solar panel
- Coordinate the communication of data between sensors, logger and server
- Develop software for easy data collecting and viewing of collected data
- Test functionality and responsiveness of sensors through collection of data sets
- Begin long-term data collection to understand baseline conditions and help with data interpretation
- Design the test bed such that it is versatile and expandable with the ability to add new sensors.

The sensors chosen for installation on the P Reactor blocks are readily available COTS sensors used for structural monitoring of bridges and buildings. Data collected from the temperature, tilt, and strain gauge sensors will be analyzed to determine the effects of diurnal and seasonal cycles on the mechanical performance of the concrete block, and the results will be used to forecast long-term material-of-construction performance of the blocks. The test bed can also accommodate additional sensors to provide validation of the materials degradation model and verification of the actual condition of the system materials.

The design and operational knowledge gained through installation and testing of the equipment will be used to develop and demonstrate installation and communication protocols prior to installation of sensors into the FIU meso-scale test bed and remaining reactor buildings at SRS.

SENSOR DESCRIPTIONS

Three types of COTS sensors from RocTest Inc. are currently being tested on this Sensor Network Test Bed: temperature sensors, biaxial tiltmeters, and surface-mount vibrating wire strain gauges. All of these sensors are hardwired to a multiplexer and require a data logger for data collection and storage before retrieval.

The RocTest groutable TH-T temperature sensors (type T temperature measurement probe in PVC) with IRC-1A cable, monitor temperature in the concrete blocks using a 3 kΩ chip thermistor. The thermistor is encapsulated and sealed into PVC cylindrical housing with two lead wires connected to the multiplexer from which data is transmitted to the data logger. The cylindrical PVC housing is grouted or epoxyed into a monolith and the sensor measures a change in resistance, which is related to a change in temperature. The temperature sensor measures from -50 to 150 degrees Celsius, with a resolution of 0.1 degrees Celcius.

In the present application, the temperature sensors are used to determine near-surface concrete temperature as an environmental parameter for concrete degradation prediction. Temperature sensors can also be used to detect moisture migration through microfractures in the concrete blocks, because as fluids saturate the concrete, a measurable temperature difference can be detected. An embedded sensor can produce temperature profiles and gradients of the grout during the pour, and that information is helpful to deduce moisture content and void spaces that might form in the grout during the pour.

The SM-5A vibrating wire strain gauges, groutable anchors, with IRC-41A cable are composed of two end pieces joined by a stainless steel wire that is encased in a protective tube. An electromagnet is located at the center of the tube to measure the change of the steel wire resonant frequency as exterior forces are applied to the gauge. Strain gauge range is 3000 µstrains with an adjustable wire tension, and a wire resolution of 1 µstrains. The operating temperature range is -50 to 150 degrees Celsius. A 3 kOhm thermistor is integrated for temperature measurements. Strain gauges are anchored with grout or bolts to concrete or steel on either side of a crack or construction joint to monitor expansion. Strain gauges are intended for long-term strain change measurements on steel structures as well as concrete or rock surfaces mounted or embedded in the surface.

The Tuff Tilt 420, 4-20mA biaxial tiltmeter, mounted with 6-conductor cables consists of a gravity-referenced electrolytic tilt transducer. The angular range is +/- 3 degrees, with a resolution of 0.0006 degrees and repeatability of 0.001 degrees.

The strain gauges and biaxial tiltmeters can be used to monitor the expansion of cracks in the concrete blocks and differential settlement. These sensors have the potential to monitor the ISD facility roof and superstructure to measure stress/strain and deterioration from normal aging and external influences and tilt induced by loading the structure with thousands of cubic yards of grout.

Sensor Installation

Two concrete blocks removed from the outer wall of the P-Reactor Building were used for the Sensor Network Test Bed. One block measures approximately 2 meters length x 1 meter width x 1 meter height and the other measures approximately 1 meter length x 1 meter width x 1 meter height. These blocks are located outside on a concrete pad along with an 8-20 aluminum frame which houses the multiplexers, data logger and solar panel controller. An adjustable solar panel was attached to the top of the frame to provide power to the sensors. The solar panel was installed because once ISD activities are completed, power to facilities will be terminated and an independent power supply will be required for the sensor network. Sensor cables from the blocks were threaded back through the frame structure to the multiplexers, which were connected in parallel to the data logger. Long and short length cables were installed to monitor signal attenuation that could occur with longer cables. It was recognized that long cable lengths will be needed at the reactor buildings because many areas to be monitored will be tens of feet below grade and hundreds of feet away from the multiplexers and data loggers that will be placed on the exterior wall of the reactor building.

Four temperature sensors were installed on the concrete blocks. Two 3 meter sensors and one 91 meter sensor was installed into preexisting holes while one 3 meter sensor was placed on the frame to record the air temperature, near the surface. Two of the sensors were cemented into pre-existing holes using Commercial Grade Quikrete exterior use anchoring cement and one was epoxyed with Quikrete Bonding Adhesive. Both the epoxy and cement were used to evaluate the best method to hold and anchor the sensors in place while ensuring reliable sensor response.

Five vibrating wire strain gauges were mounted or placed on the blocks. Mounting blocks were set onto a spacer bar to provide required spacing, and then set screws were tightened to the anchor blocks. Once the mounting blocks were cemented in place, the strain gauge was positioned correctly and tightened down with a clamp. Three 3 meter sensors cables and one 46 meter sensor cable was attached to the blocks. All of the strain gauges were placed across visible cracks on the surface and it is speculated that these cracks were created when the blocks were removed from its existing structure. One 1.5 meter sensor cable was placed on top of the block and is a “No Strain” or reference gauge. This gauge is not and should not be affected by external loads or forces exerted to the blocks. The “No Strain” gauge is at the same temperature as the blocks thus, any variation in the No Strain gauge will be due to temperature and can be used as comparison to the other tensioned sensors.

Two biaxial tiltmeters were epoxyed to the surface of the concrete blocks parallel to the ground for correct sensor orientation with respect to the gravitational field. A 9 meter cabled tiltmeter and a 91 meter cabled tiltmeter were attached.

Solar Panel

Sensor power is provided by a Sun-Saver-6 Photovoltaic Controller attached to a 50W Kyocera solar panel that charges a 12V battery. Wire connections from the solar panel to the controller to the battery and to the CR1000 data logger were straight forward. The sensor system is powered by the charged battery and needs a minimum of 9V to run the system. A completely charged battery was estimated to power the sensor system for approximately 48 days, with its current configuration and an hourly scan rate. A backup battery can be attached to the system to minimize the probability of missing data collection due to a malfunction of the solar/battery charge system. Loss of battery power will not result in the loss of data stored to the logger, as it is stored on an internal memory card.

Communication

The sensors deployed in the Sensor Network Test Bed were wired to three multiplexer units, two of which allowed a maximum of 16 separate sensors and the other allowed a maximum of 8 sensors to be connected. The three multiplexer units are connected in parallel to a CR1000 logger, giving a total of 40 sensor connections at current capacity. The system is expandable to a maximum of 255 sensors. The data logger uses the NL115 Ethernet and CompactFlash module, which enables the use of an Ethernet port for remote connectivity and allows up to a 2GB CompactFlash memory card to be connected for data storage. The NL115 module allowed for access via the ethernet port, and the logger itself had a serial port used for local data retrieval.

Data acquired from the Sensor Network Test Bed has to be manually retrieved from the system and is not automatically transferred from the logger to the server. Remote data retrieval will be a necessity once the system is deployed into ISD structures. However, any wireless device must meet SRS standards, have an approved business plan and appropriate security protocols before being implemented.

Dashboard

The dashboard design displays the data retrieved from the sensors into a format that can easily be read by users. SRNL developed a custom ‘dashboard’ which was generated at regular intervals and superimposed the most recent data readings over pictures of the sensor locations. In applying the dashboard to the test bed, users can attribute data values with the physical location of the sensors on the concrete blocks.

Figure 1. Prototype of the dashboard which can be used to display user specified data

Figure 1 displays a typical dashboard design which can be user defined. Users can query any of the sensors and view hourly, daily, weekly and monthly plots. Currently the sensor system does not automatically transfer data to the network server, but are manually retrieved. Once the data are retrieved, however, an automatic process parses the data and inserts it into the database and users are notified that new data are available to view. After automatic data transfer is established, a red light/green light display can be programmed to alert the user to any threshold conditions that may be occurring, and an email or text page can be programmed to notify personnel of alerts. This dashboard is portable and can be transferred to other test bed systems and future ISD buildings with minimal reconfiguration.

SENSOR FUNCTIONALITY

The sensors were wired and set-up according to vendor installations instructions. Tests were performed to verify sensor functionality. After installation, data collection was limited to battery charge, the logger internal temperature sensor, and the temperature sensors. Troubleshooting of the multiplexers, the tiltmeters and the strain sensors occurred over several months. Data from the concrete blocks is collected every 5 minutes but will be changed to hourly once enough data have been collected to determine representative baseline trends. This baseline data will help to understand sensor measurements and anomaly occurrences.

Temperature Sensors

Figure 2, exported from the dashboard, shows the 4 temperature sensors plotted for a period of over a week. The red and blue curves, THT1 and THT2, correspond to sensors on the front side (facing west) of the first block, trend each other, as expected. These sensors are cemented and epoxyed, respectively, about 50 millimeters in holes that are approximately 75 millimeter deep and 25 millimeters wide. THT3 is the control sensor attached to the frame (green curve), and is directly exposed to the sun and unshielded from the daily weather conditions. This sensor appears noisy because it is faster to respond to temperature fluctuations relative to the sensors insulated by the cement and epoxy. The purple curve, THT4, is the temperature sensor grouted 75 to 100 millimeters inside a 100 millimeter diameter hole on the back of Block A. This sensor was facing east so along with the THT3 sensor, it sees a temperature increase first. The difference in maximum temperature may be attributed to the sensor being grouted further inside a larger hole, being partially shaded throughout the day, or void spaces introduced during sensor placement. Confirmation of void space could be confirmed by NDE techniques such as ground-penetrating radar. Once baseline has been collected, the information relayed from the temperature sensors will be used to determine if it is possible to detect any water ingress.

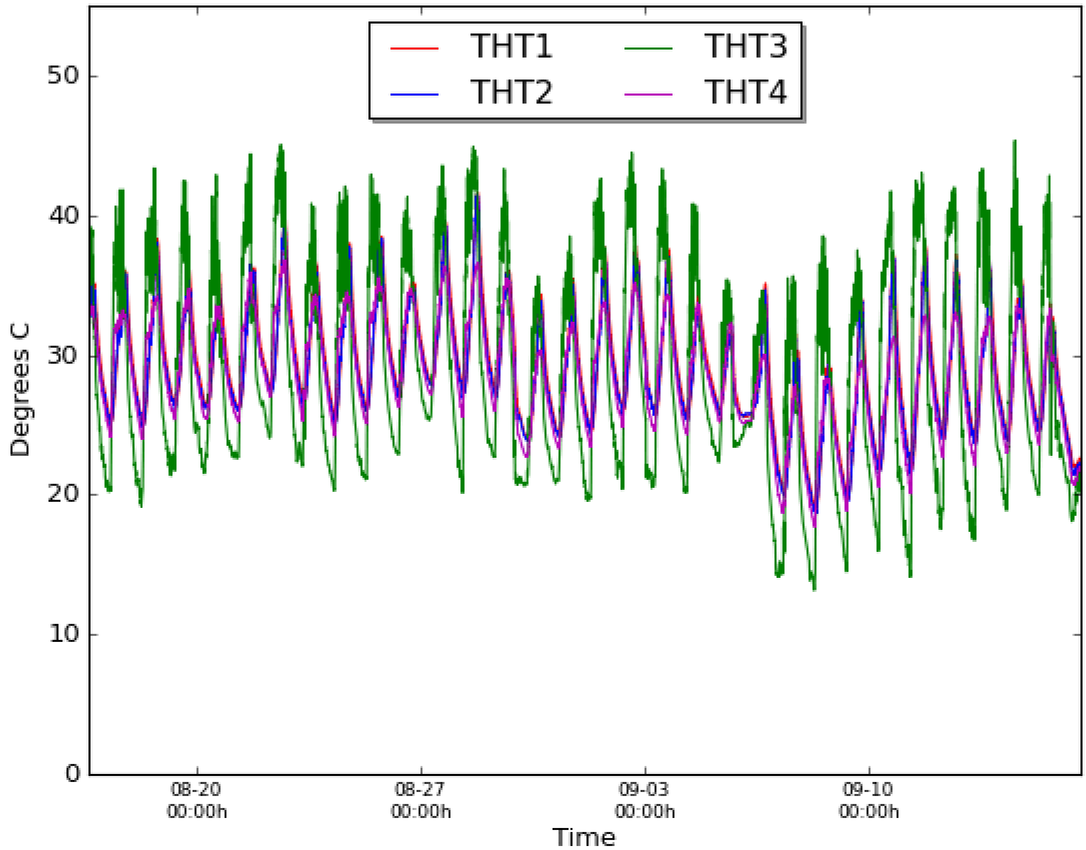

Figure 2. The diurnal cycles of the 4 temperature sensors (THT1 – 4) for a period of about a week

Temperature data were also recorded at the data logger, using a sensor internal to the CR1000. (Additionally, temperature measurements are also made by the vibrating wire and tiltmeter sensors, which can be used to verify the various sensors' functionality.) For comparison, data collected at SRNL at a local weather tower during the same time period were compared to the data retrieved from the data logger. Trending for the data logger temperature sensor and weather tower data were the same, verifying the logger temperature operation.

Strain Gauges

Typical strain gauge readings for a period of two months are plotted in Figure 3, exported from the dashboard. The reporting units of measurement, linear units or microstrains (µstrain), are calculated from the vibrating wire resonant frequency converted using a gauge factor. Offset in the graph results from variations in individual gauge tension. Because tension is induced by tightening a set screw, achieving initial identical strain readings on all sensors is difficult, and an offset results. All of the sensors were tensioned to the working range, according to vendor specifications.

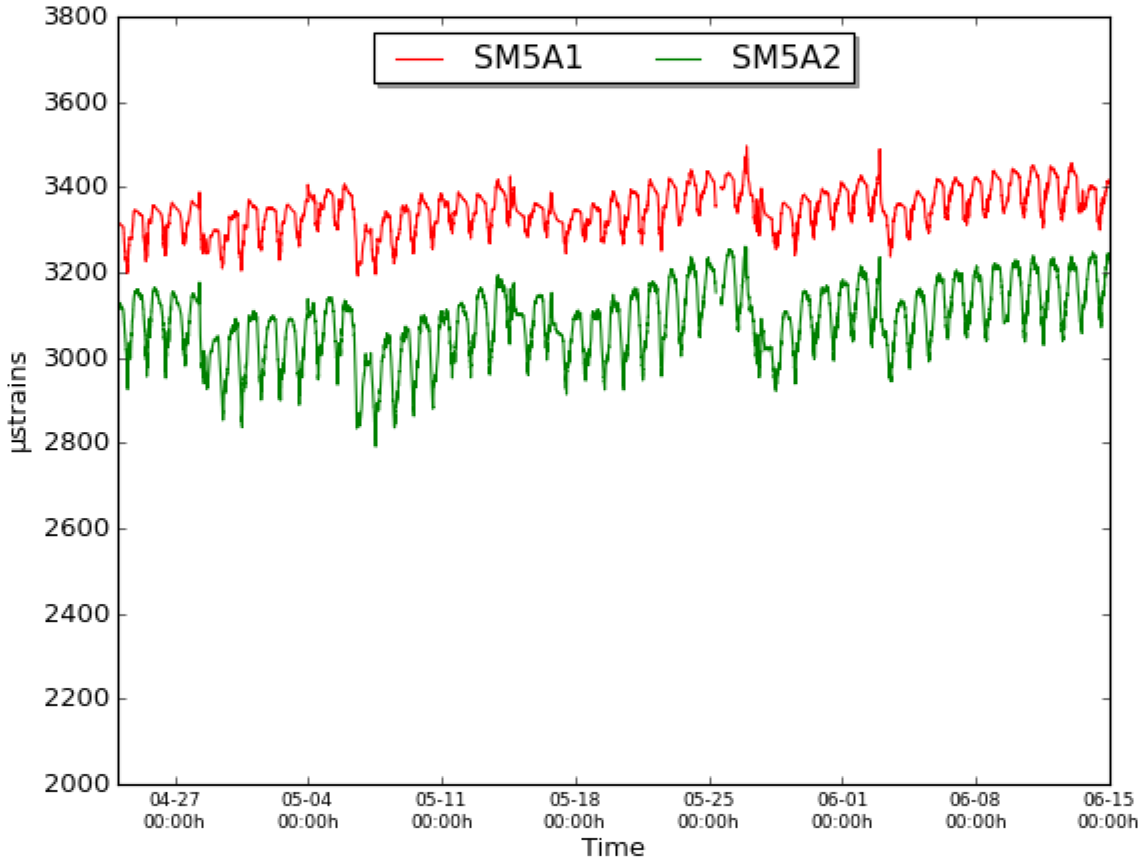

Figure 3. Graph of the strain gauge readings from SM5A1 and SM5A2 over approximately two months

The above figure is a sample of strain gauge readings from the test bed. Curves from SM5A1 (red line) and SM5A2 (green line) corresponded to the strain gauges on one of the blocks, placed one above the other on the same crack. Both curves trended the same, with a slight offset. Due to the periodic nature of the data, it is believed that the changes in the microstrains are mainly due to temperature effects and not structural deformation. By understanding diurnal effects to the strain sensor, compensation for temperature effects will be incorporated into the sensor program. Temperature effect breaks down into two main components: the part of strain due to structural variation caused by cracks and the part of the strain due to temperature fluctuations. Temperature affects the expansion of the gauge and substrate (concrete) oppositely, due to their thermal expansion coefficient values [6]. With a temperature increase, the steel wire inside the vibrating wire strain gauge will expand, and thus the tension of the wire decreases, which is reflected as a decrease in absolute strain. Coincidently, a rise in temperature also increases the distance between the two anchor points mounted on the concrete block (as the concrete expands with a temperature increase), but this expansion is insufficient to compensate for an expansion in the strain gauge wire.

To facilitate materials condition trending, the dashboard would ultimately display the relative change in the microstrains plotted over time as compared to initial conditions. However, before displaying the change in microstrains, a better understanding of the strain sensors and the diurnal and seasonal response is needed. Once the diurnal trending of the strain sensors is well understood, the plots will be changed to display the relative change in microstrains.

Tiltmeters

Representative tiltmeter readings over five days are shown in Figure 4. The left axis shows the tilt angle in degrees for the transverse, x tilt (red curve-T1 and blue curve-T2) and longitudinal, y tilt (green curve-T1 and purple curve-T2) direction while the right axis displays the temperature recorded by the data logger.

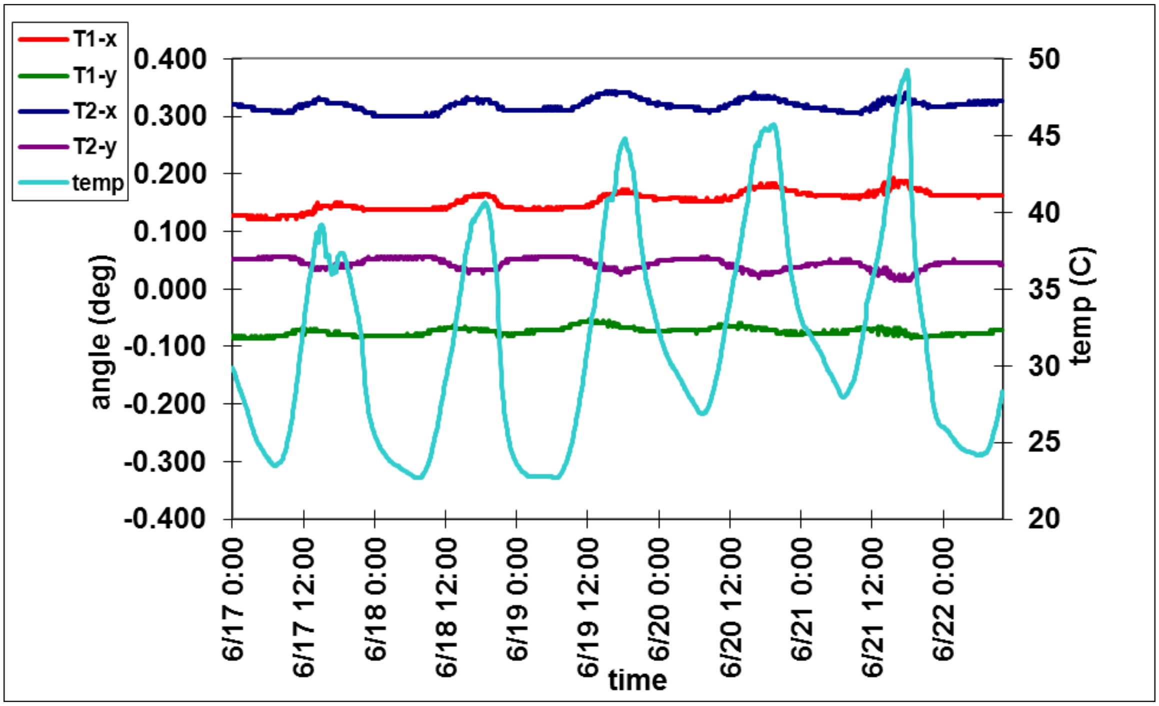

Figure 4. Typical tiltmeter graph showing angle (degrees-left axis) and temperature (Celcius-right axis) versus time of tilt data collected over five days

The tiltmeters exhibited similar small angle changes over the monitored days. The vendor suggested that the tiltmeters be shielded to prevent direct sun exposure. As with the strain gauges, the tiltmeters are also temperature dependent. This particular sensor is a gravity referenced ceramic tilt sensor that is comprised of a ceramic case and contains a conductive liquid (electrolyte), an air bubble and platinum electrodes. The effect of temperature on this type of sensor is understood and reproducible due to the thermal expansion of the fluid. Temperature fluctuations cause thermal expansion and contraction of the sensor liquid, shrinking or swelling the air bubble and changing the amount of liquid in contact with each excitation electrode. This process alters the scale factor (gain) of the sensor and can shift the zero point. A resulting small change in sensor output is seen in the absence of any real tilt movement. Temperature compensation will be built into the data program once trends are established and understood. Baseline data will continue to be collected in order to better understand the sensor response.

CONCLUSIONS

The Sensor Network Test Bed at SRNL uses COTS sensors on concrete blocks from the outer wall of the P Reactor Building to measure conditions expected to occur in ISD structures. Knowledge and lessons learned gained from installation, testing, and monitoring of the equipment will be applied to sensor installation in a meso-scale test bed at FIU and in future ISD structures.

The initial data collected from the sensors installed on the P Reactor Building blocks define the baseline materials condition of the P Reactor ISD external concrete structure. Continued monitoring of the blocks will enable evaluation of the effects of aging on the P Reactor ISD structure. The collected data will support validation of the material degradation model and assessment of the condition of the ISD structure over time.

The following are recommendations for continued development of the ISD Sensor Network Test Bed:

- Establish a long-term monitoring program using the concrete blocks with existing sensor and/or additional sensors for trending the concrete materials and structural condition
- Continue development of a stand-alone test bed sensor system that is self-powered and provides wireless transmission of data to a user-accessible dashboard
- Develop and implement periodic NDE/DE characterization of the concrete blocks to provide verification and validation for the measurements obtained through the sensor system and concrete degradation model(s).

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