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| Tennessee Valley Authority<br>Kingston Fossil Plant<br>Harriman, Roane County, Tennessee | **Perimeter Containment**<br>**North Dredge Cell (Dike C) Segment 1**<br>**Sta. A161+50 to A179+50** |

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|---|---|
| *Document Control Number* | RDP-0113-E |
| *Calculation Package* | FPGKIFFESCDX00030020100006 |

Stantec

# Exhibit 6
# Predicted Saturation Above the Phreatic Surface

*Purpose:*

- Predict degree of saturation in landfilled ash above the phreatic surface within the closed landfill.
- Results to be used in the assessment of potential liquefaction within the landfilled ash.

*Methods:*

- Hydraulic characteristics of unsaturated ash obtained from historic lab tests on Kingston ash samples.
- HYDRUS-1D finite element model.

*Results:*

- Prediction of the long-term, equilibrium water content (or saturation) variation with height above the phreatic surface, up to the ground surface of the closed landfill.

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| *Calculation Performed by:* Tennessee Valley Authority | |
| *Prepared by:* J Mark Boggs 22-Sept-10 | *Reviewed by:* AFR 20-Sept-10 |
| *Revisions:* | |

# *TVA Kingston Recovery Project*
# *Preliminary Analysis of Capillary Rise within the Closed Coal Ash Landfill*

Stantec Consulting Services, Inc. requested that TVA provide an estimate of the capillary rise above the phreatic surface within the proposed coal ash landfill following facility closure. Results are intended for use by Stantec in assessing the vertical extent of liquefiable fly ash within the landfill in connection with the landfill stability analysis. This report briefly describes the methods and results of the capillary rise analysis.

## Conceptual Model

The proposed ash landfill will ultimately encompass approximately 253 acres, and will contain existing undisturbed fly ash and bottom ash not displaced by the December 2008 failure incident, along with displaced ash and lime-treated ash recovered from the Emory River and other areas adjacent to the plant site. The relative quantities of fly ash and bottom ash ultimately contained in the landfill are unknown. However, based on typical coal combustion waste compositions the landfill would be expected to contain roughly 90 percent fly ash and 10 percent bottom ash.

In the current design concept, the landfill will be capped with a flexible membrane liner and vegetated topsoil to minimize surface infiltration of precipitation. Following closure, moisture stored within the ash deposits above the phreatic surface would begin to redistribute in response to (1) capillary and gravitational forces and (2) infiltration through the landfill cover. Movement of moisture within the ash landfill vadose zone would likely occur primarily in the vertical dimension since movement would be largely driven by surface infiltration and gravity drainage of stored moisture. Under these conditions, moisture movement, including capillary flow, can be approximated by a one dimensional (vertical) unsaturated flow model of the landfill vadose zone extending from the phreatic surface to the landfill cap.

The following specifications were provided by Stantec for the conceptual model (via 9/7/2010 and 9/9/2010 email communications from Alan Rauch):

- Vadose zone thickness of 40 feet, corresponding to an estimated phreatic surface elevation of approximately 750 feet and landfill crest elevation of approximately 790 feet.
- Vadose zone consists of a single layer of homogeneous fly ash having uniform properties.
- Average infiltration rate of 0.372 inches per year through the landfill cap.
- Initial gravimetric moisture content of fly ash within the vadose zone at the time of landfill closure of approximately 0.25. Stantec requested that the effect of initial moisture content on predicted vadose moisture distributions be evaluated for initial values ranging from 0.23 to 0.29. Initial moisture content is assumed to be uniform within the vadose zone for each case considered. Stantec moisture content values apply to fly ash having compacted void ratio of 0.67 and specific gravity of 2.31.

## Methods

The HYDRUS-1D finite element model (Simunek et al., 2005) for simulation of one-dimensional flow and solute transport in variably-saturated media was selected for the capillary rise analysis. A 40-ft (1220-cm) vertical column of fly ash was assumed to represent the vadose zone between the phreatic surface (elevation 750 feet assumed) and the top of the landfill at elevation 790 feet. Uniform grid intervals of 0.0656 ft (2 cm) were applied over the vadose zone profile. Ash hydraulic parameters for HYDRUS-1D were obtained from laboratory measured data for five fly ash samples (KIF-1 through KIF-5) collected at the KIF site in 1989 and 1990 (D.B. Stephens & Associates, 1989 and 1990). Sample data applied in the modeling analysis are summarized in Table 1. Locations where these fly ash samples were obtained are unknown. Separate model simulations were performed for each set of fly ash properties to examine the variability of results. Homogeneous physical and hydraulic properties were applied over the 40-ft fly ash profile for each case.

TABLE 1. Fly Ash Hydraulic Properties

| Sample | Dry Bulk Density (g/cc) | Particle Density (g/cc) | Calculated Porosity | α | N | Residual Moisture Content (cc/cc) | Saturated Moisture Content (cc/cc) | $K_{sat}$ (cm/s) | Source |
|---|---|---|---|---|---|---|---|---|---|
| KIF-1 | 1.30 | 2.44 | 46 | 0.0018 | 2.0259 | 15.9 | 43 | 2.0E-05 | 1, 3 |
| KIF-2 | 1.32 | 2.42 | 45 | 0.0016 | 2.1160 | 8.7 | 44 | 2.1E-05 | 1,3 |
| KIF-3 | 1.33 | 2.38 | 45 | 0.0016 | 1.9418 | 11.6 | 44 | 2.2E-05 | 1,3 |
| KIF-4 | ND | ND | ND | 0.0027 | 2.4111 | 12.0 | 43 | 2.1E-05 | 2 |
| KIF-5 | ND | ND | ND | 0.0020 | 3.6602 | 12.0 | 43 | 2.1E-05 | 2 |

*1 - D.B. Stephens & Assoc., 1989, Tables 4 & 9.*
*2 - D.B. Stephens & Assoc., 1990, Table 2A.*
*3 - D.B. Stephens & Assoc., 1990, Table 2B.*

Constant recharge of 0.372 inches/year (0.0026 cm/day) was applied at the upper model boundary consistent with Stantec's best estimate of recharge through the landfill cap. The ash moisture content at the lower boundary was fixed at the saturated volumetric moisture content of each ash sample to represent the phreatic surface.

The initial condition for each simulation consisted of application of uniform moisture content across the ash profile equal to the measured saturated moisture content for each ash sample (Table 1). This assumption provides the most conservative estimates of moisture content within the ash profile. A cursory sensitivity analysis of initial moisture

content was performed for the moisture range provided by Stantec to examine the effect of initial moisture content on subsequent predicted moisture profiles. Hydraulic parameters for fly ash sample KIF-3 were used for the sensitivity analysis because this sample exhibits mid-range hydraulic characteristics relative to the other ash samples.

## Results

Simulated landfill vadose zone moisture profiles are presented in terms of both volumetric moisture content and percent saturation. Including results in terms of percent saturation allows comparison of results for ash samples having different saturated porosity values. This is particularly useful since the ash properties used by Stantec for landfill stability analysis differ slightly from those used in the model simulations presented here.

Figure 1 provides results of the sensitivity analysis to examine the effect of initial moisture content on predicted moisture profiles. Tabulated moisture profile data corresponding to model output shown on Figure 1 are provided in file *KIF_RESULTS_FILE-1.XLSX* included with this report. Initial volumetric moisture content values of 0.35 and 0.44 were evaluated corresponding to the gravimetric moisture content range requested by Stantec based on their fly ash properties. Results indicate that predicted moisture profiles are sensitive to the initial moisture content during the first year following landfill closure. However, by the third year there is essentially no difference in moisture profiles. Furthermore, sensitivity in the region within approximately 10 feet of the phreatic surface is low even during early time.

Predicted moisture profiles at 1, 3 and 30 years after landfill closure for each of the five fly ash sample cases are shown on Figures 2 through 4, respectively. Tabulated moisture profile results are provided in *KIF_RESULTS_FILE-2.XLSX* which accompanies this report. Comparison of profiles over time indicates little change between 3 years and 30 years. It appears that once moisture initially stored in the ash has drained to the phreatic surface, the ash moisture distribution within the vadose zone approaches a near steady-state condition in the presence of the constant infiltration rate assumed through the landfill cover. Results also indicate substantial differences between the predicted moisture profiles for the five KIF ash sample cases. These differences tend to increase with height above the phreatic surface. The implications of this variability on capillary rise can be evaluated (by Stantec) once a percent saturation threshold is established for liquefiable fly ash.

A complete set of model output files for each simulation is provided in *H1D_OUTPUT.ZIP*. Simulation output includes nodal values of pressure head, volumetric moisture content, unsaturated K, and Darcy flux for selected time periods. Simulation water mass balance information for the model domain (e.g., stored water mass, mass flux in/out of the domain, and mass balance error at selected times) is also provided. A detailed description of model output files from the HYDRUS-1D user's manual is included in file *H1D_OUTPUT.ZIP*.

## Limitations

The preceding analysis is subject to the following limitations:

- The effect of spatial heterogeneity of hydraulic properties of fly ash deposits has not been evaluated in the present analysis.
- The degree to which hydraulic properties of the five KIF fly ash samples used in the analysis are representative of the overall hydraulic characteristics of ash ultimately contained in the landfill vadose zone is unknown.
- The effect of lime-treated ash on vadose zone moisture distribution during the post-closure period of the landfill has not been evaluated.
- The analysis does not account for the presence of lenses or layers of bottom ash above the phreatic surface in some areas, particularly the undisturbed relic area of the former dredge cells. In addition, gravel or sand layers included in the engineering design of the landfill for closure have not been evaluated in this analysis. Under partially-saturated conditions, hydraulic conductivities of bottom ash and engineered granular materials are expected to be substantially lower than that of fly ash, potentially resulting in regions of elevated moisture content in fly ash above these coarser materials (Hillel, 1971, p. 104-105).

## References

D.B. Stephens & Associates, Inc., 1989, "Laboratory analysis of hydraulic properties of Kingston and Colbert fly ash", August 1989, Albuquerque, New Mexico.

D.B. Stephens & Associates, Inc., 1990, "Completion of laboratory determination of selected hydraulic parameters on Kingston and Colbert fly ash samples", October 1990, Albuquerque, New Mexico.

Hillel, D., 1971, Soil and Water: Physical Principles and Processes, Academic Press, New York.

Simunek, J., M.Th. van Genuchten, and M. Sejna, 2005, "The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, Version 3.0", Department of Environmental Sciences, University of California, Riverside, California.

## List of Files Included with Report

| File | Contents |
|---|---|
| DBSA_AUG_1989.PDF | D.B. Stephens & Associates, Inc., 1989, "Laboratory analysis of hydraulic properties of Kingston and Colbert fly ash", August 1989, Albuquerque, New Mexico. |
| DBSA_OCT_1990.PDF | D.B. Stephens & Associates, Inc., 1990, "Completion of laboratory determination of selected hydraulic parameters on Kingston and Colbert fly ash samples", October 1990, Albuquerque, New Mexico. |
| H1D_OUTPUT_FILES.ZIP | HYDRUS-1D output files for five simulation cases; includes description of file contents. |
| KIF_RESULTS_FILE-1.XLSX | Tabulated results of initial moisture content sensitivity analysis. |
| KIF_RESULTS_FILE-2.XLSX | Tabulated moisture content and percent saturation data for five simulation cases. |

FIGURE 1. Initial Moisture Content Sensitivity Analysis

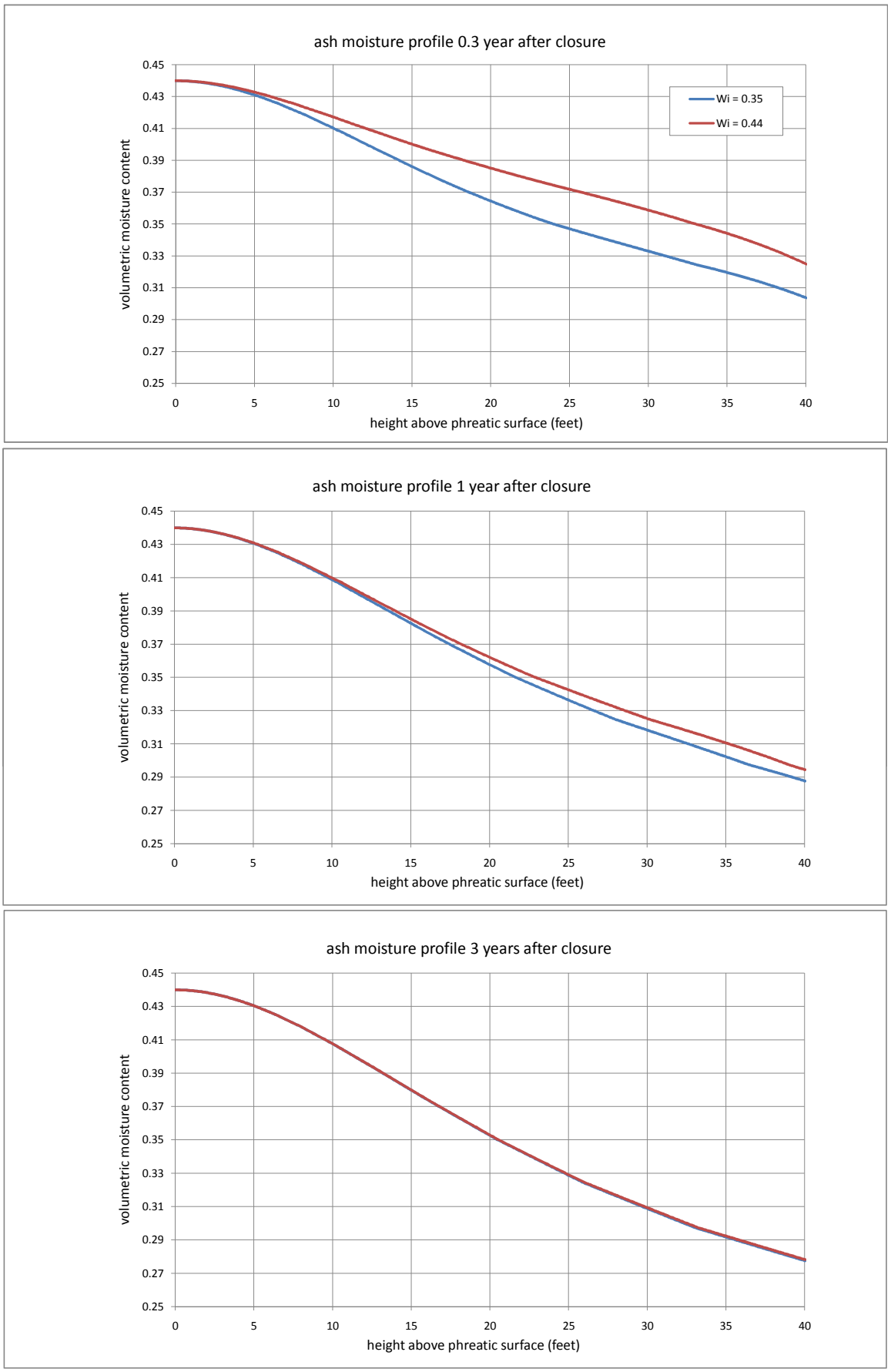
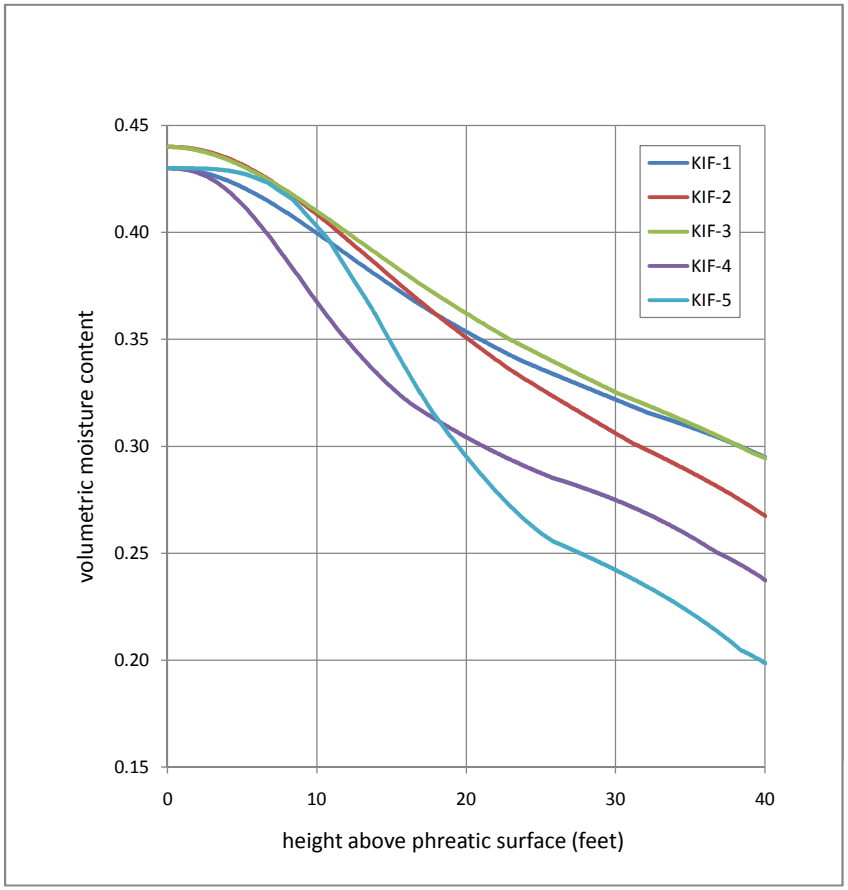


FIGURE 2. Predicted Ash Moisture Profiles 1 Year After Landfill Closure



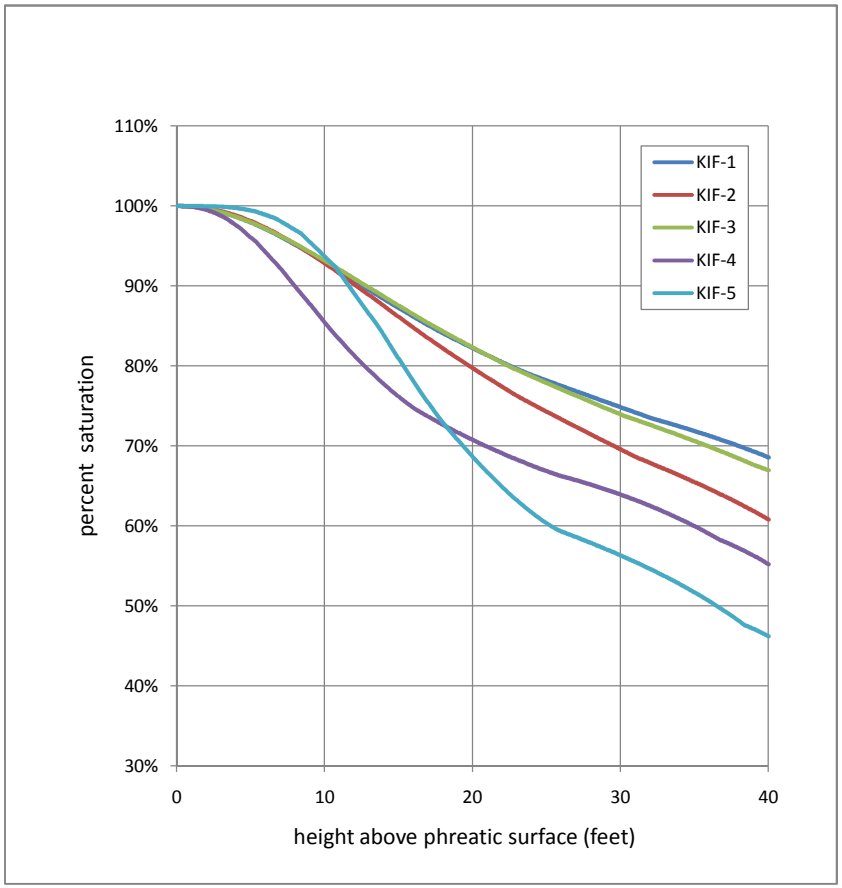
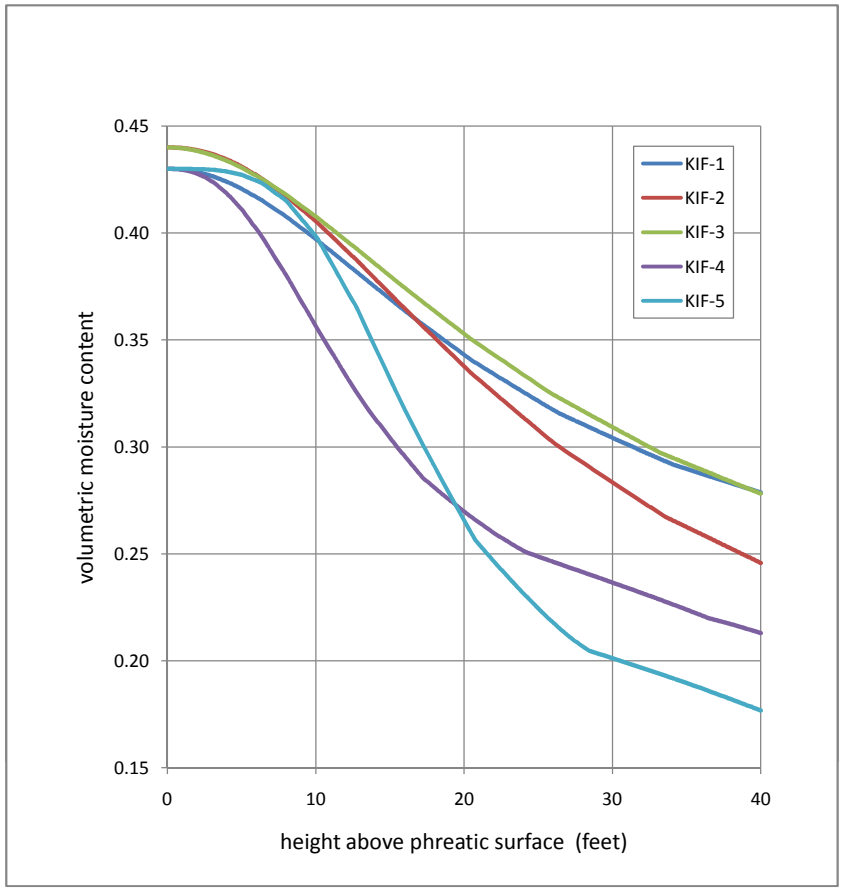



FIGURE 3. Predicted Ash Moisture Profiles 3 Years After Landfill Closure



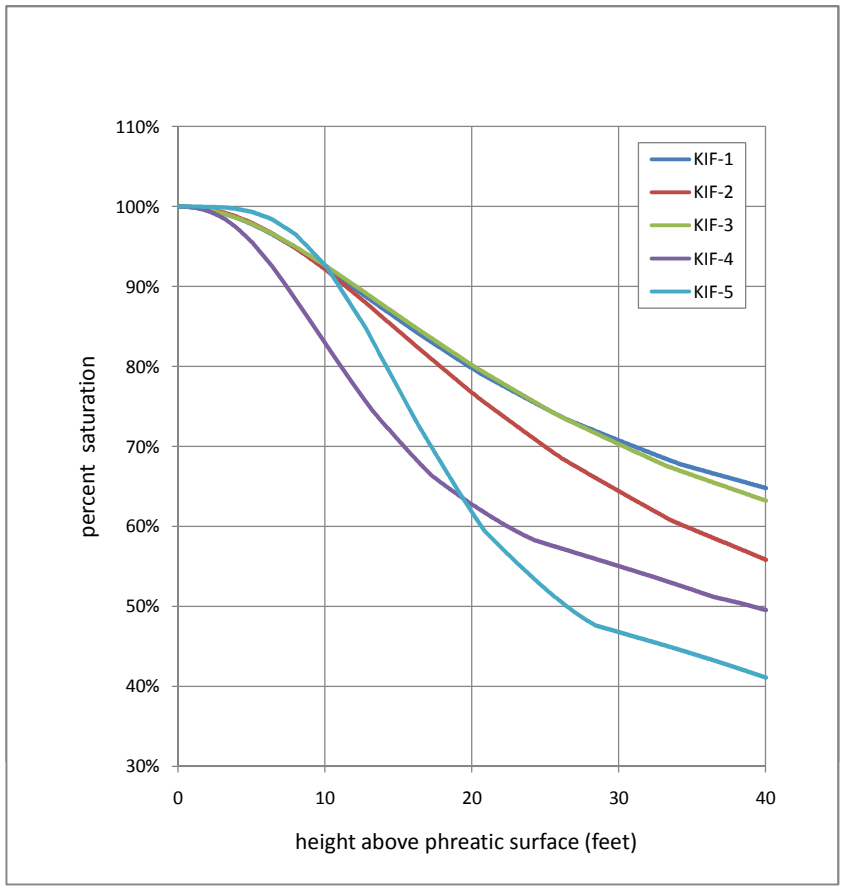
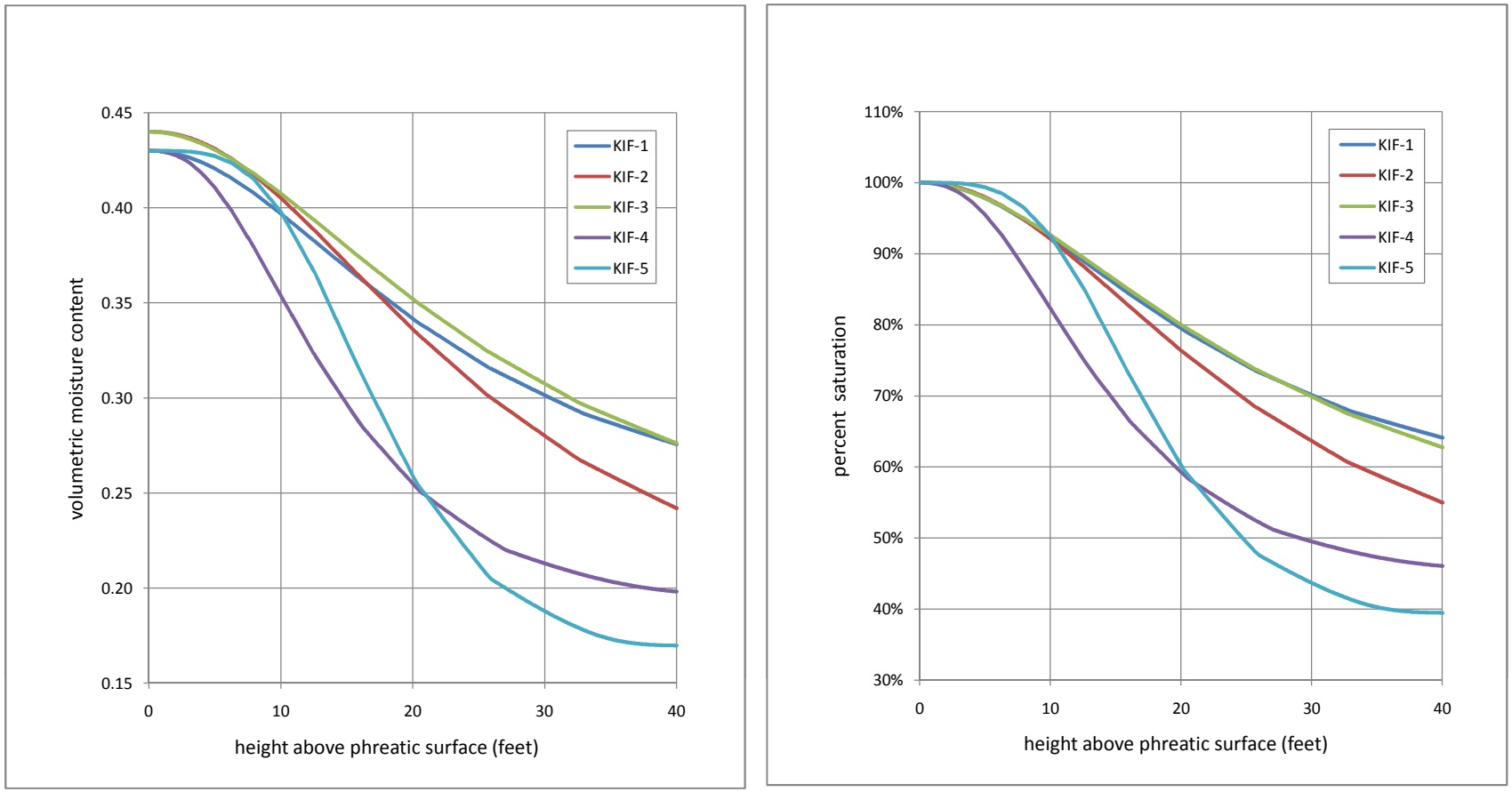




FIGURE 4. Predicted Ash Moisture Profiles 30 Years After Landfill Closure