Title:

APPLICATION OF TIME-DOMAIN REFLECTOMETRY TO
MONITORING CONDITIONS IN CRUSHED TUFF TEST
PLOTS AT LOS ALAMOS, NEW MEXICO: INTERPRETATION
AND RECOMMENDATIONS FOR LANDFILL MONITORING

Author(s):

Colleen Loeven Filippone
Tracy G. Schofield

Submitted to:

Prepared for the Department of Energy Office
of Technology Development Office of Environmental
Management. Submitted as a milestone requirement
of the Post-Closure Monitoring Technology
Development Program (TTP#A1141001)

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Form No. 836 R5
ST 2629 10/91

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

APPLICATION OF TIME-DOMAIN REFLECTOMETRY

TO MONITORING CONDITIONS IN CRUSHED TUFF TEST PLOTS

AT LOS ALAMOS, NEW MEXICO:

INTERPRETATION AND RECOMMENDATIONS FOR LANDFILL MONITORING

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Los Alamos National Laboratory

Colleen Loeven Filippone
Tracy G. Schofield

✓ August 1994

Prepared for the Department of Energy Office of Technology Development Office of Environmental Management. Submitted as a milestone requirement of the Post-Closure Monitoring Technology Development Program (TTP#AL141001).

✓

ABSTRACT

Horizontal and vertical measurements of moisture content were obtained daily using time domain reflectometry (TDR) at four sites in two crushed tuff experimental plots over a period of 287 days. Moisture contents were also measured weekly at the same locations and at two additional locations in the plots using the neutron probe method. Results are assessed to determine the influence of waveguide length and waveguide orientation on TDR moisture content measurements, the degree of spatial variability in measured moisture content in this engineered porous material, and the ability of TDR to resolve vertical moisture content gradients. Recommendations are made for TDR instrumentation of mixed waste landfill monitoring systems.

I. INTRODUCTION

Monitoring of waste disposal cell integrity is an important component of any containment system. Public and regulatory support depends on perceptions of ability to prevent release of waste to the environment. Since no system can be proven to be 100 percent fail-safe, confidence in any proposed design is always to some degree dependent on the reduction of risk of undetected release. The greatest technical difficulty associated with subsurface waste placement is that of long term in situ monitoring. Waste emplacement designs which include TDR arrays beneath cells are capable of real-time monitoring of moisture content changes, providing a window to a critical area not accessed by conventional monitoring technologies.

In the case of waste emplacement in the dry unsaturated zone, the single greatest risk of release to the environment is associated with the flow of water. Capillary or other type surface infiltration barriers are engineered to minimize or eliminate through-flow. Periodic observations of moisture content at strategic locations near the waste package provide information related to effectiveness of surface barriers and potential for waste transport from the site. Early detection of increases in moisture content can alert site managers to the need for action before migration can occur. The analysis presented here is concerned with factors which influence moisture contents measured by TDR in uniform soils, such as those in an engineered landfill cover or monitoring system beneath a waste package. Effects of TDR waveguide orientation, length, spacing, and sampling time interval are discussed. Results of the analysis are presented to assist in decision making related to instrumentation of

monitoring systems in the unsaturated zone. Recommendations for instrumentation of engineered capillary barrier waste covers and landfill monitoring based on results follow the analysis.

Current waste disposal site monitoring practices include use of neutron probes to detect moisture content increases adjacent to stored or ponded wastes and testing of nearby observation wells for contaminants. These methods are not efficient in terms of detecting waste containment breaches before significant migration has taken place. Neutron probe access tubes as a rule cannot sample directly below stored waste where leakage is most likely to occur. When unsaturated flow is mostly vertical, neutron probe readings adjacent to the waste cell may not detect leakage, or may do so only after much time has elapsed. The neutron probe method is relatively labor intensive and potentially hazardous to operators. Observation well monitoring is expensive and useful only after contaminants have reached the water table. In arid locations with deep water tables, by the time contaminants are detected in observation wells, transport over large distances has occurred, drinking water supplies may be affected, and remediation costs are greatly increased.

A method of detecting leakage beneath landfills based on changes in electrical resistivity over a scale of meters has been proposed and tested by Dewiere et al. Electrodes are installed in a regular grid pattern beneath the waste disposal site during construction. The method was found to be successful in locating engineered leaks from a waste pond overlying an unsaturated gravel bed. Leaks in the experiment were manipulated to be highly detectable, i.e., a high concentration of NaCl was introduced, 10 g/cm^3 , at high leak rates through well-defined holes in a geotextile barrier. Application of the method where leaks result in resistivity contrasts less well defined was not discussed.

Use of TDR for monitoring changes in moisture content has many advantages over the methods described above. TDR waveguides installed below the waste cell provide critical data unavailable using other methods. Spatial resolution of the measurement depends on the length and orientation of the waveguide pair and does not depend on the moisture content of the system, as is the case with the neutron probe. Most importantly, sampling can be automated, making it possible to obtain measurements on almost any chosen time schedule without requiring frequent field visits. Schofield et al. (1994) compared measurements of

moisture content by neutron probe with spatial averages of TDR measurements. High correlations between the methods were reported.

Difficulties in obtaining dependable moisture content readings under saturated and frozen conditions with TDR methods were reported by Schofield et al. (1994). For the purposes of analysis, water content data obtained under saturated conditions were corrected to be equal to the porosity of the material, estimated at 0.38. Due to uncertainty about the nature of TDR error under freezing conditions or even if there were any such effects, no adjustments were made to account for the influence of freezing. In addition, random noise resulted in very small negative readings under moisture content conditions near zero, apparent in some of the plots. These last two factors are considered to be negligibly small.

II. BACKGROUND

Two 3 m x 10 m field plots were constructed of uniformly crushed Bandelier Tuff to a depth well below the measurement locations used for this study. These plots have been monitored for soil water content by neutron probe for more than five years. As shown in Figure 1, three neutron probe access tubes were installed in each plot. Four vertical and five horizontally placed waveguides were installed adjacent to each of two access tubes in each plot (Figure 2). Beginning in October of 1992, moisture content was monitored daily by TDR at each of the four locations and weekly by neutron probe at each of the six access tubes. Temperature measurements were obtained in two of the plots adjacent to the horizontal waveguides at 15 cm, 30 cm, 45 cm and 60 cm depths (Figures 3a,b). Instrumentation details may be found in Schofield et al. (1994). Also included in this analysis are precipitation data collected nearby on a daily basis.

Variability in hydrologic properties in the study area from point to point is assumed to be minimal. For the purposes of interpretation, the porous material within the plots is visualized as uniform and of semi-infinite extent, bounded by the ground surface through which water may enter as a result of precipitation/snowmelt or exit the system as evapotranspiration. Plot surfaces are sparsely covered by grasses, and one of the two plots includes several small pine trees.

Figure 1. Plan view of study plots.

Figure 2. Cross-sectional view of instrumentation.

Figure 3a. Plot 214 temperature at 15 cm, 30 cm, 45 cm and 60 cm.

Figure 3b. Plot 217 temperature at 15 cm, 30 cm, 45 cm and 60 cm.

Horizontal TDR waveguide pairs were placed at 5 cm, 15 cm, 30 cm, 45 cm and 60 cm depths. All of the horizontal waveguides were 30 cm in length, allowing comparison of variability resulting from differences in depth below the surface. Vertical TDR waveguides included 15 cm, 30 cm, 45 cm and 60 cm long pairs of waveguides as shown in Figure 2. Since longer waveguide pairs sample larger volumes than shorter pairs, a volume averaging effect is introduced. Data from these vertically emplaced waveguides were studied to determine the effect of orientation and waveguide length on results and interpretation.

Repetition of the instrumentation series in each of the four plots provides information about the spatial variability of moisture content in an engineered uniform material typical of permeable landfill covers proposed for the Advanced Landfill Cover Demonstration. In the plots that follow, identification of data in the legends includes plot number (213-217), V for vertical or H for horizontal, and waveguide length in centimeters for vertical or waveguide depth in centimeters for horizontal waveguides. For example, 213V45 identifies Plot 213, vertical 45 cm long waveguide, and 217H5 identifies Plot 217, horizontal 5 cm deep waveguide. Temperature data are identified by the letter T, i.e. 217T15 represents temperature data from Plot 217 at 15 cm depth.

III. RESULTS

A. Horizontal TDR

Moisture contents from horizontal TDR waveguides at each of the four plots are shown in Figures 4a-d. Figures 5a-e show moisture content measured at each depth in all four plots. At the bottom of each plot is a bar graph showing precipitation measured at a site near the plots. Plots include some gaps in the data record due to difficulties in obtaining measurements. Figures 4a-d illustrate the sensitivity of the 5 cm deep waveguides to changes in surface conditions relative to those at all other depths. Response to rainfall events in November clearly demonstrates the rapid damping of moisture pulses in the soil under dry conditions. The first precipitation series (October 25 to November 10) results in relatively large moisture content increases at the 5 cm deep waveguides (Figures 4a-d, Figure 5a). It appears that moisture from these events reaches the 15 cm depth after a time lag of approximately two weeks (Figures 4a-d, Figure 5b). The second series of precipitation events

Figure 4a. Moisture content Plot 213 horizontal waveguides and precipitation.

Figure 4b. Moisture content Plot 214 horizontal waveguides and precipitation.

Figure 4c. Moisture content Plot 216 horizontal waveguides and precipitation.

Figure 4d. Moisture content Plot 217 horizontal waveguides and precipitation.

Figure 5a. Moisture content 5 cm deep horizontal waveguides all plots and precipitation.

Figure 5b. Moisture content 15 cm deep horizontal waveguides all plots and precipitation.

Figure 5c. Moisture content 30 cm deep horizontal waveguides all plots and precipitation.

Figure 5d. Moisture content 45 cm deep horizontal waveguides all plots and precipitation.

Figure 5e. Moisture content 60 cm deep horizontal waveguides all plots and precipitation.

(November 28 to December 17) do not cause significant rise in moisture content at 5 cm depth, raising the possibility that much of this moisture may have remained on the surface as snow since temperatures were low at this time (Figures 3a, 3b). In fact, at 15 cm depth, moistures are greater or equal for this December period than close to the surface, as shown in Figure 6. Waveguides below 15 cm depth do not appear to register increases in moisture due to these events (Figures 4a-d, Figures 5c-e). This may be due in part to low hydraulic conductivities under dry conditions near the surface and deeper. Although meteorological conditions during this time period are unknown, the lack of even small moisture content increases at 30 cm and greater depths during this period suggests either atmospheric and surface conditions favoring soil water losses to evapotranspiration and/or very slow vertical flux rates. Moisture contents in the deeper profile are very near zero, and the hydraulic conductivity of the dry crushed tuff, while not well characterized for this study, is very small. This pattern continues into December. Surface conditions are dry, but not as dry as below 15 cm depth. It should be noted from Figures 3a and 3b that in late November temperatures near the surface first dip below freezing and remain very near freezing continually until late February. Also notable is the delay in the fall-winter cooling deeper in the study plots relative to the surface, while warming spring temperatures track closely together at all depths (Figures 3a,b). This differential cooling may have some bearing on the delay of moisture increases at depth relative to those nearer the surface during the period of late December through January.

Figures 4a-d show a significant increase in moisture content at all soil depths by mid-January. Moisture profiles at the start of this period are plotted in Figure 7, indicating significantly higher moisture content gradients than for the earlier period represented in Figure 6. Lack of more detailed meteorological data and gaps in the data record make it difficult to assess the mechanism for moisture content increases at depth during this period. However, as shown in Figures 8a and 8b, the period of near freezing surface temperatures and cooling at depth coincides nearly identically with the deep soil wetting phase. The early January precipitation events may have been snowfall, since temperatures near that time are near or below freezing. If the January precipitation was snow, increases in soil moisture cannot be explained solely on the basis of those events. A combination of slow infiltration of

Figure 6. December 14 moisture content profiles all plots.

Figure 7. January 14 moisture content profiles all plots.

Figure 8a. Plot 214 temperature at 15 cm, moisture content at 15 cm, 30 cm, 45 cm, and 60 cm.

Figure 8b. Plot 217 temperature at 15 cm, moisture content at 15 cm, 30 cm, 45 cm, and 60 cm.

earlier precipitation during the fall months, possibly a daily snow melt/infiltration cycle, a reduction in evapotranspiration due to snow cover, dormant vegetation and cold temperatures, and condensation of soil water vapor near the cold, possibly frozen surface, may be responsible. It is noteworthy that this is the only wetting period for depths below 15 cm in the entire nine and one half month record at the four locations. As soon as temperatures begin to rise above freezing, moisture contents at all levels below 5 cm begin a monotonic decline which continues throughout the remainder of the measurement period regardless of presence or absence of precipitation (Figures 4a-d, 5c-e, 8a, 8b).

Moisture contents at 30 cm, 45 cm, and 60 cm depths track closely together for most of the study time, indicating near unit gradient conditions. Moisture content profiles typical of conditions in mid-March and mid-May are shown in Figures 9 and 10. Moisture content profiles shown above and Figures 4a-d indicate that hydraulic head gradients in the top 60 cm, and thus flow, are reasonably inferred to be directed downward almost all of the time period studied. The magnitude of the hydraulic head gradients is uncertain, however, without knowledge of the pressure-moisture content relationship, and through-flow is probably small most of the time.

B. Measurement Repeatability

Table 1 summarizes the mean, standard deviation, maximum and minimum moisture content for horizontal TDR waveguides at each of the four plots for both daily and weekly data collection schedules. Mean moisture content profiles for data collected daily at each of the plots are plotted in Figure 11a, corresponding standard deviations are shown in Figure 11b. Table 1, Figures 5a-e and Figures 11a, 11b illustrate the close similarity between moisture content data from each of the plots. Slight differences in observed moisture contents between plots are attributed to minor local variability in hydrologic properties, physical surface conditions, microclimate influences and measurement noise. Plot 217 stands out as somewhat anomalous. Below 5 cm depth soil moisture at Plot 217 is wetter than at the same depths in the other plots. In addition, the wetting front which resulted in increased water contents at all plots in January propagated much more rapidly to the 60 cm depth at Plot 217 than any of the other plots (Figure 5e). These patterns may indicate small but significant

Figure 9. March 14 moisture content profiles all plots.

Figure 10. May 14 moisture content profiles all plots.

Figure 11a. Mean moisture content horizontal waveguides all plots.

Figure 11b. Moisture content standard deviation horizontal waveguides all plots.

differences in soil retention and hydraulic conductivity characteristics of the crushed tuff matrix at Plot 217 relative to those at the other three plots.

The strong influence of surface conditions on moisture content at 5 cm depth is seen in Figure 5a. Precipitation events and dry inter-storm periods cause rapid and extreme fluctuation in moisture content near the surface relative to that deeper in the profile. As shown by Figures 5a-e, effects of surface changes are significantly damped between 5 cm and 15 cm. The range of water contents observed over the period of record is also considerably reduced below 5 cm (Table 1). Moisture content standard deviations are very similar for all depths below 5 cm (Figure 11b).

Repeatability of data results between locations is found to be very high. Correlations between water contents measured at the same depth in each of the plots are all above 97%, except for the 60 cm depth at Plot 217, for which correlations with other data at that depth were in the 92%-94% range. These results suggest that for the purposes of monitoring gradients and general moisture conditions within homogeneous materials, as in a permeable surface cap, only a few measurement locations will suffice. This is not the case where the purpose is monitoring for leaks, since in that situation the capability of sampling a large proportion of the potentially vulnerable area is important.

Table 1. Mean, standard deviation, maximum and minimum moisture content for daily and weekly data from horizontal TDR waveguides at each of four plots.

Horizontal		Daily Data				Weekly Data			
TDR	Plot	μ	σ	Max.	Min.	μ	σ	Max.	Min.
5 cm Depth	213	0.167	0.104	0.38	0.019	0.119	0.074	0.245	0.019
	214	0.186	0.116	0.38	0.024	0.119	0.079	0.309	0.024
	216	0.190	0.122	0.38	0.010	0.121	0.087	0.276	0.011
	217	0.188	0.107	0.38	0.026	0.133	0.074	0.272	0.026
15 cm Depth	213	0.117	0.075	0.261	0.023	0.111	0.075	0.256	0.023
	214	0.110	0.078	0.290	0.023	0.105	0.076	0.264	0.024
	216	0.099	0.072	0.234	0.010	0.097	0.070	0.230	0.010
	217	0.133	0.067	0.247	0.058	0.130	0.065	0.247	0.059
30 cm Depth	213	0.070	0.076	0.226	0.0	0.065	0.074	0.219	0.0
	214	0.085	0.072	0.272	0.0	0.081	0.072	0.272	0.017
	216	0.080	0.078	0.233	0.0	0.074	0.077	0.229	0.002
	217	0.106	0.082	0.255	0.023	0.099	0.080	0.251	0.024
45 cm Depth	213	0.082	0.062	0.212	0.012	0.073	0.062	0.208	0.012
	214	0.076	0.066	0.226	0.007	0.067	0.065	0.210	0.007
	216	0.085	0.070	0.218	0.010	0.075	0.069	0.215	0.010
	217	0.091	0.073	0.223	0.011	0.082	0.073	0.219	0.012
60 cm Depth	213	0.060	0.060	0.194	0.0	0.053	0.065	0.193	0.0
	214	0.065	0.065	0.193	0.004	0.057	0.061	0.192	0.004
	216	0.071	0.071	0.196	0.0	0.065	0.067	0.196	0.0
	217	0.085	0.085	0.212	0.004	0.075	0.071	0.200	0.005

C. Vertical TDR

Moisture contents from vertical TDR waveguides at each of the four plots are shown in Figures 12a-d. Figures 13a-d show moisture contents from all four plots for each waveguide length. At the bottom of each plot is a bar graph showing precipitation measured at a site near the plots. Plots include a few gaps in the data record due to difficulties in obtaining measurements.

Moisture content data from vertical waveguides at each plot are consistent with results expected normal to the boundary surface. The shortest waveguides, 15 cm, register moisture contents highly influenced by changes at the boundary, particularly rapid increases during precipitation events (Figures 12a-d, Figure 13a). Longer waveguides average the moisture content measurement over larger volumes than shorter ones. In the case of vertically oriented waveguides in a quasi-one dimensional vertical flow system, the longest dimension of the averaging volume is parallel to the moisture content gradient. Thus, when gradients are high, a larger disparity in moisture contents registered by short and the long waveguides results.

This effect is seen during the October-November-December storms which register on the 5 cm and 15 cm horizontal waveguides as clearly defined moisture content increases, neither of which reaches the 30 cm or deeper horizontal waveguides (Figures 4a-d). The vertical waveguides of all lengths register both of these pulses (Figures 12a-d, Figures 13a-d). Due to volume averaging by the vertical waveguides, lower moisture contents are recorded at the maximum of the pulses as waveguide length increases and increased volume below the wetted soil is included in the sample (Figures 12a-d). The recorded moisture content is therefore an integrated measure of the moisture in the volume, although the functional relationship between moisture distribution and recorded moisture content is not well defined by the available data. TDR measurements made by longer waveguides positioned parallel to moisture gradients will underestimate peak moistures to a greater or lesser degree depending on conditions. When maximum moisture content is a variable of interest, as it could be for predicting transport scenarios, this instrumentation pattern should be avoided.

Differences in moisture content distribution patterns are observed between the plots. March, April and May show periods of decreasing moisture content, starting from relatively

Figure 12a. Moisture content Plot 213 vertical waveguides and precipitation.

Figure 12b. Moisture content Plot 214 vertical waveguides and precipitation.

Figure 12c. Moisture content Plot 216 vertical waveguides and precipitation.

Figure 12d. Moisture content Plot 217 vertical waveguides and precipitation.

Figure 13a. Moisture content 15 cm long vertical waveguides all plots and precipitation.

Figure 13b. Moisture content 30 cm long vertical waveguides all plots and precipitation.

Figure 13c. Moisture content 45 cm long vertical waveguides all plots and precipitation.

Figure 13d. Moisture content 60 cm long vertical waveguides all plots and precipitation.

wet conditions (Figures 12a-d). Moistures in the top 15 cm of Plot 217 indicate surface drying (Figure 12d), the vertical 15 cm waveguide registers less wetness than the 30 cm vertical waveguide. Longer waveguides in this plot record higher moisture contents during the springtime period. These observations are inconsistent with the results of the horizontal waveguide data for the same plot shown in Figure 4d, in which moisture contents during March and April at 5 cm most of the time and 15 cm all of the time are greater than those at 30 cm and deeper. This pattern is observed to a lesser degree at Plot 214 (Figure 4b, Figure 12b). In contrast, plots 213 and 216 (Figures 12a,c) do not exhibit apparent surface drying to the same extent during this period. A possible explanation for the inconsistency is that warming temperatures at the surface may be conducted into the soil by the vertical waveguides, affecting the moistures in their immediate vicinity. In any case, it seems clear that vertical TDR waveguides in this arrangement do not provide reliable data about and should not be used to infer vertical moisture gradients.

Table 2 summarizes the means, standard deviations, maximums and minimums for daily and weekly moisture content from vertical TDR waveguides at each of the four plots. Table 3 includes the same information for the neutron probe readings. The neutron probe statistics are included for completeness but will not be discussed. Mean and standard deviation of moisture content for the different length waveguides at each plot are plotted in Figures 14a and 14b. Comparison with Table 1 and Figures 11a and 11b shows that except for the top 5 cm, means and standard deviations of the two sets of data are close. The effects of integrating parallel to the gradient are evident, but do not create large differences in the summary statistics. This is probably because for much of the measurement period vertical gradients below the 15 cm depth are relatively small in magnitude at this study location (Figures 6,7,9 and 10). Despite the significant differences in surface influence between vertical and deeper horizontal TDR moisture results, correlations between vertical and horizontal measurements were generally high for all waveguides except the 5 cm horizontal depth. The high correlations can be attributed to the overriding influence of the winter wetting period on moistures everywhere in the system.

Table 2. Mean, standard deviation, maximum and minimum for moisture contents from 15 cm, 30 cm, 45 cm, and 60 cm long vertical TDR waveguides.

Vertical		Daily Data				Weekly Data			
TDR	Plot	μ	σ	Max.	Min.	μ	σ	Max.	Min.
15 cm long	213	0.125	0.076	0.284	0.010	0.123	0.075	0.267	0.018
	214	0.103	0.063	0.233	0.009	0.100	0.062	0.229	0.012
	216	0.104	0.072	0.272	0.0	0.109	0.070	0.272	0.012
	217	0.118	0.065	0.274	0.025	0.116	0.066	0.274	0.029
30 cm long	213	0.087	0.069	0.261	0.0	0.083	0.066	0.232	0.006
	214	0.101	0.062	0.238	0.029	0.096	0.061	0.235	0.029
	216	0.078	0.058	0.198	0.0	0.076	0.056	0.195	0.004
	217	0.122	0.076	0.291	0.025	0.114	0.073	0.291	0.027
45 cm long	213	0.096	0.062	0.238	0.021	0.089	0.060	0.227	0.022
	214	0.092	0.062	0.225	0.0	0.088	0.058	0.222	0.029
	216	0.098	0.067	0.245	0.021	0.091	0.065	0.242	0.021
	217	0.110	0.068	0.263	0.0	0.104	0.066	0.263	0.035
60 cm long	213	0.069	0.048	0.174	0.012	0.064	0.047	0.174	0.013
	214	0.083	0.058	0.216	0.0	0.078	0.059	0.218	0.022
	216	0.095	0.066	0.239	0.021	0.087	0.064	0.239	0.022
	217	0.108	0.067	0.263	0.030	0.101	0.067	0.263	0.030

Table 3. Summary statistics of neutron probe data.

Neutron Probe		Weekly Data			
	Plot	μ	σ	Max.	Min.
15 cm Depth	213	0.092	0.052	0.192	0.031
	214	0.087	0.060	0.220	0.024
	215	0.088	0.061	0.219	0.0
	216	0.078	0.048	0.173	0.023
	217	0.093	0.063	0.221	0.0
	218	0.096	0.065	0.244	0.029
30 cm Depth	213	0.081	0.053	0.185	0.029
	214	0.080	0.056	0.198	0.029
	215	0.084	0.064	0.203	0.0
	216	0.079	0.052	0.181	0.029
	217	0.090	0.065	0.204	0.027
	218	0.086	0.065	0.218	0.029
45 cm Depth	213	0.073	0.052	0.175	0.026
	214	0.074	0.048	0.175	0.030
	215	0.077	0.058	0.184	0.0
	216	0.084	0.056	0.192	0.032
	217	0.092	0.065	0.206	0.031
	218	0.083	0.061	0.194	0.028
60 cm Depth	213	0.073	0.052	0.181	0.028
	214	0.069	0.044	0.163	0.031
	215	0.081	0.055	0.184	0.033
	216	0.087	0.057	0.198	0.040
	217	0.091	0.060	0.193	0.034
	218	0.084	0.055	0.189	0.034

Figure 14a. Mean moisture content vertical waveguides all plots.

Figure 14b. Moisture content standard deviation vertical waveguides all plots.

The plots show a clear relationship between rainfall events and recorded changes in moisture content for the 5 cm horizontal waveguide and for all the vertical waveguides. Correlations between moisture content and precipitation were found to be generally low. Even at the horizontal waveguide 5 cm depth, the highest correlation was 0.22. The low correlations are believed to be due to a number of factors including infiltration time lag, persistence of moisture for days after the end of storms and the effects of temperature, solar radiation and snowcover on infiltration and evapotranspiration. In addition, in the absence of precipitation, condensation within the pore spaces may be causing an increase in moisture content when conditions are favorable. Also, the previously mentioned influence of the winter wetting and spring drying cycle dominates the statistical analysis of the system.

D. Timing of Data Collection

Tables 1 and 2 provide summary information for moisture content data collected daily, and a subset of that data which represents a weekly collection schedule. Percent differences in estimated moisture content mean and standard deviation were calculated for each TDR location as a measure of the information loss resulting from weekly versus daily instrument readings. Results, summarized in Table 4, show that for horizontal waveguides 15 cm deep and below, and for all vertical waveguides, reductions in sampling frequency introduced estimation errors on the order of only a few percent for both the means and the standard deviations. Tables 1 and 2 also list the maximum moisture content recorded at each measurement location, a value of considerable interest in determining transport scenarios. The tables show that for all locations except the 5 cm deep horizontal waveguide, maximum moisture contents observed on the weekly schedule differ from those observed on the daily schedule by only a few hundredths of a percent.

At 5 cm deep, variability in moisture content is high. For the shallow measurement locations, reductions in the data collection frequency to weekly were found to result in underestimates of means from 29% to 36% relative to estimates from daily data, and underestimates of standard deviations by 27% to 32%. Depending on the application, these underestimates near the surface may be determined to be unacceptably high. Likewise, maximum moisture contents observed at 5 cm depth on the weekly schedule were

Table 4. Underestimate of mean and standard deviation resulting from weekly readings relative to daily readings, as a percent of estimate from daily readings.

Horizontal TDR	Plot	% μ	% σ	Vertical TDR	Plot	% μ	% σ
5 cm Depth	213	29	27				
	214	36	32				
	216	36	29				
	217	29	31				
15 cm Depth	213	5	0	15 cm Length	213	2	1
	214	5	3		214	3	2
	216	2	3		216	5	3
	217	2	3		217	2	2
30 cm Depth	213	7	3	30 cm Length	213	5	4
	214	5	0		214	5	2
	216	8	1		216	3	3
	217	7	2		217	7	4
45 cm Depth	213	11	0	45 cm Length	213	7	3
	214	12	2		214	4	6
	216	12	1		216	7	3
	217	10	0		217	5	3
60 cm Depth	213	12	-8	60 cm Length	213	7	2
	214	12	6		214	6	-2
	216	8	6		216	8	3
	217	12	16		217	6	0

considerably lower, and never reached saturation as did the moisture contents observed on a daily basis. However, where a very lengthy sampling record is available, estimates of statistical moments from weekly data should converge to the same values as estimates from daily data. This was not the case for the limited data set used in this study.

In practice, it is unlikely that conditions very near the surface are of great importance to the ultimate question of identifying breaches of a waste containment system. Where perturbations to the system are highly damped and standard deviations are low, as is the case at the deeper TDR measurement points, errors due to reduced sampling frequency are small and less frequent sampling schedules appear to be adequate. However, in an experimental demonstration project, the questions being asked require more extensive instrumentation and more frequent data collection than a standard monitoring program would.

IV. RECOMMENDATIONS FOR DEMONSTRATION INSTRUMENTATION

In designing instrumentation for a field demonstration of post closure monitoring technology for mixed waste landfills, two distinctly different needs must be considered. The first is the need to identify a basic leak detection monitoring system suitable for field application. Priorities for this system are cost, labor, maintenance, reliability and longevity. The second need is related to the testing and evaluation of the proposed monitoring system itself, i.e., for the purposes of the demonstration project, a system is needed to monitor the monitoring system. This second need is associated with the experimental nature of the project. Since implementation of this second system is intended only for the demonstration project, priorities associated with the experimental system are less associated with cost and are more heavily weighted by a need for a thorough understanding of the physical dynamics of the demonstration project and the suitability of the basic monitoring system.

The preceding analysis establishes the usefulness of TDR technology for monitoring moisture under relatively dry conditions in an engineered porous material. Where ambient conditions are relatively wet and pore space saturation occurs frequently, TDR methods alone are not necessarily the best choice. Along with hydrologic properties, knowledge of moisture content distributions or pressure distributions are essential to the understanding of water flow in unsaturated media. As discussed above, TDR waveguides oriented normal to gradients are

capable of supplying data required for flux calculations, and make it possible to follow moisture infiltration and redistribution. Waveguide orientation parallel to gradients is less useful, particularly near the surface, since boundary perturbations tend to dominate the measurement. The integrating nature of the waveguide measurement results in a loss of useful information when oriented parallel to the gradient.

Basic Field Monitoring

A schematic cross-sectional view of recommended locations for TDR waveguides in a basic, long-term field application is shown in Figure 15. The figure illustrates a generic engineered surface capillary barrier cover overlying a contained waste cell. Instrumentation proposed here for the basic monitoring system is independent of the type of surface cover (permeable or impermeable, etc.). The basic monitoring system in Figure 15 consists of two layers, one above and one below the waste cell. Shown in Figure 15 are two layers of horizontal TDR waveguide arrays, positioned to detect downward moving moisture.

Waveguides in each layer are configured to allow sampling of a maximum area above and a maximum area below the waste cell. The TDR waveguides in Figure 15 are embedded in engineered layers of porous material which have a higher sorptivity than the surroundings. This is desirable because depending on conditions nearer the surface, the phenomena known as finger flow may be very likely to occur. Detection of finger flow constitutes the greatest challenge to the monitoring system, because of the small area occupied by the finger and the ability of the finger to propagate rapidly. Using a highly sorptive material as the matrix surrounding the TDR waveguides increases the probability that a finger will be detected, since when it intercepts the sorptive layer, the water will tend to spread out within the layer rather than pass through. Selection of a material for the sorptive layers will require analysis of the host material surrounding the layers and the waste cell together with knowledge of probable moisture conditions in the field. It is important to recognize that the TDR layers are not intended to be physical barriers to flow. Depending on the physical properties of the TDR layer matrix and the areal extent of the layer, placement of vertical TDR waveguides near the outer boundaries of the layer may be useful as a means of detecting any water that may pond on top of the layer and move horizontally under some conditions.

Schematic Cross-Sectional View of Waste Emplacement and Monitoring Design

Schematic Plan View of High Sorptivity Interlayer With Embedded Waveguides

Figure 15. Schematic cross-sectional and plan views of TDR emplacement in waste disposal system.

Depending on economic constraints, it may be necessary to eliminate one of the TDR layers. Benefits of retaining the upper layer are that it is more accessible than the lower layer, and it can provide information about cover leaks before the waste cell is significantly affected. Advantages of the lower layer are that it is located at the most critical leak path leading from the waste cell to the environment.

Experimental Monitoring System

As stated above, the purpose of the experimental monitoring system is to provide data required for understanding the physical dynamics of flow in the demonstration project. Monitoring of moisture content and moisture content gradients throughout the system is required. The optimal location of TDR waveguides for the experimental system is highly dependent on the choice of cover type for the demonstration project. Basic information needs include data from near the cover boundaries and from the interior of the cover away from boundary effects. Gradients beneath the cover down to the waste cell and below it should be monitored by the experimental system.

Temporal and Spatial Sampling Frequency Requirements

Frequency of sampling in time and space depends on the variability of the process and the precision of the required results. As discussed above for the crushed tuff beds, it appeared that for the purposes of basic long-term monitoring at depth, sampling on a weekly schedule would be adequate. Bi-weekly or even monthly sampling schedules may be adequate for deep monitoring systems. However, since the dynamics of any one system are unique, it is recommended that daily monitoring, at the same time each day, be implemented for both the basic and experimental instrumentation networks during the demonstration project. With the daily data, an analysis of time-dependence of results *for that system* can be carried out. Monitoring should include meteorological conditions and subsurface temperatures on the same schedule as for moisture.

Results discussed above indicate that spatial sampling requirements for understanding system dynamics are substantially reduced in homogeneous engineered materials relative to more inhomogeneous natural materials. Due to this, the experimental monitoring system need

not be densely instrumented over homogenous areas, but a conservative number of redundant sampling locations should be included in the design.

V. CONCLUSIONS

Long-term storage of wastes requires leakage detection monitoring. In arid regions with deep water tables, TDR monitoring of moisture content around stored wastes makes it possible to evaluate the state of the system and assess release risk quickly and efficiently. When combined with engineered barriers and surface covers, TDR methods can provide essential data needed for identification of failure of the contaminant system, reducing risk of release to the environment significantly. An issue not addressed here but of major importance to the success of this project due to long term nature of post closure monitoring and the inaccessibility of emplaced TDR instrumentation is the life expectancy and long term reliability of TDR hardware in the field.

VI. ACKNOWLEDGMENTS

This work was prepared for the Department of Energy Office of Technology Development Office of Environmental Management. This work is conducted in support of the Mixed Waste Landfill Integrated Demonstration at Sandia National Laboratory, Albuquerque, New Mexico.

REFERENCES

Dewiere, L., E. Ledoux and G. de Marsily, , "Estimation and Detection of Leaks Beneath Landfills," in Land Disposal of Hazardous Waste: Engineering and Environmental Issues, J.R. Gronow, A.N. Schofield, and R.K. Jain Editors, Halstead Press. pp. 69-82.

Schofield, T.G., G.J. Langhorst, G. Trujillo, K.V. Bostick, W.R. Hansen, 1994, "Comparison of Neutron Probe and Time Domain Reflectometry Techniques of Soil Moisture Analysis".