U.S NUCLEAR REGULATORY COMMISSION
DIVISION OF WASTE MANAGEMENT

Mini-Report #8

ANALYSIS OF THE IMPORTANCE OF DIFFUSION OF RADIONUCLIDES WITHIN THE PROPOSED REPOSITORY HOST HORIZON

Salt Repository Project
Subtask 3.5

Prepared by

Daniel B. Stephens & Associates, Inc.

for

Nuclear Waste Consultants

TECHNICAL ASSISTANCE IN HYDROGEOLOGY
PROJECT B - ANALYSIS
RS-NMS-85-009

JANUARY, 1987

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Communication No. 135

U.S. Nuclear Regulatory Commission
Division of Waste Management
Geotechnical Branch
MS-623-SS
Washington, DC 20555

Attention: **Mr. Jeff Pohle, Project Officer**
Technical Assistance in Hydrogeology - Project B (RS-NMS-85-009)

Re: **Semi-Annual Update of SALT Numerical Evaluations Report**

Dear Mr. Pohle:

This cover letter transmits to the NRC staff Daniel B. Stephens and Associates (DBS) semi-annual update of the Numerical Evaluation of Conceptual Models Report for Salt (Subtask 3.5). The report has received a management and technical review by M. Logsdon of Nuclear Waste Consultants. The reports have been completed under DBS's quality assurance procedures in compliance with NWC's project-specific QA Plan.

The update report includes two new "mini-reports":

- o DBS Mini-Report #6: Analysis of Thermal Convection of Ground Water Induced by Radiogenic Heating with the Waste Repository.
- o DBS Mini-Report #8: Analysis of the Importance of Diffusion of Radionuclides Within the Proposed Repository Host Horizon.

In addition to these completed reports, DBS has two additional reports in progress, dealing with the following topics:

- DBS Report #7, dealing with the sensitivity of hydraulic conditions at the Deaf Smith site to recharge in New Mexico;
- DBS Report #9, dealing with the importance of aquitard diffusion of radionuclides during horizontal groundwater flow.

DBS anticipates completing these reports and submitting them to the NRC Staff within the next few months, without waiting for another formal update document.

Submission of this update report completes the contract deliverable for Subtask 3.5 at this time. DBS will update the Numerical Evaluation of Conceptual Models Report on a semi-annual basis, as directed in the current contract.

If you have any questions concerning this letter or the attached reports, please contact me immediately.

Respectfully submitted,
NUCLEAR WASTE CONSULTANTS, INC.

Mark J. Logsdon

Mark J. Logsdon, Project Manager

Att: Salt Numerical Evaluations of Conceptual Models Report Update

cc: US NRC - Director, NMSS (ATTN: PSB)
DWM (ATTN: Division Director) - 2
Mary Little, Contract Administrator
WMGT (ATTN: Branch Chief)

L. Davis, WWL
M. Galloway, TTI

bc: J. Minier, DBS

DANIEL B. STEPHENS & ASSOCIATES, INC.
CONSULTANTS IN GROUND-WATER HYDROLOGY

• GROUND-WATER CONTAMINATION • UNSATURATED ZONE INVESTIGATIONS • WATER SUPPLY DEVELOPMENT •

FEB 03 1987

January 31, 1987

Mr. Mark Logsdon
Nuclear Waste Consultants
8341 S. Sangre de Cristo Rd.
Littleton, CO 80127

Dear Mark:

Daniel B. Stephens & Assoc. submit the attached as the update report for Subtask 3.5, Numerical Evaluation of Conceptual Models.

This report contains the following "mini-reports":

6. Analysis of thermal convection of ground water induced by radiogenic heating within the waste repository

8. Analysis of the importance of diffusion of radionuclides within the proposed repository host horizon.

At present, two additional mini-reports, originally scheduled to be included in this Subtask 3.5 update report, are being revised as a result of report review. The additional mini-reports, which will be submitted after the revisions are completed, are:

7. The influence of increased recharge in New Mexico on ground-water travel time in the Wolfcamp

9. Analysis of the importance of aquitard diffusion of radionuclides during transport by horizontal ground-water flow.

Please contact me if you have any questions concerning this Subtask 3.5 update report.

Yours truly,
Daniel B. Stephens & Assoc.

Jeffrie D. Minier

Jeffrie D. Minier
Project Manager

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ANALYSIS OF THE IMPORTANCE OF DIFFUSION OF RADIONUCLIDES WITHIN THE PROPOSED REPOSITORY HOST HORIZON

Numerical Evaluation of Conceptual Models
Subtask 3.5
Mini-Performance Assessment #8

January, 1987

DANIEL B. STEPHENS & ASSOCIATES, INC.

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1.1 General Statement of the Problem

The movement of radionuclides may be generally described by the advection-dispersion equation. However, even where ground-water velocity is negligible (i.e. so small that mechanical dispersion is negligible relative to molecular diffusion), the movement of radionuclides from the repository may occur by molecular diffusion (described by Fick's law). Diffusion of radionuclides may be a significant migration pathway from the repository through the salt to a more permeable stratigraphic unit (aquifer) where the radionuclides may then be transported by ground-water flow to the accessible environment (Figure 1).

1.2 Statement of Relevance to NRC

In the absence of ground-water convection, transport of radionuclides towards the accessible environment may occur by molecular diffusion through the proposed repository host rock. While diffusion alone is unlikely to be a rapid or significant transport mechanism over large distances, diffusion may decrease expected travel times to the accessible environment. Diffusion/ advection processes relate to geochemical and hydrogeologic factors which would affect the ability of the geologic repository to isolate the waste (10CFR60.122).

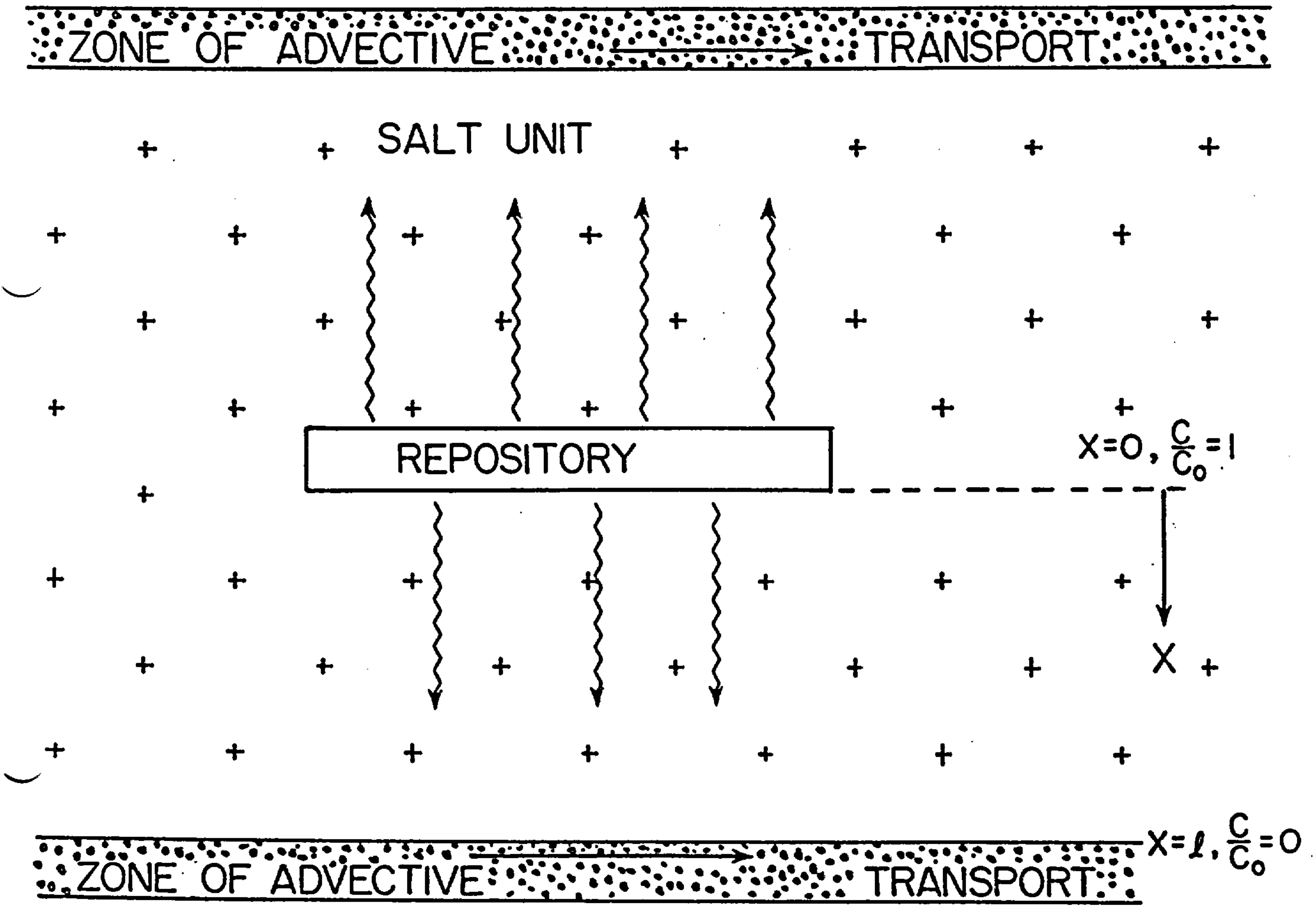

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Figure 1. Idealized Migration Pathway For Vertical Diffusion of Radionuclides Through Salt To An Aquifer Where the Radionuclides Are Then Transported To The Accessible Environment By Horizontal Ground-Water Flow Through the Aquifer.

1.3 Relationship to Other Analyses, Documents, Tasks and Subtasks

Most analyses do not incorporate diffusion effects and are performed under the assumption that ground-water flow across the evaporite aquitard is generally downward at low velocities due to low permeabilities (e.g. Kreitler and others, 1984, Stephens & Assoc., 1986a). Analyses by Stephens & Assoc. (1986b) suggest the possibility of significant horizontal groundwater velocities (with respect to travel time and cumulative release criteria) in sedimentary interbeds within the Permian evaporite aquitard. Diffusion may decrease radionuclide travel time and increase radionuclide release rates through a combination of vertical molecular diffusion and lateral advection through permeable interbeds.

2.0 OBJECTIVES

The objective of this mini-report is to determine the position of the radionuclide front migrating from the repository via diffusion as a function of time. The significance of radionuclide diffusion towards nearby zones of advective transport is also considered.

3.0 GENERAL APPROACH

3.1 Geology

The Palo Duro Basin is frequently described as being comprised of three hydrostratigraphic units (HSU A, B, and C). The upper fresh-water aquifer (HSU A) and the lower brine aquifer (HSU C) are separated by a Permian evaporite aquitard (HSU B, DOE, 1986; Figure 2). Typical rock types in the San Andres formation (proposed location for high level radioactive waste repository) include anhydritic mudstone, limestone, dolomite, anhydrite, halite and terrigenous red beds (Kreitler and others, 1984).

The hydrologic system in this analysis is modelled as a layer of halite which contains the high level waste repository. Within the salt is a sedimentary interbed which provides relatively rapid transport of radionuclides to the accessible environment by horizontal ground-water flow (Figure 1).

3.2 Flow/Transport System

Ground-water flow is assumed to occur horizontally through the permeable interbed only; vertical flow velocity is assumed to be zero. Transport of the radionuclides from the repository occurs by molecular diffusion to the sedimentary interbed where the radionuclides are then rapidly transported to the accessible environment by advection (Figure 1).

3.3 Repository and Source Term

The analysis will be performed using relative concentrations with the magnitude of the radionuclide (relative) concentration equal to unity at the repository, and equal to zero at the contact between the salt unit and the zone of advective transport.

ERA	SYSTEM	SERIES	GROUP	FORMATION	HYDROSTRATIGRAPHIC UNIT (HSU)
CENOZOIC	QUATERNARY			RECENT FLUVIAL AEOLIAN AND LACUSTRINE DEPOSITS	FRESHWATER FLOW SYSTEM *HSU A*
	TERTIARY			OGALLALA AND LACUSTRINE DEPOSITS	
MESOZOIC	CRETACEOUS	COMANCHE	WASHITA FREDRICKSBURG		
			TRINITY		
	TRIASSIC		DOCKUM	TRUJILLO (Santa Rosa)	
				TECOVAS	
PALEOZOIC	PERMIAN	OCHOA		DEWEY LAKE (Quartermaster)	SHALE AND EVAPORITE AQUITARD *HSU B*
				ALIBATES	
		GUADALUPE	ARTESIA (WHITEHORSE)	SALADO-TANSILL	
				YATES	
				SEVEN RIVERS	
				QUEEN-GRAYBURG	
			PEASE RIVER	SAN ANDRES (BLAINE)	
		LEONARD		GLORIETA	
			CLEAR FORK	UPPER CLEAR FORK	
				TUBB	
				LOWER CLEAR FORK	
				RED CAVE	
			WICHITA		
		WOLFCAMP			DEEP-BASIN FLOW SYSTEM *HSU C*
	PENNSYLVANIAN	VIRGIL	CISCO		
		MISSOURI	CANYON		
		DES MOINES	STRAWN		
		ATOKA	BEND		
		MORROW			
	MISSISSIPPIAN	CHESTER			
		MERAMEC			
		OSAGE			
	ORDOVICIAN	CANADIAN	ELLENBURGER		
	CAMBRIAN		UNNAMED SANDSTONE		
	PRECAMBRIAN				

Explanation

———— Unconformity

– – – – – Boundary in Dispute

Figure 2. Generalized Hydrostratigraphic Column for the Palo Duro Basin (DOE, 1986).

4.0 TECHNICAL APPROACH

4.1 Formal Statement of Problem

A solution has been obtained to determine the concentration distribution as a function of time for radionuclides migrating via diffusion from the repository to a nearby zone of advective transport. The one-dimensional solution is in terms of relative concentration. The analyses illustrate the dependence of the concentration distribution on the coefficient of diffusion. The analyses are performed for varying values of the distance between the repository and the zone of advective transport.

4.2 Identification of Solution Techniques

The transport of radionuclides may be described by the diffusion equation (see Appendix for governing equations, boundary and initial conditions,and solution techniques). A solution of the diffusion equation is obtained to determine the position of the radionuclide front as a function of time (Appendix).

4.3 Definitions and Assumptions

Parameters which describe the standard solution are:

C/Co - relative solute concentration

x - distance along diffusion path

t - time

D - diffusion coefficient

l - diffusion pathlength

List of Assumptions:

1. Darcy (i.e. advective) flow through the salt is nonexistent
2. Constant radionuclide concentration at the repository boundary
3. Radionuclide concentration at the contact between the salt and the zone of advective transport is zero
4. No radioactive decay occurs, i.e. no production of daughter nuclides, no loss of parent nuclides
5. Diffusion from the repository to the zone of advective transport may be reasonably approximated as a one-dimensional process

4.4 Identification of Expected Output and Judgement Criteria

The output are relative concentration profiles along the diffusion path as a function of time. The significance of the distance between the repository and zone of advective transport is examined.

4.5 Standard Solution

The relative concentration of radionuclides in homogeneous medium is

$$\frac{c}{c_0}(x, t) = 1 - \frac{x}{\ell} + \sum_{n=1}^{\infty} \frac{-2}{n\pi} \exp\left(\frac{-n^2\pi^2 Dt}{\ell^2}\right) \sin\left(\frac{n\pi x}{\ell}\right)$$

given the following boundary and initial conditions

$$\frac{c}{c_0}(0, t) = 1 \qquad t > 0$$

$$\frac{c}{c_0}(\ell, t) = 0 \qquad t > 0$$

$$\frac{c}{c_0}(x, 0) = 0 \qquad 0 < x < \ell$$

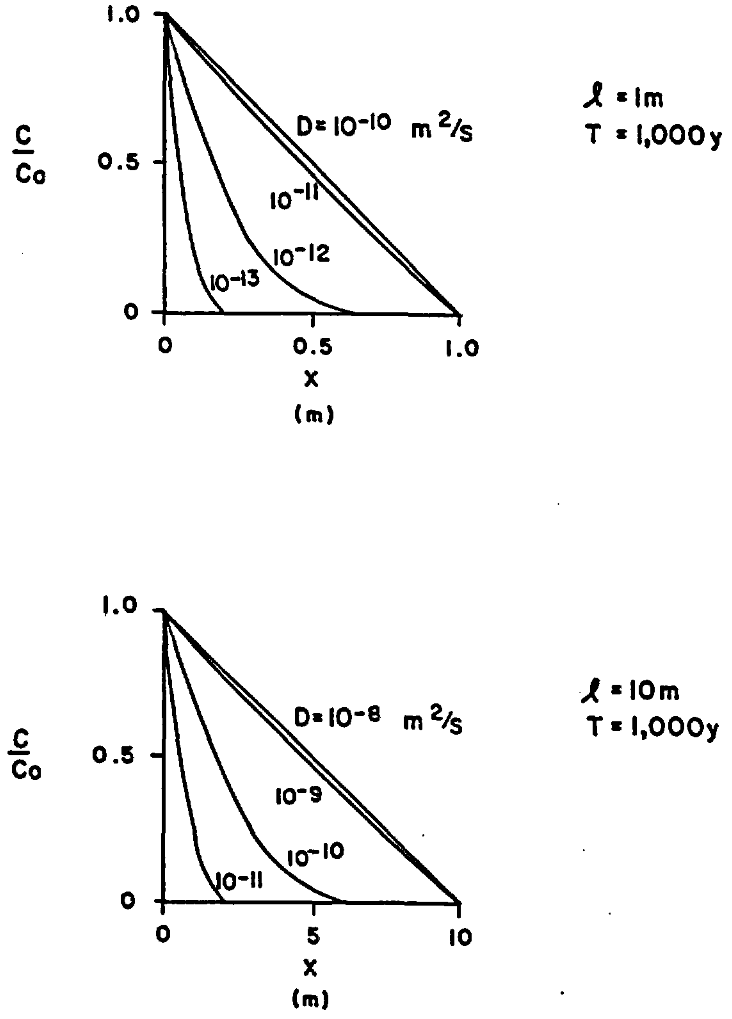
(symbols are defined in section 4.3 and the Appendix).

5.0 ANALYSES

The standard solution has been used to calculate the relative concentration of radionuclides as a function of time and distance along the diffusion path. The analyses have been performed for two diffusion pathlengths, 1 and 10 m, and at two times, 1000 and 10,000 years. The diffusion pathlength is the distance between the repository and the zone of advective transport. The magnitude of the diffusion coefficient has been varied by several orders for each case.

6.0 RESULTS

The relative concentration profiles of radionuclides along the diffusion path are presented in Figure 3. Profiles are presented for two cases. In the first case the diffusion time is 1000 years (Figure 3a). In the second case the diffusion time is 10,000 years (Figure 3b). For both cases profiles are presented for diffusion pathlengths of 1 and 10 meters.



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Date: 1 - 16 - 87

Figure 3a. Relative Concentration Profiles after 1000 years

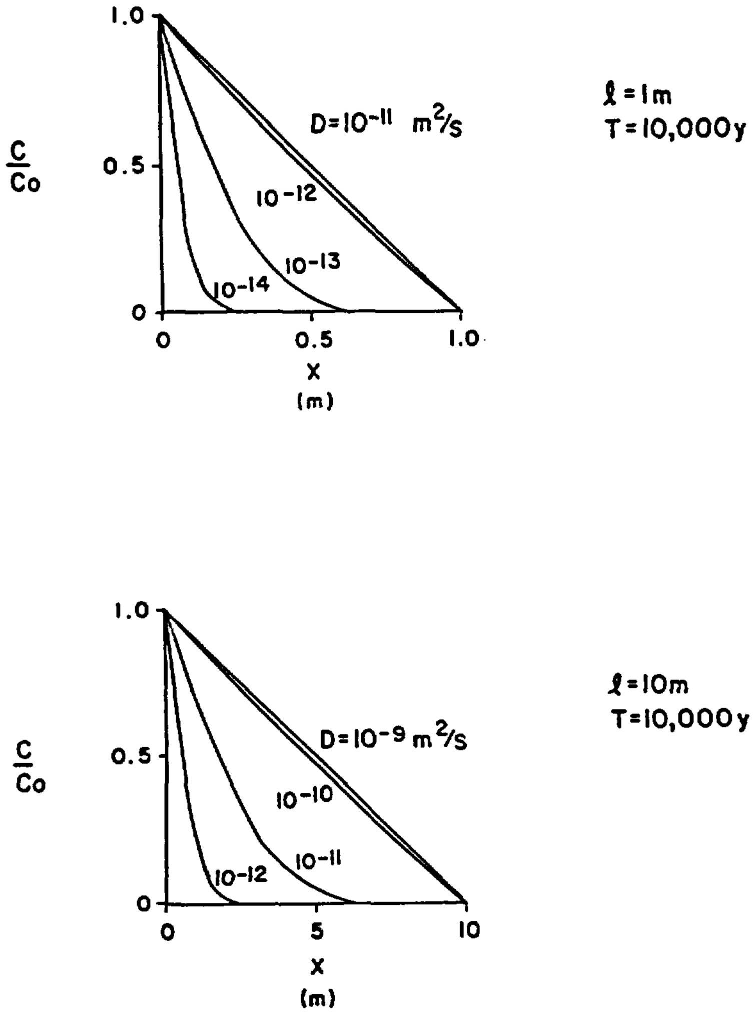

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Figure 3b. Relative Concentration Profiles after 10,000 years

7.0 CONCLUSIONS

The mass of radionuclides diffusing through the salt unit is porportional to the concentration gradient where the constant of proportionality is the diffusion coefficient(Fick's law, see Freeze and Cherry, 1979). Thus the flux of radionuclides which may be transported to the accessible environment by advection may be estimated from the concentration gradient at the contact between the salt unit and the zone of advective transport.

Consider the concentration profiles after 1000 years of diffusion since this time period relates to travel time criteria (10CFR60.122). For the case where the diffusion path length is 1 meter, Figure 3a illustrates concentration gradients approximately equal to zero at the contact between the salt unit and the zone of advective transport for diffusion coefficients less than or equal to 10^{-12} m^2/s . Therefore, if the diffusion coefficient for radionuclides in the salt unit is less than or equal to 10^{-12} m^2/s then the travel time along the diffusion/advection pathway to the accessible environment (Figure 1) will be greater than 1000 years. If the diffusion path length is 10 m then radionuclide travels times to the accessible environment will exceed 1000 years for diffusion coefficients as large as $10^{-10}m^2/s$ (Figure 3b).

Environmental standards and release limits apply to radionuclides which are predicted to move into the accessible environment within 10,000 years of disposal (40CFR191). Figure 3b illustrates concentration profiles after 10,000 years of diffusion. Concentration gradients, and thus flux of radionuclides, at the contact between the salt unit and the zone of advective transport are approximately zero after 10,000 years for diffusion coefficients less than or equal to 10^{-13} m^2/s or $10^{-11}m^2/s$ for the case where the diffusion path length is 1 or 10 m respectively.

8.0 DISCUSSION

Analyses presented in this mini report indicate that radionuclides may migrate via diffusion 1-10 m: i) in 1000 years for diffusion coefficients of 10^{-12}- $10^{-10}m^2/s$, respectively, and ii) in 10,000 years for diffusion coefficient of 10^{-13}-10^{-11} m^2/s, respectively. The expected apparent diffusivity in granite for nonsorbing radionuclides is about 10^{-10} m^2/s; weakly to strongly sorbing radionuclides will have smaller apparent diffusion coefficients (Neretnieks, 1980). The DOE (1986) presents analyses for radionuclide transport by brine diffusion using an empirically derived diffusion coefficient of 4.9 x 10^{-12} m^2/s. Therefore it is unlikely that cumulative releases of radionuclides to the accessible environment, due to diffusion alone, for 10,000 years after disposal will exceed release limits (40CFR191).

Several assumptions have been made in this report and should be briefly addressed. It has been assumed that the radionuclides migrate from the repository by molecular diffusion alone, i.e. there is no advective transport of radionuclides by ground water within the salt unit. According to the DOE (1986), ground-water flow within the evaporite aquitard, if it exists, is vertically downward. If this is the case, the analyses in this report may not accurately predict the concentration profiles in the salt unit near the repository. Advective transport of radionuclides within the salt unit has been examined in a previous mini report (Stephens & Assoc., 1986b).

Perhaps the most significant assumption in this analyses is that adsorption has been neglected. The assumption of no adsorption causes the radionuclide concentrations to be overestimated since adsorption would lower the apparent diffusion coefficient, perhaps by several orders of magnitude (see Neretnieks, 1980).

Radioactive decay will decrease the number of parent radionuclides. The analyses in this mini report did not incorporate radioactive decay and thus will overestimate the concentration of parent radionuclides at a given time and distance from the repository. Lateral molecular diffusion should cause the expected radionuclide concentration to be somewhat less than that predicted by the one-dimensional standard solution.

The effects of horizontal ground-water flow through sedimentary units within the Evaporite aquitard have been considered in previous studies (Senger and others, 1985; DOE, 1986; Stephens & Assoc., 1986b). Such a zone of advective transport near the repository may be a possible mechanism which will allow cumulative release limits to be exceeded even if there is no ground-water flow within the salt unit. For example, radionuclides may migrate from the repository by diffusion to the zone of advection where they are then transported to the accessible environment (Figure 1). The significance of this transport mechanism will depend on the distance between the repository and the zone of advective transport and also will depend on the magnitude of the diffusion coefficient of radionuclides in salt.

Analyses for radionuclide transport by brine diffusion have been performed using an empirically derived coefficient (DOE, 1986). According to DOE (1986), it is unlikely that radioactivity will escape a 40 m thickness of host rock for over 100,000 years even assuming waste package failure. The empirically-derived brine diffusion coefficient used was $4.9\text{X}10^{-12}$ m^2/s, about 4 orders of magnitude larger than the diffusion coefficient of sodium ions in salt (DOE, 1986). If the diffusion coefficient for radionuclides in salt is less than 10^{-11} m^2/s then one may expect that the radionuclides will migrate by diffusion no more than about 2 to 6 m from the repository in 1,000 to 10,000 years, respectively.

Therefore, it seems likely that molecular diffusion will not be a significant release mechanism (with respect to federal regulations) if the distance between the repository and zones of advective transport is greater than about 10 m. It is recommended that additional studies to determine the distance between zones of advection and the repository should be pursued.

9.0 REFERENCES

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Ogata, A., 1970, Theory of Dispersion in a Granular Material, U.S. Geol. Surv. Prof. Pap., 411-I, 34p.

Senger, R.K., G. E. Fogg and C. W. Kreitler, 1985, Effects of Hydrostratigraphy and Basin Development on Hydrodynamics of the Palo Duro Basin, Texas OF-WTWI-1985-37

Stephens & Assoc., 1986a, Conceptual Model Evaluation Report, Subtask 3.4

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APPENDIX

Governing Equations

The governing differential equations which describes one-dimensional unsteady diffusion in a homogeneous material is

$$D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t} \qquad (1)$$

where: D is the diffusion coefficient

C is the relative concentration of the diffusing species

x is the spatial dimension

and t is time. The diffusion equation (1) incorporates a statement of the law of conservation of mass (Ogata, 1971).

The boundary conditions for this problem are

$$\begin{aligned} c(0, t) &= 1 \qquad & t > 0 \\ c(\ell, t) &= 0 \qquad & t > 0 \end{aligned} \qquad (2)$$

The relative concentration of the radionuclide is assumed to be 1 (one) at the contact between the repository and the salt unit (x=0, Figure 1) and 0 (zero) at the contact between the salt unit and the zone of advective transport ($x = \ell$, Figure 1).

The initial condition

$$c(x, 0) = 0 \qquad 0 \leq x \leq \ell$$

states the assumption that there are no radionuclides in the salt unit prior to waste emplacement.

Solution

The Separation of Variables Technique is used to obtain a solution to equations (1) to (3) (for example, see Boyce and DiPrima, 1977). Since this problem has nonhomogeneous boundary conditions the solution will be expressed as the sum of a steady-state concentration distribution v(x) and a transient concentration distribution w(x,t):

$$c(x,\ t) = v(x) + w(x,\ t) \qquad (4)$$

The steady-state solution v(x) must satisfy equation (1)

$$\frac{\partial^2 v}{\partial x^2} = 0 \qquad 0 < x < \ell$$

and the boundary conditions (equation 2)

$$v(x = 0) = 1$$

$$v(x = \ell) = 0 \qquad (5)$$

Thus, the steady concentration solution may be expressed as a linear function of x

$$v(x) = 1 - \frac{x}{\ell} \qquad (6)$$

Substitution of equation (4) into equation (1) yields

$$D\,\frac{\partial^2 w}{\partial x^2} = \frac{\partial w}{\partial t} \qquad (7)$$

Rearranging (4) to get

$$w(x,\ t) = c(x,\ t) - v(x)$$

allows the boundary conditions of w(x,t) to be expressed as

$$w(0,\ t) = c(0,\ t) - v(0) = 1 - 1 = 0$$

$$w(\ell,\ t) = c(\ell,\ t) - v(\ell) = 0 - 0 = 0 \qquad (8)$$

The initial condition for w(x,t) may be written as

$$w(x,\ 0) = c(x,\ 0) - v(x) = 0 - v(x) = -v(x) \qquad (9)$$

Equations (7) through (9) are the diffusion equation with homogeneous boundary conditions and initial condition in terms of w(x,t). A solution to equations (7) through (9) may now be obtained using the Separation of Variables technique. The method of Separation of Variables is discussed by Boyce and DiPrima (1977).

If the form of w(x,t) is assumed to be

$$w(x,\ t) = XT \qquad (10)$$

(where X = X(x) and T = T(t))

Then equation (7) becomes

$$D\,\frac{\partial^2 X}{\partial x^2}\,T = X\,\frac{\partial T}{\partial t} \qquad (11)$$

Rearranging equation (11) separates the independant variables x and t

$$\frac{1}{X}\left(\frac{\partial^2 X}{\partial x^2}\right) = \frac{1}{DT}\,\frac{\partial T}{\partial t} = \sigma \qquad (12)$$

Through equation (12), it can be seen that equation (11) may be reduced to two ordinary differential equations each of which contain the separation constant σ :

$$\frac{\partial^2 X}{\partial x^2} - \sigma X = 0 \tag{13}$$

$$\frac{\partial T}{\partial t} - D\sigma T = 0 \tag{14}$$

Solutions of equations (13) and (14) which satisfy the boundary conditions are proportional to

$$\sin\left(\frac{n\pi x}{\ell}\right) \tag{15}$$

and

$$\exp\left(\frac{-n^2\pi^2 Dt}{\ell^2}\right) \tag{16}$$

respectively. Thus a solution of the differential equation (10) which satisfies the boundary conditions is

$$w(x,t) = \sum_{n=1}^{\infty} b_n \exp\left(\frac{-n^2\pi^2 Dt}{\ell^2}\right) \sin\left(\frac{n\pi x}{\ell}\right) \tag{17}$$

(principle of superposition, Boyce and DiPrima, 1977).

The coefficients b_n are used to satisfy the initial condition

$$w(x, 0) = f(x) = \sum_{n=1}^{\infty} b_n \sin \frac{n\pi x}{\ell} \tag{18}$$

The coefficients for the Fourier Sine Series in equation (18) are given by Boyce and DiPrima (1977) as:

$$b_n = \frac{2}{\ell} \int_{x=0}^{\ell} f(x) \sin\left(\frac{n\pi x}{\ell} \right) dx \qquad (19)$$

Substituting equations (9) and (6) into equation (19) gives

$$b_n = \frac{2}{\ell} \int_{x=0}^{\ell} -v(x) \sin\left(\frac{n\pi x}{\ell} \right) dx$$

or

$$b_n = \frac{2}{\ell} \int_{x=0}^{\ell} \left(\frac{x}{\ell} - 1 \right) \sin\left(\frac{n\pi x}{\ell} \right) dx \qquad (20)$$

Finally, the unsteady solution for the radionuclide concentration may be obtained by combining equations (4), (6), (17), and (20)

$$C(x,t) = 1 - \frac{x}{\ell} + \sum_{n=1}^{\infty} b_n \exp\left(\frac{-n^2\pi^2 Dt}{\ell^2} \right) \sin\left(\frac{n\pi x}{\ell} \right) \qquad (21)$$

where b_n is given by equation (20).

Integrating equation (20) (see Thomas, 1972)

$$b_n = \frac{-2}{n\pi}$$

simplifies equation (21) to

$$c(x, t) = 1 - \frac{x}{\ell} + \sum_{n=1}^{\infty} \frac{-2}{n\pi} \exp\left(\frac{-n^2\pi^2 Dt}{\ell^2} \right) \sin\left(\frac{n\pi x}{\ell} \right) \qquad (23)$$

which is the standard solution

A simple FORTRAN program to calculate the standard solution for this mini report follows. The program has been checked by hand calculations.

```
c       standard solution for mini report #8 salt diffusion
c       x - distance from the repository
c       l - total distance from the repository to the zone of
c       advective transport
c       c - relative radionuclide concentration
c       t - time since c=1 at x=0
c       d - diffusion coefficient
        real l
        write(5,*)' enter the distance from the repository to'
        write(5,*)' the zone of advective transport in m'
        read(5,*)l
        write(5,*)' enter the diffusion coefficient in m2/y'
        read(5,*)d
        write(5,*)' enter the time in years'
        read(5,*)t
        nl=9
        write(5,*)' l= ',l,' m'
        write(5,*)' t= ',t,' y'
        write(5,*)' D= ',d,' m2/y'
        do 1 nx=1,nl
                x=float(nx)*l/(float(nl)+1.)
                sum=0.
                do 2 n=1,200
                        rn=float(n)
                        a=-2./(rn*3.14159)
                        earg=-1.*((rn*3.14159/l)**2.)*d*t
                        a2=exp(earg)
                        sinarg=rn*3.14159*x/l
                        a3=sin(sinarg)
                        term=a*a2*a3
                        sum=sum+term
c       write(5,*)' n=',n,' term=',term,' sum=',sum
2               continue
                c=1-(x/l)+sum
                write(5,*)' x= ',x,'  c= ',c
1       continue
        stop
        end
```