INFORMATION ONLY

CIVILIAN RADIOACTIVE WASTE MANAGEMENT SYSTEM

Management and Operating Contractor

Contract #: DE-AC01-91-RW00134
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WASTE ISOLATION EVALUATION
ARTIFICIAL INFILTRATION TESTING AT UE-25 UZN-7

by

James E. Houseworth

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Prepared by:

James E. Houseworth — 3/7/94 Date
Senior Staff Consultant, Performance Assessment and Modeling Department

Reviewed by:

Evan K. Paleologos — 3/7/94 Date
Senior Staff Consultant, Performance Assessment and Modeling Department

Approved by:

Srikanta Mishra — 3/7/94 Date
Acting Manager, Performance Assessment and Modeling Department

Concurred by:

Jean L. Younker — 3/8/94 Date
Manager, Regulatory and Technical Evaluation

This waste isolation evaluation was prepared as a Category III evaluation in accordance with M&O NLP-3-17 "Development of Waste Isolation Evaluations" and the M&O "Waste Isolation Evaluation Preparation Plan #1."

The UE-25 UZN-7 infiltration tests and associated components have not been assigned QA classifications in accordance with M&O QAP-2-3.

Waste Isolation Evaluation
Artificial Infiltration Testing at UE-25 UZN-7

1. INTRODUCTION

1.1 Purpose of Evaluation

Science Applications International Corporation (SAIC), acting on behalf of the Yucca Mountain Site Characterization Project Office (YMPO), Regulatory and Site Evaluation Division (RSED) and in accordance with AP-5.21Q, Revision 3, requested Waste Isolation and Test-to-Test Interference Evaluations from the Civilian Radioactive Waste Management Systems Management and Operating Contractor (CRWMS M&O) for artificial infiltration testing at neutron borehole UE-25 UZN-7 [Weaver, 1993].

1.2 Planned Activities

The planned infiltration test will be performed using a 3 m (10 ft) diameter metal ring centered around UZN-7 to confine water for ponded artificial infiltration experiments. The water will be maintained at a constant head of approximately 10 cm (4 in). The infiltration test will use a total quantity of no more than 200,000 liters (53,000 gal). A lithium bromide tracer may be added during the application of water [Weaver, 1993].

1.3 Quality Assurance

This report was prepared as a quality-affecting activity according to CRWMS M&O Implementing Line Procedure NLP-3-17 "Development of Waste Isolation Evaluations" [Houseworth, 1993a]. Format and content guidance was provided by the M&O "Waste Isolation Evaluation Preparation Plan #1," including its associated checklist, to assure that no activities and potential waste isolation impacts were overlooked [Houseworth, 1993b].

No computer code calculations were specifically performed for this evaluation. Some of the data and referenced analyses used in this evaluation may not have been approved for quality-affecting work. The extent and possible effect of non-qualified data, analyses, and computer codes on the evaluations, conclusions and recommendations of this report were not specifically determined. However, the conservative assumptions, estimates and methods used in this evaluation address any reasonable scenario and are therefore expected to bound potential impacts on waste isolation.

2. BACKGROUND INFORMATION

2.1 Evaluation Approach

This evaluation is based on both qualitative arguments and quantitative bounding estimates of the potential impacts of the planned activity on waste isolation. The following previous waste isolation evaluation provided background information: Waste Isolation Evaluation, Exploratory Studies Facility, Surface Systems for Water Conveyance and Disposal [Houseworth, 1993c].

2.2 Relative Locations and Elevations

The planned artificial infiltration test location is shown in Figure 1 relative to the conceptual perimeter drift boundary (CPDB) and conceptual controlled area boundary (CCAB). The neutron borehole UE-25 UZN-7 is located in the center of Pagany Wash, about 0.72 km (0.45 mi) outside and northeast of the nearest point of the CPDB; inside expansion area 2; and about 2 km (1.5 mi) inside and southwest of the nearest point on the CCAB [EG&G, 1992]. UZN-7 lies between UZN-6 and UZN-8, with UE-25 UZ #4 lying between UZN-6 and UZN-7 [Brandstetter, 1993].

Table 1. Relevant Elevations

Location	Elevation above m.s.l.	Reference
Surface Elevation of UZN-7	1200 m (3940 ft)	EG&G, 1992
Hydrogeologic Units:		
Tiva Canyon welded, top	1188.1 m (3898 ft)	Loskot et al., 1992
Paintbrush nonwelded, top	1173.5 m (3850 ft)	Loskot et al., 1992
Topopah Spring welded, top	1094.3 m (3590 ft)	Loskot et al., 1992
Potential waste package emplacement, top	1000 m (3281 ft)	10 CFR 960.4-2-5 (d)
Ground-water table in vicinity of UZN-7	731 m (2400 ft)	Ervin et al., 1993
ESF north ramp invert at portal entrance	1123 m (3684 ft)	Rodgers, 1994
ESF north ramp invert at Topopah Spring main drift junction	1067 m (3501 ft)	Rodgers, 1994

2.3 Relevant Hydrogeology

The expected major near-surface lithologic units in the vicinity of the planned trenches are alluvium and colluvium, Tiva Canyon Hydrogeologic Unit, Paintbrush Hydrogeologic Unit, and Topopah Spring Hydrogeologic Unit [Loskot and Hammermeister, 1993]. The Paintbrush nonwelded (PTn) Hydrogeologic unit that underlies the infiltration site is believed to be a capillary barrier to fracture flow between the highly fractured Tiva Canyon welded (TCw) Hydrogeologic Unit and potential waste package emplacement zones in the Topopah Spring welded (TSw) Hydrogeologic Unit [YMP, 1993a; McKenzie, 1994]. This capillary barrier is only effective if the capillary pressure in the PTn is greater than the water entry pressure in the TSw fractures. Because the water entry capillary pressure for fractures is believed to be low relative to capillary pressures at unsaturated conditions in the PTn, water is not expected to be able to enter fractures in the TSw until the PTn is nearly saturated [Montazer and Wilson, 1984].

2.4 Affected Natural Barriers and Engineered Items

The proposed activities will affect the Unconsolidated Surficial Materials (USMs). The USMs include alluvial, colluvial, eolian, debris-flow, and other detrital deposits overlying the Paintbrush Tuff. Additional underlying hydrogeologic units may also be affected, depending on the quantity and behavior of the applied infiltration water. The USMs are on the Management Control List [YMP, 1993b] and the remaining underlying hydrogeologic units are on the Q-List [YMP, 1993a]. The apparatus used to perform the infiltration test are temporary items not intended to be used during operation of a potential repository.

The planned infiltration testing activities do not use engineered items on the current Q-List [YMP, 1993a] and MC-List [YMP, 1993b]. These activities could affect the characteristics of natural barriers that overlie a potential repository expansion area.

3. SPECIFIC EVALUATIONS AND INTERPRETATIONS

3.1 Hydrology

The main concern regarding the planned activity is the potential for percolating water to migrate to potential waste package emplacement zones. As discussed in section 2.3, the capillary barrier in the PTn Hydrogeologic Unit is believed to act as a barrier to water entry into fractures in the TSw unit. Matrix flow is possible across this barrier, but the TSw matrix saturated hydraulic conductivity is approximately 8.8×10^{-12} m/sec (2.9×10^{-11} ft/sec) [YMP, 1993c]. A water saturation front in the TSw matrix would advance approximately 23 m (75 ft) in 10,000 years given a unit hydraulic gradient and a porosity of 0.121 [YMP, 1993c]. Because the potential emplacement zones lie a minimum of 94 m (308 ft) below the PTn/TSw contact, water movement from the PTn/TSw contact in the TSw matrix is not expected to impact waste packages within a 10,000 year period.

Water entry into fractures across the PTn/TSw interface is not possible provided the PTn Unit is not saturated. The PTn Unit at this location is about 79.2 m (260 ft) thick (see Section 2.2) and has an approximate porosity of 0.42 and water saturation of 0.61 (a gas saturation of 0.39) [YMP, 1993c]. Therefore, the PTn can absorb roughly 13 m (42.7 ft) of water at any given location before saturating. An approximate bounding analysis, given in Attachment II, indicates that roughly 725 m^3 (191,000 gal) of water can be used before this limit is reached.

3.2 Geochemistry

The infiltration water may contain a lithium bromide tracer. Lithium bromide has been analyzed and approved for use underground at concentrations up to 20 ppm to trace construction water movement [Statton, 1993]. The natural water in the unsaturated zone contains about 34 to 106 ppm chloride, which is 9.6×10^{-4} to $3. \times 10^{-3}$ moles/liter [Yang et al., 1988]. There is no known analysis for natural aqueous bromide. However, chloride may be considered an analogue dissolved constituent because both bromide and chloride belong to the same chemical group, the halogens. Lithium bromide at 20 ppm is equivalent to aqueous concentrations of 2.3×10^{-4} moles/liter bromide. Therefore, at concentrations less than 20 ppm, lithium bromide is not expected to noticeably perturb the native geochemistry.

3.3 Thermal/Mechanical Characteristics

The proposed activities will not create any significant thermal or mechanical disturbances.

3.4 Interpretations

Water released into the ground at UE-25 UZN-7 is not expected to migrate to potential waste package emplacement zones within 10,000 years if the quantity of water applied is limited to less than 725 m^3 (191,000 gal). The addition of lithium bromide at concentrations up to 20 ppm is not expected to affect repository performance because existing concentrations of natural dissolved chlorine have much greater concentrations. Changes in water saturation or composition of dissolved constituents near potential waste package emplacement zones may affect repository performance because these changes may accelerate waste package corrosion, release of radionuclides from waste packages, or enhance aqueous radionuclide transport. However, changes that lie within the range of natural variations should not noticeably affect repository performance. Due to the lack or insignificance of hydrologic, geochemical, and thermal/mechanical impacts of the planned activities, aqueous radionuclide transport from potential repository locations to the water table and accessible environment will not be affected.

The unsaturated zone below the planned activities may lie along pathways for gaseous radionuclides from a waste emplacement horizon in the potential repository expansion area 2. However, the local increase in water saturation could only serve to inhibit the movement of gaseous radionuclides, and therefore could not adversely affect performance of the potential repository.

4. SUMMARY

4.1 Recommendations and Conclusions

The proposed infiltration test at UE-25 UZN-7 is not expected to impact waste isolation, provided the following recommendations are followed:

1. Limit the volume of infiltrating water to less than 725 m^3 (191,000 gal).

2. Limit lithium bromide tracer concentrations to 20 ppm or less.

These recommendations are in addition to existing controls for water use, spill control, spill cleanup, spoils storage, land reclamation, and recording actual use of tracers, fluids, and materials [YMP, 1991b; YMP, 1992a; YMP, 1992b].

4.2 Critical Assumptions and Data

This evaluation and its conclusions and recommendations are based on the following critical assumptions and data:

1. The steady-state infiltration rate from a point source in a homogeneous porous medium (see Attachment II) is a reasonable bound for the infiltration rate of a transient source in a heterogeneous soil and rock system.

2. The effects of evaporation are not included.

3. The Paintbrush Hydrogeologic Unit acts as a capillary barrier to water entry into fractures in the Topopah Spring Hydrogeologic Unit [YMP, 1993a].

4. The depth from the surface to the Paintbrush Hydrogeologic Unit is at least 26.5 m (ft). [Loscot and Hammermeister, 1992].

6. The Paintbrush Hydrogeologic Unit is at least 79.2 m (260 ft) thick.

7. The Paintbrush Hydrogeologic Unit has a porosity of about 0.42 and a water saturation of about 0.39 [YMP, 1993c].

8. Capillary pressure and effective conductivity parameters for flow in fractures in the Tiva Canyon Hydrogeologic Unit are bounding relative to solutions for steady infiltration. [Fewell et al., 1992].

5. REFERENCES

Bear, J., Dynamics of Fluids in Porous Media, *American Elsevier, New York*, 1972.

Brandstetter, A., Data for Simulation of Planned Infiltration Test near Borehole UZN-7, *M&O Interoffice Correspondence, LV.PA.AB.11/93-164*, November 24, 1993.

EG&G, "Yucca Mountain Site Characterization Project: Potentially Useable Areas with Topsoil and Rock Storage Areas," Map YMP-92-258.0, December 1992.

Ervin, E. M., R. R. Luckey, and D. J. Burkhardt, Summary of Revised Potentiometric-Surface Map for Yucca Mountain and Vicinity, Nevada, *in High Level Radioactive Waste Management, Proceedings of the Fourth Annual International Conference*, 1993.

Fewell, M. E., S. R. Sobolik, J. H. Gauthier, Estimation of the Limitations for Surficial Water Addition Above a Potential High Level Radioactive Waste Repository at Yucca Mountain, Nevada, *Sandia Report, SAND91-0790*, January, 1992.

Houseworth, J. E., Development of Waste Isolation Evaluations, *M&O Implementing Line Procedure NLP-3-17, B000000000-01717-5000-00014 Rev. 00*, October 1, 1993a.

Houseworth, J. E., Waste Isolation Evaluation Preparation Plan #1, *M&O Plan, B000000000-01717-4600-00025 Rev. 00*, October 22, 1993b.

Houseworth, J. E., Waste Isolation Evaluation, Exploratory Studies Facility Surface Systems for Water Conveyance and Disposal, *M&O Report, Document #: BABBD0000-01717-2200-00001 Rev. 00*, December 31, 1993c.

Loscot, C. L. and D. P. Hammerstein, Geohydrologic Data from Test Holes UE-25 UZ #4 and UE-25 UZ #5, Yucca Mountain Area, Nye County, Nevada, *USGS Open-File Report 90-369*, 1992.

McKenzie, D. G., Description and Rationale for Enhancement to the Baseline ESF Configuration, *M&O Report, B00000000-01717-0200-00089 Rev.00*, September 30, 1993.

Montazer, P. and W. E. Wilson, Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada, *USGS Water-Resources Investigations Report 84-4345*, 1984.

Philip, J. R., Theory of Infiltration, *Advances in Hydroscience, Vol. 5, pp 215-296, Academic Press, New York*, 1969.

Rodgers, D. J., ESF/Repository Interface - Integrated Layout Description, M&O Calculation # BC0000000-01717-0200-00003 Rev. 0A, February 9, 1994.

Statton, C. T., Evaluation of Potential Impacts Due to the Use of Lithium Bromide as the Chemical Tracer for All Water Used in the Exploratory Studies Facility Underground Construction, *M&O letter and report to N. Z. Elkins, LANL, Document # LV. SC. BWD.3/93-090*, March 31, 1993.

van Genuchten, M. Th., A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, *Soil Science Society of America Journal, Vol. 44, pp. 892-898*, 1980.

Weaver, J. D., Request for Waste Isolation and Test Interference Evaluations in Support of the United States Geological Survey (USGS) Project to Perform an Artificial Infiltration Test at Neutron Borehole UE-25 UZN-7, Yucca Mountain, Nevada, Test Planning Package 93-1, (SCP: 8.3.1.2.2.1), *SAIC letter to L. Dale Foust, TESS*, October 28, 1993.

Yang, C., A. K. Turner, T. M. Sayre, and P. Montazer, Triaxial-Compression Extraction of Pore Water from Unsaturated Tuff, Yucca Mountain, Nevada, *USGS Water-Resources Investigations Report 88-4189*, 1988.

YMP, Reclamation Implementation Plan for the Yucca Mountain Site Characterization Project, *YMP/91-14*, 1991b.

YMP, Technical Requirements for the Yucca Mountain Site Characterization Project Surface-Based Testing, *YMP/CM-0007, Rev. 9*, November 6, 1992a.

YMP, YMP Tracers, Fluids, and Materials Management Plan, *YMP/91-23, Rev. 1*, November 2, 1992b.

YMP, Q-List, *YMP/90-55, Revision 1*, August 1993a.

YMP, Management Control List, *YMP/93-17, Revision 0*, August 1993b.

YMP, Reference Information Base, *YMP/93-02, Rev. 2*, April 6, 1993c.

10 CFR 960, General Guidelines for Recommendation of Sites for Nuclear Waste Repositories.

Figure 1: Location of UE-25 UZN-7 relative to potential expansion areas and conceptual repository block [EG&G, 1993].

Attachment I

CHECKLIST OF ACTIVITIES AND TFM FOR WASTE ISOLATION EVALUATIONS	
ACTIVITIES / TFM	**COMMENTS**
I. Water	
A. Surface Sources	
1. Road watering for dust control	See sections 3.1, 3.4, 4.1
2. Drill pad dust control	NA
3. Equipment washdown	See sections 3.1, 3.4, 4.1
4. Natural surface runoff	NA
5. Accidental water spillage	See sections 3.1, 3.4, 4.1
6. Used in testing	NA
B. Underground	
1. Water loss during drilling	
a) Fishing	NA
b) Other	NA
2. Recovered or produced during drilling	
a) Perched water	NA
b) Water table	NA
3. Used in construction	
a) Drilling	NA
b) Construction Materials	NA
c) Dust Control	NA
d) Equipment washdown	NA
4. Used in testing	NA

CHECKLIST OF ACTIVITIES AND TFM FOR WASTE ISOLATION EVALUATIONS (CONTINUED)	
ACTIVITIES / TFM	**COMMENTS**
II. Materials (other than water)	
A. Used in surface and subsurface construction	
1. Building materials	NA
2. Leachates from rock & muck piles	NA
3. Fuels/lubricants/coolants	NA
B. Used in borehole construction and/or sealing	
1. Grout for surface casings	NA
2. Drilling fluids	NA
3. Other materials left in boreholes	NA
C. Used in testing	NA
III. Other considerations	
A. Physical and chemical characteristics of seals	NA
B. Cut-and-fill for roads, pads, trenches & pits	NA
C. Blasting	NA
D. Underground excavation	NA

ATTACHMENT II

BOUNDING ANALYSIS FOR INFILTRATION TO THE PTn HYDROGEOLOGIC UNIT

A cumulative discharge limit is determined in this analysis by calculating the quantity of water that can infiltrate before saturating the PTn Hydrogeologic Unit (see Section 2.3). The analysis is based on infiltration into a homogenous, isotropic porous medium with hydraulic properties of the TCw Hydrogeologic Unit fractures. The problem is bounded by computing the specific discharge along the centerline under the infiltration site, which has the highest vertical water flux compared with other locations in any given horizontal plane.

To simplify the analysis, transient infiltration from a circular zone around the borehole is approximated by steady-state infiltration from a point source. The steady-state solution includes the effects of three-dimensional unsaturated flow. The analogous steady-state problem is established by setting the steady-state point source discharge rate equal to an estimated volumetric flow rate at the surface for the transient problem during ponded conditions. This flow rate estimate is made using the saturated hydraulic conductivity, unit hydraulic gradient, and size of the infiltration zone at the surface. A limit for the maximum specific discharge at the top of the PTn Hydrogeologic Unit over the estimated infiltration period is determined from the available gas-filled pore space in the PTn to store the infiltrating water.

Assume that the alluvium and TCw fracture saturated hydraulic conductivities, K_s, are bounded by the value for TCw fractures, 3.8×10^{-5} m/s [Fewell et al., 1992]. A nominal specific discharge at the surface, assuming a unit hydraulic gradient, is 3.8×10^{-5} m/s. Applying this specific discharge over the 3 m diameter zone used for ponded infiltration gives a volumetic flow rate of 2.69×10^{-4} m^3/s. Therefore, an infiltration test using 200 m^3 will require about 7.45×10^5 s (8.6 days) to infiltrate. Infiltration of 13 m of water (above natural infiltration levels) is assumed to be the minimum water input required to saturate the PTn at any point (see Section 3.1). Therefore, the limiting steady specific discharge into the PTn over this time period is 13 m / 7.45×10^5 s = 1.75×10^{-5} m/s. The normalized water saturation, S_n, and effective hydraulic conductivity, K, are related though the following expression [van Genuchten, 1980]:

(1) $$K = K_s S_n^{1/2} \{1 - (1 - S_n^{1/\lambda})^{\lambda}\}^2$$

where λ for TCw fractures is estimated to be [Fewell, et al, 1992]:

(2) $$\beta = 1/(1-\lambda) = 4.23, \text{ or } \lambda = 0.7636$$

The effective hydraulic conductivity is equal to the local vertical specific discharge under steady-state flow conditions, assuming spatial gradients in the capillary pressure are negligible.

Solving equation (1) for S_n with $K = 1.75 \times 10^{-5}$ m/s gives

(3) $$S_n = 0.844$$

If we assume that the infiltrating water is discharged from a continuous point source, then the centerline saturation distribution is given by [Philip, 1969]:

(4) $$S_n^* = Q/(4\pi z)$$

where

z = depth (m) (origin at source)
Q = source flux (m^3/sec)

and

(6) $$S_n^* = \int_0^{S_n} K(\theta)\{d\Psi/d\theta\}\, d\theta$$

where
S_n^* = transformed saturation variable (m^2/s)
$\Psi(S_n)$ = moisture potential (m)
$K(S_n)$ = effective hydraulic conductivity (m/s)
$S_n = (S-S_r)/(1-S_r)$ = normalized water saturation
S_r = residual water saturation
S = water saturation

Parameterization of $\Psi(S_n)$ is given by [van Genuchten, 1980],

(7) $$S_n = \{1/(1+(\alpha\Psi)^{\beta})\}^{(1-1/\beta)}$$

Rearranging (7) to solve for Ψ with $\lambda = 1-1/\beta$ gives

(8) $$\Psi = -\alpha^{-1}\{S_n^{-1/\lambda} - 1\}^{1-\lambda}$$

where α for TCw fractures is estimated to be [Fewell, et al, 1992]:

(9) $$\alpha = 1.285\ m^{-1}$$

Substituting equations (1) and (8) into (6) gives,

(10) $$S_n^* = \int_0^{S_n} \alpha^{-1} K_s \{(1-\lambda)/\lambda\}\, \theta^{-(\lambda+2)/2\lambda} \{\theta^{-1/\lambda} - 1\}^{-\lambda} \{1 - (1 - \theta^{1/\lambda})^{\lambda}\}^2\, d\theta$$

Substituting for K_s, α, and λ into (10) gives,

(11) $$S_n^* = 9.155 \times 10^{-6} \int_0^{S_n} \theta^{-1.809} \{\theta^{-1.31} - 1\}^{-0.7636} \{1 - (1 - \theta^{1.31})^{0.7636}\}^2\, d\theta$$

Substituting the value for S_n, equation (3), into equation (11) gives

(12) $$S_n^* = 2.93 \times 10^{-6}\ m^2/s$$

The depth to the PTn, z, is 26.5 m (see Section 2.2). Substituting values for z and S_n^* into equation (4) and solving for Q gives,

(13) $$Q = 9.76 \times 10^{-4}\ m^3/s, \text{ or } 84.3\ m^3/day$$

Over the nominal duration of the infiltration test, 8.6 days, this flux would accumulate to a total limiting infiltration volume, V, of

(14) $$V = 725\ m^3$$

The assumption that the capillary pressure is negligible relative to gravity as a driving force for vertical flow at the top of the PTn may be checked. The extension of Darcy's law for unsaturated flow is [Bear, 1972]:

(15) $$q_z = -K(S_e)\,(1 + \partial\Psi(S_e)/\partial z)$$

where q_z is the specific discharge in the vertical direction. The effect of the capillary pressure gradient is negligible if it is small compared with 1. To evaluate the capillary pressure gradient, consider the following decomposition,

(16) $$\partial\Psi(S_e)/\partial z = \{d\Psi(S_e)/dS_e\}\,(\partial S_e/\partial z)$$

Using equation (8) and values given above for α and λ, the slope of the capillary pressure curve is given by,

(17) $$d\Psi(S_e)/dS_e = 0.241\ S_e^{-2.31}(S_e^{-1.31} - 1)^{0.7636}$$

and at $S_e = 0.844$,

(18) $$d\Psi(S_e)/dS_e = 1.03$$

The saturation gradient, $\partial S_e/\partial z$, may be evaluated using equations (4) and (11), giving,

(19) $$\partial S_e/\partial z = 1.09 \times 10^5\ \{ S_e^{-1.809}\{S_e^{-1.31} - 1\}^{-0.7636}\{1 - (1 - S_e^{1.31})^{0.7636}\}^2\}^{-1}\ \{-Q/(4\pi z^2)\}$$

Evaluating equation (19) at $S_e = 0.844$ and $z = 26.5$ m gives for $\partial S_e/\partial z$,

(20) $$\partial S_e/\partial z = 1.68 \times 10^{-3}$$

Therefore, using equations (16), (18), and (20), $\partial\Psi(S_e)/\partial z$ at $z = 26.5$ m and $S_e = 0.844$ is,

(21) $$\partial\Psi(S_e)/\partial z = 1.73 \times 10^{-3}$$

This result verifies that capillary pressure is negligible compared to gravity as a driving force for vertical flow at this location.