Memorandum

To: File

From: John McCain

Subject: Analysis of GCL Equivalency to Two Feet of Compacted Clay

Sherburne County Generating Plant (Sherco) Scrubber Solids Pond No. 3

Date: June 15, 2016

This memorandum evaluates compliance of the existing Sherco Scrubber Solids Pond No. 3 (Pond 3) base liner (alternative composite liner) with the liquid flow rate equivalency requirement of CCR Rule §257.70(c)(2). Specifically, the lower component of the alternative liner (GCL) must have a liquid flow rate no greater than the liquid flow rate through two feet of compacted soil with an hydraulic conductivity of $1x10^{-7}$ cm/s.

Calculations

Equation 1 in §257.70(c)(2) is a form of Darcy's Law for gravity flow of a fluid through porous media. For purposes of the liquid flow rate comparison between the GCL component of the Pond 3 liner and the reference standard, the maximum hydraulic conductivity of the GCL for which the comparison will be satisfied is calculated as follows.

1) Equate "q" (flow rate per unit area) for the reference standard liner to "q" for the alternative liner:

$$k_{std} * (h_{std}/t_{std} + 1) = k_{GCL} * (h_{GCL}/t_{GCL} + 1)$$

Where: k_{std} = hydraulic conductivity of the reference standard (i.e. $1x10^{-7}$ cm/s) (cm/s)

h_{std} = hydraulic head above the bottom of the reference standard liner (cm)

t_{std} = thickness of the reference standard liner (cm)

k_{GCL} = hydraulic conductivity of the alternative GCL liner component (cm/s)

h_{GCL} = hydraulic head above the bottom of the alternative GCL liner component (cm)

t_{GCL} = thickness of the alternative GCL liner component (cm)

Data: k_{std} = $1x10^{-7}$ cm/s

h_{std} = 2194.6 cm

t_{std} = 61.0 cm

h_{GCL} = 2133.7 cm

t_{GCL} = 0.64 cm

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2) Rearrange the equation to solve for the maximum allowable hydraulic conductivity of the GCL:

$$k_{GCL} = k_{std} * (h_{std}/t_{std} + 1) / (h_{GCL}/t_{GCL} + 1)$$

3) Substitute data:

$$k_{GCL} = (1x10^{-7} \text{ cm/s}) * (2194.6 \text{ cm}/61.0 \text{ cm} + 1) / (2133.7 \text{ cm}/0.64 \text{ cm} + 1)$$

$$k_{GCL} = 1.1x10^{-9} \text{ cm/s}$$

Therefore, $1.1x10^{-9}$ cm/s is the maximum hydraulic conductivity of the GCL component of the alternative liner that will produce a liquid flow rate no greater than the reference standard liner.

Laboratory Testing of Pond 3 GCL

During development of design and permit documents in 2003 for construction of Pond 3, CETCO Lining Technologies was consulted to determine whether the GCL product contemplated for use in the Pond 3 liner would meet desired performance requirements (see CETCO (2003)). CETCO engaged the services of JLT Laboratories, Inc., an independent geosynthetics testing laboratory, to perform index flux and hydraulic conductivity testing of the GCL product.

JLT Laboratories tested a GCL specimen furnished by CETCO (Bentomat ST) in accordance with ASTM D-5887 (measurement of index flux) and D-5084 (measurement of hydraulic conductivity). Testing was performed by hydrating the specimen with distilled water, then permeating the specimen with actual scrubber solids pond water from then-active Sherco Pond No. 2. Testing was performed with an effective confining pressure of 4 psi and an hydraulic gradient of 220.8. Test results determined the hydraulic conductivity of the specimen to be $1.1x10^{-10}$ cm/s. This value is one full order of magnitude slower than the required maximum value of $1.1x10^{-9}$ cm/s calculated above.

Manufacturing Quality Control Testing

GCL manufacturers certify their products with a maximum hydraulic conductivity for given testing conditions, however hydraulic conductivity values lower than the certified maximum are often observed. All CLAYMAX and BENTOMAT GCL products used for Pond 3N liner construction were certified by the manufacturer with a maximum hydraulic conductivity of $5x10^{-9}$ cm/s using standard test methods ASTM D5084/D5887 with a confining pressure of 5 psi (35 kPa) and head pressure of 2 psi (14 kPa). There were 49 hydraulic conductivity tests performed as part of routine manufacturing quality control during production runs for these products, with test results ranging from $1.5x10^{-9}$ to $4.9x10^{-9}$ cm/s with an average of $3.2x10^{-9}$ cm/s (see McCain – Construction Documentation and Prefill Certification Report (2004), McCain – Construction Certification Report (2009), and McCain – Construction Certification Report (2011)); however, the actual in-service hydraulic conductivity of the GCL in Pond 3 is lower than the manufacturing quality control data shown above due to differing conditions in the pond versus the quality control testing, as discussed in the following section.

Field Conditions Affecting GCL Performance

The hydraulic conductivity performance achieved by a GCL is strongly affected by three primary factors: initial hydration, confining pressure, and compatibility with the permeant. The following paragraphs describe these factors for Pond 3.

Initial Hydration

Initial hydration was provided by exposure to subgrade soil moisture for a period of at least 90 days prior to scrubber water being introduced to the pond. A confining pressure of approximately 12 kPa was present during the initial hydration period due to placement of a two-foot thick buffer soil layer over the liner. Petrov and Rowe (1996) demonstrated that confining the GCL prior to hydration (as opposed to allowing free swell), and then consolidating the GCL (by applying increased confining pressure), as is the case for the Pond 3 liner, results in lower bulk void ratios and lower hydraulic conductivity.

Confining Pressure

Confining pressure on the GCL in the Pond 3 base liner as of Spring 2016 ranges from 125 kPa to 270 kPa. When the pond reaches ultimate operating depth, the confining pressure will increase to a range from 170 kPa to 345 kPa. The range of pressure is due to varying depth to liner because of the liner slope, and varying unit weight of materials overlying the liner varies (water only vs. saturated scrubber solids). Petrov et. al. (1997) demonstrated significant decreases in hydraulic conductivity resulting from increased confining pressure. For GCLs confined prior to hydration and permeation (as is the case for the Pond 3 liner), Petrov et. al. (1997) demonstrated a well-defined linear relationship on a logarithmic scale between the GCL hydraulic conductivity and the static confining pressure. The equation predicts that a GCL tested under a confining pressure of 35 kPa will yield an hydraulic conductivity of $1.4\text{x}10^{-9}$ cm/s. This conforms well with the manufacturing quality control testing reported for the production runs from which the Pond 3 GCL was produced (summarized above). Increasing the confining pressure to 120 kPa (simulating conditions in Pond 3), the equation predicts an hydraulic conductivity of $7.3\text{x}10^{-10}$ cm/s. Calculation of the confining pressure and hydraulic conductivity values reported above are presented in Exhibit 1. Data in Petrov et. al. (1997) shows further reduction in hydraulic conductivity for confining pressures greater than 120 kPa, however the equation is reported to be valid only for confining pressures between 3 and 120 kPa. Therefore, it is reasonable to assume that the in-service hydraulic conductivity of the GCL in Pond 3 is not greater than $7.3\text{x}10^{-10}$ cm/s.

Permeant Compatibility

The laboratory testing performed by JTL Laboratories used actual scrubber pond water from the Sherco plant as the permeant for laboratory hydraulic conductivity testing of the GCL specimen (CETCO (2003)). The low permeability ($1.1\text{x}10^{-10}$ cm/s) reported from JTL Laboratory testing is a strong indication that the chemical characteristics of the pond water are compatible with maintaining low hydraulic conductivity of the GCL.

Conclusion

The liquid flow rate through the GCL component of the alternative composite liner of Sherco Pond 3 is no greater than the flow rate through two feet of compacted soil with an hydraulic conductivity of $1x10^{-7}$ cm/s.

Certification

I hereby certify under penalty of law that this memorandum was prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based upon my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware there are significant penalties for submitting false information, including the possibility of fine and imprisonment.

John R. McCain, PE
License No. 21835

June 15, 2016
Date

References

Petrov, R.J. and Rowe, R.K. (1996), "GCL-chemical compatibility by hydraulic conductivity testing and factors affecting its performance." Geotech. Res. Ctr. Per. GEOT-11-96, Dept. of Civ. Engrg, Univ. of Western Ontario, London, Canada.

Petrov, R.J., Rowe, R.K., and Quigley, R.M. (1997), "Selected Factors Influencing GCL Hydraulic Conductivity," Journal of Geotechnical and Geoenvironmental Engineering, 1997.123:683-695

Cetco Lining Technologies (2003), "Xcel Energy Sherco Pond GCL Performance Study." Report, Arlington Heights, Illlinois.

McCain and Associates, Inc. (November 2004), "Construction Documentation and Pre-Fill Certification Report, Scrubber Solids Pond No. 3N, Sherburne County Generating Plant" Permit Compliance Document, Excelsior, Minnesota.

McCain and Associates, Inc. (February 2009), "Construction Certification Report, Pond No. 3 North Vertical Expansion, Sherburne County Generating Plant" Permit Compliance Document, Maple Plain, Minnesota.

McCain and Associates, Inc. (January 2011), "Construction Certification Report, Pond No. 3 South Construction, Sherburne County Generating Plant" Permit Compliance Document, Maple Plain, Minnesota.

Exhibit 1 to Memorandum

Calculation of Confining Pressure and Hydraulic Conductivity

Carlson McCain
ENVIRONMENTAL • ENGINEERING • LAND SURVEYING

Project Sherco Pond 3 Liner Certification Project No. 3404

CALCULATION OF CONFINING PRESSURE AND HYDRAULIC CONDUCTIVITY FOR GCL LINER COMPONENT

Data

Avg dry density of scrubber solids = 73.0 lb/ft³
Avg water content of scrubber solids = 47.8 %
} see attached test report

Avg wet unit weight of scrubber solids = (73.0 lb/ft³) + (62.4 lb/ft³)(0.478) = 102.8 lb/ft³
(62.4 lb/ft³ ← unit weight of water)

High elevation of Pond 3 base liner = 951 ft MSL

Low elevation of Pond 3 base liner = 938 ft MSL

Pond 3 water elevation in Spring 2016 = 993 ft MSL

Ultimate Pond 3 water elevation = 1008 ft MSL

Calculations

Confining Pressure on GCL in Spring 2016

$\sigma_{min} = (993 - 951\ ft)(62.4\ lb/ft)(6.895\ kPa/(lb/in^2))/(144\ in^2/ft^2) = 125.5\ kPa$
(water only over base liner high point)

$\sigma_{max} = (993 - 938\ ft)(102.8\ lb/ft^3)(6.895\ kPa/(lb/in^2))/(144\ in^2/ft^2) = 270.7\ kPa$
(saturated scrubber solids over liner low point)

Ultimate Confining Pressure on GCL

$\sigma_{min} = (1008 - 951\ ft)(62.4\ lb/ft^3)(6.895\ kPa/(lb/in^2))/(144\ in^2/ft^2) = 170.3\ kPa$

$\sigma_{max} = (1008 - 938\ ft)(102.8\ lb/ft^3)(6.895\ kPa/(lb/in^2))/(144\ in^2/ft^2) = 344.6\ kPa$

Signature John McCain Date 06/15/2016

Calculations (continued)

GCL Hydraulic Conductivity based upon Petrov et. al. (1997) Fig. 5

equation relating Hydraulic Conductivity (k, cm/s) and Confining Pressure (σ, kPa)

$$\text{Log}(k) = -8.0068 - 0.5429\,\text{Log}(\sigma)$$

calculated hydraulic conductivity of GCL with 35 kPa confining pressure (to compare manufacturer's QC testing)

$$\text{Log}(k) = -8.0068 - (0.5429)(1.544) = -8.845$$

$$k = 10^{-8.845} = 1.43 \times 10^{-9}\ \text{cm/s}$$

calculated hydraulic conductivity of GCL with 120 kPa confining pressure

$$\text{Log}(k) = -8.0068 - (0.5429)(2.079) = -9.136$$

$$k = 10^{-9.136} = 7.31 \times 10^{-10}\ \text{cm/s}$$

Permeability Test Data
(Undisturbed / In-situ Samples)

Project: N.S.P. - SHERCO POND EXPANSION - #23/71-027 TJPO60   Date: 12-15-94

Reported To: BARR ENGINEERING COMPANY   Job No.: 2323

Boring No.	94-3	94-3	94-5	
Sample No.				
Depth (Ft)	7-9 (TOP)	7-9 (TOP)	12-14 (TOP)	
Location				
Type of Sample	3T	3T	3T	
Soil Type	FLY ASH (T.C.: SILT (ML))	FLY ASH (T.C.: SILT (ML))	FLY ASH (T.C.: SANDY SILT (ML))	
Atterberg Limits				
Liquid Limit	N.P.		N.P.	
Plastic Limit	N.P.		N.P.	
Plasticity Index	N.P.		N.P.	
Permeability Test				
Specimen No.				
Height (Inches)	1.54	1.54	1.62	
Diameter (Inches)	2.86	2.86	2.88	
Dry Density (pcf)	72.9	72.9	73.3	scrubber solids density data
Water Content (%)	48.7	48.7	46.0	
Type of Test (Head)	FALLING	FALLING	FALLING	
Max. Head Differential (ft)	3.7	1.1	5.0	
Confining Pressure (Effective-psi)	2.0	2.0	2.0	
Backpressure (psi)	NONE	80.1	NONE	
Water Temp. (°C)	24	24	24	
Coefficient of Permeability				
K @ 20°C (cm/sec)	8.1×10^{-6}	1.7×10^{-5}	1.5×10^{-5}	
K @ 20°C (ft/min)	1.6×10^{-5}	3.4×10^{-5}	2.9×10^{-5}	