RESERVOIR SIMULATOR FOR IMPROVED RECOVERY OF COALBED METHANE (ICBM) PART II : EFFECT OF COAL MATRIX SWELLING AND SHRINKAGE

By: **Ego Syahrial**

Technological Assessor at "LEMIGAS" R & D Centre for Oil and Gas Technology

Jl. Ciledug Raya, Kav. 109, Cipulir, Kebayoran Lama, P.O. Box 1089/JKT, Jakarta Selatan 12230 INDONESIA

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ABSTRACT

Sequestration of CO_2 in deep unmined coal seams is currently under development for improved recovery of coalbed methane (ICBM) as well as permanent storage of CO_2. Recent studies have shown that CO_2 displaces methane by adsorbing more readily onto the coal matrix compared to other greenhouse gases, and could therefore contribute towards reducing global warming. In order to carry out a more accurate assessment of the potential of ICBM and CO_2 sequestration, field based numerical simulations are required. Existing simulators for primary CBM (coalbed methane) recovery cannot be applied since the process of CO_2 injection in partially desorbed coalbeds is highly complex and not fully understood. The principal challenges encountered in numerical modelling of ICBM/CO_2 sequestration processes which need to be solved include: (1) two-phase flow, (2) multiple gas components, (3) impact of coal matrix swelling and shrinkage on permeability, and (4) mixed gas sorption. This part II of this two-part paper series describes the development of a compositional simulator with the impact of matrix shrinkage/swelling on the production performance on primary and echanced recovery of coalbed methane. The numerical results for enhanced recovery indicate that matrix swelling associated with CO_2 injection could results in more than an order of magnitude reduction in formation permeability around the injection well, hence prompt decline in well injectivity. The model prediction of the decline in well injectivity is consistent with the reported field observations in San Juan Basin USA. Also, a parametric study is conducted using this simulator to investigate the effects of coal properties on the enhancement of methane production efficiency based on published data.

Key words: swelling, shrinkage, improved recovery of coalbed methane (ICBM), CO_2 sequestration

I. INTRODUCTION

Sequestration of CO_2 in deep unmined coal seams is currently under development for improved recovery of coalbed methane (ICBM) as well as permanent storage of CO_2. Recent studies have shown that CO_2 displaces methane by adsorbing more readily onto the coal matrix compared to other greenhouse gases, and could therefore contribute towards reducing global warming. In order to carry out a more accurate assessment of the potential of ICBM and CO_2 sequestration, field based numerical simulations are required. Existing simulators for primary CBM (coalbed methane) recovery cannot be applied since the process of CO_2 injection in partially desorbed coalbeds is highly complex and not fully understood. The principal challenges encountered in numerical modelling of ICBM/CO_2 sequestration processes which need to be solved include: (1) two-phase flow, (2) multiple gas components, (3) impact of coal matrix swelling and shrinkage on permeability, and (4) mixed gas sorption.

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Coalbeds are heterogeneous and are usually characterised by two distict porosity systems – micropores and macropores. The macropores are known as the cleat that can be subdivided into the face cleat, which is continuous throughout the reservoir, and the butt cleat, which is discontinuous and terminates at intersections with the face cleat.

Permeability of coal is regarded as the most important parameter controlling coalbed methane production rate. Due to its dual-porosity structure, where the permeability is predominantly provided by the cleat network which make up the secondary porosity system, the permeability of coal is highly stress-dependent. The face and butt cleats in coal seams are usually sub-vertically oriented. Thus changes in the cleat permeability can be considered to be primarily controlled by the prevailing effective horizontal stresses that act across the cleats.

Coal matrix has been shown to shrink on desorption of gas and to expand again on readsorption. During primary methane production, two distict phenomena are known to be associated with reservoir pressure depletion, with opposing effects on coal permeability (Gray, 1987). The first is an increase in the effective horizontal stress under uniaxial strain conditions in the reservoir. The second is gas desorption from the coal matrix, resulting in coal matrix shrinkage and thus a reduction in the horizontal stress.

Recent studies indicate that matrix shrinkage/swelling is proportional to the volume of gas desorbed/adsorbed rather than the change in sorption, as reported by earlier researchers (Harpalani & Chen, 1995; Seidle & Huitt, 1995). Given that non-linear Langmuir equations are widely used to describe gas sorption on coal, this implies that the effective stress, and thus the cleat permeability of coal, does not vary monotonously with declining reservoir pressure during drawdown. There is field evidence that suggests a strong rebound in cleat permeability during the process of primary recovery (Palmer & Mansoori, 1996).

Permeability models for primary recovery that use Langmuir-type shrinkage term have been proposed by Palmer and Mansoori (1996) and more recently by Shi et al (2002) and Shi and Durucan (2003). The two models share the same compression term, but the latter has a stronger matrix shrinkage term, generally resulting in a stronger rebound in permeability in the process of coalbed reservoir depletion.

During enhanced recovery/CO_2 sequestration in coal, adsorption of CO_2 gas, which has a greater sorption capacity than methane, may cause matrix swelling and thus, in contrast to gas desorption, could potentially have a detrimental impact on cleat permeability of coal. Field evidence suggests that the well injectivity has really declined at the early stages of CO_2 injection and then rebounded at the Allison pilot in the San Juan Basin (Reeves, 2002).

This part II of this two-part paper series describes the development of a compositional simulator with the impact of matrix shrinkage/swelling on the production performance on primary and echanced recovery of coalbed methane. The numerical results for enhanced recovery indicate that matrix swelling associated with CO_2 injection could results in more than an order of magnitude reduction in formation permeability around the injection well, hence prompt decline in well injectivity. The model prediction of the decline in well injectivity is consistent with the reported field observations in San Juan Basin USA. Also, a parametric study is conducted using this simulator to investigate the effects of coal properties on the enhancement of methane production efficiency based on published data.

II. MODEL FORMULATION AND COMPARISONS

This reservoir simulator employs three main equations: gas, component and water equations (Syahrial, 2005):

$$\nabla\cdot\left[\left(\frac{[k]k_{rg}}{\mu_g}\xi_g\right)\nabla\Phi_g\right]+q_d+q_g=\frac{\partial}{\partial t}\left[\left(\phi\, S_g\,\xi_g\right)\right] \tag{1}$$

$$\nabla\cdot\left[y_i\left(\frac{[k]k_{rg}}{\mu_g}\xi_g\right)\nabla\Phi_g\right]+q_{di}+q_{gi}=\frac{\partial}{\partial t}\left[\left(y_i\,\phi\, S_g\,\xi_g\right)\right] \tag{2}$$

$$\nabla\cdot\left[\left(\frac{[k]k_{rw}}{\mu_w}\xi_w\right)\nabla\Phi_w\right]+q_w=\frac{\partial}{\partial t}\left[\left(\phi\, S_w\,\xi_w\right)\right] \tag{3}$$

where:

k = absolute coal permeability (*mD*),
k_{rg} = relative permeability to gas phase (*frac.*),
k_{rw} = relative permeability to water phase (*frac.*),
μ_g = gas viscosity (*cp*),
μ_w = water viscosity (*cp*),

ξ_g = gas molar density (*lb-mole/cuft*),

= water molar density (*lb-mole/cuft*),

ϕ = porosity (*frac.*),

S_g = gas saturation *(frac.),*

= mole fraction of component *i* (*frac.*)

S_w = water saturation *(frac.),*

q_d = gas desorption rate (*lb-mole/day*),

q_{di} = gas desorption rate for component *i* (*lb-mole/day*),

q_g = gas production or injection rate (*lb-mole/day*),

q_{gi} = gas production or injection rate for component *i* (*lb-mole/day*),

q_w = water production (*lb-mole/day*),

$\nabla\Phi_g$ = gas phase potential (*psia*),

$\nabla\Phi_w$ = water phase potential (*psia*),

These equations are highly non-linear, therefore, numerical methods are required. By linearising them by the use of the *Newton Raphson* approximation and by discretising them with finite difference scheme, the system of equations can be written into a matrix form, and this particular matrix form can be solved in each Newtonian iteration by either direct, or iterative methods in order to obtain the required changes in pressure, composition and saturation.

The model formulation utilizes an Equations of State (*EOS*) for gas mixtures property calculations, such as, gas molar density and its derivatives (Reynold, *et al*., 1990). The *EOS* has been designed to provide a consistent source for determining composition and property of real gases at various ranges of pressure and temperatures.

The *EOS* is incorporated in both initialization and simulation parts of the simulator. In this work, we use a generalized Equations of State which upon selection of appropriate parameters, can be used to represent any of two Equations of State commonly employed in the oil industry; that is, the Peng-Robinson (*PR*) and Soave-Redlich-Kwong (*SRK*) Equations of State.

Sorption isotherm equation is used to define the relationship between the flow in the matrix system (where flow is controlled by concentration gradients) and the flow in the cleat system (where flow is controlled by pressure gradients). The calculation of diffusion/sorption term (q_d) in this simulator is based on the pseudo steady-state model (King *et al*., 1986). This model allows it to be included as an extra rate term in the flow equations, hence, it simplifies the calculation and computer storage requirements.

The developed formulation described above was tested and compared with other CBM simulators to model the improved coalbed methane (ICBM) recovery with pure CO_2 injection. Data used for this comparison study was taken from a published paper (*Law. D.H.-S., van der Meer, L.G.H. and Gunter, W.D., 2002)*. In that published paper, there are five simulators participated in the comparison study, they are: (1) GEM, Canada; (2) ECLIPSE, UK; (3) COMET 2, USA; (4) SIMED II, Australia; and (5) GCOMP, USA. In this paper, results from our simulator (LEMIGAS, Indonesia) are included (Syahrial, 2005). There are two problems set selected for this comparison: the first problem set deals with a single well test with CO_2 injection and the second problem set deals with ICBM recovery process with CO_2 injection in an inverted five-spot pattern. The problems selected for comparison are intended to exercise many of the features of CBM simulators that are practical and theoretical interest and to identify areas of improvement for modeling of the ICBM process.

The results show that in general, there is very good agreement between the results from the different simulators. The differences between the predictions from different simulators may result for a variety of reasons:

- possible different initialization procedure (*e.g.*, initial gas in-place),
- possible slightly different *PVT* properties for pure gas used,
- possible different dual porosity approach in the simulators,
- handling of wells (*e.g.*, ¼ well in 5-spot pattern),
- tolerance of the convergence of iterations; and
- selection of numerical control parameters.

III. PERMEABILITY MODEL

It was shown that during primary recovery of CBM, drawdown induced changes in the absolut permeability of coal can be described by (Shi & Durucan, 2003):

$$k = k_o e^{-3c_f(\sigma - \sigma_o)} \tag{4}$$

with

$$\sigma - \sigma_o = -\frac{v}{1-v}(p - p_o) + \frac{E}{3(1-v)}\varepsilon_i\left(\frac{p}{p+P_\varepsilon} - \frac{p_o}{p_o+P_\varepsilon}\right) \tag{5}$$

where:

k_o = cleat permeability at initial reservoir pressure p_o

σ_o = effective stress at initial reservoir pressure p_o

c_f = cleat volume compressibility with respect to changes in the effective horizontal stress (σ - σ_o)

E = Young's Modulus

v = Poisson's ratio of coal matrix

In arriving at Eq. (5), one of the assumptions made is that matrix shrinkage induced by methane adsorption may be fitted to a Langmuir type curve. Parameter and P_ε are referred to as the Langmuir-type matrix shrinkage constants. By analogy to Langmuir constants, ε_l may be interpreted as the maximum volumetric strain that would be induced when the coal is fully saturated with gas ($p \to \infty$), and is the gas pressure at which the matrix strain is half of the maximum value.

Eqs. (4) & (5) describe how permeability would vary with pore pressure in a gas-desorbing coalbed under uniaxial strain conditions. The two terms in the right-hand side of Eq. (5) are refered to as the clear compression and matrix shrinkage terms respectively. During primary recovery ( ) the cleat compression term is positive, whilethe matrix shrinkage term is negative. The sign and magnitude of $\sigma - \sigma_o$ is therefore determined by the relative strength of these two opposing terms. A comprehensive analysis of the permeability behaviour of coalbed during drawdown is described elsewhere (Shi & Durucan, 2003).

Eq. (5) is applicable to desorption of a single gas during primary recovery and, in its current form, cannot be easily extended to deal with enhanced recovery involving desorption/adsorption of multi-component gas mixtures. Assuming that matrix shrinkage induced gas desorption from coal is directly proportional to the volume of desorbed gas, Eq. (5) may be rewritten as:

$$\sigma - \sigma_o = -\frac{v}{1-v}(p - p_o) + \frac{E\alpha}{3(1-v)}[V(p) - V_o] \tag{6}$$

where:

α = volumetric shrinkage/swelling coefficient (kg/m^3)

= remaining gas content (m^3/kg) at reservoir pressure

V_o = initial gas content at p_o

If it is assumed that coal matrix shrinkage/swelling associated with desorption/adsorption of a gas mixture is proportional to the net volume of gas desorbed/adsorbed, Eq. (6) may be expanded, for a *n*-component gas mixture, to

$$\sigma - \sigma_o = -\frac{v}{1-v}(p - p_o) + \frac{E\alpha}{3(1-v)}\left[\sum_{j=1}^{n} V_j - \sum_{j=1}^{n} V_{jo}\right] \tag{7}$$

where V_j is the volume of adsorbed gas for component *j*, m^3/kg.

Eqs. (4) and (7) may be used to provide a first-order estimation of permeability changes during enhanched CBM recovery/CO_2 sequestration in coal seams. The equations, in conjuction with the extended Langmuir isotherms, have been implemented in the in-house ICBM simulator LEMIGAS. The volume of adsorbed gas in equilibrium with the gas mixture pressure and composition in the cleat is given by:

$$V_{Ej} = \frac{V_{jL}\left(\dfrac{P y_j}{P_{jL}}\right)}{1 + \sum_{j=1}^{n}\left(\dfrac{P y_j}{P_{jL}}\right)} \tag{8}$$

where *VjL* and *PjL* are pure gas Langmuir parameters for gas component j and *yj* the molar fraction,

Table 1
Coalbed reservoir and elastic properties

Well spacing, acres	320
Seam depth, m	914.4
Net thickness, m	15.24
Initial reservoir pressure, kPa	10342.1
Initial water saturation, frac.	0.95
In-situ permeability, mD	10
Initial CO_2 composition, frac.	0.10
In-situ porosity, frac.	0.01
Reservoir temperature, deg C	45
Young's modulus, kPa	2.9´10^{-6}
Poisson ratio	0.35
Cleat compressibility, kPa^{-1}	1.45´10^{-6}
Shrinkage/Swelling coeff.,	0.6 – 1.2
Coal density, kg/m^3	1830
Moisture content (% by weight)	3
Ash content (% by weight)	40
Langmuir volume, m^3/kg for CH_4	0.02033
Langmuir volume, m^3/kg for CO_2	0.03187
Langmuir pressure, kPa for CH_4	2498
Langmuir pressure, kPa for CO_2	1645

IV. RESULTS – APPLICATION OF PERMEABILITY MODEL

Aiming to gain insight into the influence of matrix swelling on the performance of enhanced CBM recovery/CO_2 sequestration, a numerical simulation study was carried out. For modeling purposes, published coalbed reservoir data representative of the Allison Pilot in the San Juan Basin Fruitland formation, which is the only field CO_2 injection data currently available, was used (Reeves, 2002). A problem set deals with ICBM recovery process with CO_2 injection in an inverted five-spot pattern (Figure 1.) is chosen in this study. Table 1 shows coalbed reservoir and elastic properties used in this simulation. Figure 2 shows the relative permeability curves. Methane production from a coalbed reservoir with 320-acre well spacing over a 20-year period was simulated. It was assumed that the initial free gas phase in the cleat was 90% CH_4 and 10% CO_2. The production and injection wells are situated at blocks (11,11) and (1,1) respectively on a 11 x 11 grid, which represents a

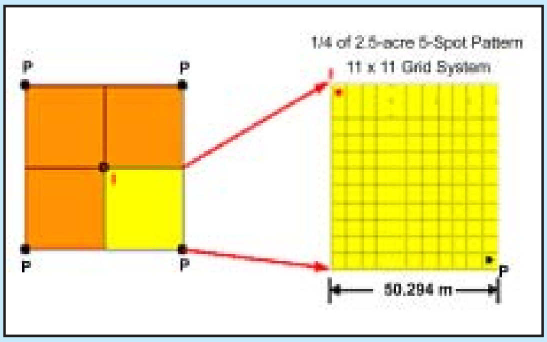

Figure 1
Schematic diagram of rectangular grid system
Production well bottomhole pressure schedule

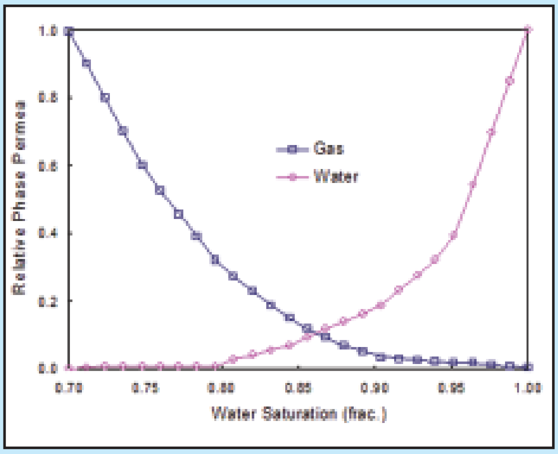

Figure 2
Relative permeability curves

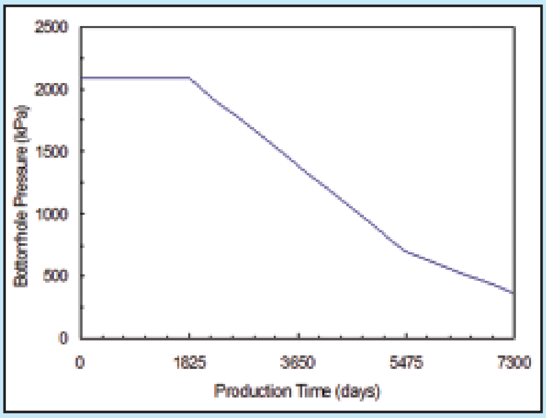

Figure 3
Production well bottomhole pressure schedule

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quarter of a 5-well pattern. After 5 years of primary recovery, CO_2 gas injection at a prescribed rate of 28,300 m^3/day was scheduled at the start of year 6. To prevent hydraulic fracturing, the maximum bottom-hole pressure allowed was 15 MPa in the simulation (see Figure 3). This implies that the prescribed injection rate may not be maintained all the time.

Injection of CO_2 gas into a coalbed causes matrix swelling, which, due to the stronger affiliation of CO_2 with coal than CH_4, could potentially have a severe impact on the cleat permeability. Figure 4 illustrates the permeability variation of the injection wellblock for the two cases (α = 0.8 and 1.0 kg/m^3, which were obtained by history matching the published field permeability data during primary recovery). It can be seen that the permeability has plunged by more than one order of magnitude shortly after the start of injection. The absolute permeability of the wellblock then remains largely unchanged at approximately 0.6 mD (α = 0.8) and 0.3 mD (α = 1.0) respectively.

The effect of CO_2 injection on well injectivity is of particular interest since field evidence at the Allison pilot in the San Juan Basin suggests that the well injectivity has declined at the early stages of CO_2 injection and then rebounded (Reeves, 2002). The

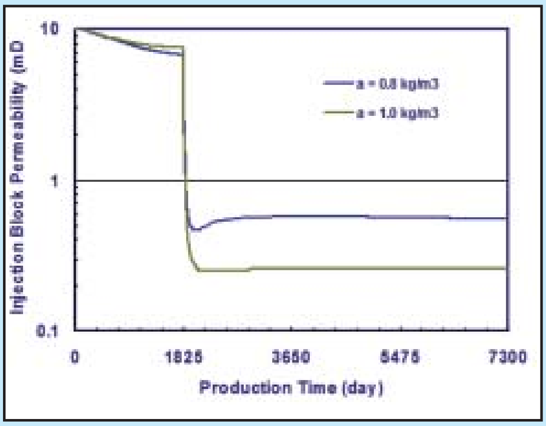

Figure 4
Variations in the injection wellblock permeability

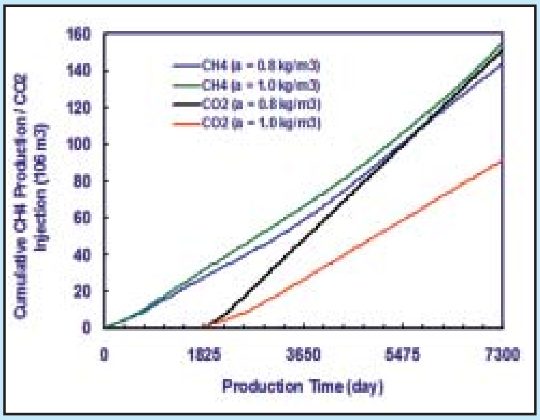

Figure 6
The effect matrix shrinkage coefficient on the cumulative CH_4 production and CO_2 injection

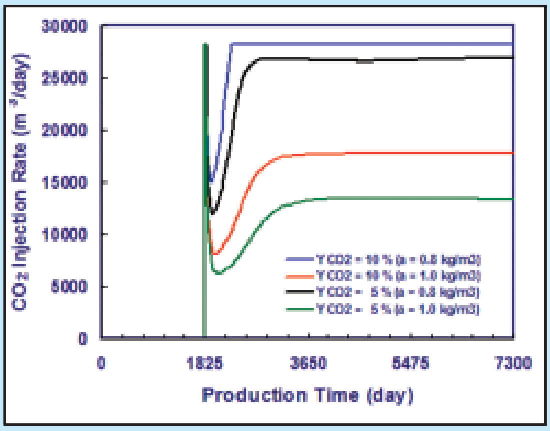

Figure 5
Variations in CO_2 injection rates

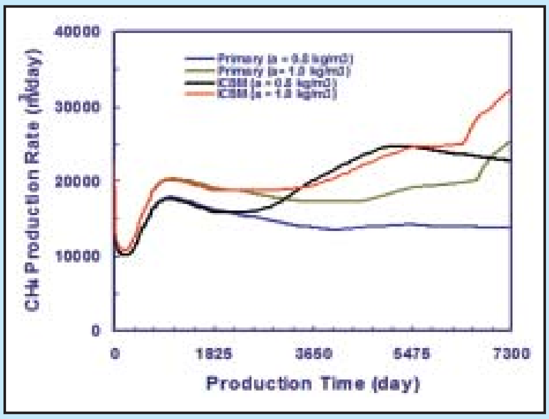

Figure 7
The effect of matrix shrinkage coefficient on enhanced recovery rates

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numerical results shown in Figure 5 are consistent with the above field observation. The results indicate that the magnitude of the matrix shrinkage/swelling coefficient has a profound impact on well injectivity. At α = 0.8, the injection rate is able to recover completely after an initial sharp dip, whereas only a partial (approximately 50%) recovery in the injection rate could be achieved when is increased to 1.0. Given that the absolute permeability of the injection wellblock remained practically constant in the same period, the recovery in the well injectivity appears to be due primarily to a continuing increase in the total mobility of the fluid in the wellblock.

It was found that the well injectivity is also strongly affected by the initial gas phase composition in the coalbed. As an illustration, if the initial CO_2 molar fraction is reduced from 0.1 to 0.05 (α = 0.8), then a full recovery could not be achieved, Figure 5. In addition, the rebound in the injection rate would also be much gradual.

The extreme reduction observed in the well injectivity for the case α = 1.0 suggests that the coalbed is less than optimal for CO_2 sequestration under the given reservoir conditions. As shown in Figure 6, approximately 91 million m^3 of CO_2 gas, compared to 151 million m^3 for the case α = 0.8, has been injected into the coalbed over the 15-year period, a reduction of more than 40%. It is interesting to note that the cumulative CH_4 production in the two cases are much closer. This implies that the improvement in methane recovery is less pronounced in the case of α = 1.0 than for α = 0.8, as illustrated in Figure 7.

V. CONCLUSIONS

The impact of matrix shrinkage/swelling on the production performance on primary and echanced recovery has been observed using the San Juan Basin Fruitland coal formation. It can be concluded that:

- Using a constant permeability for the entire reservoir needs to be cautioned during the production forecasts.
- While effect of matrix shrinkage is beneficial during primary CBM recovery, a strong shrinkage term could be transformed into a strong swelling term which would then have a detrimental effect on the cleat permeability during ICBM recovery/ CO_2 sequestration.
- CO_2 injection could result in more than an order of magnitude reduction in the formation around the injection well, and thus a sharp, often prompt decline in well injectivity. The subsequent rebound in injectivity may be due primarily to increased reservoir fluid mobility around the injection well.

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