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Scientific Notebook No. 286, Evaluation of C-Well Tracer Experiment (08/10/1998 through 05/02/2005)

EVALUATION OF C-WELL TRACER EXPERIMENT

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Objective(s)

The primary objective of this work is to ~~quantify~~ identify and quantify the factors influencing groundwater flow and mass transport in the tuffaceous rocks which underlie Yucca Mountain, Nevada. Identification and quantification of the factors which influence flow and transport at the site will be attempted through an interpretation of tracer tests performed at the site. Note that the test are being performed in the saturated zone.

(DAF 8/10/61)

The tracer tests which will be ~~utilized~~ analyzed in this work, were performed by the USGS. The tracers utilized in this work are (i) iodine (which is considered to be a conservative tracer), (ii) Other tracer-tests which will be analysed as part of this work include those reported by Reimus and Turin (Draft Report ... Yucca Mountain Site Characterization Project Report ... Milestone SP2370M4 ... March 1997). In this series of tracer-tests the following tracers were ~~considered~~ used: (i) pentafluorobenzoate (PFBA); (ii) Lithium bromide; (iii) polystyrene microspheres (~ 0.36 μm diameter).

This book will document the tracer tests performed, the model used to interpret the recorded data and changes made to the model. As a starting point in this work, the iodine tracer-test performed by the USGS is considered.

## IODINE TRACER-TEST

BRIEF OVERVIEW:

D.A.T. 8/10/98



## INITIAL ENTRIES

Objectives:

The primary objectives of this work are to identify and quantify the factors influencing groundwater flow and mass transport in the tuffaceous rocks which underlie (D.A.T. 8/10/98) Yucca Mountain, NV. Identification and quantification of the factors which influence flow and mass transport at the site has been attempted through the use of pump-tests and tracer tests conducted in the saturated zone. This work reported in this lab. book focusses primarily on (D.A.T. 8/10/98) an interpretation of the tracer tests conducted in the tuffaceous rocks at what is termed the C-hole complex.

The tracer-tests which will be analysed have been reported in three documents; (i) Geldon et al -- USGS - Yucca Mountain Project Branch, 1997 Milestone Report 3P23PM3 ... Results of hydraulic and conservative Tracer-Tests in Miocene Tuffaceous rocks at the C-hole Complex, 1995-1997, Yucca Mountain, Nye County, Nevada; and (ii) Reimus and Turin ... Yucca Mountain Site characterization Project Report, Milestone SP2370M4 ... Results, Analyses, and Interpretation of Reactive tracer-tests in the Lower Bullfrog Tuff at the C-wells, Yucca Mountain, Nevada. The tracers (D.A.T. 8/10/98) considered in the former study include: (i) iodide; (ii) 2,6 Difluorobenzoic acid (DFBA); and (iii) 3-carbomoyl-2-pyridone (pyridone), whilst for the latter study the tracer considered were (i) pentafluoro-benzoate (PFBA); (ii) Lithium bromide; and (iii) polystyrene micro-spheres (~0.36 μm diameter).

This book documents the analyses performed on each of the tracer tests outlined in the above studies. As a starting (D.A.T. 8/10/98) point, a review of the work performed in the above studies will be carried out.

INITIAL ENTRIES 8/13/98 D.A.F.

## Review of Geldon et al.

Tracer-tests were conducted at the C-hole complex starting in February, 1996 and continuing into 1997. This report documented:

(i) Iodide injection into the combined Bullfrog-Tram interval in borehole UE-25 C#2 with recovery from the same interval in borehole UE-25 C#3

(ii) 2,6 Difluorobenzoic acid (DFBA) injection into the Lower Bullfrog interval in borehole UE-25 C#2 and recovery from the same zone in borehole UE-25 C#3

(iii) 3-carbomoyl-2-pyridone (pyridone) ~~into~~ D.A.F. 8/14/98 injection into the Lower Bullfrog interval in borehole UE-25 C#1 and recovery in the same interval in borehole UE-25 C#3.

Iodide:
- inorganic ion
- considered to be conservative
- can be analyzed by high peformance chromatography

Pyridone:
- intensely fluorescent
- stable against photochemical decay
- not affected by pH
- low detection limit
- conservative (?)

DFBA:
- unique chemical signature
- can be analyzed by high peformance liquid chromatography



Proposed physical hydrogeology (C-hole complex):
- two fracture orientations are statistically significant (dip and azimuth-of-strike of the fracture planes are: 77/167 and 78/191)
- fractures are assumed to have a log-normal distribution of lengths and non-uniform spacing
- hydraulic testing indicates probable directionality in transmissivity

## DATA AVAILABILITY

Currently, the only tracer data which is available for this report is that for iodide (GS960808312315.001). ~~Data~~ This data was obtained from the analysis of the iodide-tracer-test water samples collected during the 8/13/96 convergent-tracer test with pumping in borehole UE-25 C#3 and injection in borehole UE-25 C#2. Data for the tracer-tests involving 2,6 DFBA and pyridone is not currently available.

## ~~IODIDE TRACER DATA~~ D.A.F. 8/13/98

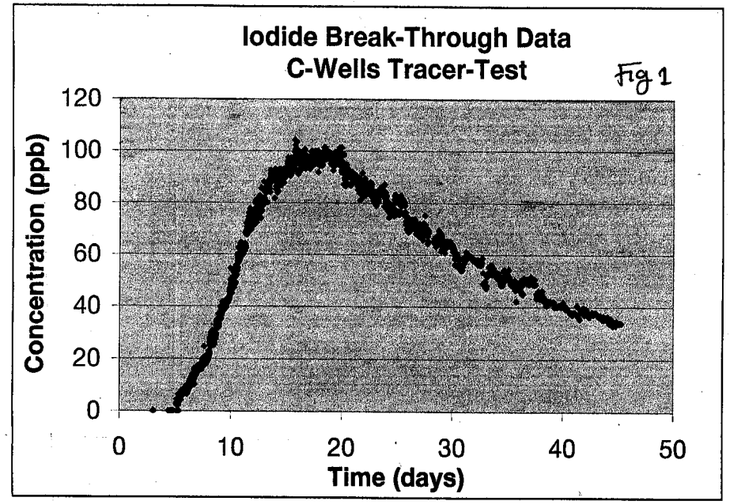
### IODIDE TRACER TEST

- steady-state conditions established after 7000 min of pumping
- injection time 28 minutes at 0.41 L/s
- tracer solution consisted of 5.9 kg of sodium iodide mixed with 550 L of water from recovery well C#3 (~ $1 \times 10^4$ ppm) chased with 182 L of water pumped into C#2 to ensure evacuation of the injection string. Later analysis showed that the injected tracer had a conc. of ~ 10,200 ppm.
- detection limit ~ 3 ug/L
- 3134 samples collected for analysis of which 2046 were analyzed.
- breakthrough occurred after ~ 5.07 days.

- pumping rate varied between 8.5 L/s and 6.2 L/s --- median value ~7.4 L/s

IODIDE TRACER DATA  INITIAL ENTRIES  8/13/98 DAF

Figure 1 shows a plot of the iodide concentration at the recovery well as a function of time.




Geldon et al. suggested that (D.A.F. 8/13/98) tracer breakthrough occurred at 5.07 days after injection with the peak concentration occurring ~~after~~ 17.75 days after injection.

(*) ~~In~~ Figure 1 indicates that tracer breakthrough is occurring ~~at the recovery wells at~~ prior to ~~5.07~~ days. Infact tracer breakthrough occurs ~~from~~ at approximately 2 days after injection. D.A.F. 8/13/98

Ignore { There does appear to be an inflection in the breakthrough curve at ~5.07 days. Does this indicate two different transport paths?

DAF. 8/13/98



INITIAL ENTRIES  D.A.F.

Figure 1 shows (D.A.F. 8/13/98) agreement with the proposed breakthrough time of Geldon et al. Note that between 3-5 (D.A.F. 8/13/98) days after injection small quantities of tracer were detected at the recovery well. An explanation of this data doesn't seem to have been provided.

Geldon et al. propose a dual permeability approach to model the tracer test. This dual permeability assumes that mass-transport occurs in both the fractures and the matrix, with an exchange of mass occurring between the two. The (D.A.F. 8/13/98) method of interpretation used is that of Moench (1995) which predicts solute concentration (breakthrough) at recovery wells in a radially convergent flow field, in a dual porosity medium. The following outlines the Moench (1995) model.

D.A.F. 8/13/98

Moench (1995)  8/14/98 D.A.F.

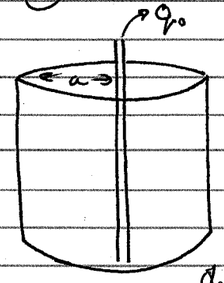
Model assumes : (i) dual porosity medium
(ii) convergent radial flow field
(iii) diffusion and instantaneous linear sorption within the rock matrix
(iv) matrix blocks are (D.A.F. 8/13/98) spherical
(v) hydraulic conductivity of the blocks is assumed to be small compared to the hydraulic conductivity of the aquifer as a whole, thus advection within the blocks is negligible.
(vi) tracer diffuses across a layer of low-diffusivity material or fracture skin and through out the rock matrix in accordance with Fick's Laws
(vii) flow into the pumped well is from the fractures only.

8/14/98
D.A.T.

Mathematical Model:

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r D_L \frac{\partial c}{\partial r}\right] - v\frac{\partial c}{\partial r} - q' = R\frac{dc}{dt} \qquad (1)$$

$D_L = \alpha_L |v|$




$\phi_f$ ≡ fracture porosity

Bear

$q_0 = A q_r = 2\pi r h q_r$

$q_r$ ≡ specific discharge in the radial direction

$\therefore q_0 = 2\pi r h K \frac{\partial \xi}{\partial r}$ $\quad \xi$ ≡ hydraulic head

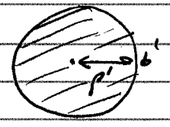
$\therefore \frac{q_0}{2\pi h} = rK\frac{\partial \xi}{\partial r} \Rightarrow \frac{q_0}{2\pi h} = rv \Rightarrow v = \frac{q_0}{2\pi r h}$

$R = 1 + \frac{d_b K_d}{\phi_f}$ $\quad d_b$ ≡ bulk density
$K_d$ ≡ distribution coefficient of tracer in fracture
$R$ ≡ retardation coefficient

Diffusion of tracer into the rock matrix $q'$

maybe able to consider other functions $\Rightarrow$

$$q' = \frac{3D'}{\mu b'}\left\langle \frac{\partial c'}{\partial \rho'} \right\rangle_{\rho'=b'} \qquad 0 \le \rho' \le b'$$




$\rho'$ ≡ radial distance from the centre of the grain
$c'$ ≡ concentration in the matrix
$D'$ ≡ effective diffusion coefficient
$\mu$ ≡ void ratio $= \phi_f/(1-\phi_f)$
$b'$ ≡ radius of grains



$D' \propto \phi'$ ($\phi'$ ≡ interconnected porosity)
$D' \propto D_F$ ($D_F$ ≡ free water diffusion coefficient)

$\therefore D' = \phi' D_F \frac{k}{\tau^2}$ $\quad \frac{k}{\tau^2}$ ≡ constant of proportionality

$k$ ≡ constrictivity
$\tau^2$ ≡ tortuosity

Transport equation in the matrix:

$$\frac{D'\partial^2(\rho' c')}{\partial(\rho')^2} = \phi' R' \frac{\partial(\rho' c')}{\partial t} \qquad (3)$$

Transport in the matrix is purely diffusive

$R' = 1 + \frac{d_b' K_d'}{\phi'}$ $\quad d_b'$ ≡ bulk density of the matrix
$K_d'$ ≡ distribution coefficient of the tracer in the matrix.

Boundary Conditions

At the pumping well: $r = r_w$

$$q_0 C_w + \pi r_w^2 h_w \frac{\partial C_w}{\partial t} = 2\pi r_w h \phi_f \left[D_L \frac{\partial c}{\partial r} - vc\right] \qquad (4)$$

$\pi r_w^2 h_w \frac{\partial C_w}{\partial t}$ accounts for well mixing

assumption: tracer moves from the aquifer into the pumped well by advection and longitudinal (radial) dispersion where it mixes with the fluid residing in the well bore before it is discharged at the surface.

8/14/98
D.A.T.

At the input well : $r = r_L$

1. Slug input :

$$2\pi r_L h \phi_f \left[ D_L \frac{\partial c}{\partial r} - vc \right] = M\delta - \pi r_i^2 h_i \frac{\partial c_b}{\partial t} \quad (5)$$

well mixing factor

$M \equiv$ mass of tracer injected
$\delta \equiv$ Dirac Delta function
$h_i \equiv$ mixing length in input well
$C_b \equiv$ concentration of the mixed fluid in the well bore.

2. Constant tracer injection : $r = r_L$

$$2\pi r_L h \phi_f \left[ D_L \frac{\partial c}{\partial r} - vc \right] = C_0 (q_i + \varepsilon q_0) - \pi r_i^2 h_i \frac{\partial c_b}{\partial t} \quad (6)$$

well mixing factor

$C_0 \equiv$ tracer input concentration
$q_i \equiv$ tracer input rate
$\varepsilon q_0 \equiv$ fraction of water recycled
$C_b \equiv$ concentration of the well-mixed fluid in the well bore.

Assumptions : well-bore mixing removes any discontinuity which would exist between the concentrations in the well bore and adjacent to the well bore. ∴ reasonable to assume $C_b = c$ in (5) and (6) and $C_w = c$ in (4)

Boundary Condition for the Diffusion Domain

$$\frac{\partial c'}{\partial \rho'} = 0 \quad \text{at } \rho' = 0$$

$$k_s \left[ \langle c' \rangle_{\rho'=b'} - c \right] = D' \left\langle \frac{\partial c'}{\partial \rho'} \right\rangle_{\rho'=b'} \quad (7)$$

$k_s \equiv$ mass transfer coefficient



Transforming to Dimensionless Coordinates (See Table 1, Moench 1995)

Flow Domain : $r_{wD} \leq r_D \leq 1$

$$\frac{1}{Pe\, r_D} \frac{\partial^2 C_D}{\partial r_D^2} + \frac{1}{r_D} \frac{\partial c_D}{\partial r_D} - \frac{2R}{(1 - r_{wD}^2)} q'_D = \frac{2R}{(1 - r_{wD}^2)} \frac{\partial c_D}{\partial t} \quad (8)$$

(9) $q'_D = 3\gamma' \left\langle \frac{\partial c'_D}{\partial \rho'} \right\rangle_{\rho'_D = 1}$ ⇒ source/sink term describing matrix-fracture interaction (D.A.T. 8/14/98)

$\gamma' \equiv \frac{\text{diffusion}}{\text{storage}}$ term $= \frac{D'(r_L^2 - r_w^2)\pi h \phi_f}{R q_0 \mu (b')^2}$ (10)

(D.A.T. 8/14/98)

— At the pumping well : $r_D = r_{wD}$
— assuming the concentration in the well bore can be equated with that in the aquifer

$$\frac{1}{Pe} \frac{\partial c_D}{\partial r_D} = \mu_w \frac{\partial c_D}{\partial t} \quad (11)$$

(D.A.T. 8/14/98) ~~$r_D = r_{wD}$~~

$\mu_w \equiv$ pumping well mixing factor

— At the injection well : $r_D = 1$ ~~(slug)~~ (D.A.T. 8/14/98)

Slug test : $\frac{1}{Pe} \frac{\partial c_D}{\partial r_D} + c_D = \delta - \mu_i \frac{\partial c_D}{\partial t_D}$ (12)

$\mu_i \equiv$ injection well mixing factor

$\mu_i \equiv \frac{\text{volume of water in the injection well}}{\text{volume of water in the aquifer}}$

constant injection : $\frac{1}{Pe} \frac{\partial c_D}{\partial r_D} + c_D = 1 - \mu_i \frac{\partial c_D}{\partial t_D}$ (13)

8/14/98
D.A7.

Diffusion Domain $0 \le \rho_D' < 1$

$$\frac{\partial^2(\rho_D' C_D')}{\partial(\rho_D')^2} = \frac{\sigma'}{\gamma'} \frac{\partial(\rho_D' C_D')}{\partial t} \quad (14)$$

Boundary condition at the centre of the grain

$$\frac{\partial C_D'}{\partial \rho_D'} = 0 \quad (15)$$

B.C. at the interface between the two domains

$$C_D' = C_D - S_K \left\langle \frac{\partial C_D'}{\partial \rho_D'} \right\rangle_{\rho_D'=1} \quad (16)$$

$S_K \equiv$ skin factor $= \frac{D'}{k_s b'}$

Laplace transform of the Solute equations

~~Consider the flow Domain~~ (D.A7 8/14/98)

Laplace Transform

$$\mathcal{L}[f(t)] = \int_0^\infty e^{-st} f(t)\, dt = F(s)$$

Inverse Laplace Transform

$$\mathcal{L}^{-1}[F(s)] = f(t)$$

~~flow domain (example)~~ (D.A7 8/14/98)

~~let $f(t) = \frac{1}{r} \frac{\partial}{\partial r}\left[ r D_L \frac{\partial C}{\partial}\right.$~~ (D.A7 8/14/98)



8/14/98
D.A7.

Flow domain example

$$\text{let } f(t) = \frac{1}{Pe\, r_D} \frac{\partial^2 C_D}{\partial r_D^2} + \frac{1}{r_D} \frac{\partial C_D}{\partial r_D} - \frac{2R}{(1-r_{wD}^2)} q_D' - \frac{2R}{(1-r_{wD}^2)} \frac{\partial C_D}{\partial t} = 0$$

$$\mathcal{L}[f(t)] = \mathcal{L}\left[\frac{1}{Pe\, r_D} \frac{\partial^2 C_D}{\partial r_D^2}\right] + \mathcal{L}\left[\frac{1}{r_D} \frac{\partial C_D}{\partial r_D}\right] - \mathcal{L}\left[\frac{2R}{(1-r_{wD}^2)} q_D'\right]$$

$$- \mathcal{L}\left[\frac{2R}{(1-r_{wD}^2)} \frac{\partial C_D}{\partial t}\right]$$

$$\Rightarrow \mathcal{L}\left[\frac{1}{Pe\, r_D} \frac{\partial^2 C_D}{\partial r_D^2}\right] = \frac{1}{Pe\, r_D} \frac{\partial^2}{\partial r_D^2}\left[\mathcal{L}[C_D]\right] = \frac{1}{Pe\, r_D} \frac{\partial^2 \bar{C}_D}{\partial r_D^2}$$

$$\Rightarrow \mathcal{L}\left[\frac{1}{r_D} \frac{\partial C_D}{\partial r_D}\right] = \frac{1}{r_D} \frac{\partial \mathcal{L}[C_D]}{\partial r_D} = \frac{1}{r_D} \frac{\partial \bar{C}_D}{\partial r_D}$$

$$\Rightarrow \mathcal{L}\left[\frac{2R}{(1-r_{wD}^2)} q_D'\right] = \frac{2R}{(1-r_{wD}^2)} \mathcal{L}[q_D'] = \frac{2R}{(1-r_{wD}^2)} \mathcal{L}\left[3\gamma' \left\langle \frac{\partial C_D'}{\partial \rho_D'} \right\rangle\right]$$

$$= \frac{6R\,3\gamma'}{(1-r_{wD}^2)} \frac{\partial \bar{C}_D'}{\partial \rho_D'}$$

– now assume that the diffusive flux into the matrix can be represented as a flux vector in the fracture domain

then $\bar{C}_D \bar{q}_D = \bar{q}_D' = 3\gamma' \left\langle \frac{d\bar{C}_D'}{d\rho_D'} \right\rangle_{\rho_D'=1}$

$$= \frac{2R\, \bar{C}_D \bar{q}_D}{(1-r_{wD}^2)}$$

$$\Rightarrow \mathcal{L}\left[\frac{2R}{(1-r_{wD}^2)} \frac{\partial C_D}{\partial t}\right] = \frac{2R}{(1-r_{wD}^2)} \mathcal{L}\left[\frac{\partial C_D}{\partial t}\right] = \frac{2R}{(1-r_{wD}^2)} \left[s\bar{C}_D - C(t=0)\right]$$

$$= \frac{2R}{(1-r_{wD}^2)} \left[s\bar{C}_D\right]$$

8/14/98
D.97.

~~Done~~ (D.97 8/14/98)

∴ Flow equation in the Laplace Domain is

$$\frac{1}{Pe\, r_D}\frac{\partial^2 \bar{C}_D}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial \bar{C}_D}{\partial r_D} - \frac{2R\bar{C}_D\bar{q}_D}{(1-r_{wD}^2)} - \frac{2Rs\bar{C}_D}{(1-r_{wD}^2)} = 0$$

$$\frac{1}{Pe\, r_D}\frac{\partial^2 \bar{C}_D}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial \bar{C}_D}{\partial r_D} = \frac{2R\bar{C}_D}{(1-r_{wD}^2)}(\bar{q}_D + s) \qquad (17)$$

Applying Laplace Transform to the boundary conditions:

Injection well:

Slug test $\Rightarrow$ $\frac{1}{Pe}\frac{\partial \bar{C}_D}{\partial r_D} + \bar{C}_D = 1 - M_i s\bar{C}_D \quad \Rightarrow r_D = 1$ (18)

constant injection $\Rightarrow$ $\frac{1}{Pe}\frac{\partial \bar{C}_D}{\partial r_D} + \bar{C}_D = \frac{1}{s} - M_i s\bar{C}_D \quad \Rightarrow r_D = 1$ (19)

$$\bar{C}_D\bar{q}_D = \bar{q}'_D = 3\gamma'\left\langle \frac{\partial \bar{C}'_D}{\partial \rho'_D}\right\rangle_{\rho'_D=1} \qquad (20)$$

Diffusion Domain

$$\frac{\partial^2(\rho'_D\bar{C}'_D)}{\partial(\rho'_D)^2} = \frac{s\sigma'}{\gamma'}(\rho'_D\bar{C}'_D) \qquad (21)$$

Boundary condition at the center of the domain

$$\frac{\partial \bar{C}'_D}{\partial \rho'_D} = 0 \qquad \rho'_D = 0 \qquad (22)$$



Boundary condition at the surface of a sphere matrix block

$$\bar{C}'_D = \bar{C}_D - S_K\left\langle \frac{\partial \bar{C}'_D}{\partial \rho'_D}\right\rangle_{\rho'_D=1} \qquad (23)$$

## Solving The Boundary Value Problem for the Matrix

General form of the solution to (21)

$$\rho'_D\bar{C}'_D = A\cosh(m\rho'_D) + B\sinh(m\rho'_D) \qquad (24)$$

where $m^2 = \frac{s\sigma'}{\gamma'}$

Considering the bc at the center of the domain (22)

$$\left.\frac{d\bar{C}'_D}{d\rho'_D} = 0\right|_{r'_D=0} \Big\} \text{ implies that } \bar{C}'_D \text{ must be finite}$$

$\sinh(0) = 0 \quad \therefore \quad \rho'_D\bar{C}'_D = A\cosh(0)$

$0 = A\cosh(0)$

$\therefore A = 0$ since $\cosh(0) = 1$

$\therefore \rho'_D\bar{C}'_D = B\sinh(m\rho'_D) \iff \bar{C}'_D = \frac{B}{\rho'_D}\sinh(m\rho'_D)$

Considering the outer boundary condition

$$\frac{d\bar{C}'_D}{d\rho'_D} = -\frac{B}{\rho'^2_D}\sinh(m\rho'_D) + B\frac{m}{\rho'_D}\cosh(m\rho'_D)$$

subing in (23) gives

$$\left\{\frac{B}{\rho'_D}\sinh(m\rho'_D)\right\}_{\rho'_D=1} = \bar{C}_D - S_K\left\{B\frac{m}{\rho'_D}\cosh(m\rho'_D) - \frac{B}{\rho'^2_D}\sinh(m\rho'_D)\right\}$$

8/14/98
D. AT.

$$\therefore \beta \sinh(m) = \bar{C}_D - Sk\left\{\beta m \cosh(m) - \beta \sinh(m)\right\}$$

$$\Rightarrow \beta = \frac{\bar{C}_D}{\sinh(m) + Sk\left\{m\cosh(m) - \sinh(m)\right\}}$$

$$\therefore \bar{C}'_D = \frac{\sinh(m\beta')\,\bar{C}_D}{\beta' \sinh(m)\left[1 + Sk\left\{m\coth(m) - 1\right\}\right]}$$

Computing $\bar{q}_D$ from (20)

$$\frac{d\bar{C}'_D}{d\beta'} = -\frac{1}{\beta'^2}\left\{\frac{\sinh(m\beta')\,\bar{C}_D}{\sinh(m)\left[1+Sk(m\coth(m)-1)\right]}\right\} + \frac{\bar{C}_D\, m\cosh(m\beta')}{\beta'\left[1+Sk(m\coth(m)-1)\right]}$$

Evaluating $\left\langle \frac{d\bar{C}_D}{d\beta'} \right\rangle_{r'_D=1}$

$$\left\langle \frac{d\bar{C}'_D}{d\beta'} \right\rangle_{r'_D=1} = \frac{-\sinh(m)\,\bar{C}_D}{\sinh(m)\left[1+Sk(m\coth(m)-1)\right]} + \frac{m\cosh(m)\,\bar{C}_D}{\left[1+Sk(m\coth(m)-1)\right]}$$

$$= \frac{\bar{C}_D\left[m\cosh(m)-1\right]}{\left[1+Sk(m\coth(m)-1)\right]}$$

$$\therefore \bar{C}_D \bar{q}_D = 3\gamma'\left\{\frac{\bar{C}_D\left[m\cosh(m)-1\right]}{\left[1+Sk(m\coth(m)-1)\right]}\right\}$$

$$\therefore \bar{q}_D = \frac{3\gamma'\left[m\cosh(m)-1\right]}{1+Sk(m\coth(m)-1)}$$



(D. AT. 8/14/98)
Considering Solving the flow equation

Use the substitutions:

$$y = r_D Pe + 1/4\omega$$
$$x = \omega^{1/3} y$$
$$G = \bar{C}_D e^{\gamma/2} \Rightarrow \bar{C}_D = G e^{-\gamma/2}$$

$$\frac{d\bar{C}_D}{dr_D} = \frac{d}{dr_D}\left\{G e^{-\gamma/2}\right\}$$

$$= \frac{dG}{dr_D}\left\{e^{-\gamma/2}\right\} + G\frac{d e^{-\gamma/2}}{dr_D}$$

$$\frac{dG}{dr_D} = \frac{dG}{dx}\cdot\frac{dx}{dr_D}$$

where

$$\frac{dx}{dr_D} = \frac{d}{dr_D}\left\{\omega^{1/3}\left(r_D Pe + \frac{1}{4\omega}\right)\right\} = \omega^{1/3} Pe$$

$$= e^{-\gamma/2}\,\omega^{1/3} Pe\,\frac{dG}{dx} - \frac{1}{2} Pe\, G\, e^{-\gamma/2}$$

$$\therefore \frac{d^2\bar{C}_D}{dr_D^2} = \frac{d}{dr_D}\left\{\frac{dG}{dx}\left(\omega^{1/3} e^{-\gamma/2} Pe\right)\right\} - \frac{d}{dr_D}\left\{\frac{1}{2} Pe\, G\, e^{-\gamma/2}\right\}$$

$$= \frac{d}{dx}\left\{\frac{dG}{dx}\left(\omega^{1/3} e^{-\gamma/2} Pe\right)\right\} - \frac{d}{dr_D}\left\{\frac{1}{2} Pe\, G\, e^{-\gamma/2}\right\}$$

(A) (B)

Evaluating (A)

$$= \left(\omega^{1/3} e^{-\gamma/2} Pe\right)\frac{d}{dx}\left(\frac{dG}{dr_D}\right) + \frac{dG}{dx}\frac{d}{dr_D}\left(\omega^{1/3} Pe\, e^{-\gamma/2}\right)$$

$$= \omega^{1/3} Pe^2 e^{-\gamma/2}\frac{d^2G}{dx^2} - \frac{1}{2}\omega^{1/3} Pe^2 e^{-\gamma/2}\frac{dG}{dx}$$

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evaluating (B)

$$\frac{d}{dr_D}\left\{\frac{1}{2} Pe\, G\, e^{-Y/2}\right\} =$$

$$= \frac{1}{2} Pe\, e^{-Y/2} \frac{dG}{dr_D} + \frac{1}{2} Pe\, G \frac{d}{dr_D} e^{-Y/2}$$

$$= \frac{1}{2} Pe\, e^{-Y/2}\left(\frac{dG}{dx}\omega^{1/3} Pe\right) + \frac{1}{2} Pe\, G\left(\frac{-1}{2} Pe\right) e^{-Y/2}$$

$$= \frac{1}{2}\omega^{1/3} Pe^2 e^{-Y/2}\frac{dG}{dx} - \frac{1}{4} Pe^2 G e^{-Y/2}$$

$$\therefore \frac{d^2\bar{G}_D}{dr_D^2} = \frac{d^2G}{dx^2}\left(\omega^{1/3} Pe^2 e^{-Y/2}\right) - \frac{dG}{dx}\left(\frac{1}{2}\omega^{1/3} Pe^2 e^{-Y/2}\right) - \frac{dG}{dx}\left(\frac{1}{2}\omega^{1/3} Pe^2 e^{-Y/2}\right) +$$

$$\frac{1}{4} Pe^2 e^{-Y/2} G$$

Using the above substitutions

$$\frac{1}{Pe}\frac{d^2\bar{C}_D}{dr_D^2} + \frac{d\bar{C}_D}{dr_D} = \frac{2r_D \bar{C}_D R}{(1-r_{wD}^2)}\ (s+\bar{q}_D)$$

reduces to

$$\frac{d^2G}{dx^2} = Gx$$

The complete solution to this expression is

$$\bar{C}_D(s) = \Psi \exp\left[\frac{Pe}{2}(1-r_{wD})\right]\bar{G}(s)$$

$$\bar{G}(s) = \frac{A_1B_2 - A_2B_1}{F + F_w + F_i + F_{iw}}$$



$$F = \omega^{1/3}(A_1B_3 - A_3B_1) + 0.5(A_3B_2 - A_2B_3) + 0.5(A_1 - B_1) +$$

$$0.25\,\omega^{-1/3}(B_2 - A_2)$$

$$F_w = \mu_w S\left[(A_3B_2 - A_2B_3) + 0.5\,\omega^{1/3}(B_2 - A_2)\right]$$

$$F_i = \mu_i S\left[(A_1 - B_1) + 0.5\,\omega^{-1/3}(B_2 - A_2)\right]$$

$$F_{iw} = \mu_i \mu_w S^2 \omega^{-1/3}(B_2 - A_2)$$

$$A_1 = \frac{A_i'(\omega^{1/3} y_o)}{A_i(\omega^{1/3} y_L)} \qquad A_2 = \frac{A_i(\omega^{1/3} y_o)}{A_i(\omega^{1/3} y_L)}$$

$$A_3 = \frac{A_i'(\omega^{1/3} y_L)}{A_i(\omega^{1/3} y_L)} \qquad B_1 = \frac{B_i'(\omega^{1/3} y_o)}{B_i(\omega^{1/3} y_L)}$$

$$B_2 = \frac{B_i(\omega^{1/3} y_o)}{B_i(\omega^{1/3} y_L)} \qquad B_3 = \frac{B_i'(\omega^{1/3} y_L)}{B_i(\omega^{1/3} y_L)}$$

$$y_o = Pe\, r_{wD} + 0.25\,\omega^{-1} \qquad y_L = Pe + 0.25\,\sigma^{-1}$$

If the well bore volume at the pumping well is not negligible then

$$\bar{C}_{DF} = \bar{C}_D + \mu_w S \bar{C}_D$$

where $\bar{C}_{DF}$ is the dimensionless flux-averaged concentration in Laplace space.

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## C-WELL TYPE CURVES

These are type curves generated with the program supplied by Moench. The code [CV2amos.f. Associated with this code are three smaller supplimental subroutine packages machcon.f, zbsubs.f and zbsubs2.f. The code solves the dual permeability problem discussed by in Moench 1995.

The type curves consider the special case of a dual permeability medium in which

(a) diffusion in grains and blocks does not occur
(b) the source is a Dirac Delta function
(c) both insitu and flux-averaged concentrations are explored
(d) matrix is composed of a single sized grains
(e) retardation is ignored
(f) fracture skin is ignored
(g) storage is ignored.
(h) well bore mixing is ignored

Note the type curves represent (D.A7: 8/19/98) differing values of Peclet number. This simplified model is used to estimate the representative Peclet number for the tracer test. The following shows the input data file for one simulation.

FIGURE 1

```
C-WELLS TRIAL FIT #4 (PE=40)
1       3       30                      ! LogT, NLC, NOX
0.1D0   0.0D0   0.D0    0.D0    0.D0    ! TDFIRST, DELTD, TDP, XMUI, XMUW
1       0       3       0               ! INPTRA, NTS, KT, IFLUX
40.D0   8.25E-03 1.0D0  0.000           ! Pe, RWD, RTARD, XMULT
10.D0   3       40                      ! BIGT, METH, NN
1       0                               ! N, IQD
1.0D0                                   ! FB(I), I=1,N ... number of size fractions
7.000D-3                                ! GAMMA(I), I=1,N ... dimensionless diffusion
0.D0                                    ! SIGMA(I), I=1,N ... dimensionless storage
0.00D0                                  ! SK(I), I=1,N ... fracture skin parameter
```

$r_{WD} = \frac{0.251}{30.4} = 8.25 \times 10^{-3}$



LOGT : 0 EQUAL TIME-STEP INTERVALS ON ARITHMETIC PLOT
1 EQUAL TIME-STEP INTERVALS ON LOGARITHMIC PLOT

NLC : NUMBER OF LOG CYCLES
NOX : NUMBER OF POINTS PER LOG CYCLE

TDFIRST : FIRST VALUE OF DIMENSIONLESS TIME
DELTD : INCREMENTAL INCREASE FOR DIMENSIONLESS TIME
TDP : DIMENSIONLESS TIME DURATION FOR TOPHAT PULSE
XMUI : DIMENSIONLESS WELLBORE MIXING FACTOR : INPUT WELL
XMUW : DIMENSIONLESS WELLBORE MIXING FACTOR : PUMPING WELL

PE : PECLET NUMBER
RWD : DIMENSIONLESS RADIUS OF PUMPING WELL
RTARD : RETARDATION COEFFICIENT
XMULT : MULTIPLIER FOR COMPUTING DIFFERENT TYPE CURVES.

BIGT : MAXIMUM VALUE OF DIMENSIONLESS TIME
METH } : PARAMETERS USED IN DE HOOG ET AL. (1982) ALGORITHM FOR INVERTING
NN } THE LAPLACE TRANSFORM CONCENTRATIONS.

N : NUMBER OF SIZE FRACTIONS
IQD : 0 DIFFUSION IN GRAINS OR BLOCKS DOES NOT OCCUR
1 DIFFUSION IN GRAINS OR BLOCKS

INPTRA : 0 CONSTANT INPUT
1 DIRAC INPUT
2 TOPHAT INPUT

NTS : NUMBER OF TIME STEPS
KT : NUMBER OF TYPE CURVES

IFLUX : 0 INSITU CONCENTRATION
1 FLUX-AVERAGED CONCENTRATION

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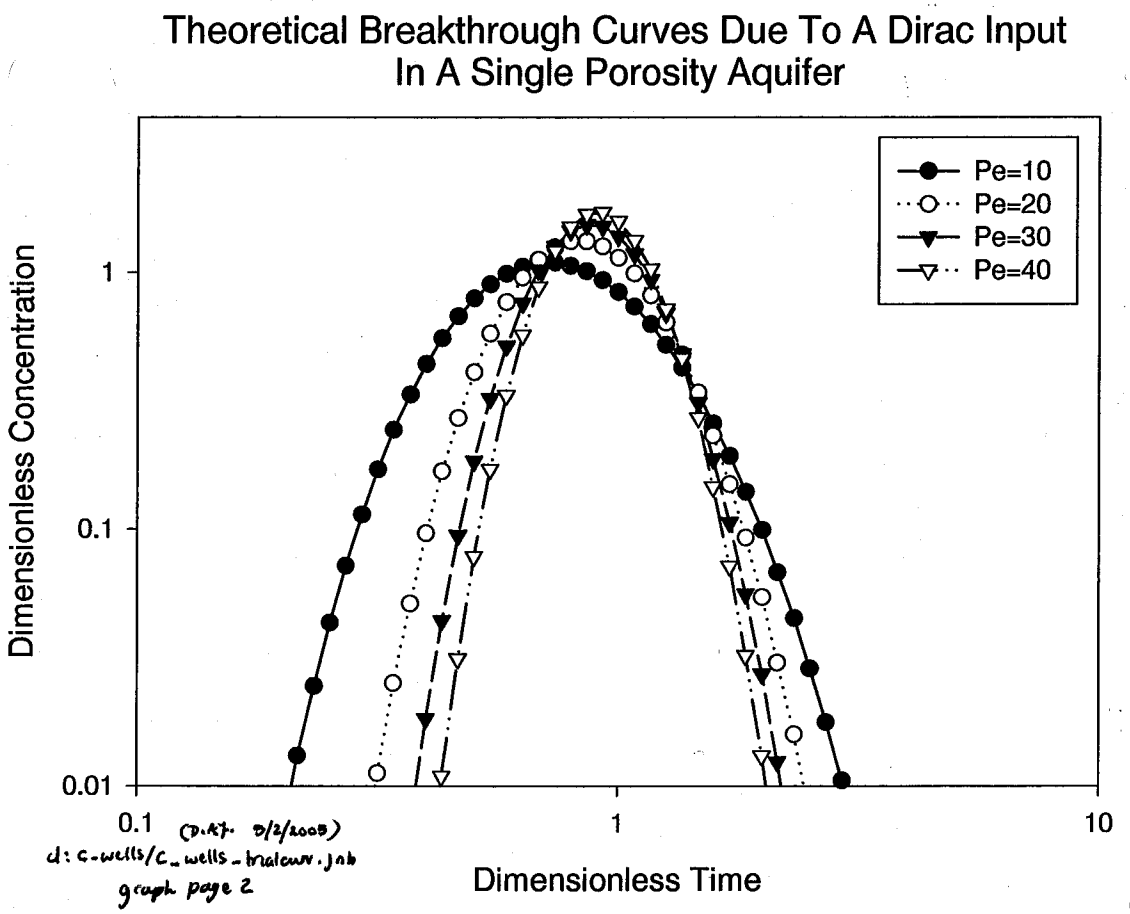
FB (I) : percent of total aquifer volume composed of size fraction I

GAMMA (I) : Dimensionless diffusion parameter for size fraction I
SIGMA (I) : Dimensionless storage parameter for size fraction I
SK (I) : Dimensionless skin parameter for size fraction I

The following figure shows breakthrough curves generated by the simulator for the case of a single porosity aquifer subjected to a Dirac input concentration. The input file for this figure is shown in figure 2.

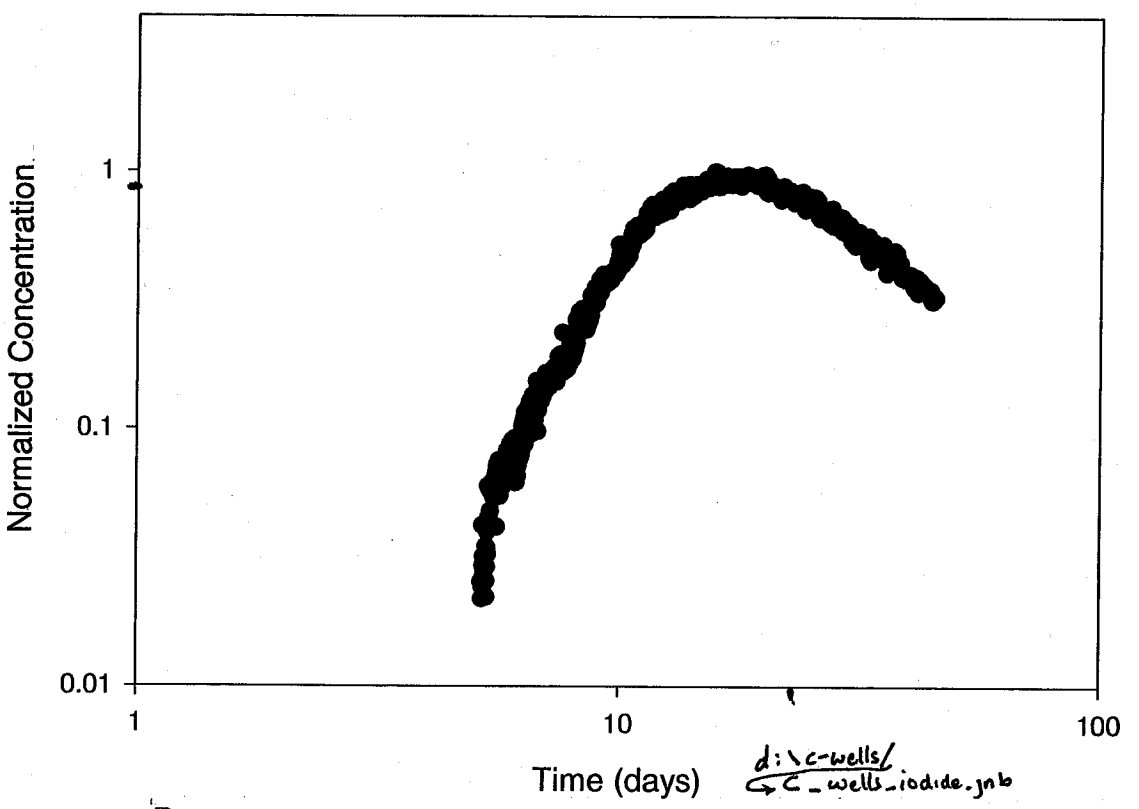
~~FIGURE 2~~



## DETERMINATION OF PECLET NUMBER

Determination of the Peclet number for the experimental data requires comparing the normalized concentration data with computed type curves similar to those shown in figure 2. Figure 3 shows our best curve match.

Figure3

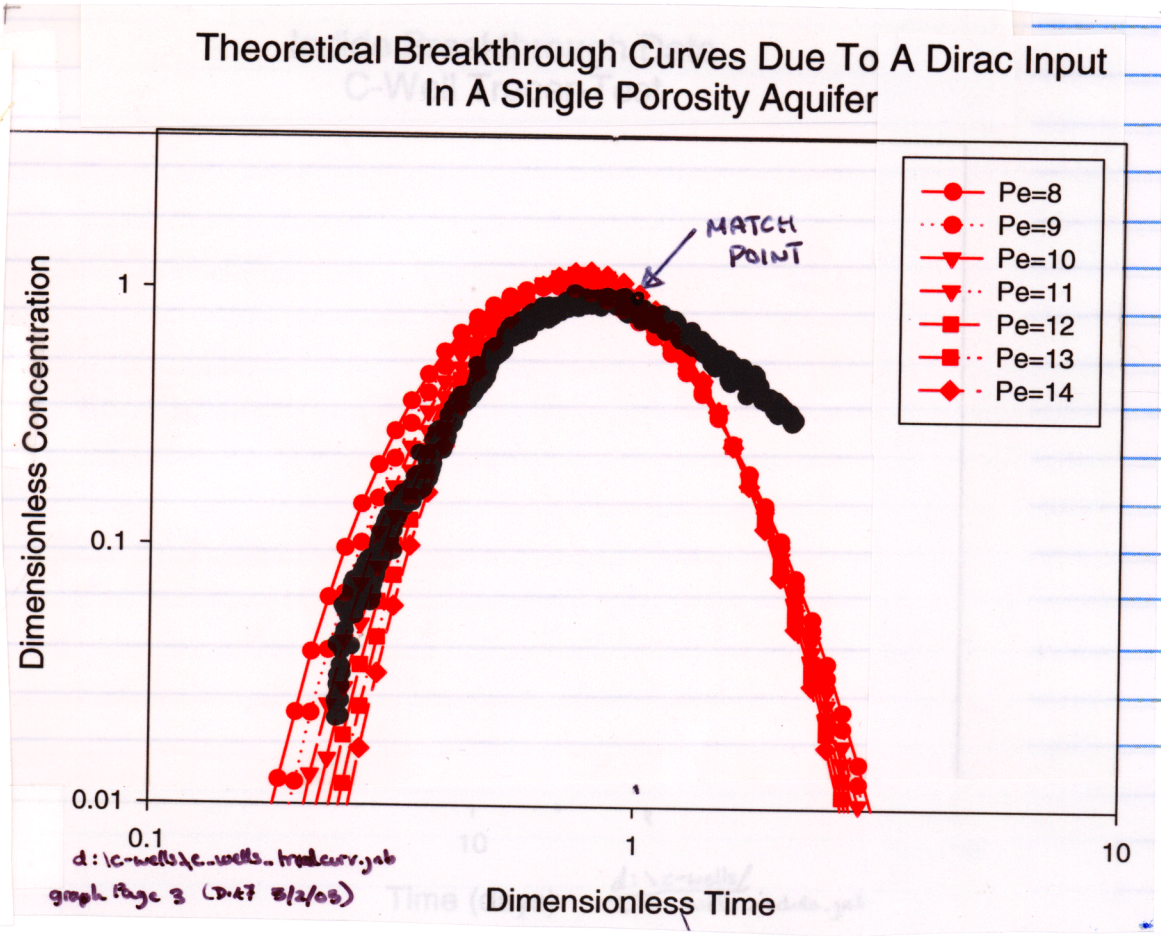



The above type curves were generated using IFLUX = 0 (i.e., INSITU concentrations estimated). Identical curves were generated when IFLUX = 1 (i.e., flux averaged concentration). This is to be expected since well mixing was ignored. The data for both cases are stored in a SIGMA PLOT NOTE BOOK files : d:\C_wells\C-wells_trialcurv. JNB
File data stored in SIGMA PLOT NOTE BOOK : d:\C_wells\C_wells_iodide. JNB

## DETERMINATION OF PECLET NUMBER

Determination of the Peclet number for the experimental data requires comparing the normalized concentration data with computed type curves similar to those shown in Figure 2. Figure 3 shows our best curve match.

Figure 3




The above type curves were generated using IFLUX = 0 (i.e., insitu concentrations estimated). Identical curves were generated when IFLUX = 1 (i.e., flux averaged concentration). This is to be expected since well mixing was ignored. The data for both cases are stored in a SIGMA PLOT NOTE BOOK files : d:\C_wells\C_wells_trialcurv. JNB
File data stored in SIGMA PLOT NOTE BOOK : d:\C_wells\C_wells_iodide. JNB

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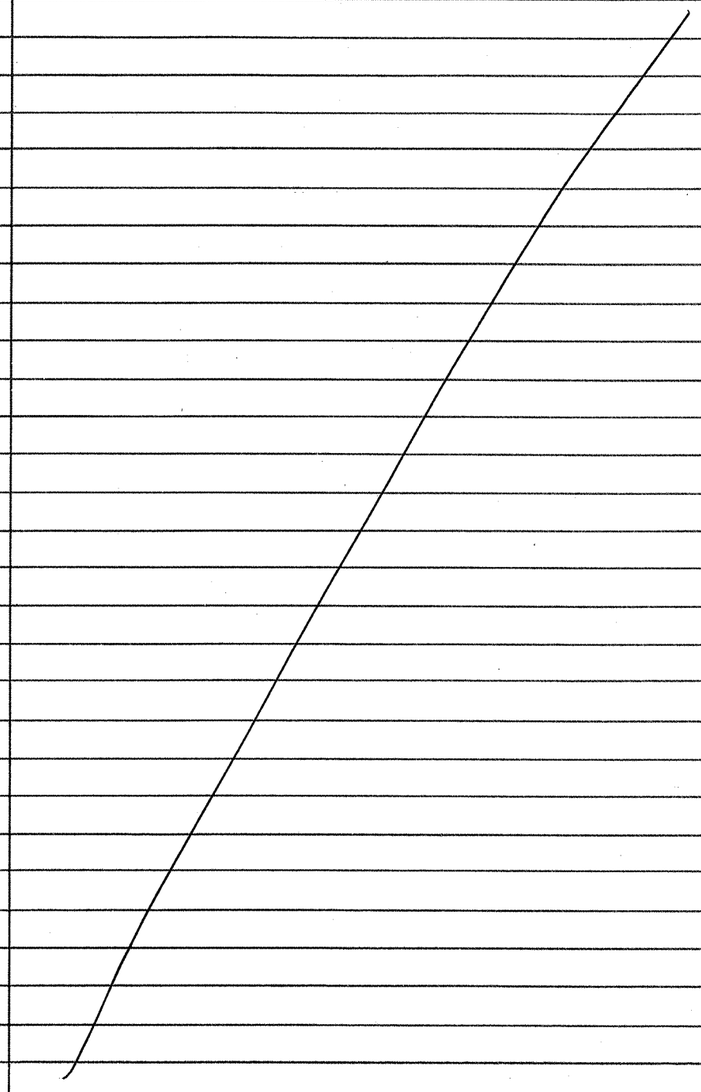



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From Figure 3, it appears that the best curve match is obtained with Pe = 10 to 9.

The match point for this fit ($C_D = 1.0$, $t_D = 1.0$ where $C_D$ ≡ dimensionless concentration on the type curve plot, and $t_D$ ≡ dimensionless time on the type curve plot) is ~~given~~ $C_w \approx 0.88$, $t_a \approx 21$ days where $C_w$ represents the normalized concentration, and $t_a$ represents the advective travel time (see Moench, 1995).

PARAMETER ESTIMATION 8/20/98 D.A.F.

Estimating $\alpha_L$

$$Pe = \frac{r_L}{\alpha_L} \Rightarrow \alpha_L = \frac{r_L}{Pe}$$

$r_L = 30.4$ m

$Pe \approx 10$

$$\therefore \alpha_L = \frac{30.4}{10} = 3.04 \text{ m}$$

$Pe \approx 9$

$$\therefore \alpha_L = \frac{30.4}{9} = 3.38 \text{ m}$$

These values are consistent with those of similar scale reported by Gelhar et al. (1992) [see also Gelhar et al. (1992), Figure 1, 2].

If one assumes that Neuman's universal scaling relationships are accurate and acceptable [see Neuman, 1990, WRR, 26(8), 1749-1758] then one can consider use equation (29) to model the expected longitudinal dispersivity for a scale of 30.4 m.

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Equation (9)

$$\alpha_{aL} \approx 0.017\, L_s^{1.5} \qquad \text{for } L_s \leq 100\ m$$

for the pumptest $L_s = 30.4$ ≡ scale of study

$\alpha_{aL}$ ≡ apparent longitudinal dispersivity.

Then $\boxed{\alpha_{aL} = 0.017\,(30.4)^{1.5} = 2.85\ m}$

This value of longitudinal dispersivity calculated using the universal scaling relationship is consistent with that calculated based on the field data.

Some criticisms of the dispersivity estimates

Gelhar et al. (1992) : " A common difficulty with the interpretation of concentration data using breakthrough curve matching to determine dispersivity is the assumption that the dispersivity is constant. The field data assembled in this review suggest that this assumption is not valid, at least for small-scale Tests (tens of meters). At larger scales (hundreds of meters) an asymptotic constant value of dispersivity is predicted by some theories."
[P. 1966]

If this is the case then the physical interpretation of the dispersivity estimated and its application in predictive models is questionable.

Gelhar et al. (1992) : " The radial converging flow test is generally considered less satisfactory than the diverging test because breakthrough curves at the pumping well for the converging test frequently exhibit tailing, which complicates the interpretation of these tests. ... One
[P. 1965]



possible explanation of the tailing in radial convergent tests is sometimes termed "borehole flushing," where the tail of the breakthrough curve is attributed to the slow flushing of the input slug of tracer out of the injection borehole by the ambient groundwater flow." ~~Note that this~~ D.A.T. 8/20/98

Note that the impact of borehole flushing on plume evolution has been reproduced numerically by Goblet [1982, Rep. LHM/RD/82/11, Cent. d'Inf. Geol., Ecole Natl. Super. des Mines de Paris, Fontainebleau, France, 1982].

Criticisms of Universal Scaling Model

Mary Anderson [WRR, 27(6), 1381-1382, 1991] :

1. " Universal scaling laws does not necessarily describe conditions at any given locale but accounts for the self-similarity of log K in a mean sense over a large range of length scales in a broad variety of geologic media under diverse conditions of flow and transport"

2. The model may not be useful where preferential flow paths exist, since in cases such as channeling and funneling (which may occur in fractured media) concepts (D.A.T. 8/20/98) parameters such as Fickian ~~diffusion~~ dispersion (D.A.T. 8/20/98) and effective parameters such as dispersivity may be meaningless.

3. Geologic units possess finite dimensions whereas fractal models are based on an infinite scale, suggesting that fractal models may have to be adjusted to account for upper and lower cutoffs. ~~Both~~ For example within a facies unit, Neuman's fractal model is plausible. Maybe more appropriate to consider nested structures.

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Gelhar et al. (1992) WRR 29(6), 1867-1869):

1. concerns expressed about the quality and approach used to construct the hydraulic conductivity database used in the analysis.

2. In a fractal medium with an infinite number of scales it is impossible to distinguish between mixing (due to heterogeneity smaller than the scale of the plume) and location uncertainty (caused by the heterogeneity much larger than the scale of the plume)

3. Initial plume size impacts dispersivity estimates from field data --- this impact is reduced under the fractal approach. Plume size should be considered in the dispersivity vs scale relationship.

Neuman (1993, 29(6), 1863-1865):

1. "...log hydraulic conductivities are not self-similar in a local sense, but exhibit self-similarity in a global or average sense when a large number of data from varied hydrogeological settings are examined as a group... "self similarity (in this work) recognises that hydrogeological conditions are unique at each site but views the local scaling of log hydraulic conductivities at individual sites as fluctuations about a mean scaling rule $\gamma(s) \approx c\sqrt{s}$"

2. "... The proposed scaling rule should not be used to predict local conditions at an individual site unless information about site-specific conditions is lacking, in which case such predictions must be recognised to be highly uncertain."



## Calculating the fracture porosity and transmissive interval

$$t_a = \frac{\pi h \phi_f (r_L^2 - r_w^2)}{q_0}$$

Now Geldon et al. (1997) gave a value of $\phi_f = 8.6\% = 0.086$. Let us estimate the thickness of the transmissive interval they used. (p.A7. 8/20/98)

$$h = \frac{t_a q_0}{\pi \phi_f (r_L^2 - r_w^2)}$$

$\phi_f$ - (p.A7. 8/20/98)

$q_0 = \bar{q}_0 = 7.4\ l/s = 639.4\ m^3/day$ (in report)

$r_L = 30.4\ m$ (in report)

$r_w = 0.251\ m$ (obtained from Jim)

$t_a = 17.75$ days (Geldon's estimate)

$$\therefore h = \frac{17.75 * 639.4}{\pi (0.086)\left[(30.4)^2 - (0.251)^2\right]} \Rightarrow \text{transmissive interval}$$

$h = 45.46\ m \Rightarrow$ Geldon's et al (1997) assumed transmissive interval

$= 149.15\ ft$

Geldon et al. (1997): "... injection intervals tested were (168 ft for the Bullfrog (Tracer-test 9) and close to 600ft for the Bullfrog-Tram interval)"

This implies a form thicknesses of { Bullfrog interval = 168ft ≈ 51.21m (Tracer Test 9); Bullfrog-Tram " = 600ft ≈ 182.88m

Clearly flow must be limited to zones within these units.

Geldon et al. (1997) (Hydraulic Tests - 29): { Bullfrog-Tram transmissive thickness ≡ 168ft = 51.21m; Lower Bullfrog " " = 98ft = 29.87m; Upper Tram " " = 70ft = 21.34m

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If one looks at pages Geldon et al. (1997, hydraulic tests - 37 & 38) then there appears to be some confusion about the definition of the transmissive interval. Here the transmissive thickness at UE-25c#2 ranges from 541ft → 474 ft

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Geldon (1996) [WI94-4177] page 15 :

UE25C#2
- interval 651.66 – 651.97 m / 2138 – 2139 ft (0.31m) — 7 % of observed discharge
- interval 725.42 – 736.40 m / 2380 – 2416 ft (10.98m) — 79 % of observed discharge
- interval 742.80 – 761.70 m / 2437 – 2499 ft (18.90m) — 14 % of observed discharge

Tot. = 30.19m

~~UE25C#3~~
- interval ~~780.29 – 793.70 m / 2560 – 2604 ft (13.41m) — 64 % of observed discharge~~
- interval ~~840.94 – 850.39 m / 2759 – 2790 ft (9.45m) — 25 % of observed discharge~~
- interval ~~880.87 – 888.49 m / 2890 – 2915 ft (7.62m) — 11 % of observed discharge~~

Tot. = 30.48m

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UE25C#3
- interval 725.60 – 725.73 m / 2374 – 2381 ft (0.13m) — 17 % of observed discharge
- interval 737.92 – 755.29 m / 2421 – 2478 ft (17.37) — 55 % of observed discharge
- interval 762.91 – 770.23 m / 2503 – 2527 ft (7.32m) — 3 % of observed discharge
- interval 840.64 – 868.98 m / 2758 – 2851 ft (28.34m) — 25 % of observed discharge

Tot. = 55.16

→ not a significant contributor to flow

⇒ Let us ~~assume~~ at the moment assume that the transmissive intervals at C#2 and C#3 are connected ... then the average transmissive thickness is $(30.19 + 55.16)/2 = 42.68$ m

Although not identical to the value (45.46m) used by Geldon et al. (1997) this value is nevertheless quite close.
Using $h = 42.68$ m yields

$$\phi_f = \frac{t_a q_0}{\pi h (r_i^2 - r_w^2)} = \frac{17.75 * 639.4}{\pi (42.68)(30.4^2 - 0.251^2)} = 0.092$$

This represents a 6.98% difference from the value estimated by Geldon et al. (1997)



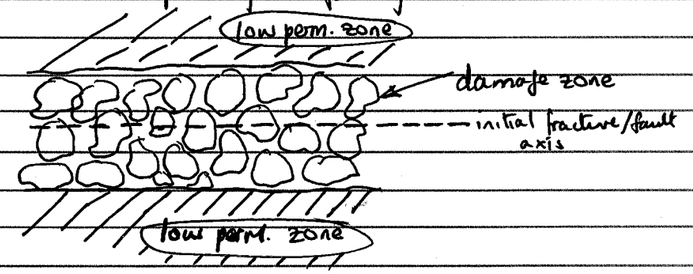
Estimating $\phi_f$ based on our curve fitting estimates

$t_0 \approx 21$ days (see p.25)
$q_0 = 7.4$ L/s $= 639.4$ m³/day
$h = 42.68$ m (based on our estimate)

$$\phi_f = \frac{21 * 639.4}{\pi (42.68)(30.4^2 - 0.251^2)} = \boxed{0.108}$$

This represents a 25.6 % difference from the value estimated by Geldon et al. (1997).

→ The ≈10% porosity estimate (D.AF. 8/21/98) agrees ~~is exactly as that~~ falls within the range given by Freeze and Cherry (1979, Table 2.4, p. 37), for fractured crystalline rock and shale.
This 10% porosity may represent the porosity of the damaged zone associated with fracturing and faulting.




~~Let~~

Consider now the case of the transmissive interval being on the order of the injection zone. For this case $h = 768$ ft $\approx 234.09$ m [see Geldon et al. (1997, tracer-test 9)].

$$\phi_f = \frac{21 * (639.4)}{\pi (234.09)(30.4^2 - 0.251^2)} = 0.019$$

$\therefore \phi_f \approx 2\%$ ⇒ This is the value one would obtain without prior detailed geologic information of the site

1/4/99 D.AJ

## CASE WHERE MATRIX DIFFUSION IS CONSIDERED

In the previous analysis matrix diffusion and storage were ignored. In the following analysis both matrix diffusion and storage are considered. As described earlier matrix diffusion is controlled by the "GAMMA" parameter while storage is controlled by the "SIGMA" parameter. In the software the parameter IQD must be set to 1 in order to perform this analysis.

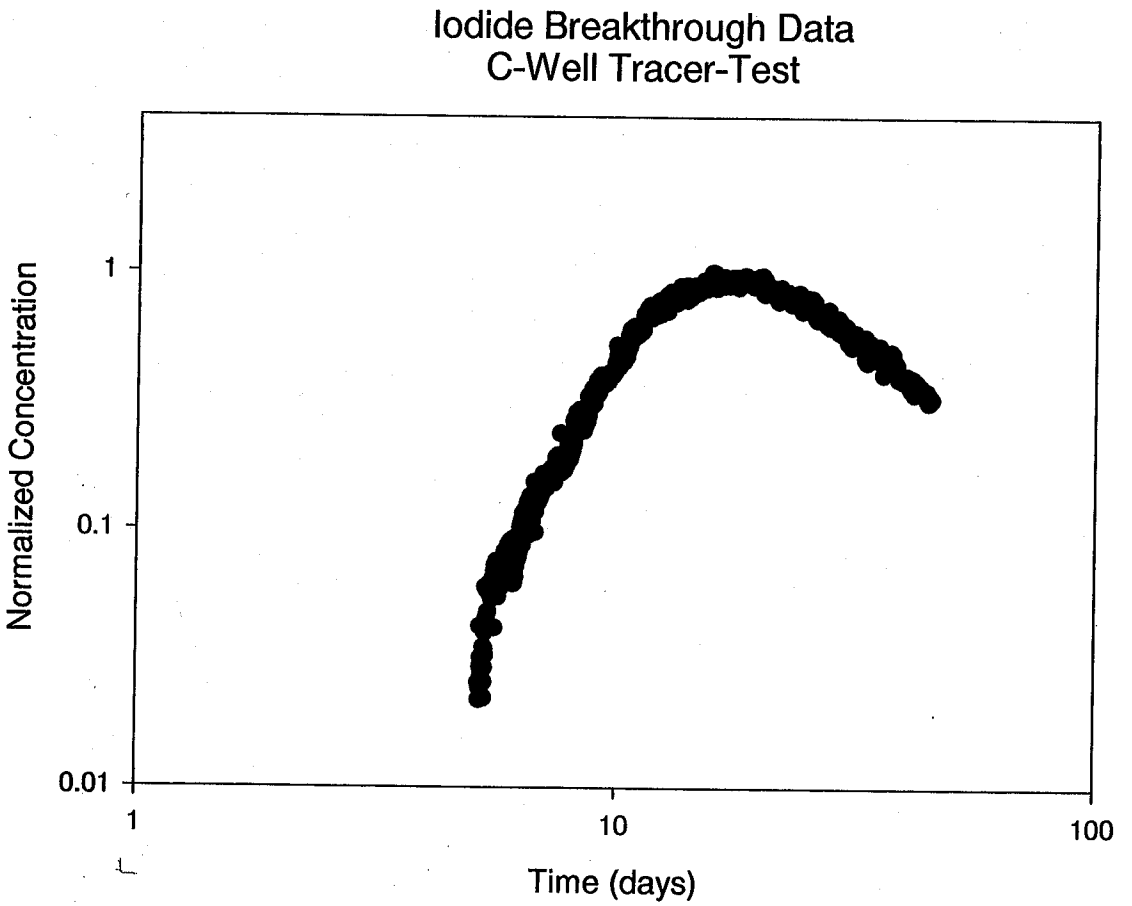
Here we consider the following range in the sigma and gamma parameters

≤ GAMMA ≤

≤ SIGMA ≤

Note that for this analysis a Peclet number of 10 is used based on the previous analysis. Recall a Pedet number in the range 9–10 was considered to provide the best fit to the observed data.

Figure includes data up to C-wells-sing. out




Here GAMMA in the range 0.06 to 0.10 appears to yield the best fit to the data.

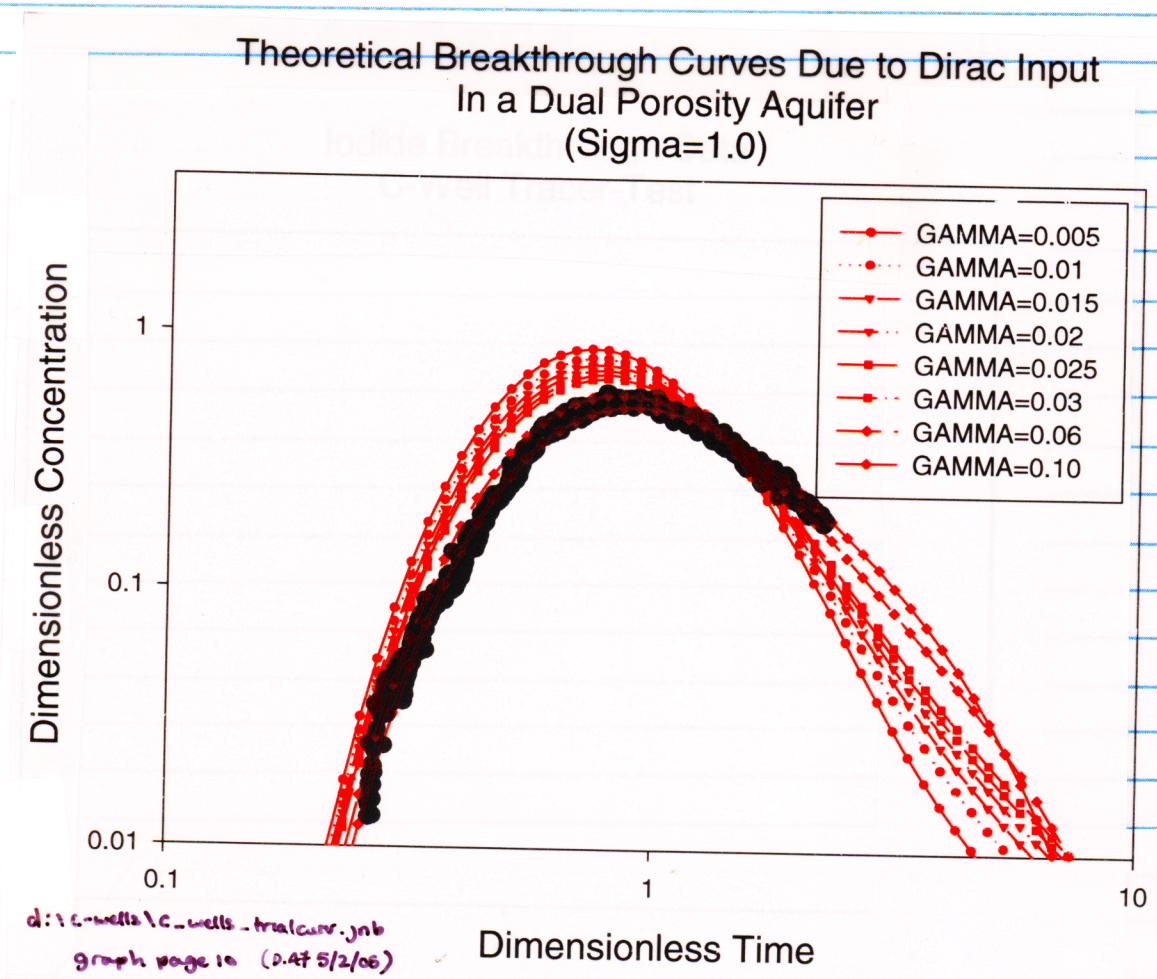



figure includes data up to c_wells_sum8.out

Here GAMMA in the range 0.06 to 0.10 appears to yield the best fit to the data.

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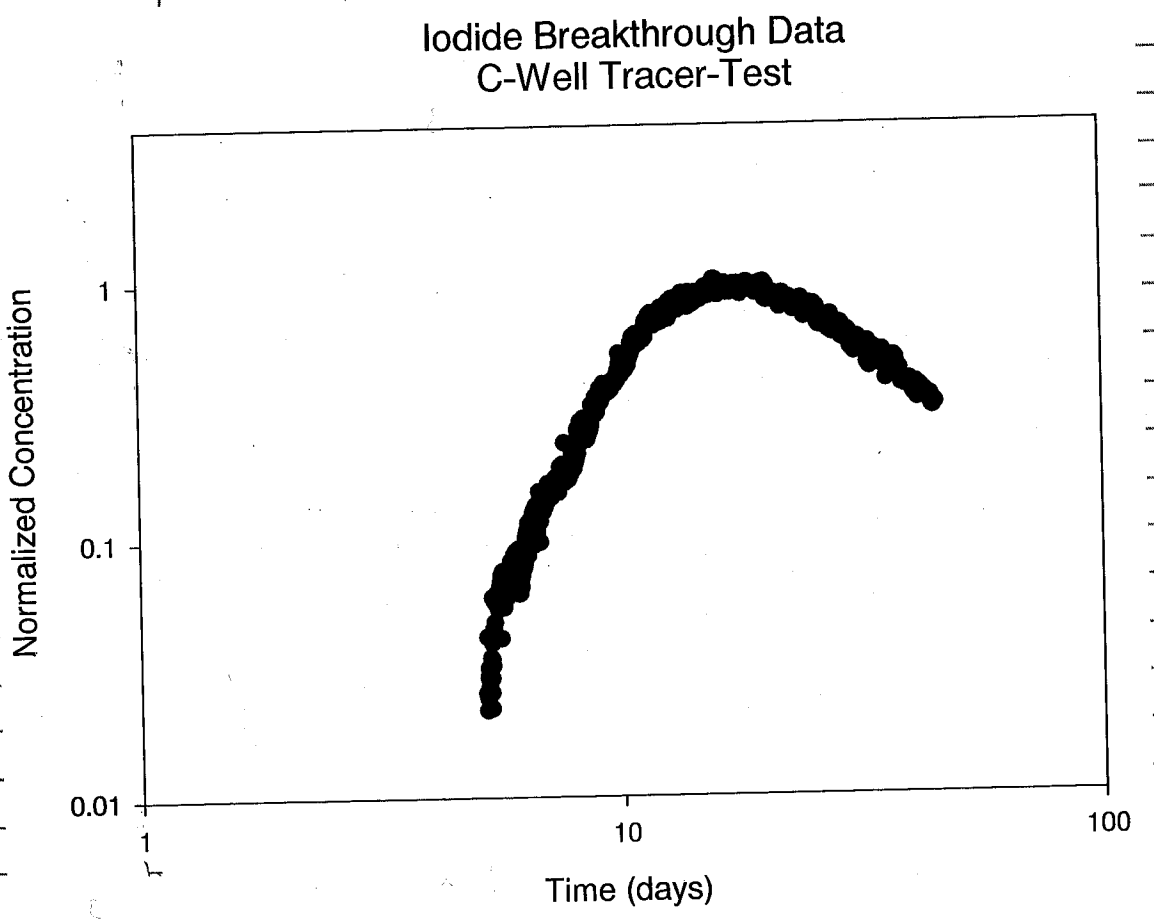

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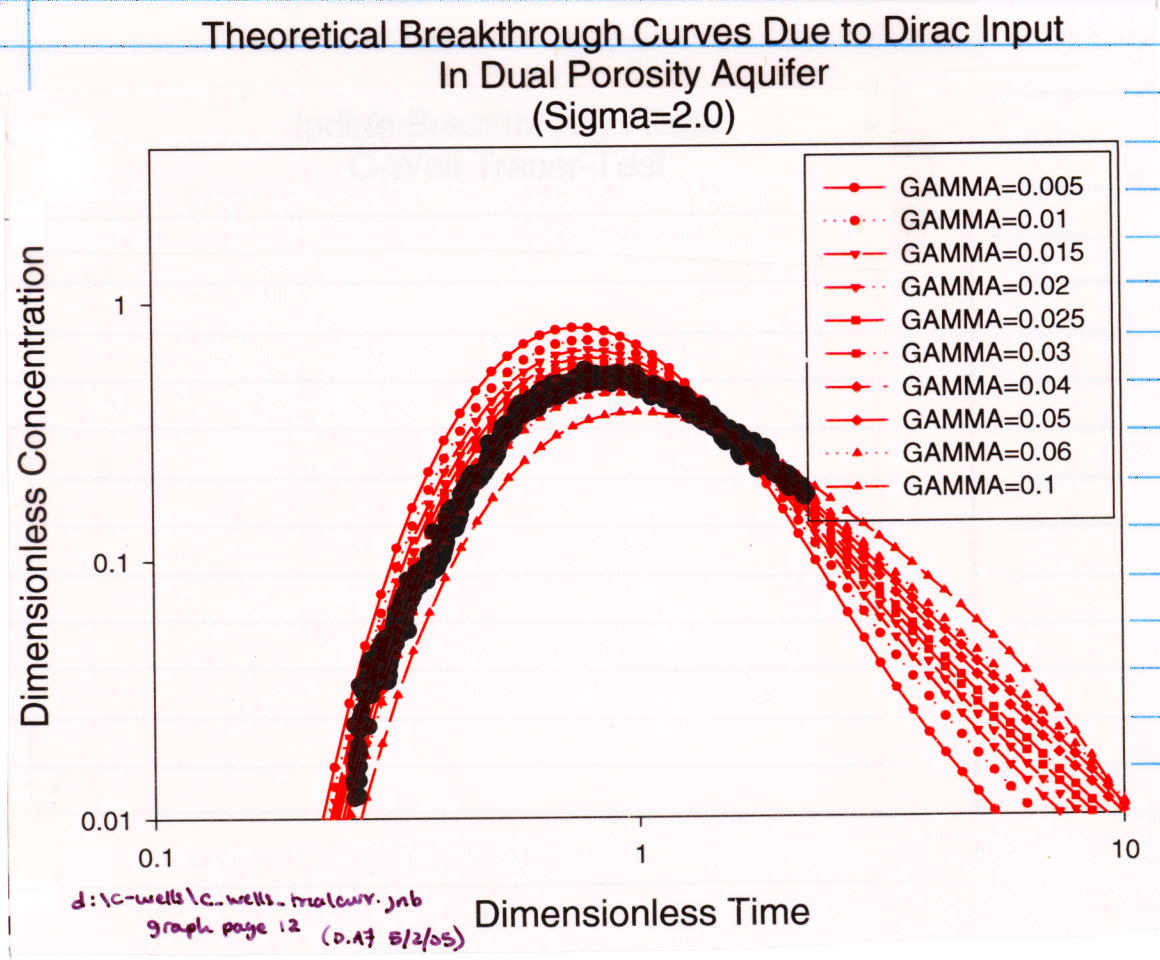
5/02/05



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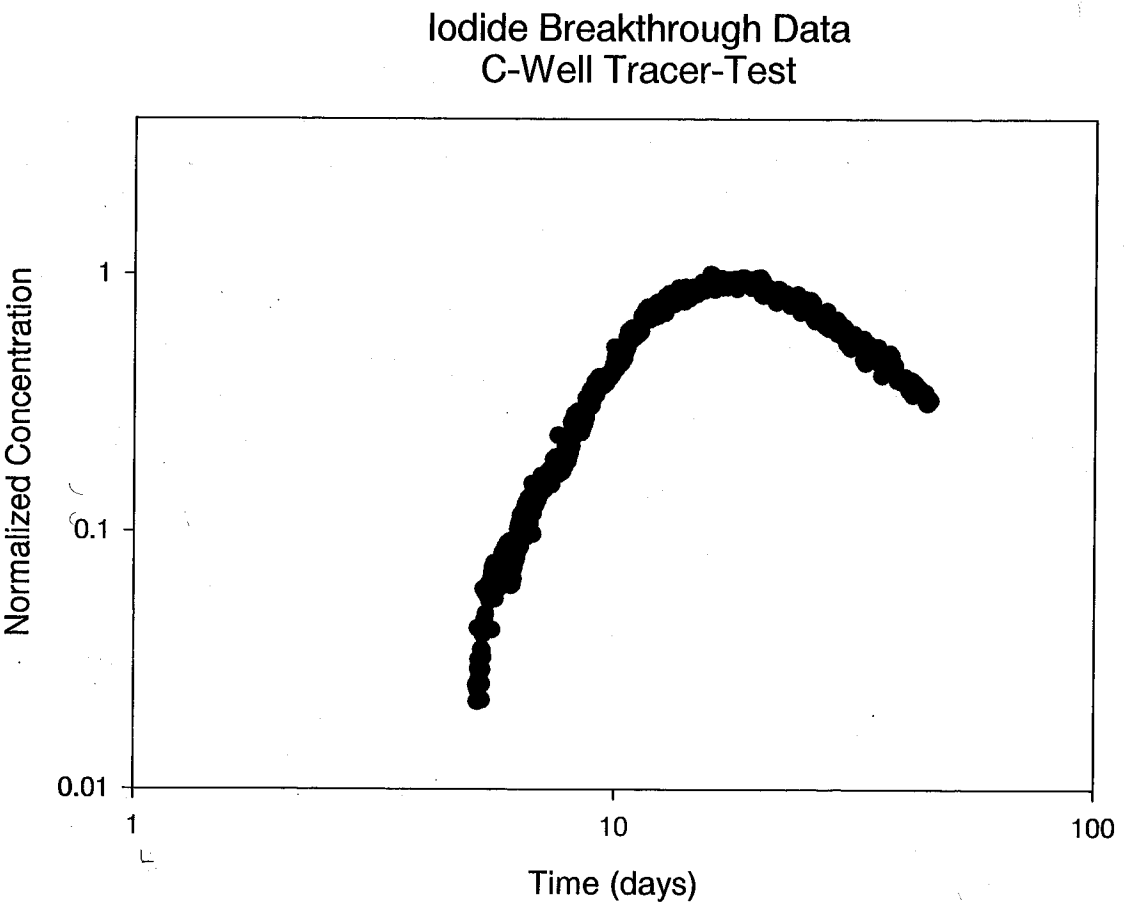
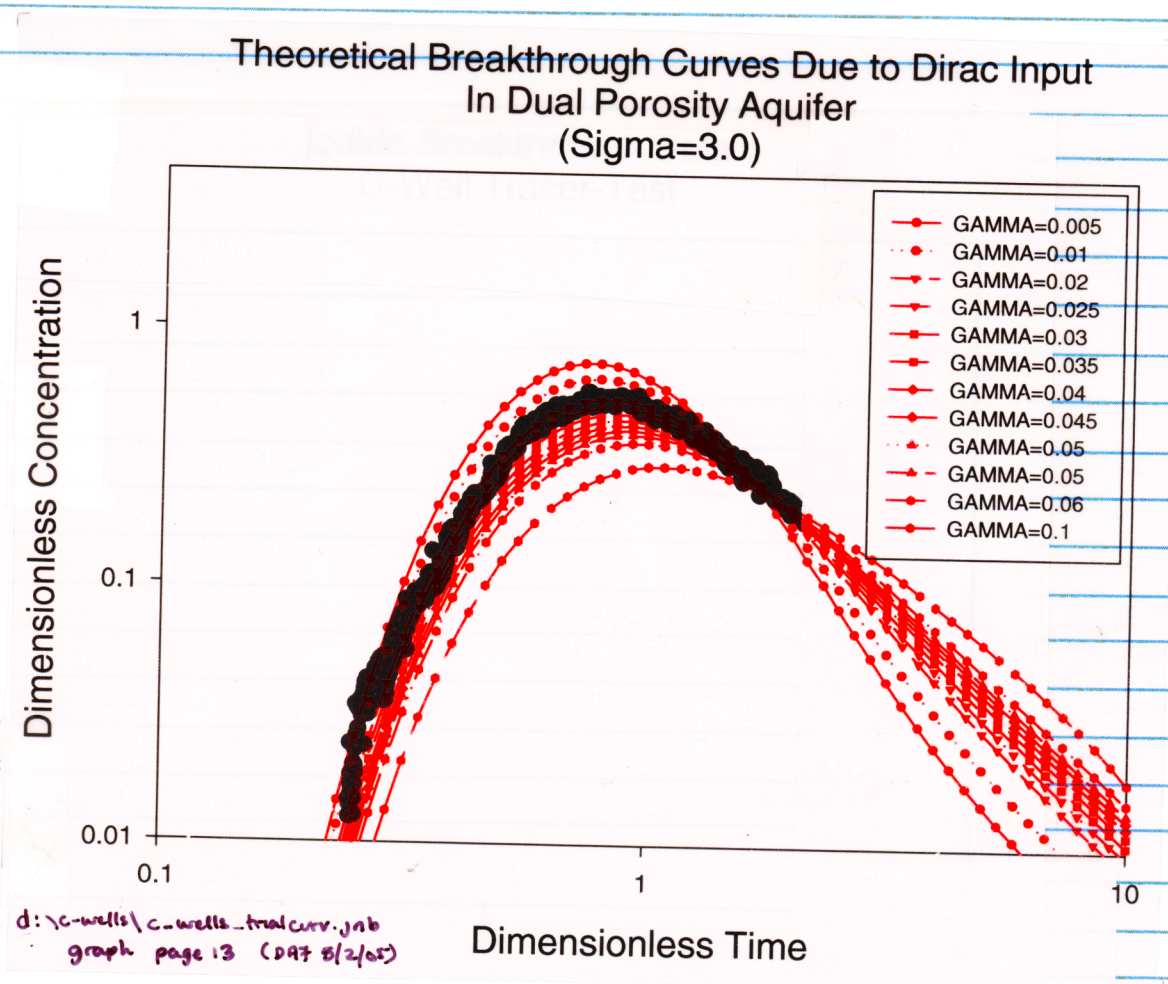


~~1/4/99~~ D.A.
5/02/05




d:\c-wells\c_wells_trialcurv.jnb
graph page 13 (DA7 8/2/05)

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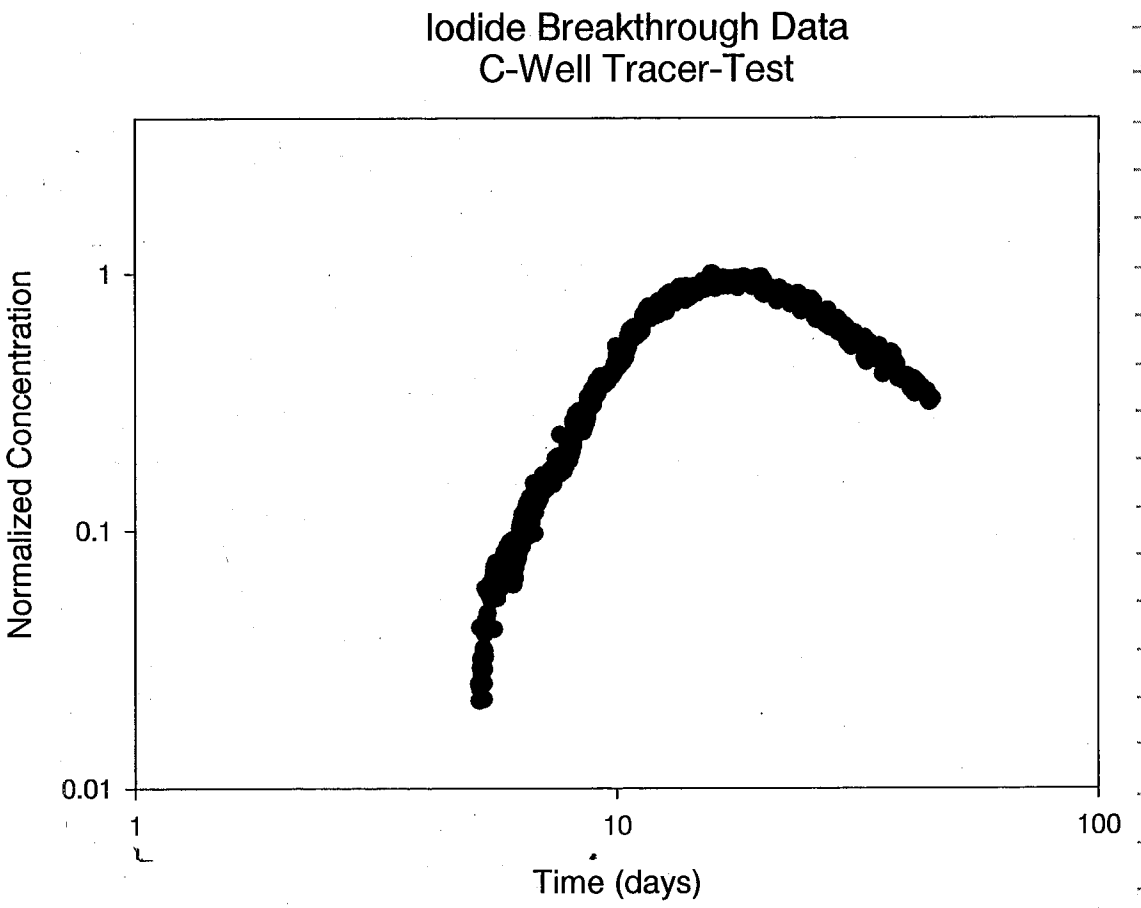


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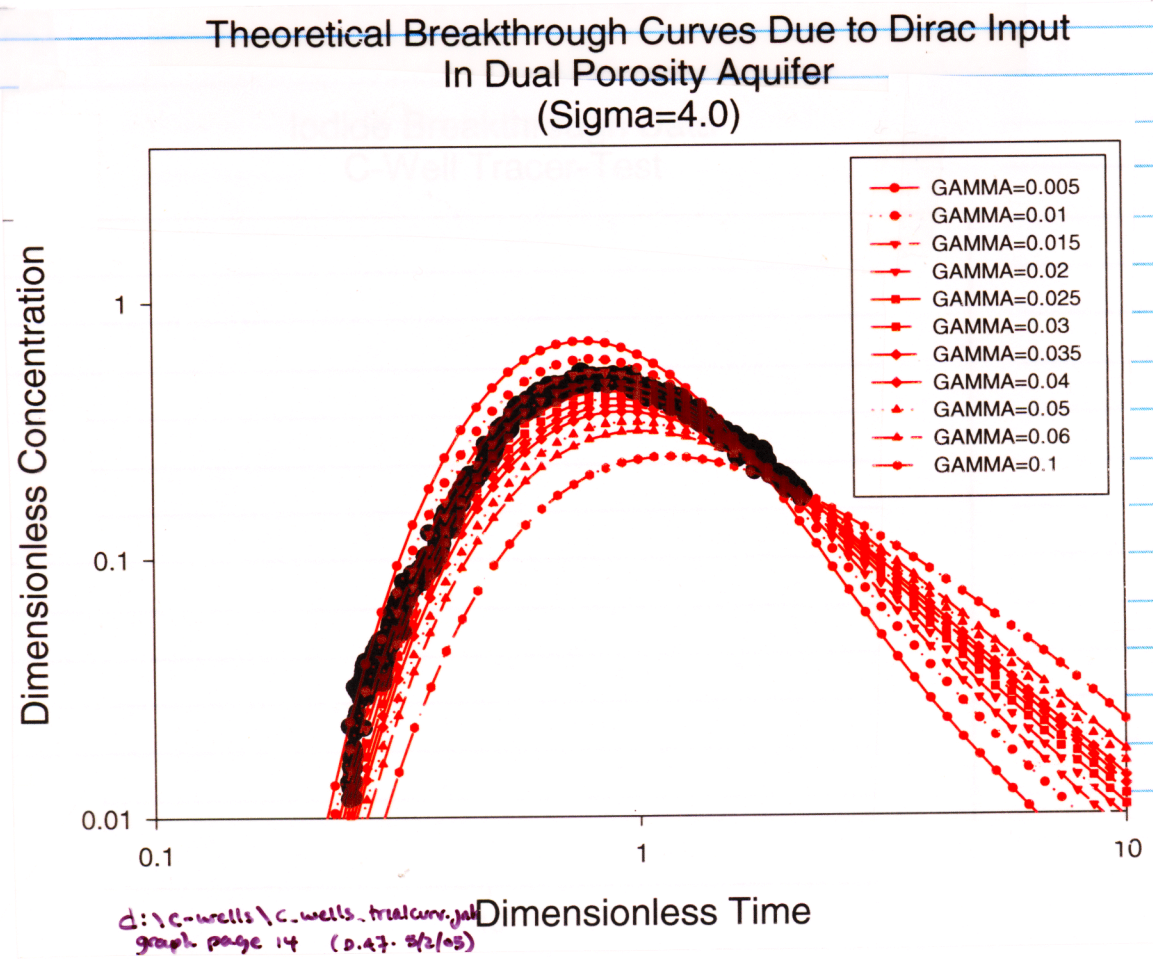


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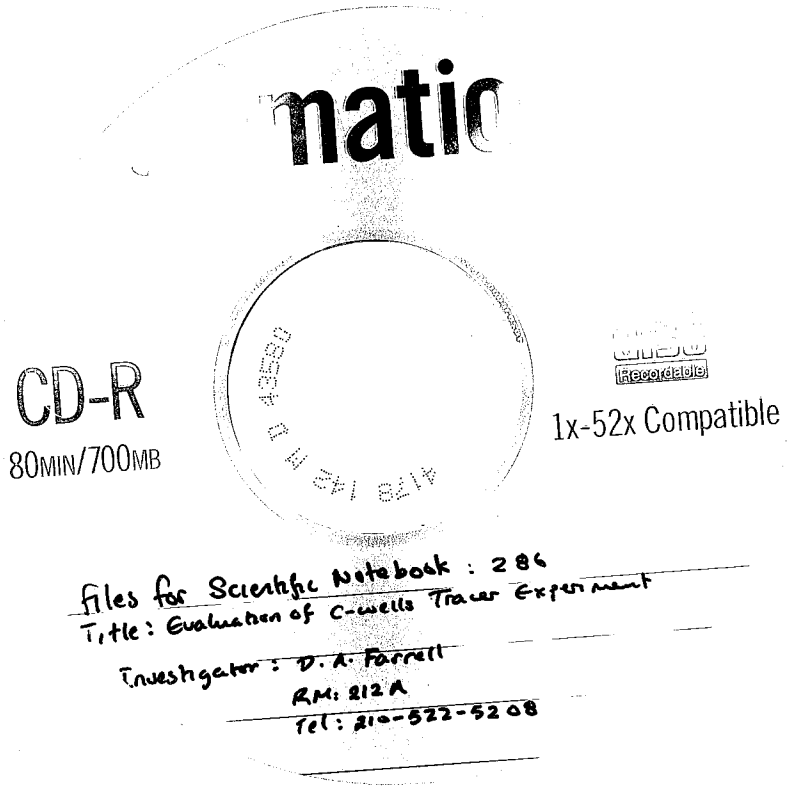
D. A F 5/02/05

No further entries will be made to this note book.

David A Farnell 5/02/05

I have reviewed this SN and determined that it complies with QAP-001.

Gordon Wittmeyer 5/13/2005




Files for Scientific Notebook : 286
Title: Evaluation of C-wells Tracer Experiment
Investigator: D. A. Farrell
RM: 212A
Tel: 210-522-5208

## ADDITIONAL INFORMATION FOR SCIENTIFIC NOTEBOOK NO. 286

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