Brine Displacement and Leakage Detection Using Pressure Measurements in Aquifers Overlying CO2 Storage Reservoirs

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Abstract

Through the use of analytical solutions derived from a simplified geologic model, this paper investigates the magnitude of pressure transients in permeable zones overlying CO2 storage reservoirs associated with brine migration through the sealing cap rock. A wide range of geologic settings and injection parameters is evaluated from which a generalized correlation is constructed to relate the hydrologic properties of the storage reservoir and seal to the magnitude of expected pressure buildups associated with brine migration across the seal. This correlation, referred to as the detection factor (DF), provides insight into the feasibility and interpretation of pressure changes measured in zones overlying CO2 storage reservoirs as a means of monitoring and leakage detection.

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1. Introduction

Monitoring the long-term integrity of CO2 storage reservoirs will be a critical aspect of deploying carbon capture and sequestration (CCS) at a meaningful scale. Ideally, monitoring techniques should be cost-effective, easy to implement, and provide unambiguous information about whether or not a storage reservoir leaks. One method that may have many of these attributes is monitoring pressure changes in observation wells open to a permeable monitoring zone overlying the target storage reservoir. Once equipped with downhole pressure gauges, reservoir pressure can be continuously monitored for any unexpected change which may indicate a fluid leak out of the storage reservoir (Fig. 1). This idea was proposed in the context of natural gas storage by Katz [1] and evaluated for the purpose of monitoring stored CO2 by Benson and Trautz [2]. Although this concept is mentioned anecdotally throughout the literature [3][4][5], there is little to be found in the way of published case studies or actual field data. Another observation noted from the literature is that faults, fractures, and leaky wellbores are often considered the most probable pathways for leakage out of the target storage reservoir and thus, the likely cause of pressure changes in overlying zones. As CO2 is injected, however, the resident formation fluid will be displaced laterally within the storage reservoir as well as vertically through the cap rock, potentially resulting in measurable pressure changes in overlying permeable zones. This study focuses on the vertical fluid migration across the cap rock and the associated pressure changes in the overlying monitoring zone for a wide range of formation parameters.

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2. Analytical Approach

2.1. Simplifying the Geological Model

Reducing the complex geologic structure of the CO₂ storage site to a simplified model allows the use of established analytical solutions to predict the pressure changes associated with the migration of resident fluid from the storage reservoir to the monitoring zone through the sealing cap rock. Neuman and Witherspoon [6] present solutions to the governing equations and boundary conditions (Eq. 1-3) describing the geologic system depicted in Figure 2. Table 1 summarizes the subsurface conditions of a possible CO₂ storage reservoir that were used in carrying out the subsequent pressure calculations.

### Table 1. Reservoir Conditions used in Calculations

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (km)</td>
<td>2</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>65</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>20</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;water&lt;/sub&gt; (kg/m³)</td>
<td>989.1</td>
</tr>
<tr>
<td>μ&lt;sub&gt;water&lt;/sub&gt; (Pa-s)</td>
<td>4.38e⁻⁴</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;CO₂&lt;/sub&gt; (kg/m³)</td>
<td>691.7</td>
</tr>
<tr>
<td>μ&lt;sub&gt;CO₂&lt;/sub&gt; (Pa-s)</td>
<td>5.61e⁻⁵</td>
</tr>
<tr>
<td>φ&lt;sub&gt;c&lt;/sub&gt;</td>
<td>0.05</td>
</tr>
<tr>
<td>φ&lt;sub&gt;sm&lt;/sub&gt;</td>
<td>0.2</td>
</tr>
<tr>
<td>c&lt;sub&gt;i&lt;/sub&gt; (Pa⁻¹)</td>
<td>1e⁻⁹</td>
</tr>
</tbody>
</table>

\[
\frac{d²s}{dr²} + \frac{1}{r} \frac{ds}{dr} + \frac{K_r}{h_j} \frac{ds}{dz} = \frac{S_r}{K_r} \frac{ds}{dt} \quad (1a)
\]

\[s_j(r,0) = 0 \quad (1b)\]

\[s_j(\infty, t) = 0 \quad (1c)\]

\[\lim_{r \to \infty} \frac{ds}{dr} = -\frac{Q}{2\pi K_j h_j} \quad (1d)\]
The symbols used in the above figure, table, and equations are defined as formation thickness \( h_i \), formation permeability \( k_i \), formation porosity \( \phi_i \), total formation compressibility \( c_t \), volumetric injection rate \( Q \), injection duration \( t \), radial distance from injector well \( r \), dimensionless pressure \( s_i \), specific storage \( S_i \), hydraulic conductivity \( K_i \), fluid density \( \rho \), and fluid viscosity \( \mu \), where the subscript \( i \) represents either the storage reservoir \( s \), monitoring zone \( m \), or the cap rock \( c \). Solutions to the boundary value problems described by Equations 1(a-d) and 2(a-d) are presented in terms of dimensionless pressure in Equations 4 and 5.

\[
\frac{\partial^2 s_i}{\partial z^2} = \frac{S_i}{K_i} \frac{\partial s_i}{\partial t} \quad (3a)
\]

\[
s_i(r,z,t) = 0 \quad (3b)
\]

\[
s_i(r,0,t) = s_i(r,t) \quad (3c)
\]

\[
s_i(r,h_i,t) = s_iw(r,t) \quad (3d)
\]

where \( S_i = \rho_g \cdot g \cdot (\phi_i \cdot c_i) \), \( (i = s, m, c) \) and \( K_i = \frac{k_i \cdot \rho_f \cdot g}{\mu_f} \), \( (i = s, m, c) \).

Due to the complexity of the integrand functions, the integrals were evaluated numerically using the recursive adaptive Simpson method [7]. Also, due to strong singularities at multiples of \( \pi \), the integration was performed as a summation of definite integrals over each continuous interval until the desired tolerance was achieved. The results of this quadrature method were compared to those yielded by the automatic functions programmed by Shan [8], to which a correspondence of the second or third significant figure was common. Full details of the calculations performed are presented in the next section.

### 2.2. Sensitivity Analyses

In order to bound the range of pressure changes associated with fluid migration through the cap rock, it was necessary to perform the calculations for a reasonable range of formation parameters and injection criteria. Table 2 lists values of the input parameters used to compute the theoretical pressure change in the monitoring zone. While parameter values must be expressed in SI units for the calculations, the units presented in Table 2 are more convenient and commonly used. Nomenclature is consistent with that described in the previous section.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (MT-CO2/yr)</th>
<th>Dimensionless permeability</th>
<th>Formation thickness</th>
<th>Radial distance</th>
<th>Injection duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>0.25</td>
<td>1</td>
<td>0.01</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>10</td>
<td>0.01</td>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>100</td>
<td>100</td>
<td>300</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>10000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The values chosen for each parameter do not represent any particular geologic environment or case study, but rather a range that is typically found in the literature or might be encountered in practice. Pressure calculations were carried out for every possible combination of the parameter values shown in Table 2, resulting in over 50,000 calculated pressure changes, which will be referred to as the “data set” for the remainder of the paper. Generating such a dense and inclusive data set is thus the primary advantage of the analytical approach, since the computational time required is nominal. One drawback to this analytical method
is the instability of the integrand functions and the susceptibility to generating inconsistent, non-physical values during numerical integration. These erroneous results did not appear to have any simple relationship to the particular combination of input parameters, except that they occurred more frequently for the smaller values of time ($t$). In other words, the non-physical results did not correspond solely to the cases when pressure build-up in the monitoring zone was expected to be small (i.e. extremely low cap rock permeability or a thick, permeable monitoring zone). In total, these non-physical anomalies comprised nearly 35% of the entire data set. Due to the unpredictability of this phenomenon, it is proposed that the root of the problem may lie with the robustness of the integration algorithm and its ability to deal with the strong, periodic singularities of the integrand functions. The nature of this problem is also noted by Shan [8] and is one the primary focuses of continuing work in this particular study.

Actual pressure build-up (Pa), as opposed to some dimensionless pressure build-up, was chosen as the basis for determining if the build-up is detectable since the accuracy and resolution of the downhole pressure gauge will ultimately limit the sensitivity of this method. In addition, to ensure positive detection, the pressure will need to be distinguished from natural pressure fluctuations caused by gravitational Earth tides and barometric pressure fluctuations, which can be on the order of 100 – 1000 Pa [9]. The cyclical nature of Earth tide fluctuations allows them to be mathematically filtered from the overall signal. Barometric pressure fluctuations can also be filtered from the data if atmospheric pressures are measured simultaneously. Finally, over long time periods (years), pressure transducers are known to “drift,” which can interfere with detecting the pressure build-up caused by leakage. Recognizing these potential “sources of noise” and, based on published specifications of downhole gauges, a cutoff range between 1,000 – 10,000 Pa was used to categorize the detection potential as either unlikely (<1,000 Pa), marginal (1,000 to 10,000), or likely (>10,000 Pa).

2.3. Initial Results

Once pressure build-up in the monitoring zone was calculated for each combination of input parameters, and then filtered for erroneous points, the collection of more than 35,000 pressure values was analyzed for any systematic trends. A frequency histogram of pressure (Fig. 3), with the aforementioned detection criteria overlaid, reveals that a majority of the cases investigated - over 75% - result in a pressure signal that will either be marginally or likely detectable. This is a particularly notable result since a wide range of reasonable formation parameters and likely injection criteria were chosen as the basis for the calculations. Thus, over a ten-year period, for the suite of hydrological properties evaluated in this study, a change in pressure is likely even when there is no short-circuit leakage pathway out of the storage reservoir.

Pressure data alone, however, do not provide any insight into which formation parameters and injection criteria result in either detectable or undetectable signals in the monitoring zone. Furthermore, due to the size of the data set, it is not practical to tabulate the associated inputs for each pressure value in a lookup table, for example. Thus, it would be useful to construct a single parameter derived from the fundamental input parameters which can then be correlated to the computed pressure change in the monitoring zone. Ideally, this parameter should reflect the magnitude of the expected pressure change and, in turn, give insight as to whether the signal will be detectable in a particular geologic storage setting. Such a parameter, called the Detection Factor (DF), was constructed and the process through which it was formulated is described in the next section.
2.4. Defining the Detection Factor

Three fundamental criteria underlie the construction of the Detection Factor (DF): 1) it should have an intuitive relationship with the expected pressure in the monitoring zone (i.e. a larger value of DF implies a larger change in pressure); 2) it should be constructed from the critical input parameters used to calculate the pressure change; 3) it should be easily computable in order to have value as a predictive assessment tool. The DF has a form that is intuitively consistent with the expected input parameters and the magnitude of the pressure buildup. For example, injection rate \(Q\) and pressure in the monitoring zone \(P_m\) should have a direct relationship, since an increase in volumetric flow rate should result in larger pressure changes. Conversely, cap rock thickness \(h_c\) and \(P_m\) should have an inverse relationship, since a thicker sealing cap rock will allow less fluid to migrate into the monitoring zone, resulting in a smaller pressure change. Table 3 summarizes all the underlying relationships used to construct the functional form of the Detection Factor (DF) defined in Equation 6 below. Note that the nomenclature used in Table 3 and Equation 6 is the same as that previously defined.

Table 3. Relationships between Input Parameters and Detection Factor (DF)

| Parameter Change: | r ↑ | h_c ↑ | k_c ↓ | h_m ↑ | k_m ↑ | h_r ↑ | k_r ↑ | Q ↓ | φ ↑ | c_i ↑ | t ↓ | ρ_f ↑ |
| Desired Response: | DF ↓ | DF ↓ | DF ↓ | DF ↓ | DF ↓ | DF ↓ | DF ↓ | DF ↓ | DF ↓ | DF ↓ | DF ↓ |

\[
DF = sf \cdot \frac{Q t}{r} \cdot \frac{1}{S_k S_h} \cdot \frac{1}{S_{m/k_m}} \cdot \frac{k_c}{S_{c/h_c}} \quad (6)
\]

As constructed, the Detection Factor is a dimensionless number and, for the range of input parameters previously mentioned, takes on values between \(10^{13}\) and \(10^{33}\). The variable \(sf\) included in Equation 6 represents an arbitrary scalar shift factor, which may be used to shift the range of DF values to a more intuitive, practical scale. For example, if \(sf = 10^{-13}\), then values of DF will fall in the range of \(10^0\) and \(10^{20}\).

Values of pressure in the monitoring zone \(P_m\) are plotted versus DF on a logarithmic scale in Figure 4. Included in the figure is the functional form of the linear correlation, the residual error in the regression, and both the 95% and 50% confidence interval lines. As before, only the physically meaningful pressure values have been plotted and factored into the statistical regression. Equation 7 reiterates the functional form of the correlation between DF and the expected pressure in the monitoring zone, \(P_m\).

\[
P_m = \left(6.84 \times 10^{-12} \text{ Pa}\right) \cdot DF^{0.612} \quad (7)
\]

Figure 4. Scatter plot of pressure in monitoring zone \(P_m\) versus DF.
3. Interpretation

Although the data presented includes over 35,000 pressure calculations, there is a strong correlation between DF and the magnitude of the pressure build-up. It is clear, however, that the relationship is not unique since one value of DF corresponds to multiple values of $P_m$. Despite this fact, the utility of this dimensionless metric, DF, is that it allows a quick determination as to whether or not a measurable pressure change is likely over the course of CO$_2$ injection in a particular geologic setting. Another convenient attribute of DF, is that the required inputs are common parameters that are likely to be part of the preliminary storage site characterization and injection design. Furthermore, it will enable CCS project planners to compare candidate sites and determine how the above-zone pressure monitoring technique can be applied and interpreted. For example, if the same pressure detection cutoffs previously defined are applied to the data, then for a given confidence level, a range of DF values can be defined in which detection is either likely, marginal, or unlikely (Fig. 5). If a 95% confidence is required, then DF values greater than or equal to $10^{26}$ will predict monitor zone pressures that are either marginal or likely to be detected with a typical downhole gauge. Alternatively, DF values less than $10^{20}$ suggest that the pressure changes in the monitor zone are unlikely to be detected within a 95% confidence interval.

![Detection Likely, Marginal, Detection Unlikely](image)

Figure 5. Scatter plot of pressure in monitoring zone ($P_m$) versus DF with detection thresholds overlaid.

Computing the value of DF for a particular CCS project and plotting it within the detection thresholds can aid in determining whether or not the above-zone monitoring technique will be applicable and, if implemented, how to interpret any observed pressure changes. Project planners of a CCS storage site whose DF value lies in the “Detection Likely” regime, should expect the pressure in the monitoring zone to change during the injection period due to fluid migration through the seal. Furthermore, they will have an estimated value for the expected pressure change. Therefore, pressure changes exceeding the estimated value may indicate leakage out of the storage reservoir through an alternate pathway (i.e. fracture, fault, wellbore annulus, etc.). Alternatively, if the value of DF lies in the “Detection Unlikely” regime, project planners should not expect detectable pressure changes in the monitoring zone throughout the duration of injection. If a pressure change is positively detected, however, then the injected fluid has found a “short-circuit” path into the monitoring zone. In either case, knowing the value of DF provides important insight into the interpretation of pressure measurements from the overlying monitoring zone. A frequency histogram of the resulting DF values, for all combinations of input parameters, is plotted in Figure 6. In this figure, the detection cutoffs have been selected to distinguish the values of DF for which the pressure estimated by Equation 7 lies in the marginal zone (i.e. 1,000 – 10,000 Pa). This figure reveals that in over 70% of the valid cases examined, the estimated pressure change is either marginal or likely to be detected.
To illustrate its ease of use, the value of DF can be computed for the Cranfield Unit Stacked Storage Project: a potential long-term CO₂ storage site near Cranfield, Mississippi, U.S.A. where residual oil is currently being produced through CO₂ enhanced oil recovery (CO₂-EOR). The Cranfield Project is also under investigation as a demonstration project for CCS by researchers from the Gulf Coast Carbon Center (GCCC) and the Bureau of Economic Geology in Austin, Texas, U.S.A. Moreover, researchers have incorporated an above-zone pressure observation well into the suite of monitoring tools, since the geologic structures are amenable to this technique. Through collaboration with researchers at the GCCC, the necessary information was acquired to compute the value of DF as well as the expected pressure buildup in the monitoring zone. Based on the geologic parameters and current injection rate and duration of 90 days, the value of DF is 1.4e24. When plotted on Figure 5, this falls in the “Marginal” range. If the duration of injection is extended to 1 year, then DF becomes 5.6e24 which corresponds to a pressure buildup near the upper limit of the “Marginal” range.

4. Conclusions and Future Work

The correlation between the proposed Detection Factor, DF, and the calculated pressure changes in the monitoring zone is promising and potentially quite useful. In addition, the value of DF can be determined from reservoir data that can either be estimated or acquired directly from well logs, core samples, and formation fluid samples. Through the use of Equations 6 and 7, CCS project planners have a quick and easy method to assess whether or not the above-zone pressure monitoring technique will be valuable for a particular storage setting and what the expected pressure response is likely to be during an extended injection period. Ultimately, this provides valuable insight when diagnosing unexpected pressure transients in the monitoring zone and creates a more effective monitoring approach.

Future work is planned in order to address several issues surrounding the current form of DF. First, further testing of the sensitivity to individual input parameters is necessary in order to improve the overall correlation to calculated pressures, which may result in the modification of the overall functional form. Second, refinement of the numerical integration method is needed to reduce the number of erroneous, non-physical pressure values in the data set. Third, numerical simulation of various injection scenarios will allow comparison to the analytical results and thus, validate the method or provide insight for reevaluation. Finally, investigation of additional leakage scenarios (i.e. faults and leaky wellbores) will be carried out to determine whether or not the risk of leakage can be quantified with additional factors, like DF. Ultimately, the goal is to construct an informative set of criteria that will allow both detection and recognition of the underlying leakage mechanism as well as the mobile fluid.

5. Acknowledgements

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6. References