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ENHANCE ENERGY CLIVE MMV PLAN
APPENDICES M:

Study on Effectiveness of Observation Wells in Detecting Loss of Containment

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Appendix a

Study on Effectiveness of Observation Wells in Detecting Loss of Containment

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Physics of leakage problem

The physical configuration and the variables used in the analysis are shown in **Figure 1**. Consider a reservoir and one aquifer above it: the target reservoir to be tested for appropriateness for storage/disposal (through injection of aqueous fluid), and the upper monitoring aquifer where pressure is to be monitored. A single-phase 1-D radial flow system is considered in two formations (reservoir and aquifer), which are separated by an impermeable aquitard.

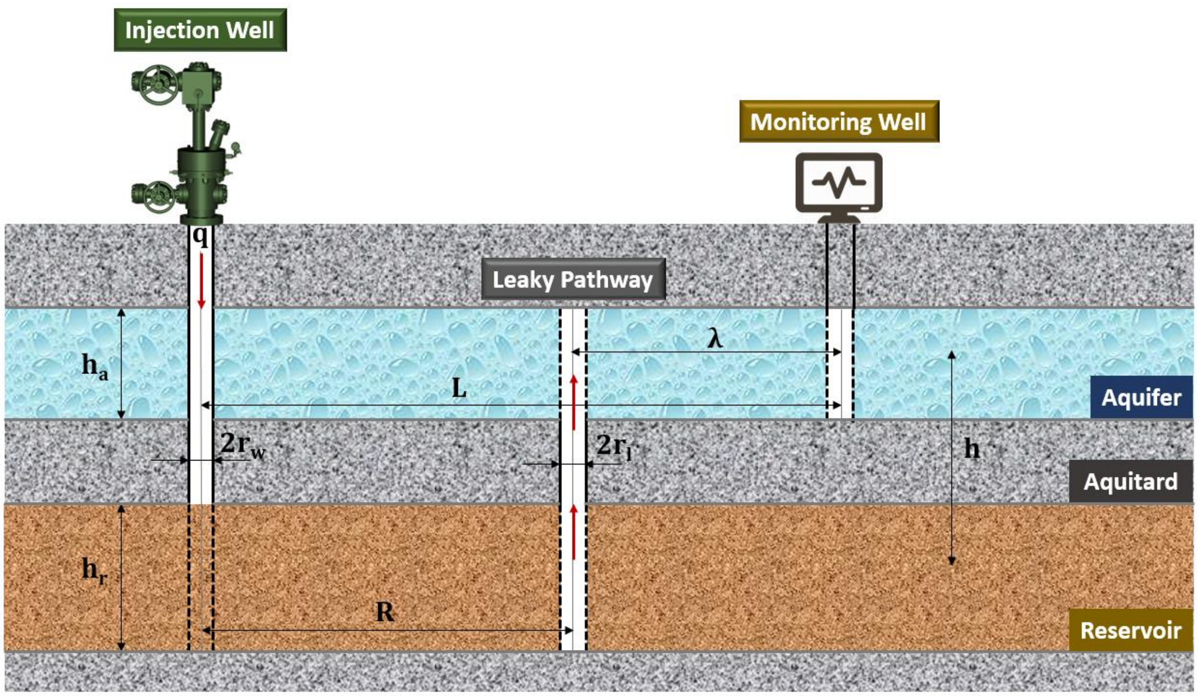

Figure 1:Schematic view of the reservoir-leak-aquifer system

The leakage occurs in the vertical direction through a single leakage pathway of radius r_l and permeability k_l. The leakage pathway is at a distance R from the injection well and distance λ from the monitoring well. Knowing that the reservoir and aquifer are very large, the time to the end of the infinite-acting flow period is very long. However, if any of the formations are limited by a boundary (e.g., a sealing fault), one can use the image (superposition) method to account for the effect of such boundary on the leakage rate using an infinite-acting solution. The reservoir and the aquifer are also considered isotropic and homogeneous with known and constant properties (e.g., permeability, porosity, thickness, and compressibility). The injection fluid is injected at a constant rate q and considered to have identical properties as the reservoir and aquifer brine. Also, the aquifer is not in communication with a second aquifer.

Analytical model

To obtain the pressure variation and leakage rate, we decompose the system into four (components) and then combine the results. The starting point is the pressure variation in the monitoring aquifer in response to an unknown and time-dependent leakage rate (q_l) which is the solution to the pressure diffusivity equation centered at the leakage pathway (component A). Based on Darcy's equation, the leakage rate is a function of the pressure difference between the reservoir and the aquifer at the location of the leak (component C). To obtain the pressure at the location of the leak in the reservoir, the superposition principle can be used (component B, which is not replicated here for sake of brevity but may be found in the referenced Ph. D. Dissertation). The pressure response to injection can be obtained by solving the diffusivity equation centered at the injection well under a constant rate boundary condition (component B-1). Pressure response to leakage is obtained by solving the diffusivity equation considering the leakage path as the center (component B- 2). Superposition of the two solutions evaluated at the location of the monitoring well provides an equation for the pressure variation at the monitoring well location in the reservoir. Combination of such equation with pressure variation in the top aquifer gives an equation for the time-varying leakage rate.

Here the differential equations governing the problem A and C, and also the final asymptotic solution (late time solution) for the combined problems are presented. Please refer to the cited reference for the details of the governing equations for each problem individually and also the related solutions.

Definition of Dimensionless Parameters

To present results in dimensionless form, the following dimensionless parameters are defined:

$$R_D = \frac{R}{r_w} \quad \lambda_D = \frac{\lambda}{r_w} \quad L_D = \frac{L}{r_w} \quad r_{lD} = \frac{r_l}{r_w}$$

$$T_D = \frac{k_a h_a}{k_r h_r} \quad \eta_D = \frac{\eta_a}{\eta_r} \quad \alpha = \frac{r_l^2}{2k_r h_r h_l} \quad P_D = \frac{2\pi k_r h_r}{q\mu B}(P_i - P)$$

$$t_D = \frac{\eta_r t}{r_w^2} \quad q_{lD} = \frac{q_l}{q}$$

Nomenclature section provides a complete list of variable names and definitions.

Component A: Equation governing pressure change in the top aquifer

The diffusivity equation for the aquifer is solved for the pressure (P) at the monitoring aquifer in response to the unknown leakage rate

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P_a}{\partial r}\right) = \frac{1}{\eta_a}\frac{\partial P_a}{\partial t}$$

Initial & boundary conditions:

$$P_a(r,t) = P_{ai} \qquad @\, t = 0$$

$$P_a(r,t) = P_{ai} \qquad @\, r \to \infty$$

$$q_l(t) = \frac{2\pi k_a h_a}{\mu B} r \frac{\partial P_a}{\partial r} \qquad @\, r = r_l$$

where:

$$\eta_a = \frac{k_a}{\mu \phi_a c_t}$$

Component C: Rate of leakage

Based on Darcy's equation, the rate of leakage is given by:

$$q_l = \frac{k_l A_l}{\mu B} \frac{P_a(r_l,t) - P_r(r_l,t) + \rho g h}{h_l}$$

Re-writing in dimensionless form based on dimensionless variables defined above gives:

$$q_{lD} = \alpha \left(P_{rD} - P_{aD} + \frac{2\pi k_r h_r (\rho g h - P_{ri} - P_{ai})}{q\mu B} \right)$$

where:

$$\alpha = \frac{r_l^2 k_l}{2\pi k_r h_r h_l}$$

is called the leakage coefficient.

Asymptotic solution

A late-time asymptotic solution for pressure change at the monitoring well and corresponding leakage rate can be summarized as follow:

$$\boldsymbol{P_{Dreservoir}} = \frac{-1}{2}\left(\gamma + Ln\left(\frac{L_D^2}{4t_D}\right)\right) + \frac{1}{2\left(1 + \frac{1}{T_D}\right)}\left(\gamma + Ln\left(\frac{R_D^2}{4t_D}\right)\right) + \frac{q_{lD}(t_D)}{2}\left(\kappa + Ln(\lambda_D^2)\right)$$

$$\boldsymbol{P_{Daquifer}} = \frac{-1.0}{2(1 + T_D)}\left(\gamma + Ln\left(\frac{R_D^2}{4t_D}\right)\right) - \frac{q_{lD}(t_D)}{2T_D}\left(\kappa + Ln\left(\frac{\lambda_D^2}{\eta_D}\right)\right)$$

$$\boldsymbol{q_{lD}} = \frac{1.0}{\left(1 + \frac{1}{T_D}\right)}\left(1 - C(t_D)\left(\kappa + Ln(R_D^2)\right)\right)$$

Where:

$$\boldsymbol{C(t_D)} = \frac{1}{\kappa - 2\gamma + \mathrm{Ln}(4t_D)} - \frac{\gamma}{\left(\kappa - 2\gamma + \mathrm{Ln}(4t_D)\right)^2} + \frac{\gamma^2 - \frac{\pi^2}{6}}{\left(\kappa - 2\gamma + \mathrm{Ln}(4t_D)\right)^3} - \frac{\gamma^3 - \frac{\pi^2}{2}\gamma + 2\xi(3)}{\left(\kappa - 2\gamma + \mathrm{Ln}(4t_D)\right)^4}$$

where

$$\boldsymbol{\kappa} = \frac{2T_D}{\alpha(1+T_D)} + Ln\left(\frac{\eta_D^{\frac{1}{1+T_D}}}{r_{lD}^2}\right)$$

After calculation of q_l as a function of time, the radius of leakage penetration radius in the top aquifer can be calculated as follow:

$$\boldsymbol{Penetration\ Radius} = \sqrt{\frac{q_l}{\pi h_a}} + r_l$$

It should be noted that time zero in the above formulations is the moment at which the pressure change in the monitoring well is greater than zero. In other words, time zero for the monitoring well corresponds to a time greater than zero for injection well. Therefore, for all the time before that specific moment, any value less than zero is defaulted to zero value for both pressure and leakage rate.

Nomenclature:

A	*cross sectional area, m^2*
B	*formation volume factor, vol. @ Res. cond./ vol. @ St. cond.*
r	*radius*
R	*distance from injection well to leakage, m*
λ	*distance from monitoring well to leakage, m*
L	*distance from monitoring well to injection well, m*
k	*formation permeability, m^2*
h	*formation thickness, m*
P	*pressure, Pa*
q	*Injection rate, m^3/s*
t	*time, s*
η	*formation diffusivity coefficient = permeability / (porosity × fluid viscosity × total compressibility) , m^2/s*
µ	*Fluid viscosity, Pa.s*
T	*formation transmissivity = permeability × thickness, m^3*
γ	*Euler constant = 0.5772*
ξ(3)	*Riemann zeta function = 1.2020*
α	*leakage coefficient, dimensionless*
ϕ	*porosity, fraction*

ρ	*density, kg/m^3*
g	*gravity acceleration = 9.8 m^2/s*

Subscripts:

D	*Dimensionless*
i	*initial*
l	*leakage*
a	*aquifer*
r	*reservoir*
w	*well*
t	*total*

Plots in the body of this document were calculated using the following assumptions:

Property	Unit	Value
Leakage Properties		
Permeability	md	50000
Permeability	m2	5.00E-11
Radius	m	0.1
Leakage Interval	m	24
Aquifer		
Compressibility	1/Pa	1.00E-09
Viscosity	Pa.s	5.00E-04
Porosity	fraction	0.1
Permeability	md	1300
Permeability	m2	1.30E-12
Thickness	m	10
Reservoir		

Compressibility	1/Pa	1.00E-09
Viscosity	Pa.s	5.00E-04
Porosity	fraction	0.1
Permeability	md	5000
Permeability	m2	5.00E-12
Thickness	m	30

Distance		
Injection to Leak - R	m	1
Leak to Monitor - λ	m	200
Injection to Monitor - L	m	201

Injection Well		
Qinj	m3/day	400
Qinj	m3/s	4.63E-03
Well Radius	m	0.1

Constant Parameters		
Difiusivity of Monitoring Aquifer	1/s	26
Difiusivity of Storage Aquifer	1/s	100
Pressure Multiplier	Pa	2.46E+03

Dimensionless Parameters		
RD		10
LambdaD		2000
LD		2010

rlD		1
TD		0.086666667
EthaD		0.26
Alpha		6.94444E-05
Kappa1		2296.932515
Kappa2		0.2894889
Kappa		2295.692877

Constant Parameters		
Euler		0.577215665
Riemann		1.202056903

References:

Zeidouni, M., Analytical and Inverse Models for Leakage Characterization of CO_2 Storage. Diss. Ph. D. Dissertation, University of Calgary, Calgary, Canada, 2011.