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SX Tank Farm Interim Surface Barrier Vadose Zone Monitoring

September 2019

Z Fred Zhang
Jonathan N Thomle
Gao L Dai
Kenton A Rod

U.S. DEPARTMENT OF ENERGY

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Abstract

The Hanford Site, in southeastern Washington State, has 149 underground single-shell tanks to store hazardous radioactive waste. A number of these tanks and their associated infrastructure (e.g., pipelines, diversion boxes) have leaked. While some of the leaked waste has entered the groundwater, the majority still resides in the vadose zone. Corrective measures are being taken to mitigate the groundwater impacts from past leaks and spills from contaminants that still reside within the vadose zone. Washington River Protection Solutions, LLC, constructed three interim surface barriers (identified as south, north, and expansion barriers, respectively) in 2018 over the 241-SX Tank Farm to minimize the migration of the residual contaminants in the vadose zone. Two monitoring instrument nests were installed in the south and north barriers, respectively, in 2018 and the data acquisition system was put into operation in September 2019. This document summarizes the monitoring methods, the instrument calibration and installation, and the vadose zone monitoring plan for the interim barriers in the SX tank farm.

Summary

The Hanford Site has 149 underground single-shell tanks (SSTs) to store hazardous radioactive waste. A number of these tanks and their associated infrastructure (e.g., pipelines, diversion boxes) have leaked and the majority of the leaked waste still resides in the vadose zone. The surface barrier technology is being used to mitigate the groundwater impacts from past leaks and spills from contaminants that still reside within the vadose zone.

The 241-SX Tank Farm (SX tank farm, SX farm) was constructed between years 1953 and 1954. The SX tank farm contains fifteen 100-series SSTs, each with a diameter of 23 m (75 ft) and a capacity of 3,785,000 L (1 million gallons), waste-transfer lines, leak-detection systems, and tank ancillary equipment. Ten of the fifteen tanks in the SX tank farm are suspected leakers (i.e., tanks SX-104, and SX-107 through SX-115). The construction of three modified asphalt interim surface barriers (ISBs) over the contaminant plume within the SX farm was completed in 2018. The expansion barrier covers tanks 101 through 103 and the north part of tanks SX-104 through SX-106. The north barrier covers the south part of tanks SX-104 through SX-106 and entirely covers tanks SX-107 through SX-109. The south barrier entirely covers tanks SX-110 through SX-115. This document summarizes the monitoring methods, the instrument calibration and installation, and the vadose zone monitoring plan for the interim barriers in the SX tank farm.

Instruments and Calibration

Two types of sensors are used to monitor the soil moisture condition beneath the SX ISBs and measure soil matric potential (h) indirectly. The heat dissipation units (HDUs) were manufactured by Campbell Scientific, Inc. (CSI, called "229 Heat Dissipation Matric Water Potential Sensor") and measure temperature change (ΔT, °C) before and after heating for a pre-defined time (usually 30 s). The Watermark 200 (CSI sensor Model 257-L) soil matric potential sensors were manufactured by Irrometer Company, Inc. and distributed by Campbell Scientific, Inc. and measure electrical resistance (R, kΩ).

The relationship between h and ΔT is described by an exponential equation for the HDUs and by a quadratic equation for Watermark sensors. The coefficients for the regression relationships were obtained through laboratory calibration for each of the sensors. The calibration results were comparable with those in literature.

Instrument Layout

Two instrument nests, SX1 and SX2, were installed beneath the south and north ISBs, respectively.

- Instrument Nest SX1 for the south ISB consists of two sensor arrays:
  - Array A: The HDUs are located at depths of 1, 2, 3, and 5 m. This array is referred to as the sensor Array SX1A.
  - Array B: The HDUs are located at depths of 10, 15, and 20 m. The Watermark sensor is located at 1-m depth. This array is referred to as the sensor Array SX1B.
- Instrument Nest SX2 for the north ISB consists of one HDU array. The HDUs are located at depths of 1, 3, 5, and 10 m. This array is referred to as the sensor Array SX2.

Monitoring Plan and Data Files

A data acquisition system was installed for each of the two instrument nests. For both monitoring nests, each sensor is logged once every 12 hours. The data are stored in the dataloggers associated with the corresponding monitoring nest. The data can be retrieved regularly from the dataloggers to a computer outside of the fence via wireless radio communication.

The data from the dataloggers are in ASCII format. The retrieved data are stored in two files, which include comma-delimited data, for the two monitoring nests, respectively. Each file contains four rows of headings and multiple rows of comma-delimited data measured at different times.

Acknowledgments

This work was funded by the Washington Rivers Protection Solutions, LLC (WRPS). The hook-up of the data acquisition system was completed by WRPS and coordinated by Alex Pappas.

Acronyms and Abbreviations

CSI	Campbell Scientific, Inc.
DOE	U.S. Department of Energy
HDI	How Do I…
HDU	heat dissipation unit
ISB	interim surface barrier
PAAA	Price Anderson Amendments Act
PNNL	Pacific Northwest National Laboratory
QA	quality assurance
SST	single-shell tank
WRPS	Washington River Protection Solutions, LLC

Contents

Abstract ii
Summary iii
Acknowledgments v
Acronyms and Abbreviations vi
Contents vii
1.0 Introduction 1
1.1 SX Tank Farm 1
1.2 Surface Barriers and Monitoring 1
1.3 Objectives and Scope 3
2.0 Instruments and Calibration 4
2.1 HDU and Watermark Sensors 4
2.2 Sensor Normalization and Calibration 4
2.2.1 HDU Normalization 5
2.2.2 HDU and Watermark Sensor Calibration 5
2.2.3 Regression Relationships 7
2.2.4 Evaluation of Sensor Calibration 8
2.2.5 Comparison with Other Available Calibrations 9
3.0 Instrument Layout 11
4.0 Monitoring Plan and Data Files 13
4.1 Data Acquisition System 13
4.2 Data Files 13
5.0 Quality Assurance 16
6.0 References 17
Appendix A – Calibration of Heat Dissipation Units and Watermark Water Potential Sensors using the Pressure Chamber Apparatus A.1
Appendix B – Procedures for Installing the Heat Dissipation Units and Watermark Sensors in the SX Tank Farm B.1
Appendix C – Datalogger Programs C.1

Figures

Figure 1. Location of the SX tank farm in the 200 West Area (DOE-ORP 2008). 2
Figure 2. The SX tank farm with the interim surface barriers and the evapotranspiration basin. 3
Figure 3. (a) A 229 Heat-Dissipation Matric Water Potential Sensor is shown at the top (the dashed line is in clear color). The hypodermic assembly (without epoxy and ceramic) is shown just below. A cutaway view shows the longitudinal section of the needle with heater and thermocouple junction. (b) A Model 257-L (Watermark 200) Matric Potential Sensor with capacitor circuit and completion

resistor installed in cable. The orange rectangles marks the sensing portion of the sensors. 4
Figure 4. Comparison of calibration results for HDUs for the SX tank farm and other purposes. 9
Figure 5. Comparison of calibration results for the Watermark sensors for the SX tank farm and other purposes. 10
Figure 6. Locations of the monitoring stations (After Figure 3 of Henderson 2011b). 11

Tables

Table 1. The mean and standard deviation of temperature changes (°C) for the HDUs under the dry and wet conditions. 5
Table 2. The mean of resistance (kOhm) for the Watermark sensors and temperature changes (°C) for HDUs under different pressure conditions. 6
Table 3. The standard deviation of resistance (kOhm) for the Watermark sensors and temperature changes (°C) for HDUs under different pressure conditions. 7
Table 4. The coefficients for the regression relationships for the calibrated sensors. 8
Table 5. Sensor number, wire length, and installation depths at Array SX1A for the south barrier. 12
Table 6. Sensor number, wire length, and installation depths at Array SX1B for the south barrier. 12
Table 7. Sensor number, wire length, and installation depths at Array SX2 for the north barrier. 12
Table 8. Environment line in the data file. 14
Table 9. Description of data items in the data file for monitoring Nest SX1. 14
Table 10. Description of data items in the data file for monitoring Nest SX2. 15

1.0 Introduction

The Hanford Site, in southeastern Washington State, has 149 underground single-shell tanks (SSTs) to store hazardous radioactive waste. A number of these tanks and their associated infrastructure (e.g., pipelines, diversion boxes) have leaked. While some of the leaked waste has entered the groundwater, the majority still resides in the vadose zone. Corrective measures are being taken to mitigate the groundwater impacts from past leaks and spills from contaminants that still reside within the vadose zone.

Washington River Protection Solutions, LLC (WRPS) has constructed three interim surface barriers (ISBs, identified as south, north, and expansion barriers, respectively) in 2018 over the 241-SX Tank Farm (SX tank farm, SX farm) in the 200 West Area to minimize the migration of the residual contaminants in the vadose zone. The ISBs at SX farm are the first few of the ISBs called for in the Hanford Federal Facility Agreement and Consent Order Milestone M-045-92.[1] The monitoring plans for the south and north ISBs are given in Henderson (2011a) and Henderson (2011b). The following provides the background of the SX tank farm and other ISBs at the Hanford, followed by the objectives and scope of this document.

1.1 SX Tank Farm

According to Henderson (2011a) and Henderson (2011b), the SX tank farm was constructed between years 1953 and 1954. The SX tank farm contains fifteen 100-series SSTs, each with a diameter of 23 m (75 ft) and a capacity of 3,785,000 L (1 million gallons), waste-transfer lines, leak-detection systems, and tank ancillary equipment. The soil depth from the ground surface above the tanks to the apex of the tank domes is approximately 2.4 m (8 ft). Figure 1 shows the SX tank farm within the S-SX waste management area and surrounding facilities in the 200 West Area. The SX tank farm was constructed into the upper Hanford formation sediments. The upper 12 m (40 ft) of the Hanford formation was locally excavated and backfilled with gravelly sand during installation of the SSTs. Stratigraphic units in the vadose zone underlying or adjacent to these tank farms (from top to bottom) include backfill materials and naturally occurring Hanford formation sediments, the Plio-Pleistocene unit, and the Miocene- to Pliocene-age Ringold Formation (CHG 2002).

A detailed discussion of the historical information associated with tank leaks and unplanned releases is provided in Johnson and Field (2010), which identified the numerous evaluations that have been performed using both in-tank and ex-tank data to investigate the nature and extent of subsurface contamination in the SX tank farm. Ten of the fifteen tanks in the SX tank farm are suspected leakers (i.e., tanks SX-104, and SX-107 through SX-115).

1.2 Surface Barriers and Monitoring

The construction of an ISB using felt with a polyurea coating was completed in the T tank farm in April 2008. The construction of a modified asphalt ISB over the contaminant plume within the TY farm was completed in August 2010. There is an ongoing monitoring program in place for the T and TY farm ISBs (Zhang et al. 2010).

[1] https://www.hanford.gov/files.cfm/HFFACO.pdf

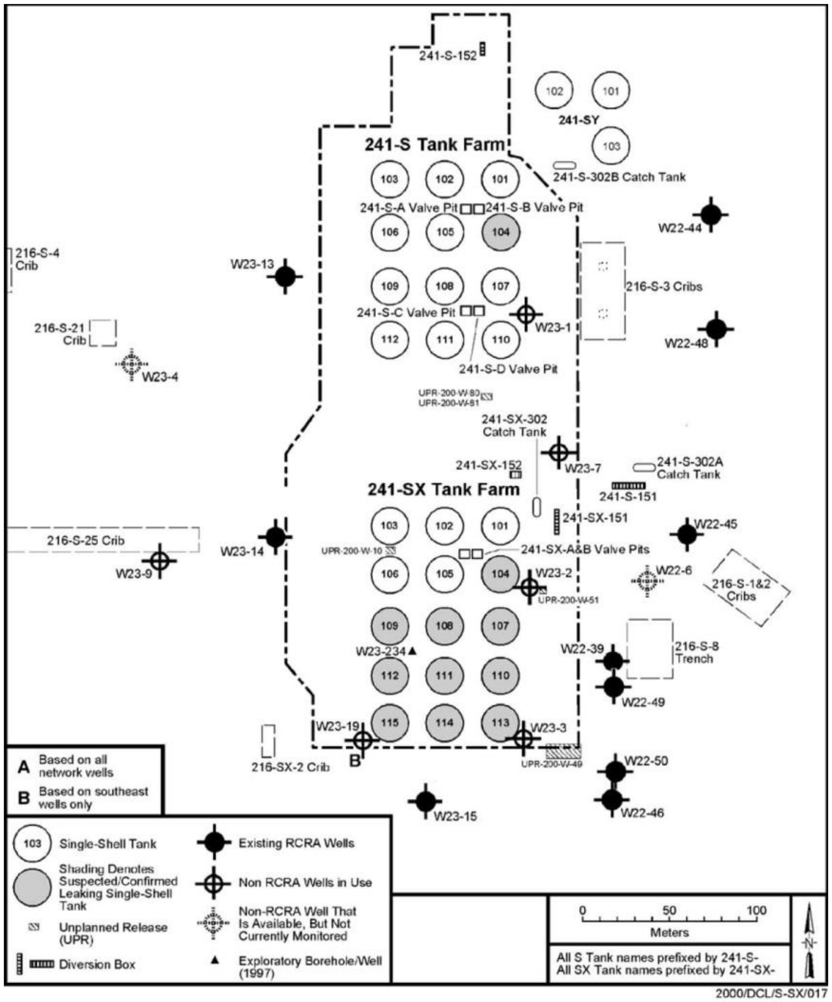


Figure 1. Location of the SX tank farm in the 200 West Area (DOE-ORP 2008).

The construction of the three modified asphalt ISBs over the contaminant plume within the SX farm was completed in 2018. The approximate footprints of the three barriers are shown in Figure 2. The expansion barrier covers tanks 101 through 103 and the north part of tanks SX-104 through SX-106. The north barrier covers the south part of tanks SX-104 through SX-106 and entirely covers tanks SX-107 through SX-109. The south barrier entirely covers tanks SX-110 through SX-115.

These ISBs intercept the natural precipitation and divert the intercepted water to the evapotranspiration basin outside of the tank farms (Figure 2). It is expected that the ISBs will prevent the meteoric water from entering soil and consequently reduce the rate of downward movement of flow and dissolved contaminants. At shallower depths, there will be no water supply from above to replace the draining water, and hence, the drainage rate will decrease more quickly. At larger depths, the soil will keep receiving drainage from the soil above for some time, and the drainage rate will decrease relatively more slowly. Therefore, it may take a very long time (e.g., years or decades) for drainage rates deep in the profile to decrease significantly. As the soil below the ISBs becomes drier, the soil in the uncovered region near the vertical plane directly beneath the barrier edge will also become drier than it would be if there were no surface barrier.

Subsurface monitoring is integral to achieving acceptance of the ISBs. The subsurface water conditions are monitored to document changes in soil moisture over time and demonstrate that the ISBs are effectively reducing the water flux into a contaminated region.

Figure 2. The SX tank farm with the interim surface barriers and the evapotranspiration basin.

1.3 Objectives and Scope

The objective of monitoring the SX ISBs is to measure the water condition of the soil beneath the ISBs and demonstrate that the ISBs perform as intended. This document summarizes the monitoring system in the SX tank farm. After a brief introduction in Section 1, Section 2 presents the measurement sensors used and their calibration results. Section 3 summarizes the layouts and installation of the sensors in each of the instrument nests. Section 4 presents the schedule of data collection, data validation, and data reporting. Section 5 discusses the quality assurance plan used to verify the quality of the work.

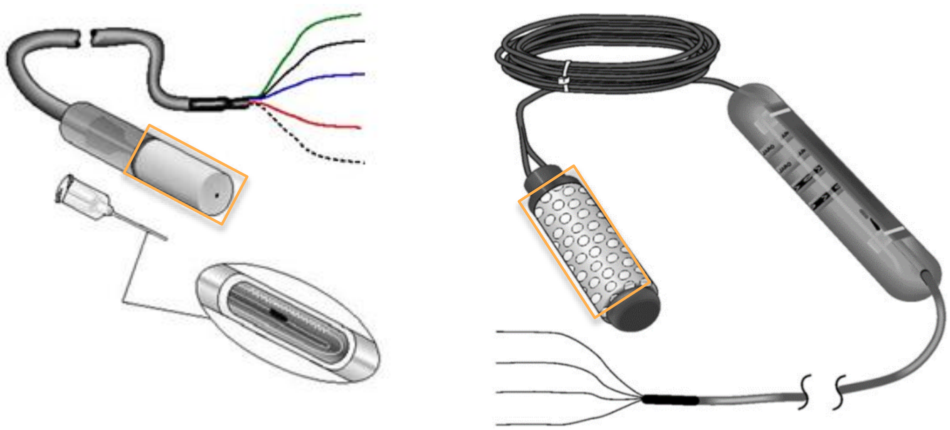
2.0 Instruments and Calibration

This section documents the instruments and their calibrations in addition to the normalization of the heat dissipation units (HDUs). The instruments in the SX farm are grouped into two nests: SX1 for the south ISB and SX2 for the north ISB.

2.1 HDU and Watermark Sensors

Two types of sensors are used to monitor the soil moisture condition beneath the SX ISB. The HDUs were manufactured by Campbell Scientific, Inc. (CSI, called "229 Heat Dissipation Matric Water Potential Sensor", Figure 3a). The ceramic cylinder of the HDU has a diameter of 1.5 cm (0.6 in.) and a length of 3.2 cm (1.26 in.).

The Watermark 200 (CSI sensor Model 257-L) soil matric potential sensors were manufactured by Irrometer Company, Inc. and distributed by Campbell Scientific, Inc. (Figure 3b). The Watermark sensor has a diameter 1.91 cm (0.75 in.) and length of 8.26 cm (3.25 in.).



(a) (b)

Figure 3. (a) A 229 Heat-Dissipation Matric Water Potential Sensor is shown at the top (the dashed line is in clear color). The hypodermic assembly (without epoxy and ceramic) is shown just below. A cutaway view shows the longitudinal section of the needle with heater and thermocouple junction. (b) A Model 257-L (Watermark 200) Matric Potential Sensor with capacitor circuit and completion resistor installed in cable. The orange rectangles marks the sensing portion of the sensors.

2.2 Sensor Normalization and Calibration

The thermal and/or hydraulic properties of the sensing part of each HDU or the Watermark sensor are slightly different from those of other sensors of the same types because of the variation of the materials used, requiring that instrument normalization be performed (HDUs only) and calibrations be developed (HDUs and Watermark).

2.2.1 HDU Normalization

A normalization process is used to minimize instrument-dependent readings. Flint et al. (2002) evaluated calibration equations for six HDUs and suggested normalizing the temperature increase according to:

$$S_{\Delta T} = \frac{\Delta T_d - \Delta T}{\Delta T_d - \Delta T_w} \quad (1)$$

where $S_{\Delta T}$ is the scaled temperature rise during a fixed time period (30 seconds for the HDUs used in the T and TY farms), ΔT is the temperature increase, and subscripts “d” and “w” denote the temperature increases for a dry and water-saturated ceramic matrix, respectively. This relation results in a range of 0 to 1 for dimensionless temperature. The matric potential is related to the dimensionless temperature rise by an empirical model.

The procedures for normalizing these HDUs are given in Appendix A. The normalization of HDUs for the SX tank farm lasted for at least 24 hours and data were collected every 15 minutes. The mean (μ) and standard deviation (σ) of temperature changes were calculated for the data over the last 24 hours. During this period, there were 96 observations for the dry condition and 97 for the wet condition.

The mean and standard deviations of temperature changes for the 13 HDUs normalized are summarized in Table 1. The standard deviation ranged between 0.008 and 0.013 °C, indicating very a small error that is acceptable.

Table 1. The mean and standard deviation of temperature changes (°C) for the HDUs under the dry and wet conditions.

		Mean		Standard Deviation	
HDU S/N	HDU No.	Dry	Wet	Dry	Wet
15590	1	3.565	0.915	0.011	0.011
15591	2	3.546	0.906	0.008	0.011
15594	3	3.450	0.853	0.011	0.010
15596	4	3.108	0.896	0.009	0.011
15598	5	3.356	0.912	0.009	0.013
15599	6	3.490	0.841	0.010	0.011
15601	7	3.214	0.827	0.008	0.013
15589	8	3.220	0.934	0.010	0.012
15593	9	3.168	0.853	0.009	0.009
15595	10	3.144	0.844	0.010	0.010
15597	11	3.421	0.857	0.009	0.013
15600	12	3.445	0.875	0.010	0.010
15602	13	3.346	0.859	0.011	0.010

2.2.2 HDU and Watermark Sensor Calibration

The HDUs installed in the SX tank farm were calibrated in the laboratory with the soil water potential range from 0.1 to 0.9 bar using a pressure chamber. The calibration was performed following an approved procedure (Appendix A).

After the system reached the equilibrium condition, the pressure was released and at least five observations were taken for each pressure. The mean and standard deviations of temperature changes (for each of the HDUs) or resistance (for each of the Watermark sensors) were calculated over the last five observations after the temperature effects were corrected to 20°C.

Table 2 tabulates the mean of resistance (kOhm) for the Watermark sensors and temperature changes (°C) for HDUs under different pressure conditions. HDU #6 did not respond at the 200 mbar pressure. Except for HDU #6, all the other sensors responded to all the pressure. The results indicate HDU #6 might have a high air-entry that is over 200 mbar. The higher air-entry pressure makes HDU #6 unable to measure a matric potential wetter than -200 mbar.

Table 3 tabulates the standard deviation of resistance (kOhm) for the Watermark sensors and temperature changes (°C) for HDUs under different pressure conditions. Note that the measurement for HDU #6 at 200 mbar was not considered in this calculation. The small σ values indicate that the sensors provide sufficient measurement resolution.

Table 2. The mean of resistance (kOhm) for the Watermark sensors and temperature changes (°C) for HDUs under different pressure conditions.

Sensor No.	200 mbar	350 mbar	500 mbar	650 mbar	800 mbar
SX1	3.856	5.169	6.420	8.060	9.371
SX2	3.935	5.176	6.391	7.883	9.116
1	1.226	1.402	1.556	1.693	1.785
2	1.193	1.372	1.512	1.661	1.747
3	1.128	1.293	1.432	1.553	1.661
4	1.160	1.329	1.455	1.549	1.644
5	1.196	1.376	1.501	1.621	1.712
6	0.779[a]	1.342	1.478	1.617	1.722
7	1.067	1.254	1.369	1.523	1.597
8	1.235	1.384	1.529	1.659	1.731
9	1.162	1.313	1.433	1.564	1.629
10	1.103	1.276	1.395	1.517	1.595
11	1.123	1.303	1.437	1.616	1.719
12	1.181	1.363	1.490	1.628	1.709
13	1.155	1.327	1.443	1.563	1.651

(a) HDU #6 did not respond at the 200 mbar pressure. This value was not used in the development of the regressions.

Table 3. The standard deviation of resistance (kOhm) for the Watermark sensors and temperature changes (°C) for HDUs under different pressure conditions.

Sensor No.	200 mbar	350 mbar	500 mbar	650 mbar	800 mbar
SX1	0.041	0.090	0.056	0.021	0.012
SX2	0.054	0.128	0.084	0.007	0.012
1	0.015	0.004	0.004	0.008	0.004
2	0.005	0.007	0.006	0.005	0.013
3	0.010	0.016	0.011	0.007	0.010
4	0.005	0.008	0.006	0.011	0.004
5	0.005	0.010	0.013	0.007	0.010
6	0.007	0.011	0.012	0.005	0.008
7	0.010	0.005	0.006	0.008	0.006
8	0.005	0.010	0.008	0.005	0.011
9	0.007	0.007	0.008	0.015	0.014
10	0.015	0.007	0.023	0.005	0.008
11	0.014	0.006	0.011	0.023	0.010
12	0.016	0.009	0.007	0.014	0.011
13	0.016	0.007	0.014	0.013	0.008

2.2.3 Regression Relationships

Before developing the regression relationships, the temperature effect on measurements was corrected to 20 °C. As such, future field observations at different temperatures will need to be corrected to 20 °C as well for the use of these relationships.

The relationship between soil matric potential, h (-m), and temperature changes, ΔT (°C), for the HDUs is described by an exponential equation:

$$h = a\exp^{b\Delta T} \qquad (2)$$

The relationship between soil matric potential, h (-m), and resistance, R (kOhm), for Watermark sensors is described by a quadratic equation:

$$h = aR^2 + bR + c \qquad (3)$$

The coefficients for the regression relationships for the calibrated sensors are summarized in Table 4. The high R^2 values (>0.97) indicate very significant correlation at 99% confidence level for HDUs. The non-linear correlation for the Watermark sensors was not tested statistically, but the correlation is better than a linear one at 99% confidence level. Note that the measurement for HDU #6 at 200 mbar was not considered in the regression.

Table 4. The coefficients for the regression relationships for the calibrated sensors.

Sensor Name	Sensor No.	a	b	c	r^2
HDU	1	646.15	-6.4349	-	0.9889
	2	701.59	-6.4661	-	0.9879
	3	895.15	-6.7110	-	0.9863
	4	588.20	-6.3735	-	0.9949
	5	706.58	-6.5530	-	0.9934
	6	376.61	-5.6961	-	0.9937
	7	535.66	-6.1208	-	0.9884
	8	467.80	-6.1576	-	0.9856
	9	707.15	-6.6589	-	0.9872
	10	640.74	-6.4148	-	0.9936
	11	413.08	-5.8081	-	0.9760
	12	759.65	-6.6485	-	0.9916
	13	977.69	-6.9371	-	0.9918
	Average	646.10	-6.4305	-	0.9900
Watermark	SX1	-0.01689	1.3360	-2.8194	0.9987
	SX2	-0.01384	1.3663	-3.0797	0.9991
	Average	-0.015	1.351	-2.950	-

2.2.4 Evaluation of Sensor Calibration

- All the sensors listed in Table 4 were calibrated according to the approved procedure OP-DVZ-SX-001, Rev 1.0, *Calibration of Heat Dissipation Units and Watermark Water Potential Sensors using the Pressure Chamber Apparatus*, which is given in Appendix A of this report and the calibration was compliant with the procedure.
  – The procedure was approved by WRPS on 10/31/2017. The calibration started on 11/3/2017.
  – The procedure requires at least 4 pressures in the calibration. In the actual work, observations were obtained for 5 pressures.
  – The data for the calibration were complete.
- The calibration meets the requirements stated in the Statement of Work. A total of 11 HDUs and 1 Watermark sensor are needed for the SX soil moisture monitoring. A total of 13 HDUs and 2 Watermark sensors were calibrated. The extra 2 HDUs and 1 Watermark were spare sensors.
- HDU #6 did not respond at 200-mbar pressure, indicating this sensor has a higher air entry pressure than other HDUs. This means HDU #6 will not respond in the field when the soil is wetter than the condition of -200 mbar of matric potential. During the installation, a calibrated spare HDU may be used as a replacement for HDU #6.
- The wire lengths of the calibrated sensors have been verified for use in the SX tank farm as described in the Statement of Work.
- The regressions between measurements and soil matric potential show very significant correlation at 99% confidence level.

2.2.5 Comparison with Other Available Calibrations

Calibration of HDUs has been reported in Flint et al. (2002). The calibration of the HDUs for the T and TY tank farms is reported in Zhang et al. (2010). Comparison of calibration results for HDUs is shown in Figure 4. The results for the SX HDUs are very close to that from Flint et al. (2002) and similar to that for the TY farm, and hence are acceptable.

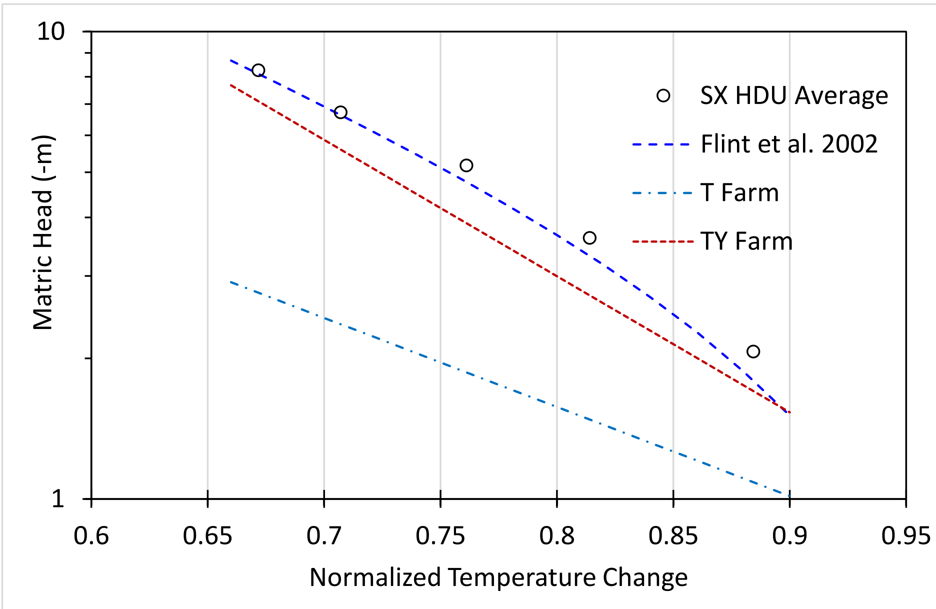


Figure 4. Comparison of calibration results for HDUs for the SX tank farm and other purposes.

For the Watermark soil matric potential sensors, a default calibration relationship is provided by the vendor (Section 7.3.2 of CSI 2017). The water potential (WP, kPa) is calculated from resistance (R, kOhm) by the default calibration relationship as:

$$WP = \begin{cases} -(20R - 11) & If \quad R \le 11kOhm \\ -(aR^3 + bR \;\; + cR + d) & Otherwise \end{cases} \tag{4}$$

where

a = -0.00279
b = 0.19109
c = 3.71485
d = 6.73956

A regression was reported in Thomson et al. (1996). The vendor's and the Thomson calibrations differ substantially, while the calibration results in this report are either close to the vendor's calibration or the Thomson calibration (Figure 5). These differences could be due to the variation of sensor properties. Hence, the calibration given by Eq. (3) is acceptable.

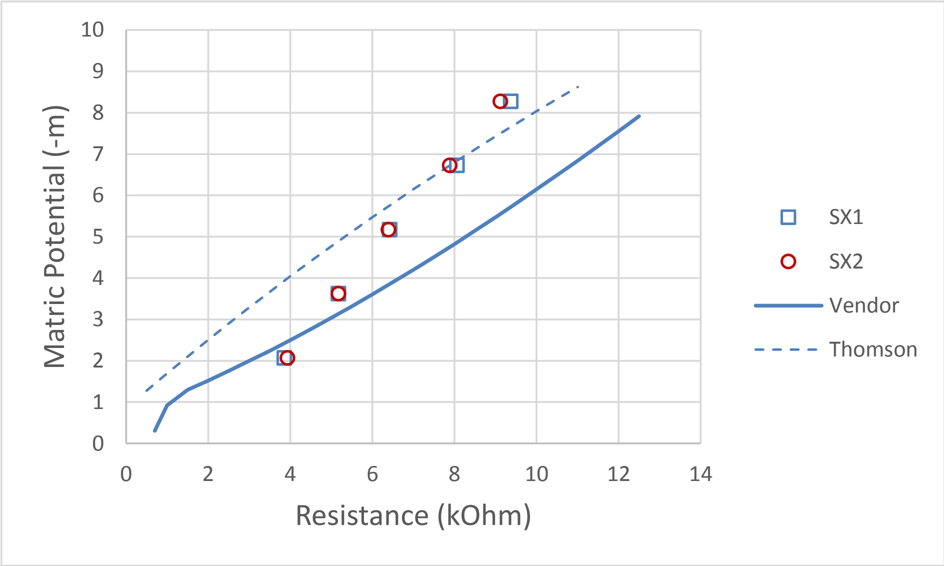


Figure 5. Comparison of calibration results for the Watermark sensors for the SX tank farm and other purposes.

3.0 Instrument Layout

This section describes the layout and installation of HDUs and Watermark sensors and their functionality after the data acquisition system was in operation.

The instrument nests are referred to as Monitoring Station #1 for the south ISB and #2 for the north ISB in the H-14-109447-Sheet7-R0. The locations of these two stations (nests) are shown in Figure 6 These instrument nests are referred to as the Nest SX1 for the south ISB and Nest SX2 for the north ISB. The sensors were installed per the procedures given in Appendix B.

- Instrument Nest SX1 for the south ISB consist of two sensor arrays:
  - Array A: The HDUs are located at depths of 1, 2, 3, and 5 m. This array is referred to as the sensor Array SX1A.
  - Array B: The HDUs are located at depths of 10, 15, and 20 m. The Watermark sensor is located at 1-m depth. This array is referred to as the sensor Array SX1B.
- Instrument Nest SX2 for the north ISB consists of one HDU array. The HDUs are located at depths of 1, 3, 5, and 10 m. This array are referred to as the sensor Array SX2.

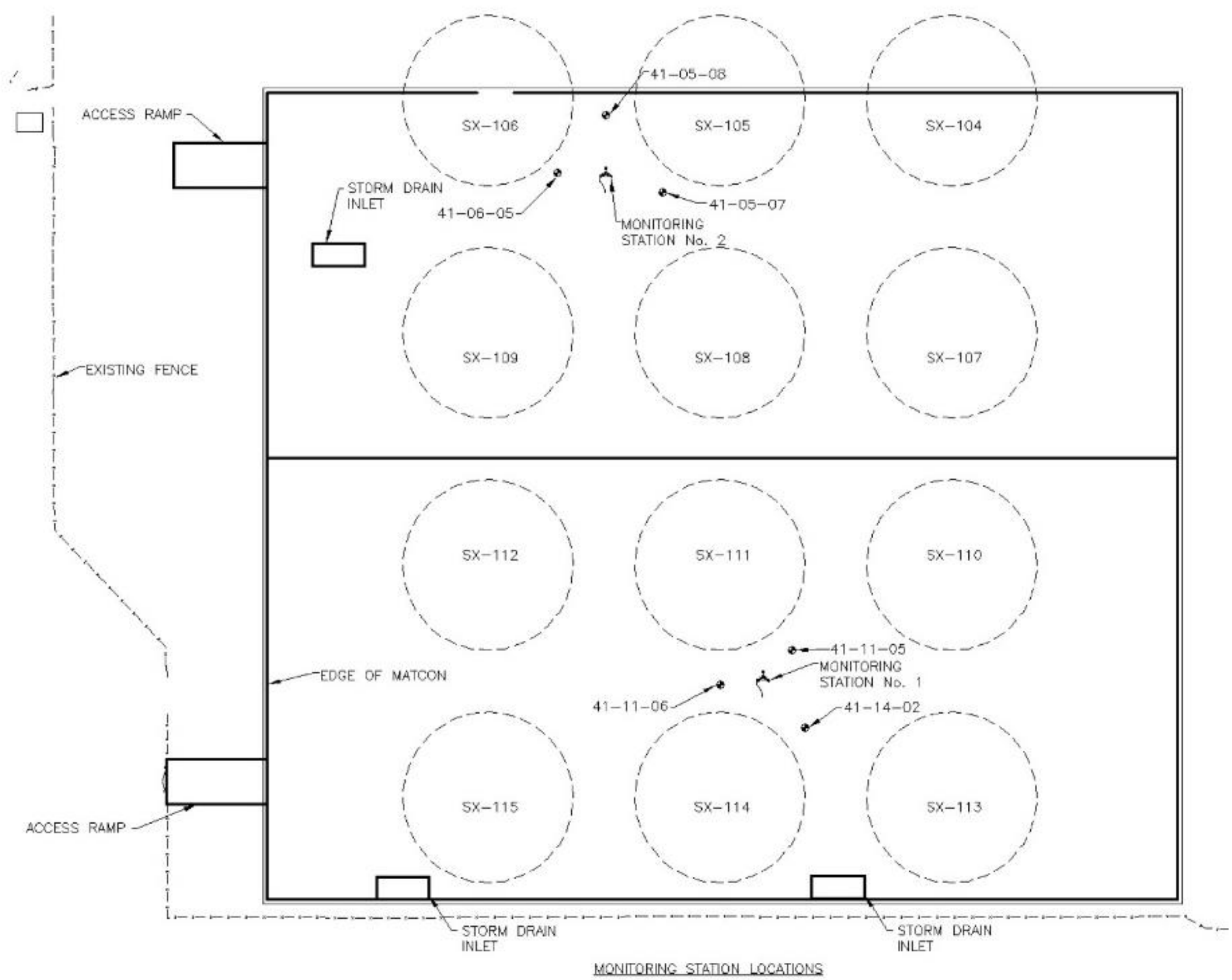


Figure 6. Locations of the monitoring stations (After Figure 3 of Henderson 2011b).

The sensor depths for each of the instrument nests are summarized in Tables 5, 6 and 7 per table 1 of (Steffler 2018). Both metric and English units of measurements are reported to be consistent with the metric units in the Statement of Work and with the English units used by the drillers. The layouts and depths in Tables 5, 6, and 7 correspond to plots H, G, and J, respectively, in drawing H-14-109447-Sheet7-R0. Note that HDU #13 (S/N15602) was a replacement of #7 (S/N15601), which was damaged during installation.

Table 5. Sensor number, wire length, and installation depths at Array SX1A (Borehole C8429) for the south barrier.

Sensor	Depth, m (ft)	Sensor Number (Serial Number)	Wire Length (ft)
HDU	1 (3.3)	#1 (15590)	14
HDU	2 (6.6)	#2 (15591)	17
HDU	3 (9.8)	#3 (15594)	20
HDU	5 (16.4)	#4 (15596)	27

Table 6. Sensor number, wire length, and installation depths at Array SX1B (Borehole C8428) for the south barrier.

Sensor	Depth, m (ft)	Sensor Number (Serial Number)	Wire Length (ft)
Watermark	1 (3.3)	SX1	14
HDU	10 (32.8)	#5 (15598)	43
HDU	15 (49.2)	#12 (15600)	60
HDU	20 (65.6)	#13 (15602)	76

Table 7. Sensor number, wire length, and installation depths at Array SX2 (Borehole C8430) for the north barrier.

Sensor	Depth, m (ft)	Sensor Number (Serial Number)	Wire Length (ft)
HDU	1 (3.3)	#8 (15589)	14
HDU	3 (9.8)	#9 (15593)	20
HDU	5 (16.4)	#10 (15595)	27
HDU	10 (32.8)	#11 (15597)	43

4.0 Monitoring Plan and Data Files

This section presents a monitoring plan to document vadose zone response to the placement of an ISB in the SX tank farm.

4.1 Data Acquisition System

A data acquisition system was installed for each of the instrument nests per procedures given in Section B.4 of Appendix B. The dataloggers were equipped with the corresponding programs (i.e., SX1_Monitor.CR1 and SX2_Monitor.CR1) given in Appendix C.

After the data acquisition system was set up, it was initiated per procedures in Section B.5. The data can be retrieved outside of the SX farm fence wirelessly per procedures given in Section B.6. The data acquisition system started in operation in September 2019.

For both monitoring nests, each sensor is logged once every 12 hours, at 9:00 am and 9:00 pm. These times can be changed as needed by modifying the datalogger programs. The data are stored in the dataloggers associated with the corresponding monitoring nest. The data can be retrieved at any desired time from the dataloggers to a computer via wireless radio communication without entering the SX farm. The CR1000 datalogger has the 2 MB for program and data storage.

4.2 Data Files

The data from the dataloggers are in ASCII format and are treated as raw data, which are the measurements at the sensor temperature. Proper temperature correction is needed before converting the data into soil matric potential using Eq. (2) for HDUs and (3) for the Watermark sensor.

The raw data are reviewed before they are archived. When the data are incomplete, the data can be re-retrieved from the dataloggers. The files from the instrument nests have the same or similar format as described below. However, the file formats are subject to change if needed. The actual format of each data file is described in a data-configuration-information file, which is prepared when a data file is archived.

The retrieved data will be stored in two files, which include comma-delimited data, for the two monitoring nests. Each file contains four rows of headings and multiple rows of comma-delimited data measured at different times. The first heading row contains relevant information about the monitoring environment for the nest and is described in Table 8. The second and third rows contain the symbols and units corresponding to the variable of each column and are described in Table 9 for monitoring Nest SX1 and Table 10 for SX2. The fourth row contains entries describing the type of processing performed in the CR1000 to produce corresponding data, e.g., Smp indicates samples, Min indicates minima.

Each data row corresponds to a logging of all the sensors for the corresponding monitoring station. The columns of the data for the two monitoring stations (nests) are different and are described in Table 9 for monitoring Nest SX1 and Table 10 for SX2.

Table 8. Environment line in the data file.

Column #	SX1	SX2	Description
1	TOA5	TOA5	ASCII File Format
2	SX1	SX2	Monitoring Nest (Station) Name
3	CR1000	CR1000	Datalogger Model
4	40134	87163	Datalogger Serial Number
5	CR1000.Std.31.08	CR1000.Std.31.08	Datalogger OS Version
6	CPU:SX1_Monitor.CR1	CPU:SX2_Monitor.CR1	Datalogger Program Name
7	27527	40469	Datalogger Program Signature
8	SX1_Data	SX2_Data	Table Name

Table 9. Description of data items in the data file for monitoring Nest SX1.

Column #	Sensor # (Serial #)	Depth, m (ft)	Description
1	-	-	Date-Time
2	-	-	Record Number
3	-	-	Battery Voltage (V)
4	-	-	Reference Temperature at the Datalogger (°C)
5	#1 (15590)	1 (3.3)	HDU-Measured Initial Temperature (°C)
6	#2 (15591)	2 (6.6)	
7	#3 (15594)	3 (9.8)	
8	#4 (15596)	5 (16.4)	
9	#5 (15598)	10 (32.8)	
10	#12 (15600)	15 (49.2)	
11	#13 (15602)	20 (65.6)	
12	#1 (15590)	1 (3.3)	HDU-Measured Initial Temperature Change (°C) between 1 s and 30 s.
13	#2 (15591)	2 (6.6)	
14	#3 (15594)	3 (9.8)	
15	#4 (15596)	5 (16.4)	
16	#5 (15598)	10 (32.8)	
17	#12 (15600)	15 (49.2)	
18	#13 (15602)	20 (65.6)	
19	SX1	1 (3.3)	Watermark-Measured Resistance (kOhm)

Table 10. Description of data items in the data file for monitoring Nest SX2.

Column #	Sensor # (Serial #)	Depth, m (ft)	Description
1	-	-	Date-Time
2	-	-	Record Number
3	-	-	Battery Voltage (V)
4	-	-	Reference Temperature at the Datalogger (°C)
5	#8 (15589)	1 (3.3)	HDU-Measured Initial Temperature (°C)
6	#9 (15593)	3 (9.8)	
7	#10 (15595)	5 (16.4)	
8	#11 (15597)	10 (32.8)	
9	#8 (15589)	1 (3.3)	HDU-Measured Initial Temperature Change (°C) between 1 s and 30 s
10	#9 (15593)	3 (9.8)	
11	#10 (15595)	5 (16.4)	
12	#11 (15597)	10 (32.8)	

5.0 Quality Assurance

This work was performed in accordance with the *DVZ-AFRI Quality Assurance Plan* (QAP). The QAP complies with the United States Department of Energy Order 414.1D, *Quality Assurance,* and 10 CFR 830 Subpart A, *Quality Assurance Requirements*. The QAP uses NQA-1-2000, *Quality Assurance Requirements for Nuclear Facility Application* as its consensus standard and NQA-1-2000 Subpart 4.2 as the basis for its graded approach to quality.

The work for this report was performed under the technology level of Development.

6.0 References

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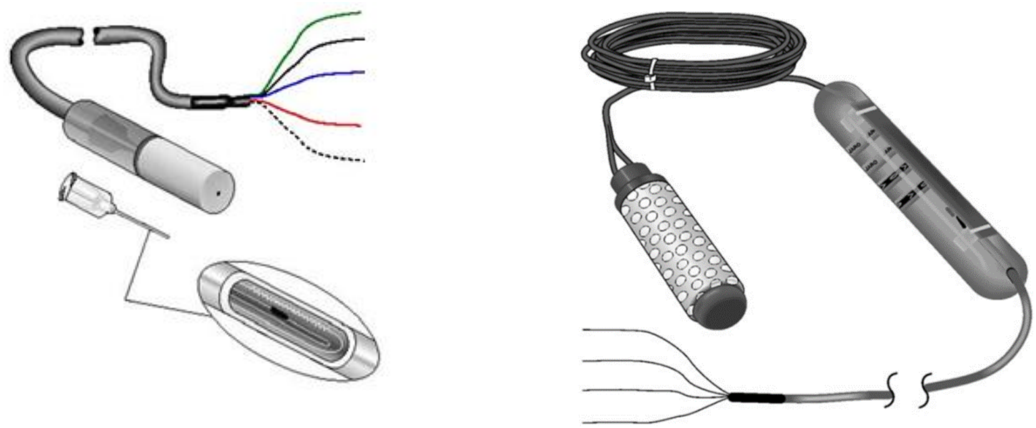
Appendix A – Calibration of Heat Dissipation Units and Watermark Water Potential Sensors using the Pressure Chamber Apparatus

A.1 Introduction

A.1.1 Purpose

This procedure describes the calibration of the Heat Dissipation Unit (HDU) manufactured by Campbell Scientific, Inc. (CSI, called "229 Heat Dissipation Matric Water Potential Sensor", Figure A.1a) and the Watermark 200 (CSI sensor Model 257-L) soil matric potential sensors manufactured by Irrometer Company, Inc. and distributed by Campbell Scientific, Inc. (Figure A.1b).



(a) (b)

Figure A.1. (a) A 229 Heat-Dissipation Matric Water Potential Sensor is shown at the top (the dashed line is in clear color). The hypodermic assembly (without epoxy and ceramic) is shown just below. A cutaway view shows the longitudinal section of the needle with heater and thermocouple junction. (b) A Model 257-L (Watermark 200) Matric Potential Sensor with capacitor circuit and completion resistor installed in cable.

A.1.2 Scope/Applicability

This procedure applies to the general calibration of the heat dissipation units (CSI Model 229 Heat-Dissipation Matric Water Potential Sensor) and the Watermark sensors (CSI Model 257-L Soil Matric Potential Sensor) designed for soil matric potential measurements.

A.1.3 Definitions

Heat Dissipation Unit is manufactured by CSI and is called "229 Heat Dissipation Matric Water Potential Sensor."

Watermark Sensor is manufactured by Irrometer Company, Inc. and distributed by CSI and is called soil matric potential sensor.

Pressure Chamber Apparatus (PCA) is manufactured by the Soil Moisture, Inc. is also called pressure plate extractor.

Pressure Controller is manufactured by the Alicat Scientific and is calibrated before use.

LoggerNet is a datalogger support software package developed by CSI.

A.1.4 References

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A.2 Work Instructions

This work includes two parts: 1) HDU normalization and 2) HDU and Watermark sensor calibration. The calibration establishes a relationship between the sensor output and soil matric potential. It is planned to be performed only once, prior to the burial of the sensors.

Use a calibrated pressure controller that is accurate to ±1.25 mbar between 0.1 to 0.9 bar to measure and control pressures in the pressure chamber apparatus. Prior to each use of the pressure controller verify that it is:

- properly labeled with a valid sticker from the calibrator;

- within its calibration period for the period it will be used;
- operational and not damaged (i.e., it will display a zero when it is turned on and there is no visual damage);
- properly suited for the intended purpose (i.e. accurate to ±1.25 mbar between 0.1 to 0.9 bar).

Calibration of the HDUs and the Watermark sensors will be recorded on Exhibit A.

The following procedures were developed based on Reece (1996), Flint et al. (2002), and Thomson and Armstrong (1987).

A.3 HDU Normalization

The following procedures were developed based on Flint et al. (2002).

1) Dry the HDUs. First, air dry the HDUs in the laboratory for at least 24 hours. Then place the HDUs in a sealed desiccator and allow to equilibrate for a minimum of 24 hours. A type of indicating desiccant will be used. The drying processing is complete if the desiccant still shows the dry color after 24 hours. Otherwise, replace the used desiccant with dry desiccant and repeat the process.
2) Measure temperature rise of each HDU for dry HDU ceramic. Measure temperature rise using a heating time to be used for the field measurements, 30 seconds for this case.
   i. Hook up the sensors and the data requisition system including a datalogger, a 12-V power supply, and a laptop equipped with LoggerNet.
   ii. Take measurements of temperature changes for HDUs and resistance for Watermark sensors using LoggerNet.
   iii. Download data using LoggerNet and record relevant information using Exhibit A.
3) Wet the HDUs. Place the HDUs in de-aired water under vacuum of -0.3 bar or less and allow to equilibrate for a minimum of 24 hours. De-aired water can be made under vacuum of -0.3 bar or less until air bubbles are no longer visible. The sensors do not have to be disconnected from the data requisition system when being wetted.
4) Measure HDU temperature rise for saturated HDU ceramic. Measure temperature rise using the same heating time to be used for the field measurements, 30 seconds for this case.
   i. Hook up the sensors and the data requisition system if it has not been done.
   ii. Start datalogger program LoggerNet to take measurements of temperature changes for HDUs and resistance for Watermark sensors.
   iii. Download data using LoggerNet and record relevant information using Exhibit A.

A.4 HDU and Watermark Sensor Calibration

The following procedures were developed based on Reece (1996) and Thomson and Armstrong (1987). The HDUs and Watermark sensors can be calibrated at the same time. For automated data logging during the process, a datalogger program will be prepared and approved before sensor calibration. Figure A.2 is a schematic showing the main components of the calibration system.

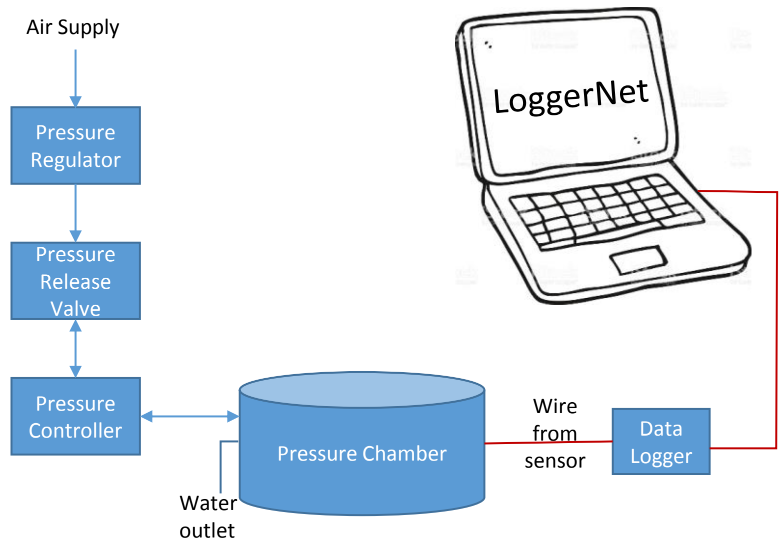

Figure A.2. Schematic showing the main components of the calibration system

1) Saturate the sensors and the pressure plate.

   i. HDUs: Place the HDUs in de-aired water under vacuum of -0.3 bar of less and allow to equilibrate for a minimum of 24 hours. This step is not needed if the HDUs are already saturated after normalization.

   ii. Watermark sensors: Place the Watermark sensors in de-aired water for 24 hours. Remove the Watermark sensors from water and allow to air dry for 48 hours. Re-wet Watermark sensors in de-aired water for 24 hours.

   iii. Saturate the 1-bar ceramic pressure plate. Connect the outlet of the plate to a water source and fill the space between the rubber backing sheet and the porous plate. When about 2/3 or more of the space is filled, disconnect the supply tubing and remove the air from the space between the plate and the rubber sheet. Terminate the filing process once the rubber backing sheet is extended about 2 cm. Let the plate sit until considerable sweating of the ceramic plate is observed. Place the plate under water for use.

   iv. Make sufficient (about 2 L) slurry of loam soil by mixing it with water (about 2 L of soil with 1 L of water; more water can be added if necessary).

2) Arrange sensors in the pressure chamber apparatus

   i. Drain most of the water from the space between the plate and the rubber sheet and make sure no air will enter this space. Place ceramic plate in the pressure chamber apparatus. Connect one end of the pressure tubing to the plate and the other end to the inside end of the pressure chamber outlet. Make sure that the tubing on the outside end of the pressure chamber outlet is submerged under water (e.g., in a water-filled beaker or other type of container, which sits in a larger open container; the latter is used to catch overflow).

   ii. Lay a thin (a few mm) layer of soil slurry on the ceramic plate. Note that the calibration is independent of the type or quantity of soil used.

   iii. Arrange the sensors (i.e., HDUs and the Watermark) horizontally in the soil on the ceramic plate. The adjacent sensors should not contact each other.

iv. Add more soil slurry to cover the sensors. Ensure good contact among the sensors, ceramic plate, and soil. Wires from the sensors should be routed through pressure fittings to the datalogger.

v. Seal the top of the pressure chamber and attach to pressure controller and a pressure release valve. Connect the pressure controller to the supply of pressurized air.

3) Set up and start the data logging system

   i. Hook up the sensors with the data requisition system, including a datalogger, a 12-V power supply, and a laptop equipped with LoggerNet.

   ii. Upload the approved program “HDU_CAL.CR3” to the datalogger.

   iii. Start the datalogging and take measurement of temperature changes for HDUs using the same heating time to be used for the field measurements (30 seconds) and resistance for Watermark sensors hourly or more frequently.

4) Set pressure to first pressure between 100 and 900 mbar, starting from the lowest. Record the pressure shown at the pressure controller. With the air supply, pressure controller, pressure release valve, and the pressure chamber hooked up, turn on the air supply. The pressure will desaturate the soil and sensors. Note that excessive (generally uncountable) air bubbling from the outflow tubing is an indication of a leak in the porous plate. If a leak occurs, measurements should be stopped and restarted with another porous plate.

5) Keep the pressure until all the measurements stop changing with time. The suggested pressures are 150, 300, 500, 700, and 900 mbar. However, the pressures can be different from these values as long as they are within the range between 100 and 900 mbar and reasonably represent the low, intermediate, and high pressures. It usually takes several hours at low pressure and several days at high pressure for the system to reach equilibrium. At equilibrium, pinch the outlet water tube with a clamp (to prevent water flow back to the outlet) and release the pressure by setting the pressure controller to zero. Let the data collection continue for three cycles or more. Record relevant information using Exhibit A. Then remove the clamp on the outlet water tube so water can move freely.

6) Repeat steps 4) and 5) using incrementally larger pressures. Obtain a minimum of four calibration points within the pressure range between 100 and 900 mbar.

7) Stop the measuring system when all measurements are completed.

   i. Turn off the air supply.

   ii. Slowly release the pressure from using the set point on the Alicat pressure controller (set pressure to zero).

   iii. Download data from datalogger, record relevant information using Exhibit A, and stop the datalogging system.

Exhibit A. M&TE information in normalization and/or calibration of the HDUs and the Watermark sensors

☐ HDU Normalization OR ☐ Calibration of Sensors

Name of calibrator: ______________

Start date/time:__________________ Start condition or pressure: ___________

End date/time: __________________ End condition or pressure: ____________

File name of results: ____________________

Notes (as appropriate):

____

____

____

____

____

____

Pressure Controller ID: __________________ Calibration Due: ___________________

List of sensors:

Sensor Name	Sensor #	Sensor Name	Sensor #

Name of data reviewer: __________________ Date of data review: __________

Are the results acceptable (Yes/No)? _____________

Appendix B – Procedures for Installing the Heat Dissipation Units and Watermark Sensors in the SX Tank Farm

These work instructions are for the installation of two instrument nests, one for the South SX barrier and the other for the North SX barrier. These instrument nests are referred to as Nest SX1 and Nest SX2 for the south and north barriers, respectively.

- Instrument Nest SX1 for the South SX barrier shall consist of two sensor arrays:
  - Array A: The HDUs are located at depths of 1, 2, 3, and 5 m. This array will be referred to as the sensor Array SX1A.
  - Array B: The HDUs are located at depths of 10, 15, and 20 m. The Watermark sensor is located at 1-m depth. This array will be referred to as the sensor Array SX1B.
- Instrument Nest SX2 for the North SX barrier shall consist of one HDU array. The HDUs are located at depths of 1, 3, 5, and 10 m. This array will be referred to as the sensor Array SX2.

NOTE
The instrument nests are referred to as Monitoring Station #1 for the south barrier and #2 for the north barrier in the H-14-109447-Sheet7-R0.

The sensor depths for each of the instrument nests are summarized in Table B.1, Table B.2, and Table B.3. Both metric and English units of measurements are reported to be consistent with the metric units in the Statement of Work and with the English units used by the drillers. The layouts and depths in Table B.1, Table B.2, and Table B.3 correspond to plots H, G, and J, respectively, in drawing "H-14-109447-Sheet7-R0."

NOTE
Sensors may be replaced by a calibrated spare one if any of the sensors is in question. In this case, the wire length of the replacing sensor should be kept unchanged.

Calibrated spare sensors:
- HDU #12, 15600 (60')
- HDU #13, 15602 (76')
- Watermark 2, SX2

Spare sensor HDU #12 is used to replace HDU #6 per the recommendation of CALC-DVZ-SX-0003.

Table B.1. Sensor number, wire length, and installation depth at Array SX1A for the south barrier.

Sensor	Depth, m (ft)	Sensor Number (Serial Number)	Wire Length (ft)
HDU	1 (3.3)	#1 (15590)	14
HDU	2 (6.6)	#2 (15591)	17
HDU	3 (9.8)	#3 (15594)	20
HDU	5 (16.4)	#4 (15596)	27

Table B.2. Sensor number, wire length, and installation depth at Array SX1B for the south barrier.

Sensor	Depth, m (ft)	Sensor Number (Serial Number)	Wire Length (ft)
Watermark	1 (3.3)	SX1	14
HDU	10 (32.8)	#5 (15598)	43
HDU	15 (49.2)	#12 (15600)	60
HDU	20 (65.6)	#7 (15601)	76

Table B.3. Sensor number, wire length, and installation depth at Array SX2 for the north barrier.

Sensor	Depth, m (ft)	Sensor Number (Serial Number)	Wire Length (ft)
HDU	1 (3.3)	#8 (15589)	14
HDU	3 (9.8)	#9 (15593)	20
HDU	5 (16.4)	#10 (15595)	27
HDU	10 (32.8)	#11 (15597)	43

B.1 Before Installation

Moist silica flour preparation. Mix approximately 5 kg (11 lb) of 120-mesh silica flour with approximately 1 L (~0.25 gal) of water in a bucket. Add more silica flour or water as needed so the mixture is in a moist state. Cover the bucket with a lid to prevent the silica flour from drying. Mix more moist silica flour as needed.

Sensor preparation. All the sensors are to be kept in a moist condition (e.g., water or silt loam slurry) for at least 24 hours.

B.2 Installation Procedures

NOTE: The operation of the hydraulic hammer to create a borehole is beyond the scope of the procedure.

A diagram of sensor installation and packing material layering scheme is shown in Figure B.1.

1. Determine the locations of the monitoring nest based on Figure B.2. Record the actual well location in Exhibit B. The two instrument arrays for Nest SX1 (south) shall be approximately 1 m (3 ft) apart.
2. Create borehole. Using the hydraulic hammer, drive a 6.99-cm-outside diameter (OD) (2.75-inch-OD) steel drive shaft and drive head set to a depth that is 1.0 m (3.3 ft) deeper than the depth for the deepest HDU, namely
    a. 6.0 m (19.7 ft) for Array SX1A
    b. 21.0 m (68.9 ft) for Array SX1B
    c. 11.0 m (36.1 ft) for Array SX2
3. Disconnect drive cone. Once the drive shaft is at the desired depth, the drive cone is disconnected from the drive shaft.

4. Add 20/40 clean sand. As the hollow shaft is removed, add the clean sand through the drive shaft to bring the level to approximately 0.15 m (6 in.) below the target depth of the sensor to be installed. Sensor must be installed from the largest depth to the smallest depth in sequence.
5. Add moist silica flour for a total of 0.1 m (4 in.) thickness. Moderately pack the silica flour.
6. Mark sensor wire denoting the ground surface position at installation depth. Carefully lower the sensor to the bottom of the borehole, taking note of the location of the mark. If the mark is above ground level, the sensor may not have reached the bottom of the borehole. It should be pulled up slightly and re-lowered to the bottom of the borehole. The mark should be slightly lower than the ground surface because the sensor is too light to make the wire straight.
7. Add moist silica flour for a total of approximately 0.10 m (4 in.) thickness. Gently pack the silica flour around the HDU to supply optimum contact between the sensor and surrounding silica flour. When done, pull the wire gently. The ground-level mark at the wire should be near the ground surface. Record the actual depth of the sensor in Exhibit B.
8. If the sensor is out of the position of the silica flour, repeat steps 6 and 7. Now the total thickness of the silica flour is larger than the thickness shown in H-14-109447-Sheet7-R0. This is acceptable if the difference is no more than 0.2 m (8 in.). The ground-level mark at the wire is also higher by the thickness of the additional silica flour.
9. Add 20/40 clean sand. Approximately 0.20 m (0.66 ft; 8 in.) of 20/40 sand is added on top of the silica flour.
10. Add bentonite crumbles to a depth of approximately 0.30 m (1.0 ft; 12 in.) below the next instrument depth.
11. Repeat steps 4 to 10 for the sensor at the next shallower location. If all sensors are installed in the borehole, move on to step 12.
12. Add 20/40 clean sand. Approximately 0.20 m (0.66 ft; 8 in.) of 20/40 sand was then added on top of the bentonite crumbles.
13. Add bentonite crumbles to ground surface.

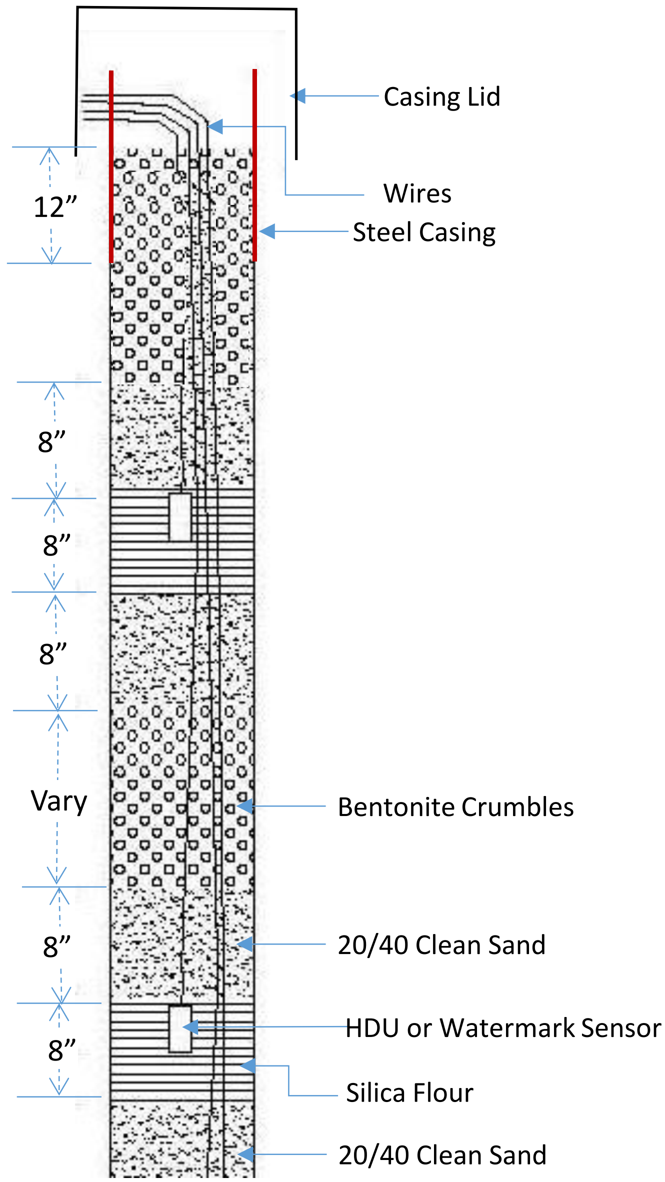

Figure B.1. Diagram of sensor installation and packing material layering scheme.

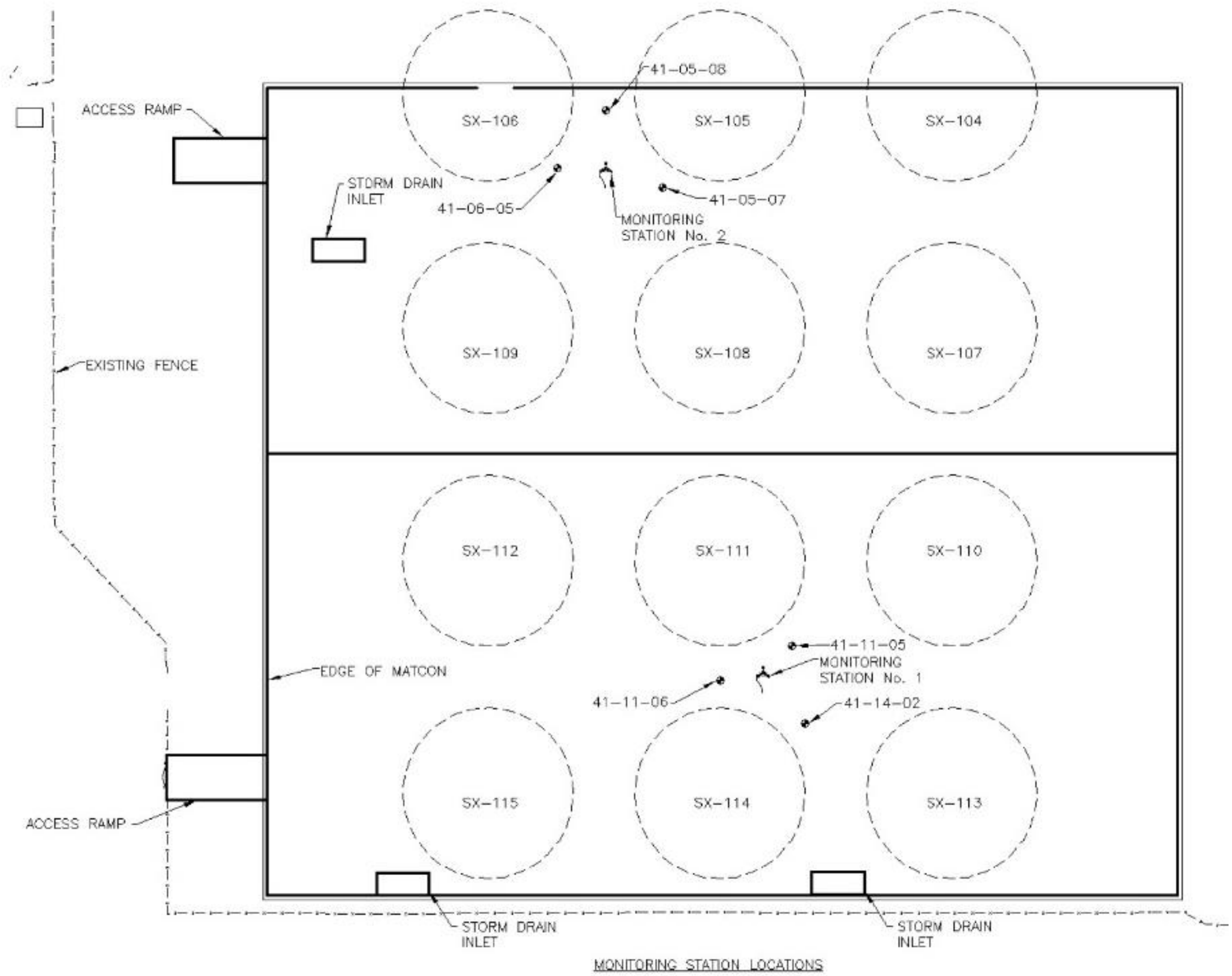

Figure B.2. Locations of the monitoring nests stations (After Figure 3 of Henderson 2011b).

B.3 Surface Completion

After all the sensors for a borehole are installed, conduct surface completion according to H-14-109447-Sheet7-R0.

B.4 Setup the Data Acquisition System

NOTE: All hardware was from the Campbell Scientific, Inc. unless otherwise specified.

1. Set up the CM6 tripod at approximately 1.5 m (5 ft) away from the instrument nest. This distance may vary based on the surface condition near the instrument nest.
2. Complete the following in any order if they have not been done
    a. Attach the ENC16/18 weather-resistance enclosure for datalogger to the CM6 tripod. Install a datalogger, the CE4 or CE8 excitation module, and the BP12 battery in the enclosure. The CE8 excitation module is used for south Nest SX1 and the CE4 excitation module is used for north Nest SX2.

b. Attach the SP20 solar panel to the tripod.

c. Set up the transmitter of the RF451 900MHz Spread Spectrum Radio system.

d. Arrange one or more conduits (from any hardware store) between the tripod and the instrument arrays. Pull the wires through the conduits.

e. Hook up the wires from sensors according to Table B.4 through Table B.10.

f. Upload the datalogger program (SX1_Monitor.CR1 or SX2_Monitor.CR1) to the CR1000 datalogger if it has not been uploaded. The datalogging program will be prepared before the setup of the data requisition system. Be sure the time is in Pacific Standard Time (PST) all year round.

Table B.4. Sensor connections at the south nest (SX1, see Table B.6 and Table B.7 for wire colors).

Sensor	SN#	CR1000 Channel	CE8 Excitation Channel
Watermark	SX1	SE 15	EX2 CR1000
HDU	15590	Diff 1	CE8 Ch 1
HDU	15591	Diff 2	CE8 Ch 2
HDU	15594	Diff 3	CE8 Ch 3
HDU	15596	Diff 4	CE8 Ch 4
HDU	15598	Diff 5	CE8 Ch 5
HDU	15600	Diff 6	CE8 Ch 6
HDU	15601	Diff 7	CE8 Ch 7

Table B.5. Sensor connections at the north nest (SX2, See Table B.6 for wire colors).

Sensor	SN#	CR1000 Channel	CE4 Excitation Channel
HDU	15589	Diff 1	Ch 1
HDU	15593	Diff 2	Ch 2
HDU	15595	Diff 3	Ch 3
HDU	15597	Diff 4	Ch 4

Table B.6. HDU connections by wire color.

HDU Wire Color	Connection
Blue	Diff H on CR1000
Red	Diff L on CR1000
Clear	Shield CR1000
Green	+ Excitation Module
Black	- Excitation Module or shield

Table B.7. Watermark connections by wire color.

Watermark Wire Color	Connection
Black	EX2 CR1000
Red	SE15 CR1000
White	G CR1000
Clear	Shield CR1000

Table B.8. CE4/8 excitation module connections.

CE4/8 Excitation Modules	
Terminal	Connections
Ctrl	C1 CR1000
Shield	G CR1000
12V	12V CR1000

Table B.9. Charge regulator (CH100) hookup connections.

Charge Regulator	
Terminal	Connections
Batt +	Positive Terminal of Battery and 12V CR1000
Batt -	Negative Terminal of Battery and G CR1000
CHG +	Red Wire from Solar Panel
CHG -	Black Wire from Solar Panel

Table B.10. RF451 radio hookup connections.

Radio	
Terminal	Connections
Power Plug Positive	12V CR1000
Power Plug Negative	G CR1000
CS I/O	CS I/O CR1000
Antenna	900MHz, 1/4 Wave Whip Antenna

B.5 Start and Test the Data Acquisition System

1. Install Software LoggerNet and datalogging programs for each instrument nest on a laptop.
2. Connect the laptop to the datalogger.
3. Manually conduct datalogging to check that data are logged from each of the sensors and are stored in a file.
4. If the system does not function as intended, check the wire hook-up according to Table B.4 through Table B.10.
5. Start the datalogger program.

B.6 Transfer Data from the Data Acquisition System

1. Install Software LoggerNet and configure LoggerNet for each instrument nest, if this has not been done.
2. Select a place outside the fence of the SX farm but near the instrument nest.
3. Hook up the laptop, radio, and antenna.
4. Set up the antenna so that it points to a monitoring nest.
5. Start LoggerNet
    a. Press “Status” and check any errors.
    b. Find the name of the datalogger for this instrument nest.
    c. Press “Connect” and wait until the connection is set. Repeat steps 5a and 5b if the connection cannot be set.
    d. Check the percentage of the errors in signal and wait until it is less than approximately 5%. Otherwise, the communication may be lost if data collection is attempted.
    e. Press “Collect” to retrieve data.
    f. If the communication is lost during the data retrieving process, repeat steps 5c to 5e until all the data for a nest is retrieved.
    g. Verify that the data in the electronic file is complete for all the sensors and the data are logged at 12-hour intervals.
6. Repeat steps 1 to 5 for the other instrument nest.

Exhibit B. Recording form for well locations and sensor installation depths

Array SX1A for the South Barrier

Well Name: Well Coordinates:

Sensor	Sensor Number (Serial Number)	Planned Depth, m (ft)	Actual Depth (ft)	Staff Name	Date
HDU	#1 (15590)	1 (3.3)			
HDU	#2 (15591)	2 (6.6)			
HDU	#3 (15594)	3 (9.8)			
HDU	#4 (15596)	5 (16.4)			

Array SX1B for the South Barrier

Well Name: Well Coordinates:

Sensor	Sensor Number (Serial Number)	Depth, m (ft)	Actual Depth (ft)	Staff Name	Date
Watermark	SX1	1 (3.3)			
HDU	#5 (15598)	10 (32.8)			
HDU	#12 (15600)	15 (49.2)			
HDU	#7 (15601)	20 (65.6)			

Array SX2 for the North Barrier

Well Name: Well Coordinates:

Sensor	Sensor Number (Serial Number)	Depth, m (ft)	Actual Depth (ft)	Staff Name	Date
HDU	#8 (15589)	1 (3.3)			
HDU	#9 (15593)	3 (9.8)			
HDU	#10 (15595)	5 (16.4)			
HDU	#11 (15597)	10 (32.8)			

Name of Reviewer: _____________ Date:____________ Data Acceptable? Yes No

Appendix C – Datalogger Programs

The datalogger programs SX1-Monitor.CR1 for the south nest and SX2-Monitor.CR1 for the north nest are given below.

Installation Instruction

1. Connect CR1000 to laptop using a serial cable.
2. Open LoggerNet program. Click on the icon that says "Connect".
    a. Under "Stations" scroll down until the correct logger ID is found and select that logger. Click on "Collect Now" to retrieve the data if there are any. Click on "Connect" at the top left of the window.
    b. Click on the icon that says "Send New…" and a browser will pop up. Select the program you wish to send to the datalogger and open it. Once opened, it will ask if you want to send a new program. Click on "Send". The new program will be installed and start running on the logger. Note that if there is data on the datalogger, the data might be lost when a new program is sent to the datalogger.

SX1-Monitor.CR1 (version 0)

```
'CR1000`
'In "sequentialMode" everything below happens sequentially as written below
'in the order written.
'SX1 (south location)
SequentialMode

'Constants used. There is one CE8 used for 7 HDU's.
Const Num229 = 7
Const Num257 = 1

'These variables are used in "For loops" below. These loops are used for
'calculated variables within this program.
Dim LoopCount

'Below are the measured and calculated variables
Public BattV,T_Ref,Ti(Num229),T_30sec(Num229)
Public T_1sec(Num229), dT(Num229)
Public Vratio(Num257)
Public Resist(Num257)

'Below is a flag that is used to indicate when the program should take a
'measurement
Public Flag(1) As Boolean

'These are the units of final variable.
Units dT()=Deg c
Units Ti()=Deg C
Units T_Ref=Deg C
Units Resist()=kilohms

'Below is the table that is called to output the data collected
DataTable(SX1_Data,Flag(1),-1)
```

```
 Sample(1,BattV,FP2)
 Sample(1,T_Ref,FP2)
     Sample(Num229,Ti(),FP2)
     Sample(Num229,dT(),FP2)
     Sample(Num257,Resist(),FP2)
EndTable

'Below is the program that sets Flag(1) equal to true. The program scans to
'see if Flag(1) is true every 30 seconds, but it is set to to true every 15
'minutes.
BeginProg
     Scan(30,sec,1,0)
          If TimeIntoInterval (9,12,hr) Then Flag(1)=True
          If Flag(1)=True Then
           'The PanelTemp is the logger temperature which is recorded as the
           'variable T_Ref and Battery is the battery voltage of the datalogger
           'power supply system
           Battery (BattV)
           PanelTemp(T_Ref,250)
           'TCDiff is a command to measure a thermocouple. This command measures
           'all 7 thermocouples at once using T_Ref as a reference as described in
           'the HDU manual.
               TCDiff(Ti(),Num229,mV25C,1,TypeT,T_Ref,true,0,_60Hz,1,0)
               'PortSet (1,1) turns on control port 1 (C1) so that the heaters for the
               'HDU's turn on and the thermocouples within the HDU's are measured after
               'the heaters are on for 1 second, but only the HDU's that have heaters
               'controlled by C1.
               PortSet (1,1)
               Delay (0,1,Sec)
               TCDiff(T_1sec(),Num229,mV25C,1,TypeT,T_Ref,True,0,_60hz,1,0)
               'After 30 seconds these HDU's that have the heaters turned on are
               'measured again after 30 seconds and C1 is then turned off (Portset(1,0)).
               Delay(0,29,Sec)
               TCDiff(T_30sec(),Num229,mV25C,1,typeT,T_Ref,True,0,_60hz,1,0)
               PortSet(1,0)
               'The "For loop" below calculates delta temperature (dT) between the 30
               'and the 1 second thermocouple measurements of the HDU's seen above
               For LoopCount=1 To Num229
                    dT(LoopCount)=T_30sec(LoopCount)-T_1sec(LoopCount)
               Next LoopCount
               'The "BrHalf" measurement function measured the voltage ratio of the
               'measured voltage across the Watermark sensor over the excitation voltage.
               'with the excitation channel EX2 and the measurement channel SE15.
               BrHalf(Vratio(),1,mV250,15,Vx2,1,200,True,0,250,1,0)
               'The function below is used to convert the voltage ratios of
               'the measured voltage over the excitation voltage into resistance using
               'Ohms law (see sensor 257 manual).
                    Resist =Vratio/(1-Vratio)
          EndIf
          '"CallTable" writes the current measured parameters with a the appropriate
          'timestamp in the table called "Sensor_Cal", which when collected via
          '"LoggerNet" will write a text file called "SX1_Monitor_SX1_Data.dat"
          CallTable(SX1_Data)
          '"Flag(1)" is then called "false" again until it is manually called "true"
          'via "LoggerNet" or if 15 minutes since the last measurement.
          'Note that if manually called sufficient time must be given between
```

```
            'measurements so to reach thermal equilibrium.
            Flag(1)=False
            'scan repeats every 30 seconds
      NextScan
EndProg
```

SX2-Monitor.CR1 (version 0)

Provide source code or location

```
'CR1000`
'In "sequentialMode" everything below happens sequentially as written below
'in the order written.
'SX2 (North location)
SequentialMode

'Constants used. There is one CE4 used for 4 HDU's.
Const Num229 = 4

'These variables are used in "For loops" below. These loops are used for
'calculated variables within this program.
Dim LoopCount

'Below are the measured and calculated variables
Public BattV,T_Ref,Ti(Num229),T_30sec(Num229)
Public T_1sec(Num229), dT(Num229)

'Below is a flag that is used to indicate when the program should take a
'measurement
Public Flag(1) As Boolean

'These are the units of final variable.
Units dT()=Deg c
Units Ti()=Deg C
Units T_Ref=Deg C

'Below is the table that is called to output the data collected
DataTable(SX2_Data,Flag(1),-1)
 Sample(1,BattV,FP2)
 Sample(1,T_Ref,FP2)
      Sample(Num229,Ti(),FP2)
      Sample(Num229,dT(),FP2)
EndTable

'Below is the program that sets Flag(1) equal to true. The program scans to
'see if Flag(1) is true every 30 seconds, but it is set to to true every 15
'minutes.
BeginProg
      Scan(30,sec,1,0)
            If TimeIntoInterval (9,12,hr) Then Flag(1)=True
            If Flag(1)=True Then
             'The PanelTemp is the logger temperature which is recorded as the
             'variable T_Ref.
             Battery (BattV)
             PanelTemp(T_Ref,250)
```

```
            'TCDiff is a command to measure a thermocouple. This command measures
            'all 7 thermocouples at once using T_Ref as a reference as described in
            'the HDU manual.
                TCDiff(Ti(),Num229,mV25C,1,TypeT,T_Ref,true,0,_60Hz,1,0)
                'PortSet (1,1) turns on control port 1 (C1) so that the heaters for the
                'HDU's turn on and the thermocouples within the HDU's are measured after
                'the heaters are on for 1 second, but only the HDU's that have heaters
                'controlled by C1.
                PortSet (1,1)
                Delay (0,1,Sec)
                TCDiff(T_1sec(),Num229,mV25C,1,TypeT,T_Ref,True,0,_60hz,1,0)
                'After 30 seconds these HDU's that have the heaters turned on are
                'measured again after 30 seconds and C1 is then turned off (Portset(1,0)).
                Delay(0,29,Sec)
                TCDiff(T_30sec(),Num229,mV25C,1,typeT,T_Ref,True,0,_60hz,1,0)
                PortSet(1,0)
                'The "For loop" below calculates delta temperature (dT) between the 30
                'and the 1 second thermocouple measurements of the HDU's seen above
                For LoopCount=1 To Num229
                    dT(LoopCount)=T_30sec(LoopCount)-T_1sec(LoopCount)
                Next LoopCount
            EndIf
            '"CallTable" writes the current measured parameters with a the appropriate
            'timestamp in the table called "Sensor_Cal", which when collected via
            '"LoggerNet" will write a text file called "SX2_Monitor_SX2_Data.dat"
            CallTable(SX2_Data)
            '"Flag(1)" is then called "false" again until it is manually called "true"
            'via "LoggerNet" or if 12 hours have past since the last measurement.
            'Note that if manually called sufficient time must be given between
            'measurements so to reach thermal equilibrium.
            Flag(1)=False
            'scan repeats every 30 seconds
        NextScan
EndProg
```

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