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Work Plan for Vadose Zone Moisture Monitoring at Material Disposal Area T at Technical Area 21

Los Alamos
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Responsible project manager:

Bruce Wedgeworth	[signature]	Project Manager	Environmental Programs	7/28/11
Printed Name	Signature	Title	Organization	Date

Responsible LANS representative:

Michael J. Graham	[signature]	Associate Director	Environmental Programs	7/28/11
Printed Name	Signature	Title	Organization	Date

Responsible DOE representative:

George J. Rael	[signature] for	Manager	DOE-LASO	7/28/11
Printed Name	Signature	Title	Organization	Date

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1.0 INTRODUCTION

This work plan describes a proposed moisture-monitoring network to be installed in the vadose zone beneath Material Disposal Area (MDA) T at Technical Area 21 (TA-21) at Los Alamos National Laboratory (LANL or the Laboratory). The moisture-monitoring network was recommended in the Technical Area 21 Groundwater and Vadose-Zone Monitoring Well Network Evaluation and Recommendations (the network evaluation) (LANL 2010, 109947). The network evaluation addressed the adequacy of the existing groundwater and vadose zone monitoring networks for detecting known or potential hazardous constituent and radionuclide sources at TA-21. The evaluation recommended moisture and vapor monitoring near the waste disposal units at MDA T combined with groundwater monitoring of the regional aquifer (LANL 2010, 109947). Specifically, moisture-monitoring wells will be used to characterize and monitor vadose zone moisture content to evaluate potential corrective measures and long-term performance monitoring (LANL 2010, 109947). The moisture-monitoring network will focus on moisture migration because subsurface moisture can mobilize and transport soluble contaminants from the wastes buried at the site. The combination of moisture monitoring, as proposed in this work plan, and vapor monitoring near the disposal units with regional aquifer monitoring at regional wells R-64 and R-65 will provide a defense-in-depth program for monitoring MDA T. The New Mexico Environment Department (NMED) approved with modifications these recommendations and required submittal of a work plan proposing the methods, procedures, and design for the installing the proposed vapor-monitoring well and moisture-monitoring wells at MDA T (NMED 2010, 111462).

Moisture monitoring is proposed at MDA T because of the radiological inventory stored in the shafts and elevated residual moisture in the vadose zone resulting from infiltration beneath the MDA T adsorption beds. Vadose zone moisture in contact with the waste in the shafts and with the radiological contaminants present in and beneath the adsorption beds is considered the carrier for mobilizing and transporting soluble contaminants in the subsurface from the wastes buried at the site. In particular, water-soluble radionuclides present in the disposed waste will not transport to groundwater unless moisture present near the waste migrates downward. Therefore, monitoring of moisture migration will provide direct and timely evidence for potential radiological contaminant migration. The moisture data also will be used to establish baseline moisture distributions that can be used to guide and evaluate remedial alternatives. In addition, chemical analyses of core samples collected during borehole installation will further characterize the distribution of radiological contaminants beneath waste disposal units at MDA T.

The nature and extent of hazardous constituents in soil has been defined at MDA T (LANL 2006, 094151; LANL 2007, 100484; LANL 2009, 108012; LANL 2010, 108864); however, some uncertainty related to the extent of volatile organic compounds (VOCs) in pore gas remains. A work plan for installing a proposed vapor-monitoring well to monitor for tritium and for VOCs is provided in the Phase III investigation work plan for MDA T (LANL 2009, 105645) and is therefore not included in this work plan. A work plan for two downgradient regional wells near MDA T has also been completed (LANL 2011, 111604), and one of the regional wells (R-64) is being installed.

The site addressed in this monitoring work plan is potentially contaminated with both hazardous and radioactive components. NMED, pursuant to the New Mexico Hazardous Waste Act, regulates cleanup of hazardous wastes and hazardous constituents. The U.S. Department of Energy (DOE) regulates cleanup of radioactive contamination, pursuant to DOE Order 5400.5, Radiation Protection of the Public and the Environment; DOE Order 435.1, Radioactive Waste Management; and DOE Order 458.1, Administrative Change 1, Radiation Protection of the Public and the Environment. Information on radioactive materials and radionuclides, including the results of sampling and analysis of radioactive constituents, is voluntarily provided to NMED in accordance with DOE policy.

Corrective actions at the Laboratory are subject to the Compliance Order on Consent (the Consent Order). This work plan describes activities that will be executed and completed in accordance with the Consent Order.

This moisture-monitoring work plan provides details of the well-specific work plan for vadose zone moisture-monitoring wells at MDA T. This work plan also provides a conceptual model of flow and transport based on characterization and modeling studies for MDA T, including a discussion of uncertainties in section 2; a description of four activities, including the installation of a vadose zone moisture-monitoring system for MDA T, in section 3; a sampling and analysis plan for drilling at MDA T in section 4; and a schedule in section 5. Appendix A includes reviews of moisture-monitoring technologies.

1.1 Objectives

This vadose zone moisture-monitoring work plan outlines the basis for, and general approach to, moisture monitoring at MDA T.

The objectives of this work plan are to

- collect moisture-monitoring data to establish a baseline dataset for moisture conditions at MDA T,
- monitor movement of subsurface water beneath the absorption beds and shafts,
- determine if radionuclides have migrated from shafts (by sampling and analysis),
- assess the source(s) of elevated moisture beneath MDA T (by sampling and analysis), and
- provide data on unsaturated flow and transport and use for calibration/validation of model simulations.

2.0 CONCEPTUAL MODEL

2.1 Hydrology and Contaminant Transport at DP Mesa

Under natural conditions, DP Mesa fits the “dry and disturbed mesa conceptual model” for the Pajarito Plateau as defined by Birdsell et al. (2005, 092048). It is a dry finger mesa; the hydrologic conditions on the surface and within such dry mesas generally lead to slow unsaturated flow and transport. Dry mesas shed precipitation as surface runoff to the surrounding canyons such that most deep infiltration occurs episodically following snowmelt, and even then much of the water is lost through evapotranspiration. As a result, annual net infiltration rates for dry mesas are less than 10 mm/yr and are more often estimated to be on the order of 1 mm/yr or less (Kwicklis et al. 2005, 090069). Because dry mesas are generally composed of nonwelded to moderately welded unsaturated tuffs with low water content, water flow is matrix-dominated rather than fracture-dominated. Under natural or undisturbed conditions, travel times for contaminants migrating through dry mesas to the regional aquifer are expected to be several hundred to thousands of years (Nylander et al. 2003, 076059.49; Birdsell et al. 2005, 092048). However, beneath disturbed sites or those where liquid wastes were disposed of, travel times to groundwater may be shorter.

MDA T was used for disposal of liquid waste. Enhanced moisture migration and decreased contaminant travel times to groundwater are expected beneath liquid waste disposal sites where infiltration beneath absorption beds increased the moisture content, decreased matric potential, and increased downward driving forces in the underlying tuffs. Field observations indicate moisture migration may have included components of both fracture and matrix flow during periods of liquid discharge (Nyhan et al. 1984, 058906; LANL 2004, 085641). With discharges discontinued, the adsorption beds and underlying tuff are no longer saturated, and moisture migration is expected to occur as matrix flow under present-day and future conditions (Soll and Birdsell 1998, 070011; Birdsell et al. 2005, 092048). Also, infiltration rates at the ground surface are expected to have returned to near-background levels. However, an extended period of greater than normal, downward water flow likely continues at depth under MDA T based upon elevated vadose zone moisture contents.

A reported total of approximately 18 million gallons of wastewater containing plutonium was disposed of in the MDA T absorption beds between 1945 and 1967, 14 million gallons of which was disposed of between 1945 and 1950 (Rogers 1977, 005707). During disposal operation, water movement from the beds was probably primarily vertical. Water from the absorption beds may have moved rapidly through vertical fractures (primarily in units Qbt 3 and Qbt 2) and paleochannel soils during near-saturated conditions. Water may also have moved laterally at hydrologic contacts (e.g., at the vapor phase notch between Qbt 1v/1g, in Cerro Toledo interval and Tsankawi Pumice Bed).

The disposal shafts were installed between 1968 and 1974, 18 to 24 yr after 14 million gallons of the 18 million gallons of wastewater had been disposed of (LANL 2006, 094151). Over 99% of the radiologic inventory disposed of at MDA T was disposed of in the shafts, while less than 1% was disposed of in the beds with wastewater. Wastes disposed of in the shafts were primarily radiological waste mixed with cement for stabilization. This process is thought to immobilize the radiological constituents through a mineralization reaction with the cement. Therefore, the vast majority of the radiologic inventory of MDA T should not be affected by water movement because it is bound in a cement-based waste. Figure 2.1-1 shows the percentages of radiologic inventory between the absorption beds and the shafts at MDA T.

There is no direct evidence of high residual moisture from wastewater disposed of in absorption beds being present in the shaft field during shaft installation, which began in 1968. In contrast, Purtymun et al. reported volumetric water contents (VWCs) of 7% to 10% in a borehole (TH-7) located 2 ft (to the north) from a shaft drilled in 1968, which correspond to gravimetric water contents (GWCs) of approximately 5% to 7%, consistent with the data shown in Figure 2.1-2 (Purtymun et al. 1978, 005730). Purtymun et al. also reported that water contents in a separate borehole (TH-7A) drilled in 1969 and located 2 ft (to the east) from the same shaft had VWCs of 4% to 8% (GWCs of 3% to 5%), indicating apparent drying because of cement hydration. They concluded that disposing of wet cement wastes in the shafts at MDA T may not have increased the subsurface moisture content because the cement removed water from the surrounding formation as it cured. Also, these reported water contents are low and indicate that the area of boreholes TH-7 and TH-7A located 60 cm from an unidentified shaft were either unaffected by disposed wastewater in the absorption beds or else elevated water contents had decreased in the time since most of the approximately 18 million gallons had been disposed of in the absorption beds (Purtymun et al. 1978, 005730).

2.2 Vadose Zone Moisture Field Observations

Vadose zone moisture data from the vicinity of MDA T have been compiled in the form of gravimetric water content versus depth. Core samples from seven boreholes at or near MDA T are included. Water content data from deep boreholes at MDAs A and V are included, along with data from boreholes LADP-3 and LADP-4 for comparison. These data are used to define the extent of moisture beneath MDA T so the vadose zone monitoring network will target the appropriate strata to detect moisture migration. Information on these 11 boreholes is summarized in Table 2.2-1.

The MDA A borehole is included because it was drilled in a dry site that was unaffected by liquid disposal activities and should represent near-ambient conditions. Unfortunately, this borehole is only 360 ft deep and does not penetrate into the Otowi Member. The MDA V borehole is included because it was drilled in the center of MDA V, which consists of three absorption beds where approximately 40 million gallons of wastewater was disposed of between 1945 and 1961 (LANL 2006, 094361), so these data should represent wet conditions, perhaps throughout the Otowi Member. The water contents in borehole LADP-3 represent wet conditions in Los Alamos Canyon where the canyon floor is subjected to large runoff and infiltration events, and the canyon has a shallow alluvial aquifer. The water contents in borehole LADP-4 represent drier conditions beneath DP Canyon compared with Los Alamos Canyon. Although borehole LADP-4 is located at the bottom of a canyon, DP Canyon is a small canyon that experiences smaller runoff events than occur in Los Alamos Canyon. Figure 2.2-1 shows the locations of the seven boreholes at MDA T plus borehole LADP-4 in DP Canyon.

Figure 2.1-2 shows water content profiles from all 11 boreholes, with the profiles from boreholes LADP-3 and LADP-4 repositioned to align stratigraphic contacts to the approximate equivalent depths of the MDA T borehole data (since they are located within canyons below the ground surface [bgs] elevation of MDA T). The water content data are fairly consistent in the top 350 ft of the profile. The profile from MDA A appears to have lower water contents, but the data density from this borehole is lower than for the other boreholes for a direct comparison. The water contents in the Otowi Member (between about 350 and 625 ft deep) from boreholes 21-25262 and 21-607955 (both drilled near MDA T) are similar to the water contents from the MDA V borehole where 40 million gallons of wastewater was disposed of. In addition, these two MDA T boreholes have similar water contents to those measured in the Otowi Member in borehole LADP-3 located in wet Los Alamos Canyon. The water contents from borehole LADP-4 in dry DP Canyon are considerably lower than for all other borehole data from the Otowi Member. These data suggest that throughout the Otowi Member under MDA T, conditions are wetter than ambient dry mesa conditions. Since the water contents do not decline in borehole 21-607955 until a depth of between 800 and 875 ft, it is possible that the gravimetric water contents are elevated to this depth as a result of previous wastewater disposal in the MDA T absorption beds. Comparison to the gravimetric water contents in the Otowi Member from TA-49 (Stimac et al. 2002, 073391) and TA-54 (Krier et al. 1997, 056834) also suggests the water contents observed in the Otowi Member beneath MDA T are elevated relative to these other two TAs.

2.3 Nature and Extent of Contamination

The nature and extent of contamination at MDA T are described in detail in the MDA T investigation report (LANL 2006, 094151); the Phase II MDA T investigation report (LANL 2007, 100484); the Phase III MDA T investigation report (LANL 2009, 108012); and the replacement pages for the Phase III MDA T investigation report (LANL 2010, 108864).

To summarize the findings in those reports, the radionuclides plutonium and americium were detected to depths of 342 and 109.5 ft bgs, respectively, and tritium was detected to 340 ft bgs. Strontium-90 was detected at a concentration of 0.348 pCi/g at a depth interval of 800 to 802 ft bgs in borehole 21-607955. These data are anomalous because strontium-90 was not detected between depths of 179 ft and 799 ft bgs. No samples were collected beneath the shafts during the investigations at MDA T, so it is not known if radionuclides have migrated from the shafts.

The nature and extent of hazardous constituents have been defined: perchlorate and nitrate appear to have migrated to depths of 335 and 373 ft bgs, respectively, while VOCs appear to have reached depths of 575 ft bgs as vapors (LANL 2009, 108012; LANL 2010, 108864). Metals have not migrated as deep as other hazardous constituents (LANL 2006, 094151).

2.4 Numerical Modeling of Flow Using the Finite-Element Heat- and Mass-Transfer Model

The numerical model Finite-Element Heat- and Mass-Transfer Code (FEHM) (Zyvoloski et al. 1997, 070147) was used to simulate the flow of water from the four absorption beds to define expected moisture profiles and to assist with monitoring system design (i.e., what conditions can be expected now and in the future). A full three-dimensional model was constructed from the ground surface to the regional water table. Water was applied to the absorption beds in the time series described in (Rogers 1977, 005707). The model assumed 40%, 30%, 10%, and 10% of the total wastewater was applied to absorption beds 1, 2, 3, and 4, respectively, and the shafts did not contribute water to the subsurface. Ambient infiltration/recharge conditions were set to 1 mm/yr. A two-dimensional (2-D) cross-section that runs along a west-east line through absorption beds 1 and 4 was used to display model results.

Model results are shown in Figure 2.4-1 as 2-D profiles of percent saturation in 1950, 1970, and 2010. The geologic contacts shown in the figure are from borehole 21-607955 and may not extend through all of MDA T. The results indicate the wetting front reaches a depth of about 500 ft bgs in 2010. These results are not consistent with the observations of water content shown in Figure 2.1-2, particularly for borehole 21-607955 that appears to show elevated water content to greater than 800 ft bgs. This discrepancy may be the result of the hydraulic properties used in the model (i.e., more flow via fractures than simulated) or it could be because greater amounts of water were disposed of than the 18 million gallons reported. For example, operational spills and leaks of unknown quantity may have occurred at MDA T (LANL 2006, 094151).

Model results are also shown as a time series of saturation and estimated gravimetric water content (Figure 2.4-2) and water potential (Figure 2.4-3). Water potential can be related to water content using the water retention curve data for each hydrogeologic unit. Figure 2.4-2 illustrates that calculated water contents are currently (in July 2011) decreasing at depths of 70, 155, and 320 ft bgs and increasing at a depth of 588 ft bgs (under bed 1) from the wastewater disposed of in the absorption beds. Figures 2.4-1 and 2.4-2 also indicate that the moisture added to the beds is now distributed beneath the shafts so there is little difference beneath the two areas, and elevated moisture contents (relative to background conditions) may currently be present in the shaft field. Figure 2.4.3 illustrates water potentials for the same depths and areas and shows the range of water potentials that can be expected between 2011 and 2045. This range of −0.6 to −2.4 bars falls within the range of measurement capabilities for heat dissipation probes (HDPs) (see Appendix A). Figures 2.4-2 and 2.4-3 also show that the water contents and water potentials are not expected to change much with time after 2011.

2.5 Uncertainties in Vadose Zone Conceptual Model

During the process of evaluating information for this work plan, two key uncertainties related to the conceptual model of the vadose zone were identified.

1. The first uncertainty is related to the depth to which the water contents are elevated beneath MDA T. Water contents appear to be elevated in deep boreholes beneath MDA T to depths between 800 and 875 ft bgs compared with water content data from borehole LADP-4 in DP Canyon. However, contaminants have not migrated as deep as the apparent elevated moisture front. In terms of monitoring moisture to indicate contaminant transport, uncertainty related to the extent of the moisture front is important where contaminants are also present.

2. The second uncertainty is related to migration of radionuclides from the shafts. Since no samples have been taken directly beneath the shafts, it is uncertain whether radionuclides have migrated out of the cement in the shafts.

The deepest penetration of wastewater is presumed to be beneath absorption bed 1 (which reportedly received the most wastewater) or beneath the center of the shaft field, as a result of converging wetting fronts from all four beds. No deep boreholes are located in the center of MDA T.

These uncertainties can be reduced by (1) drilling a borehole in the center of the MDA T shaft field to a depth of approximately 400 ft to determine the extent of a moisture front caused by wastewater disposal in the absorption beds and by measuring radioactive constituents in core collected in this borehole; (2) drilling a 400-ft borehole in an undisturbed area of TA-21 (probably near the eastern end of DP Mesa) to determine ambient water content and to collect data to compare with data from the borehole located in MDA T; and (3) drilling angled boreholes beneath the shafts and measuring radioactive constituents in core collected in these boreholes.

To determine whether the water content values in the Otowi Member beneath MDA T are elevated because of wastewater disposal, or if they represent ambient conditions unaffected by disposal activities, this work plan proposes drilling a new deep borehole in a relatively undisturbed area of TA-21 to provide data on ambient conditions unaffected by liquid disposal activities. Data from this borehole will also support calibration and/or validation of numerical flow and transport models that are used for the performance assessment of MDA T.

The monitoring approach described below collects data specifically to address these uncertainties.

3.0 APPROACH

The vadose zone monitoring system described in this work plan consists of four activities.

- Activity 1: Conduct a vadose zone moisture-monitoring pilot study in an undisturbed area of TA-21
- Activity 2: Install a deep borehole in an undisturbed area of TA-21
- Activity 3: Install a vadose zone moisture monitoring system at MDA T
- Activity 4: Conduct chemical analyses of core samples

Activities 2 and 3 will provide data to address the uncertainty related to the extent of elevated moisture where contaminants are also present. Activity 4 is designed to address uncertainty related to radionuclide migration from the shafts.

3.1 Activity 1: Conduct a Vadose Zone Moisture Monitoring Pilot Study

Moisture-monitoring techniques and equipment options are described and evaluated in Appendix A of this work plan. The evaluation concluded heat dissipation probes (HDPs) are an appropriate technology for moisture monitoring in the strata beneath MDA T and their use is assumed in the proposed activities. However, because these probes have not been deployed previously at a Laboratory field site, a pilot study is proposed for Activity 1 to test probe installation and well completion techniques and to confirm their applicability in the local subsurface environment. Currently, the water content and water potential in the subsurface beneath MDA T may be changing only slowly (Figures 2.4-2 and 2.4-3). Therefore, data collected by the HDPs deployed at MDA T may not measure transient behavior. To provide confidence in the use of the HDPs, the pilot test will include an infiltration test by applying water at the ground surface to demonstrate the probes work well under transient conditions.

The purpose of the vadose zone moisture monitoring pilot study is to provide a testing environment for the moisture-monitoring system to be installed at MDA T (described below under Activity 3). The pilot study will include three 140-ft-long (100-ft-deep) 45-degree angled boreholes. One borehole will be cased with polyvinylchloride (PVC) pipe and used for neutron logging. The other two boreholes will be drilled, instrumented with HDPs, and backfilled. One of the HDP boreholes will be backfilled with crushed tuff, and the other will be backfilled with a well-sorted sand to test the time it takes for HDPs to reach equilibrium with the native tuff. This pilot study will also enable testing methods for backfilling boreholes using tremie pipe.

The area of the pilot study will be built with a berm around the boreholes to allow for an infiltration test. After installation of these three boreholes, the sensors will be allowed to equilibrate for several months. Then, water will be applied to the bermed area to demonstrate sensor response and to allow comparison of the water contents measured using a neutron probe to water potential measured with HDPs. Neutron probes have been used successfully to measure moisture content at the Laboratory, including transient events, and this comparison will provide confidence in the use of HDPs beneath MDA T.

Calibration of the neutron probe is required for neutron logging at the pilot study site. Neutron probe calibration will be accomplished using one or more of these methods, depending on the quality of a site-specific calibration: (1) calibration of neutron moisture meter to site-specific conditions (borehole casing and type, neutron meter, and media); (2) factory calibrations; and/or (3) previous information (other Laboratory calibrations).

3.2 Activity 2: Install a Deep Borehole in an Undisturbed Area of TA-21

The purpose of Activity 2 is to collect water content and water potential data from an undisturbed location for comparison with water content data collected near MDA T. This borehole (vadose zone monitoring borehole [VZM] 01) will be used to establish ambient water content conditions in the vadose zone, including at the interface between the Cerro Toledo interval and the Otowi Member and into the Otowi Member. Analyses of water potential and water content will provide information on whether or not the water content data shown in Figure 2.1-2 indicate moisture conditions that are above background conditions. This borehole will be drilled to 400 ft bgs, samples will be collected, neutron logging will be conducted once, and then the borehole will be backfilled. These data will reduce uncertainty related to the depth of elevated moisture beneath MDA T to a depth that is consistent with observations of contaminant nature and extent beneath MDA T. These data will also enable calibration and validation of numerical models of flow and transport that are used for the radiological dose assessment of MDA T.

3.3 Activity 3: Install a Vadose Zone Moisture Monitoring System at MDA T

The MDA T moisture-monitoring system consists of

- 1400-ft-deep vertical borehole drilled in the middle of the shaft field instrumented with HDPs, and
- four 140-ft-long (100-ft-deep) 45-degree angled boreholes drilled under the absorption beds and shaft field and instrumented with HDPs.

Figure 3.3-1 shows the proposed locations of the one vertical and four angled boreholes at MDA T. The drilling, completion, and instrumentation of at these boreholes will be contingent upon the results of the moisture-monitoring pilot study (Activity 1).

One 400-ft-deep vertical borehole drilled in the middle of the shaft field (VZM-02) is proposed. This borehole will be instrumented with HDPs and backfilled. The HDPs installed in VZM-02 will provide moisture-monitoring data at depths into the Otowi Member. Figure 3.3-2 shows a cross-section schematic diagram of the vertical borehole in the shaft field.

Four 140-ft-long (100-ft-deep) 45-degree angled boreholes drilled under absorption beds and shafts (VZM-03, -04, -05, -06) will also be used to collect more data to determine the nature and distribution of radionuclides beneath the disposal units. These four boreholes will be instrumented with HDPs and backfilled to provide high-density moisture data beneath the shafts. Figure 3.3-3 shows a cross-section schematic diagram of an angled borehole under the shaft field.

The exact numbers of sensors and citing of sensors in the boreholes will depend on the water content values observed during drilling. Sensor citing will also consider the locations of hydrogeologic units and minimum numbers of sensors per unit. Water contents and water potentials will be measured in the field during drilling as well as at an analytical laboratory using core samples collected during drilling. A maximum of 64 HDPs can be wired into one datalogger using one multiplexer. If one datalogger is sited with each borehole, then 64 HDPs can be installed in each borehole. If HDPs are installed with two sensors at each location (for redundancy in case of failure), then a total of 32 depths can be instrumented in each borehole. It is more likely that about 20 HDPs will be installed in each of the four angled boreholes, and about 32 installed in the vertical borehole for a total of 112 HDPs.

3.4 Activity 4: Conduct Chemical Analyses of Core Samples

Chemical analyses of core collected from the five MDA T boreholes proposed under Activity 3 will be used to define the extent of radionuclides beneath the shafts. Specifically, since no samples have been collected directly beneath the shafts, it is uncertain whether the radionuclides in cement wastes disposed of in the shafts are immobile or if they have migrated. The priority of this activity is to address this uncertainty.

The analyses may also enable “fingerprinting” of vadose zone pore water to help determine if the moisture source at a given depth is from the absorption beds or the shafts. Fingerprinting of the water is a secondary priority that may provide information about shaft waste mobility, inform the site conceptual model, and be useful for modeling related to long-term site performance.

Laboratory analyses that will be conducted include

- water content,
- water potential, and
- pH.

Radionuclides

The set of radionuclide analyses of core samples proposed in this work plan is the typical suite that is conducted generally for Laboratory investigation reports and includes the following:

- Americium-241
- Cesium-137
- Europium-152
- Plutonium-238
- Plutonium-239

- Strontium-90
- Tritium
- Uranium-234
- Uranium-235
- Uranium-238

In addition, nonstandard radionuclide analyses will include neptunium-237 because it is a daughter of americium-241 and is generally more mobile than either americium-241 or plutonium.

Pore-Water and Isotopic Analyses

Additional pore-water samples will be analyzed by the Laboratory's Earth Systems Observations Group of Earth and Environmental Sciences Division (EES-14). Activities for the radionuclides listed above will also be analyzed from extracted pore-water samples and compared with core sample data to evaluate mobile versus bound radiological constituents. In addition, isotopic analyses of pore water will be conducted and include the following:

- Chloride (to evaluate pore water age and the degree to which pore water has been subjected to infiltration and evaporation). Although chloride is usually most useful for estimating natural infiltration, comparison of chloride profiles between disturbed and undisturbed locations will help identify the source of MDA T pore water.
- Sulfur stable isotopes ($\delta^{34}S$) (to differentiate water from beds or shafts). Sulfur is found in minerals used in cement, and the isotopic analysis should help to identify whether any water has migrated from the MDA T shafts.
- Oxygen and hydrogen stable isotopes ($\delta^{18}O$, δD) (to differentiate water sources, the degree to which water has been subjected to evaporation, and combined with chloride to evaluate relative age).
- Nitrogen stable isotopes ($\delta^{15}N$) of nitrate (to differentiate water source from beds or shafts). Nitric acid may have been disposed of with the wastewater into the absorption beds, so isotopic analysis of nitrate will help to identify whether the pore waters are from absorption beds.

3.5 Borehole Summary

Table 3.5-1 summarizes the five vadose zone moisture monitoring boreholes (VZM-02 through VZM-06, Activities 3 and 4) proposed for monitoring moisture movement beneath MDA T as well as the borehole (VZM-01, Activity 2) proposed for measuring moisture in an undisturbed area. In addition, three boreholes are proposed for the pilot study (Activity 1).

4.0 SCHEDULE

This work scope will be conducted following NMED approval of this work plan. The proposed start date is fiscal year 2012, with the pilot study conducted first and then the monitoring boreholes in MDA T installed and instrumented.

5.0 REFERENCES

The following list includes all documents cited in this work plan. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate's Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the NMED Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

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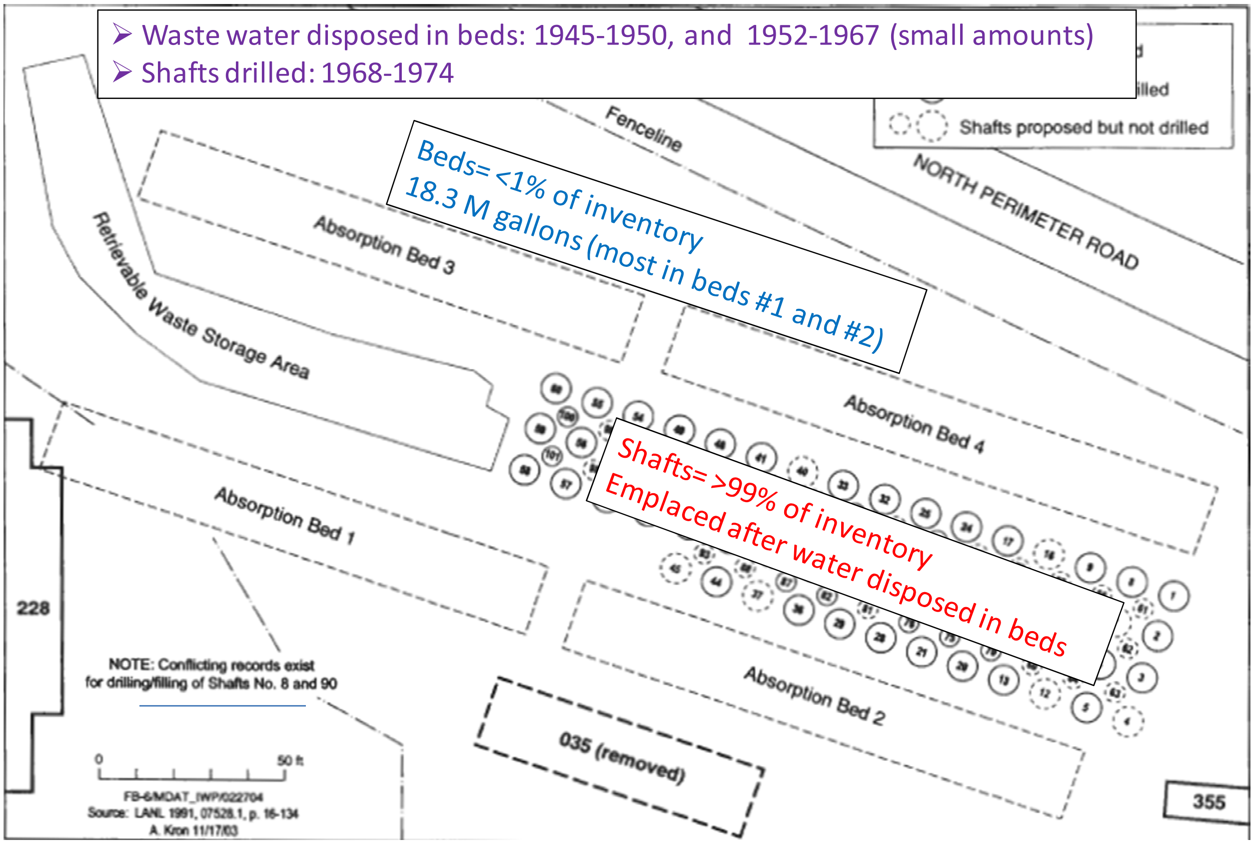

Figure 2.1-1 Locations of absorption beds and shafts at MDA T illustrating relative radionuclide inventory estimates

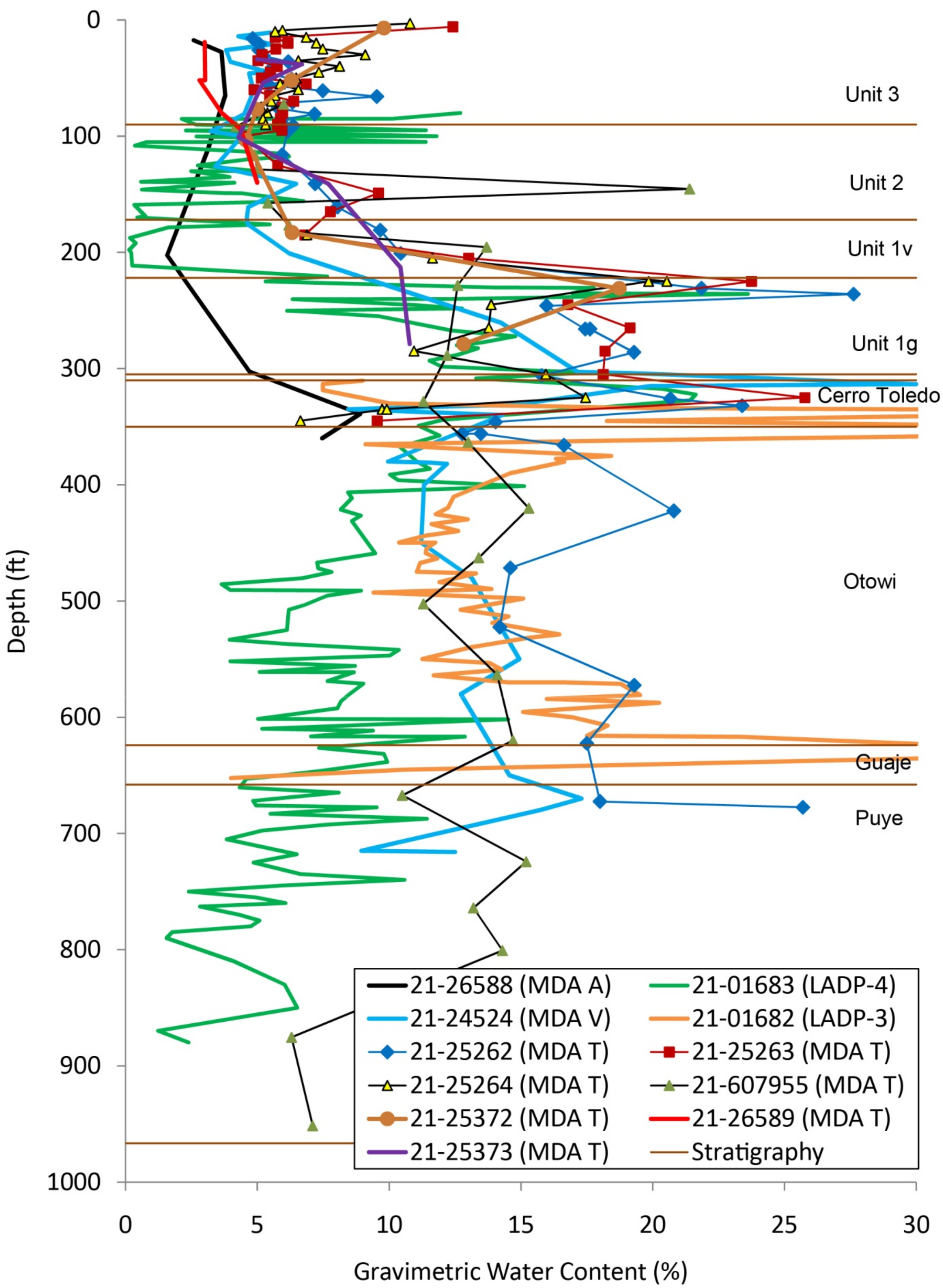

Figure 2.1-2 Water-content data from boreholes at and near MDA T

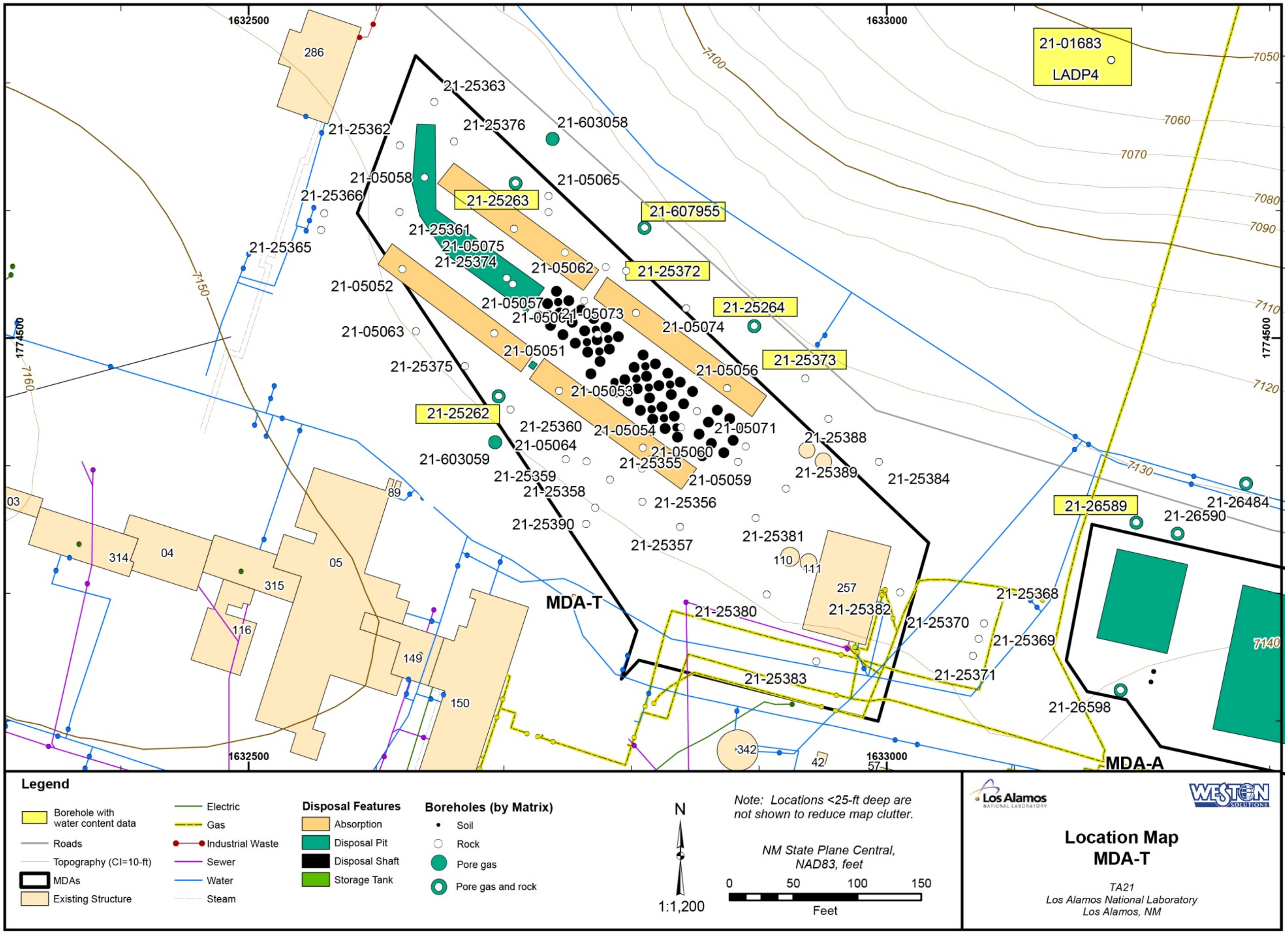

Figure 2.2-1 Locations of boreholes with water-content data at MDA T and in DP Canyon

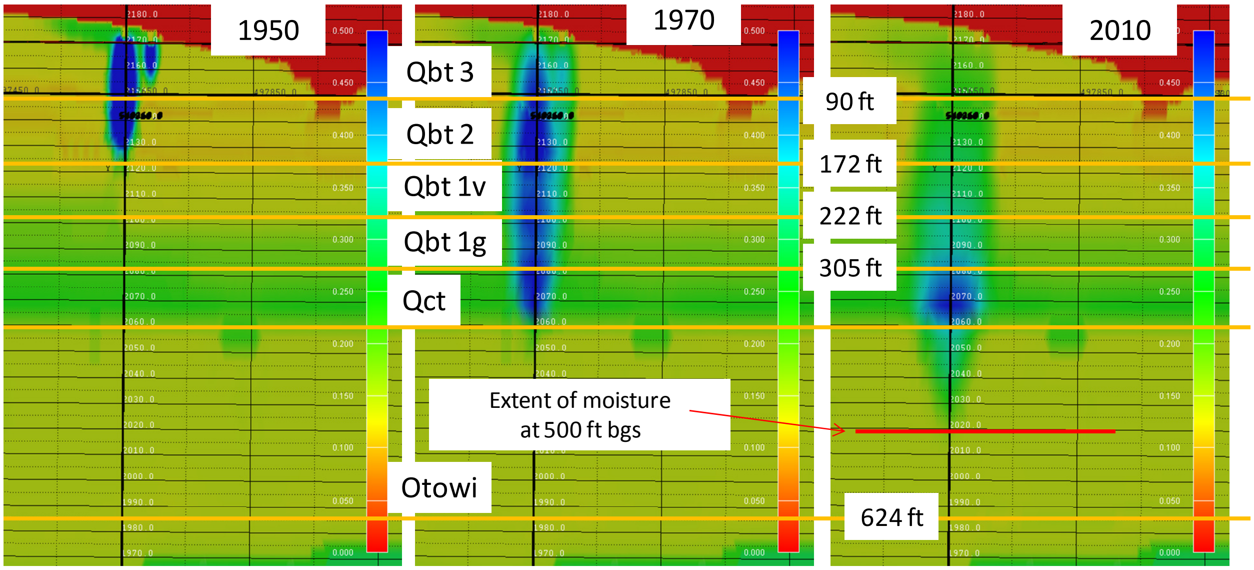

Figure 2.4-1 FEHM model results showing saturations under MDA T in 1950, 1970, and 2010

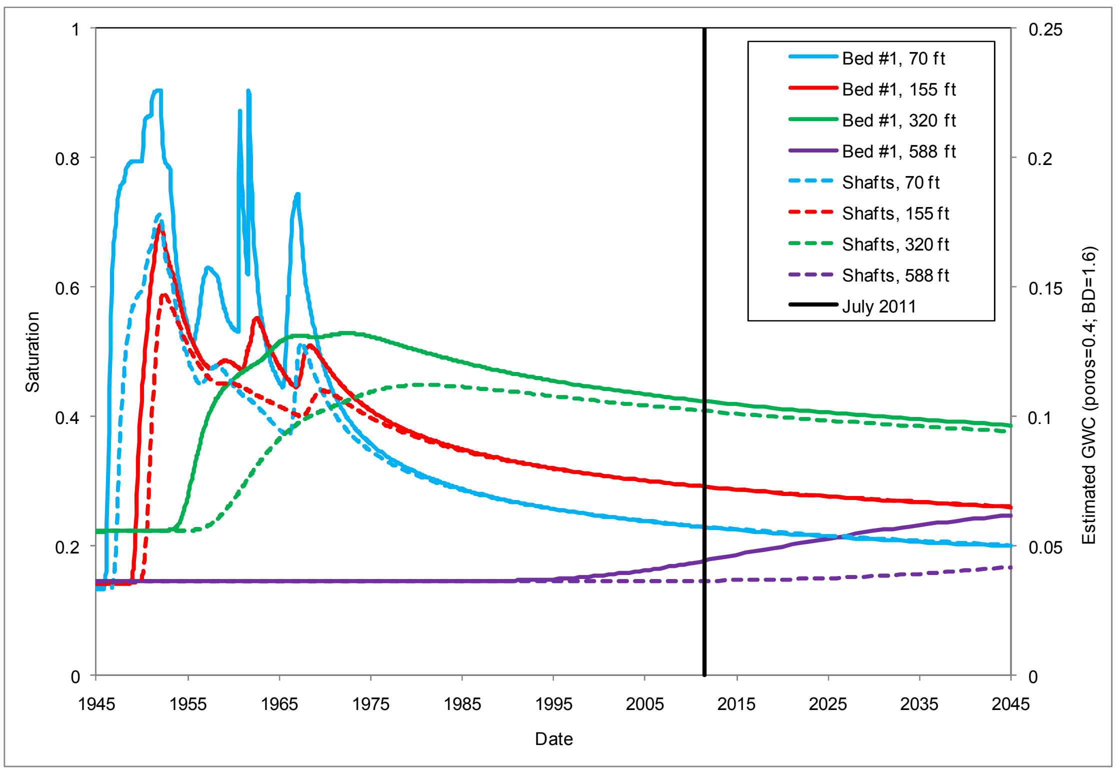

Figure 2.4-2 FEHM model results showing time series of saturation at four depths beneath absorption bed 1 and the shaft field

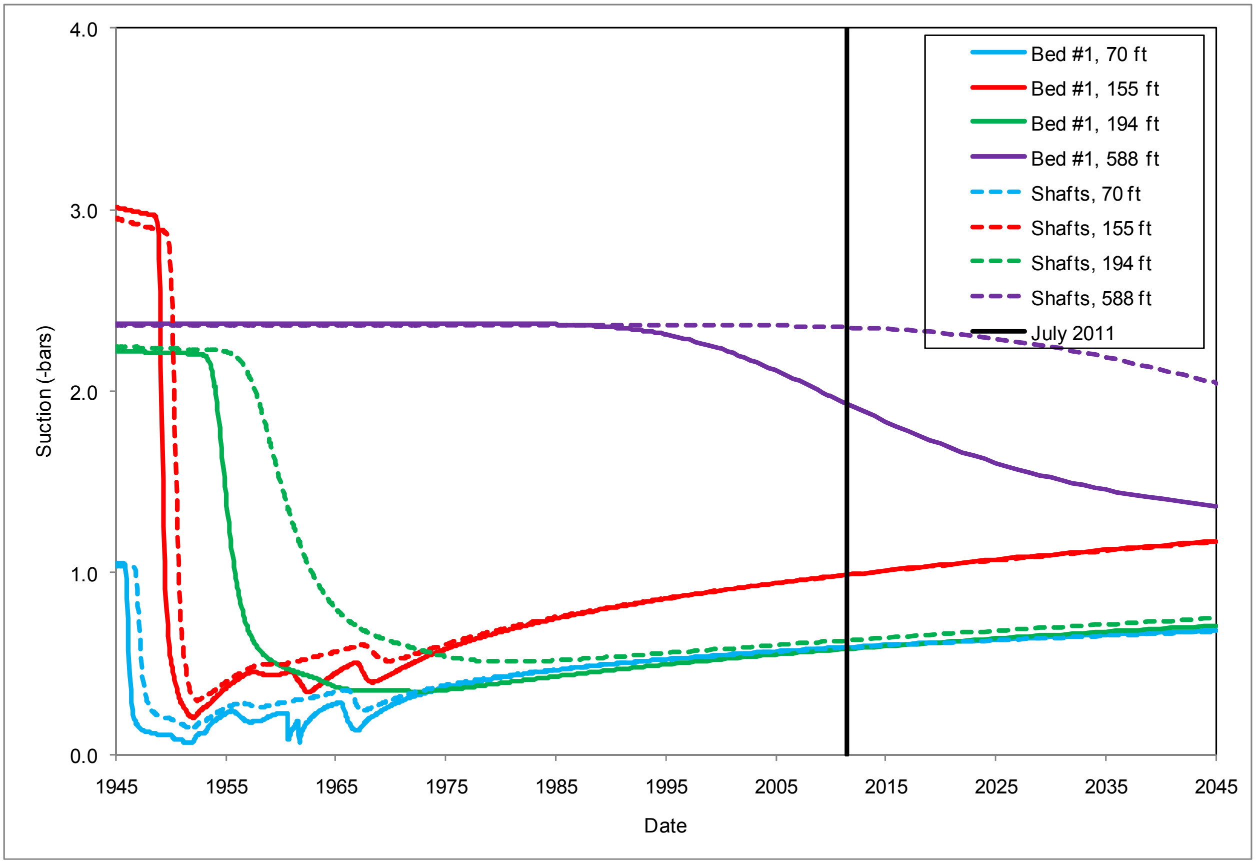

Figure 2.4-3 FEHM model results showing time series of water potentials at four depths beneath absorption bed 1 and the shaft field

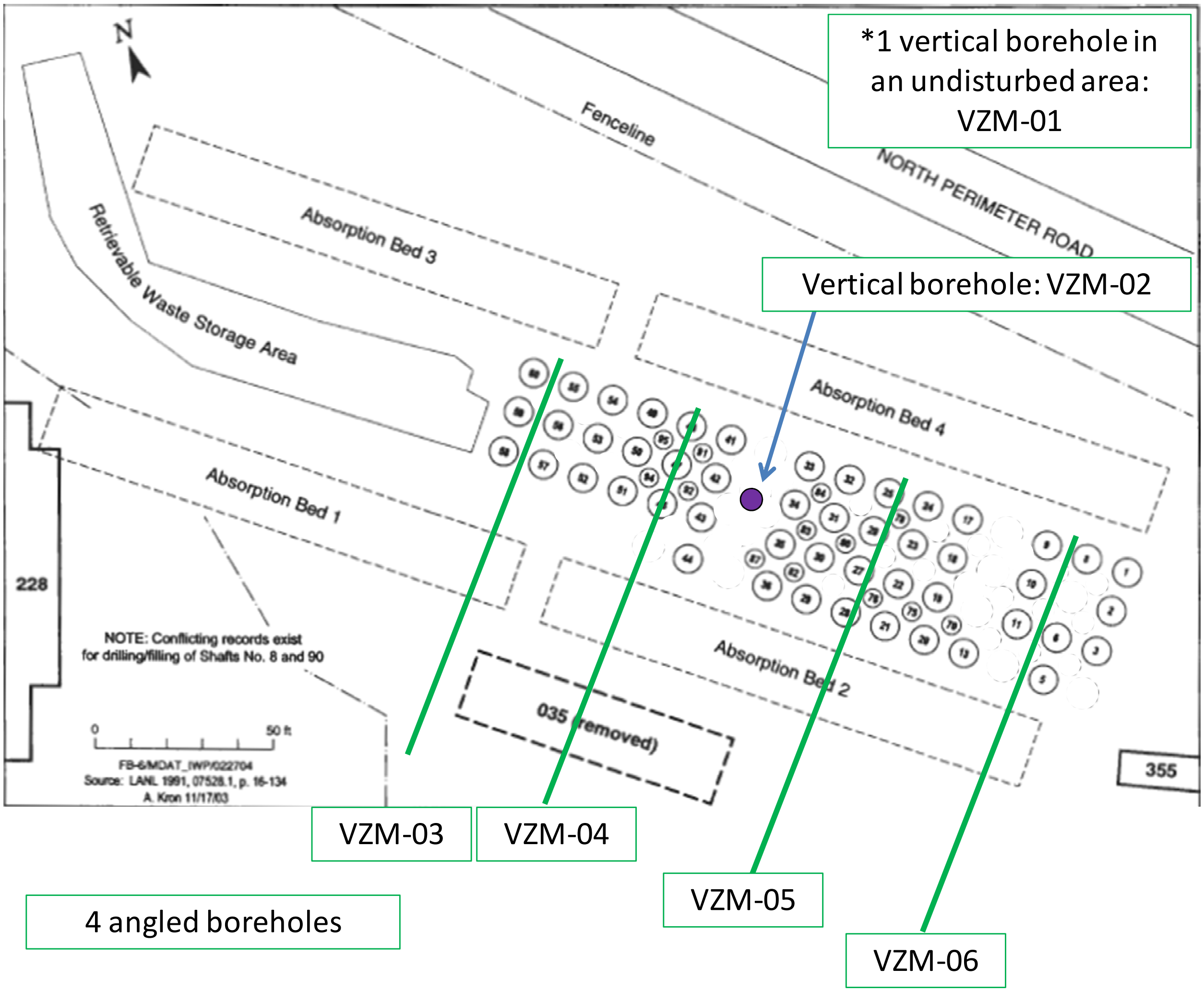

Figure 3.3-1 Locations of proposed vertical and angled boreholes at MDA T

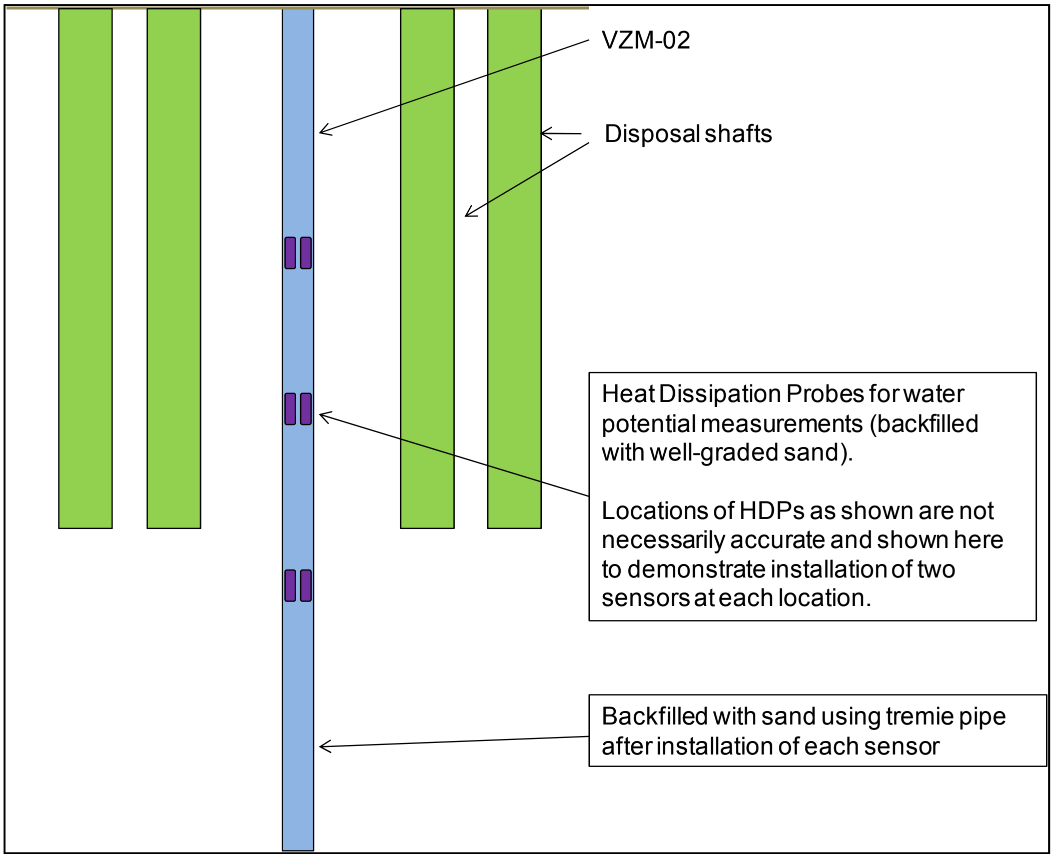

Figure 3.3-2 Cross-section schematic diagram of vertical boreholes in shaft field

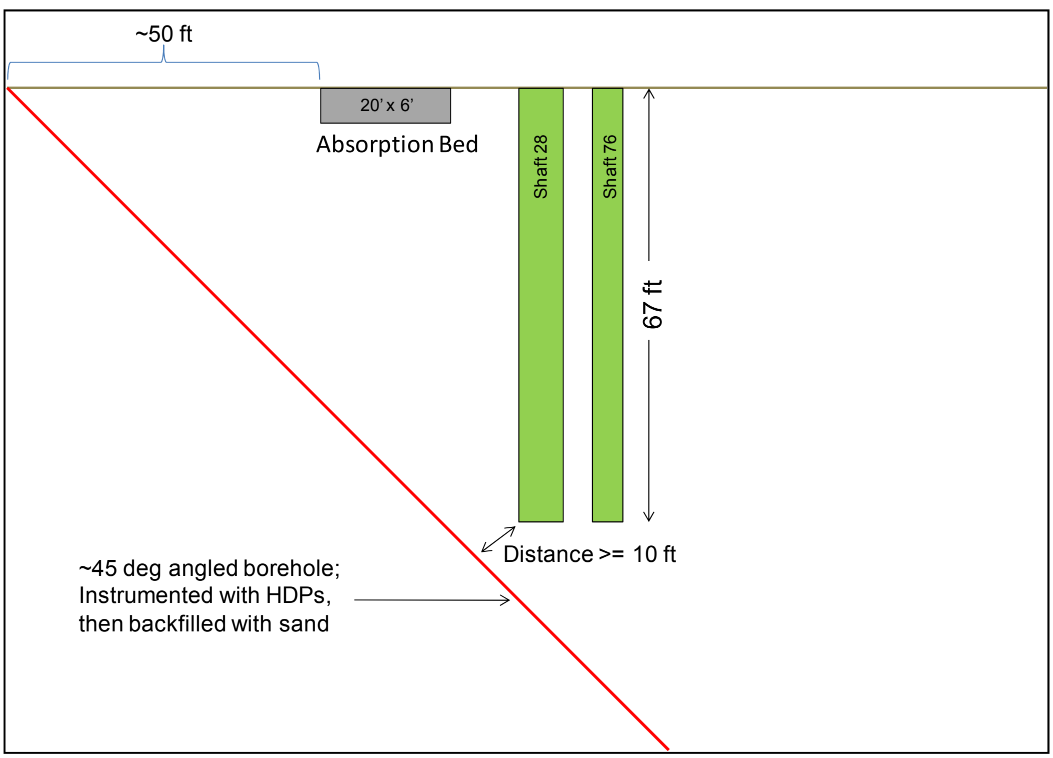

Figure 3.3-3 Cross-section schematic diagram of angled boreholes under shaft field

Table 2.2-1
Summary of MDA T and Nearby Boreholes with Moisture Data

Borehole ID	Depth (ft)	Location	Conditions
21-25262	680	S of bed #1	Potentially affected by MDA T wastewater
21-25263	345	N of bed #3	Potentially affected by MDA T wastewater
21-25264	345	N+E of bed #4	Potentially affected by MDA T wastewater
21-60755	953	N of bed #4	Potentially affected by MDA T wastewater
21-25372	279	N of bed #4	Potentially affected by MDA T wastewater
21-25373	279	N+E of bed #4	Potentially affected by MDA T wastewater
21-26589	140	E side of MDA T	Unlikely to be affected by MDA T
21-26588	360	MDA A	Dry; no known liquid disposed of
21-24524	716	MDA V	Wet; 40 million gallons disposed of
21-01682 (LADP-3)	342	LA Canyon	Wet
21-01683 (LADP-4)	800	DP Canyon	Dry; especially in Otowi

Table 3.5-1
Summary of MDA T Vadose Zone Monitoring Boreholes

Borehole ID	Borehole Description	Purpose	Methods
VZM-01 Vertical	8-in.-diameter vertical, 400-ft deep, uncased, backfilled; located in undisturbed area of TA-21	Measure undisturbed water content and water potential	Drill using hollow-stem auger (HSA); Collect samples for water content/potential
VZM-02 Vertical	8-in.-diameter vertical, 400-ft deep, uncased, backfilled with sand around HDPs; located in middle of shaft field	Measure water potential at ~16 depths once per day using datalogger and sensors	Drill using HSA; Collect samples for full radionuclide analyses plus water content/potential
VZM-03 45-degree angle	8-in,-diameter angled, 100-ft deep, uncased, backfilled with sand around HDPs; located 50 ft south of absorption bed 2	Measure water potential at ~10 depths once per day using datalogger and sensors	Drill using HSA; Collect samples for full radionuclide analyses plus water content/potential
VZM-04 45-degree angle	8-in,-diameter angled, 100-ft deep, uncased, backfilled with sand around HDPs; located 50 ft south of absorption bed 2	Measure water potential at ~10 depths once per day using datalogger and sensors	Drill using HSA; Collect samples for full radionuclide analyses plus water content/potential
VZM-05 45-degree angle	8-in,-diameter angled, 100-ft deep, uncased, backfilled with sand around HDPs; located 50 ft south of bed absorption 2	Measure water potential at ~10 depths once per day using datalogger and sensors	Drill using HSA; Collect samples for full radionuclide analyses plus water content/potential
VZM-06 45-degree angle	8-in,-diameter angled, 100-ft deep, uncased, backfilled with sand around HDPs; located 50 ft south of absorption bed 2	Measure water potential at ~10 depths once per day using datalogger and sensors	Drill using HSA; Collect samples for full radionuclide analyses plus water content/potential

Appendix A

Review of Moisture-Monitoring Technologies

A-1.0 WATER CONTENT

This appendix presents reviews of vadose zone moisture-monitoring technologies and concludes with a recommendation of technologies that should be employed at Material Disposal Area (MDA) T at Los Alamos National Laboratory (the Laboratory).

A-1.1 Neutron Moisture Meter (Neutron Probe)

For many decades, neutron moisture meters, also called neutron probes, have been used to measure and monitor moisture in soil and rock. Neutron moisture meters have a neutron source that is typically lowered down a cased borehole where measurements are taken at the depth of interest. Measurements typically take less than one minute, but cannot be easily automated and are therefore labor intensive. Boreholes can be vertical, angled, or horizontal. McLin et al. (2005, 204544) describe applications using horizontal access boreholes under waste facilities to monitor changes in moisture.

Advantages: well-accepted, simple, reliable, has been used for more than 50 yr.

Disadvantages: requires calibration (to media, to meter, and to borehole geometry and casing material), labor intensive, infrequent observations. Neutron probe contains a radioactive source: there is a risk of losing a radioactive source in unstable boreholes.

A-1.2 Time Domain Reflectometry

Topp et al. (1980, 204680) first described the application of time-domain reflectometry (TDR) for measuring soil water content. Since then, Topp et al. (1980, 204680) has been cited thousands of times. TDR probes are generally about 30 cm long and rigid and not applicable for downhole installation. However, flexible TDR (FTDR) sensors have been also been used in boreholes (e.g., Dahan et al. 2009, 204542), although this type of application requires very good contact between the TDR probes and the surrounding media. If the borehole is backfilled, then the backfill material must be very similar to the surrounding media for TDR (or any other water content sensor) to be accurate.

Advantages: accurate, well-accepted.

Disadvantages: difficult to ensure good contact against tuff in open borehole; can be used in crushed tuff, but only if good contact is ensured (e.g., no air gaps from bridging).

A-2.0 WATER POTENTIAL

A-2.1 Heat Dissipation Probes

Heat dissipation probes (HDPs) (e.g., Flint et al. 2002, 204543) are water potential sensors whose premise is that water potential is proportional to thermal conductivity. When a constant power is dissipated from a line heat source, the temperature increase is proportional to the thermal conductivity of the media, and dry and wet media have different thermal conductivities. HDPs can measure a very wide range of water potentials (and inferred moisture content). Figure A-2.1-1 shows the measurement range of HDPs, and other water potential sensors, as well as the range of water potentials that might be expected in boreholes beneath MDA T (see predicted water potentials in Figure 2.4-3 of the work plan).

Advantages: accurate, well-accepted, very high resolution and large range of measurement, small sensor that can be installed in any type of backfill material (e.g., crushed tuff or sand), no cable length limitation.

Disadvantages: sensors are ceramic and subject to damage during installation. Sensor measures water potential, not water content.

A-2.2 Thermocouple Psychrometers

Thermocouple psychrometers (TCPs) are used to infer water potential of the surrounding media by measuring the relative humidity of the media. These sensors have been in use for decades (Rawlins and Campbell 1986, 204547) and have a much smaller measurement range than HDPs (see Figure A-2.1-1).

Advantages: accurate, well-accepted, high resolution, small sensor that can be installed in any type of backfill material (e.g., crushed tuff or sand).

Disadvantages: thermocouple wires are known to break after many measurements (due to heating). No known commercial manufacturer. Sensor measures water potential, not water content.

A-2.3 Tensiometers

Tensiometers are very simple water potential sensors that consist of a vacuum gauge that measures the suction caused by a tube filled with water coming into equilibrium with unsaturated media via a porous membrane (that allows water but not air to pass). Tensiometers have been in use since around 1922 (Cassel and Klute 1986, 204546). Sisson et al. (2002, 204545) describe an advanced tensiometer for use in shallow or deep vadose zones. Installation of these sensors at the Laboratory has been suggested by the Northern New Mexico Citizens' Advisory Board (NNMCAB) at its September 19, 2007 meeting (https://plus44.safe-order.net/nnmcab//minutes/2007_Attachments/9-19-07_CAB_MINUTES_FINAL_Part1.pdf). These sensors are not well suited for most sites at the Laboratory because conditions are too dry for any type of tensiometers. Ambient water potential conditions beneath the dry mesas at the Laboratory commonly exceed (are drier than) −10 bars while tensiometers have a range of suction of zero to about −700 cm (−0.7 bars) (see Figure A-2.1-1). Although conditions beneath MDA T are expected to be wetter than ambient conditions under dry mesas, they may not be wetter.

Advantages: simple design.

Disadvantages: measurement range is too limited, requires water in sensor (can dry out). No known commercial manufacturer. Sensor measures water potential, not water content.

A-3.0 WATER FLUX

Although water fluxmeters have been described in the literature for decades in various designs, they have recently become well-known in the soil science and vadose zone hydrology community since Dr. Glendon Gee wrote his first paper on them (Gee et al. 2002, 204679). Fluxmeters are unique in that they are the only method for measuring vertical water flux directly (i.e., deep infiltration or recharge). Fluxmeters are generally installed just below the root zone rather than in deep settings such as beneath MDA T.

Advantages: accurate, well-accepted, the only method for direct measurement of water flux.

Disadvantages: device is large (8 in. × 5 ft) and difficult to install in boreholes (must be greater than 12 in. diameter), some depth limitations (~100 ft maximum). Only a limited number of meters can be deployed because of their size and wire-length limitations.

A-4.0 POTENTIAL ISSUES WITH SENSORS

Sensor Damage during Installation

Sensors can be damaged while on the ground surface before installation, during installation into a borehole, or during backfilling of media around the sensors. The impacts of sensor damage can be mitigated by installing duplicate sensors at each location of interest and by testing sensors before/during/after installation.

Sensor Longevity

Little data on sensor longevity are available. Some sensors are known to last longer than others. For example, the fine-wire thermocouple in thermocouple psychrometers can break after many readings. Sensor longevity can be increased by taking limited measurements (daily versus hourly).

Time to Reach Equilibrium

Sensors can take anywhere from days to years to come into equilibrium with the surrounding media after drilling and sensor installation. In the case of HDPs, the manufacturer recommends installing sensors with their ceramic porous casing wetter than the surrounding media. Numerical modeling results suggest that sensor equilibrium will be reached faster using a well-graded sand that using a well-sorted (poorly graded) silica sand.

A-5.0 RECOMMENDED MOISTURE-MONITORING TECHNOLOGY FOR MDA T

Based on the information summarized in this appendix and given the constraints of sensor size, sensor contact requirements, and sensor measurement ranges, HDPs are the recommended moisture-monitoring technology for installing downhole sensors at MDA T.

A-6.0 REFERENCES

The following list includes all documents cited in this appendix. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate's Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the New Mexico Environment Department Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

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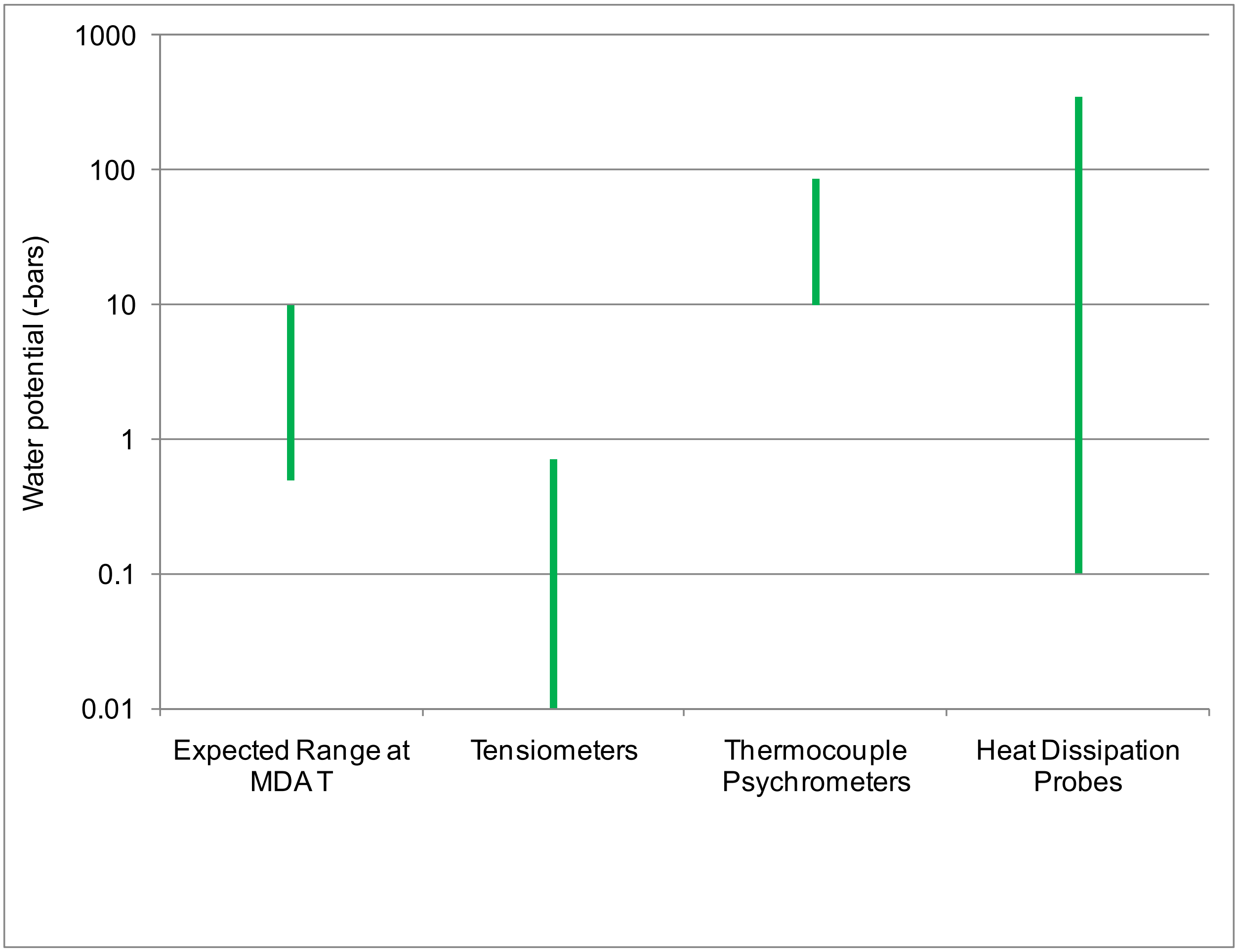

Figure A-2.1-1 Comparison of water potential sensor measurement ranges with the range expected beneath MDA T