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Wabamun Area Sequestration Project: Risk-based Leakage Model

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REPORT

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1.0 INTRODUCTION

The Wabamun Area Sequestration Project (WASP) is a desktop study led by the University of Calgary that is investigating the feasibility of geologically storing one gigatonne of carbon dioxide (CO_2) in the Wabamun Lake area of Alberta where four coal-fired power plants collectively emit over 30 MT of CO_2 each year. The primary WASP study area contains substantial oil and gas activity and includes the presence of thousands of producing and abandoned wells dating back to the 1950s. The success of a geological storage program will depend in part on the ability to choose storage formations from which only minimal amounts of CO_2 will leak back to the surface (NKCB, 2009). Wells, in particular those that are long abandoned and completed to uncertain standards, are generally considered to be one of the major potential pathways for release of CO_2 from a storage reservoir.

Within the High Grade Study Area, the Devonian Nisku formation was selected as the prime target for CO_2 storage by the WASP investigators. There are 18 abandoned wells penetrating the Nisku within a few kilometers of a potential CO_2 injection location. In the same area there are over 100 well penetrations in the overlying Banff formation, separated from the Nisku by the Calmar Aquiclude. While the potential leakage of CO_2 through the abandoned wells in the Nisku formation is of obvious importance, leakage through the more prevalent wells in the overlying Banff formation via indirect pathways must also be evaluated.

As a participant in WASP, Golder Associates was tasked to develop a probabilistic analytical simulator capable of evaluating alternative leakage scenarios associated with legacy wells in multiple formations. The scope of the initial simulation tool included the simplest scenario of leakage to the surface via a single abandoned well in the Nisku formation and was extended to leakage through a combination of wells in the Nisku and Banff formations. The simulator that was developed is based to a large extent on the analytical solutions developed by Nordbotten, Celia and Bachu (Nordbotten et al., 2004 and Nordbotten et al., 2005). The use of analytical expressions in the simulator allows the uncertainty in the input parameters to be explicitly represented and propagated in the model calculations using the Monte Carlo simulation method. The probabilistic method facilitates sensitivity analysis for prioritizing the site characterization data needs for reducing the overall uncertainty in system performance. The simulator is scalable and can be expanded to represent CO_2 release through additional leakage pathways such as faults, fracture networks and spill points.

The simulator includes an intuitive, user interface for defining the input parameters and describing different release scenarios (i.e., 'what if' analysis) that are fundamental in CO_2 sequestration risk analysis and useful for developing a diagnostic understanding of the different leakage scenarios. The user interface provides a number of predefined model outputs including time histories of formation pressure, CO_2 plume migration within the injection formation, and CO_2 flux rates from breached wells. The default input parameters in the simulator that describe the potential leakage characteristics of the abandoned wells in the Wabamun region were developed by members of the WASP research team.

This report describes the conceptual model of the geologic sequestration system represented in the simulator and the analytical expressions used to approximate the movement of CO_2 through an injection formation and it's potential release through one or more abandoned wells. The mathematical implantation of the analytical solutions in the simulator is summarized and the input parameters identified. Initial estimates for the input parameter for the model developed by the WASP team are defined. The user interface for the simulator is then described and example outputs are presented.

2.0 CONCEPTUAL MODEL DESCRIPTION

The Wabamun Lake area of Alberta has supported substantial oil and gas activity dating back to the 1950s involving thousands of producing and abandoned wells drilled to intersect multiple formations in the area. Within what is referred to as the High Grade Study Area, there are a total of 95 wells, 56 of which have been abandoned. The wells, in particular those long abandoned and completed to uncertain standards, represent potential pathways for release of CO_2 if one or more of the reservoir formations in this area are used for geologic sequestration.

The WASP study team has identified the Devonian Nisku formation as a prime candidate for potential CO_2 sequestration in the Wabamun Lake area. Out of the 52 abandoned wells in the High Grade Study Area, 32 were completed in formations above the Nisku and twelve were completed below. Well integrity in the High Grade Study Area has been studied by Nygaard (2009) who concluded that approximately 50% of the cement plugs in the abandoned wells were likely to be fractured. Of the five wells that were studied in detail, one well was an open hole (i.e., was not plugged). These preliminary results demonstrate the uncertainty associated with the abandoned wells as potential leakage mechanisms if the area is eventually used for CO_2 sequestration. While the potential leakage of CO_2 through the abandoned wells in the Nisku formation is of obvious importance, leakage through the more prevalent wells in the overlying Banff formation via indirect pathways must also be evaluated.

As a member of the WASP Team, Golder Associates was tasked to develop a probabilistic simulator based on the methodology and equations developed in Nordbotten et al. [2004, 2005a, 2005b and 2009]. The scope of the initial phase of the simulator consists of two scenarios: 1) the leakage of CO_2 from the injection formation (i.e., the Nisku) to the surface via a single abandoned well assumed to intersect the Nisku (Figure 1), and 2) the leakage rate for a cross-formational flow through two wells, from the injection formation into an overlying aquifer and then to the surface (Figure 2). The Monte Carlo method is used to explicitly represent the uncertainty in the analytical expressions based on the existing site information or expert opinion where little to no data exists.

Figure 1: Conceptual Model of Leakage from Injection Formation through Single Well in the Nisku Formation

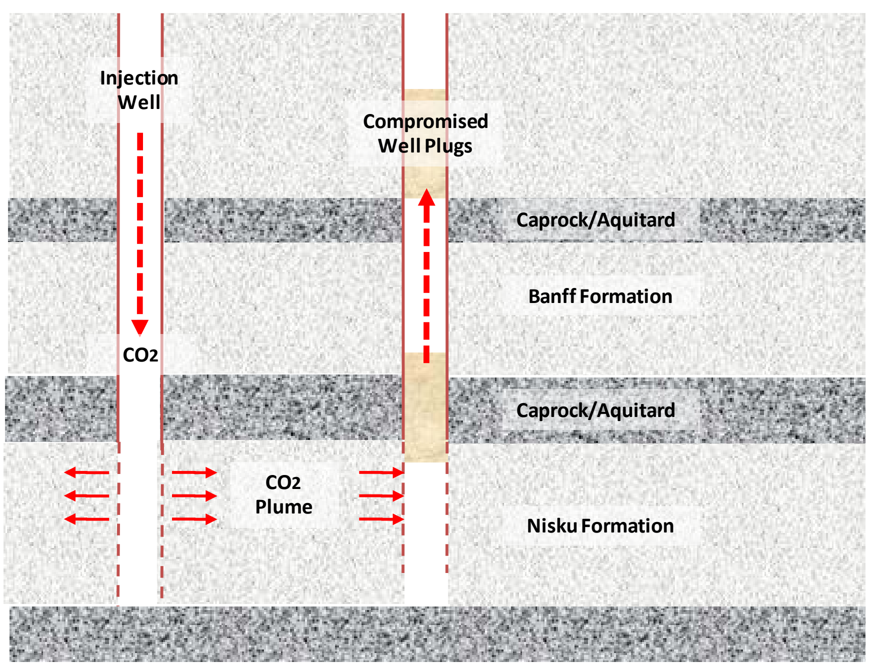
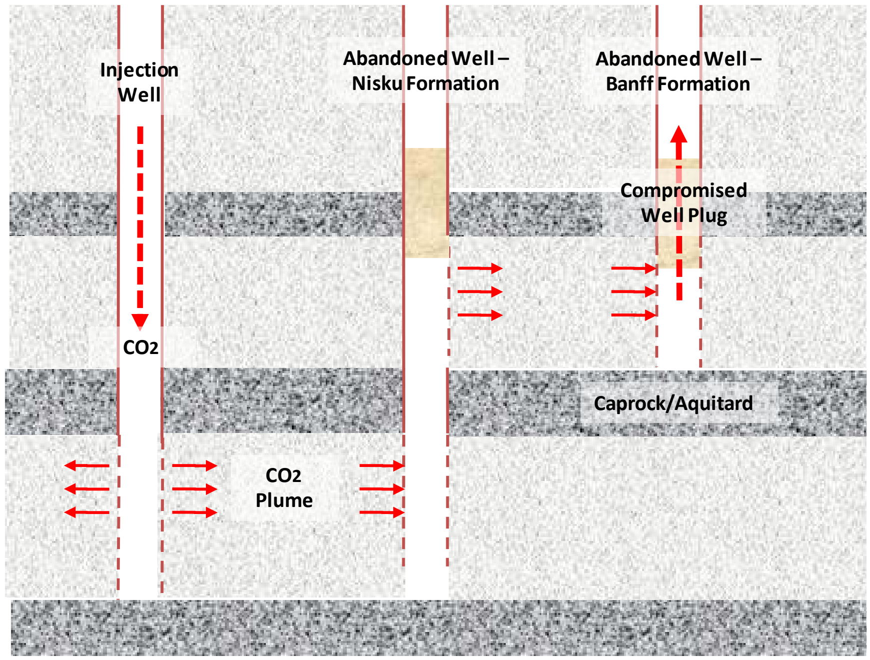


Figure 2: Conceptual Model of Cross-Formational Leakage through Multiple Wells



The simulator was developed in the following steps:

- Define the mathematical models – The analytical expressions and algorithms for plume migration and well leakage from Nordbotten et al. were reviewed and modified to represent single and two-well scenarios in Figures 1 and 2.
- Implement the mathematical models in a simulation software package – The analytical expressions and algorithms were implemented using the GoldSim simulation software code. This step included the development of a user interface to facilitate use by other WASP Team members.
- Verify and benchmark the simulator – Benchmark component calculations in the simulator against independent calculations developed in Excel.
- Coordinate a preliminary data set for the simulator - Gather input data including probability distributions for uncertain input parameters in the simulator.
- Sensitivity analysis – Perform sensitivity analyses for the major performance metrics (e.g., formation pressure, plume migration, CO_2 flux) in the simulator to determine the input parameters that have the greatest influence on projected performance.

The simulator, based on a set of assumed conditions and properties, can be used to evaluate the following performance metrics:

- arrival times for the CO_2 plume reaching abandoned wells in the Nisku or Banff formations (i.e., cross-formational flow through scenario);
- transient formation pressure at the base of the abandoned wells;

- leakage rates from abandoned wells in the Nisku and Banff formations; and
- sensitivity of the plume and leakage rate projections to variations in the input parameters in the simulator.

These performance metrics are important considerations for planning purposes for both geological sequestration and enhanced oil recovery. The performance metrics are calculated based on the following input parameters to the model:

- injection rate;
- injection duration;
- distance between the injection and abandoned wells;
- well radius;
- length, permeability and radius of the wellbore plug in the abandoned wells;
- formation hydrogeologic properties; and
- CO_2 properties.

2.1 Transient Pressure in an Injection Reservoir

The starting point for developing the simulator was estimating the transient pressure in the reservoir formation during CO_2 injection. The change in the formation pressure as CO_2 is injected into a reservoir is approximated using the standard Theis well pumping equation (Nordbotten et al., 2004):

$$p(r,t) = p_{init} + \frac{\mu Q_0}{4\pi k_1 b_1} W(u) \quad (1)$$

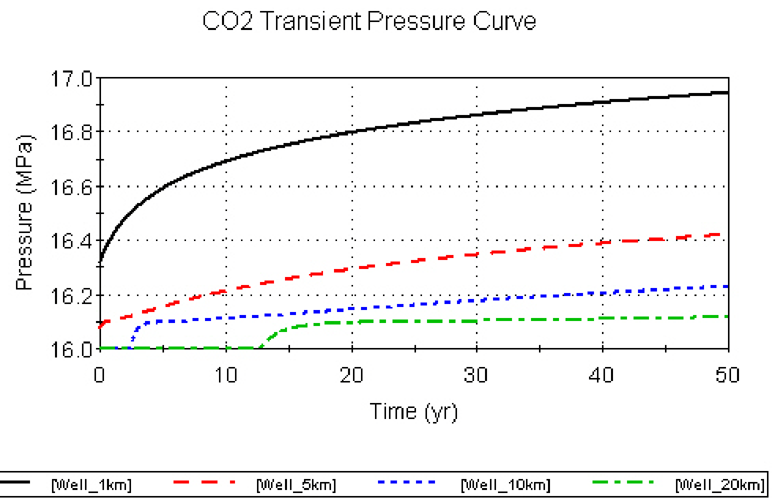
where $W(u)$ is the familiar well function from hydrogeology (Freeze and Cherry, 1979) which is an exponential integral function of the first order $E_1(u)$ For evaluation of the exponential integral see (Gautsch and Cahill, 1964). The argument u of the well function is given by

$$u = u(r,t) = \frac{c\mu r^2}{4k_1 b_1 t} \quad (2)$$

Where c is the compressibility of the CO_2-rock system, μ is CO_2 viscosity, r is the radial horizontal distance from the injection site, k_1 is the permeability of the reservoir formation, b_1 is the thickness of the reservoir formation and t is time.

Figure 3 shows the transient pressure curves in the CO_2 reservoir at variable distances from the injection location for an injection period of 50 years.

Figure 3: Transient Pressure at Distances of 1 to 20 km from the Injection Location



Note that the transient pressure curves follow a "smoothed" step function in time which decreases in overall magnitude with distance for a given injection period.

2.2 Radial Extent of the CO_2 Plume

The radial extent of the CO_2 plume from an injection well is calculated using a 2-phase radial flow analytical solution developed by Nordbotten et al. (2005). Assuming the CO_2 injection rate (Q_0) is constant, the radial extent of the CO_2 plume r_{max} is given by

$$r_{max} = \sqrt{\frac{\lambda_c V(t)}{\pi \varphi \lambda_w b_1}} \quad (3)$$

Where λ_c is mobility of CO_2, λ_w is the mobility of water, $V(t)$ is the cumulative CO_2 volume injected at time t, ϕ is porosity of the reservoir and b_1 is the thickness of the reservoir. The mobility values are related to the viscosities μ_α and relative permeability values k_α by

$$\lambda_\alpha = \frac{k_\alpha}{\mu_\alpha} \quad (4)$$

Where $\alpha = c$ or w. The two relative permeability values are a function of the CO_2 saturation fraction S_{res} and have been measured and tabulated for the Wabamun formation by Benion and Bachu (2005).

In the case where S_{res}=0.384, the relative permeability values for the two phase are equal and then

$$\frac{\lambda_c}{\lambda_w} = \frac{\mu_w}{\mu_c} \quad (5)$$

Note that for constant injection rate, $V(t)$ can be replaced by $Q_0 t$. Figure 4 shows the radial extent of the plume as a function of time. Plume arrival times at a distance 5 km from an injection well are tabulated for different values of S_{res} in Table 1. The arrival times are based on the expected value for all the model parameters.

Figure 4: Maximum Radial Extent of Plume in Reservoir Formation for S_{res}=0.384

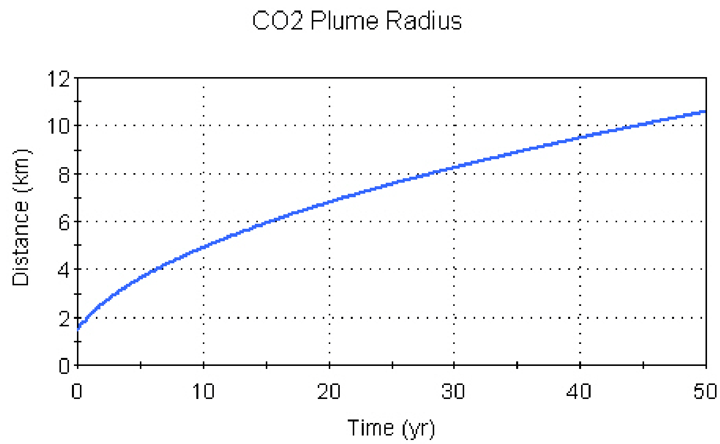


Table 1: Time to Reach 5 km Distance from Injection vs. S_{res}

Saturation Fraction Sres	Time to Reach 5 km (yr)
0.36	7.4
0.37	6.6
0.38	5.9
0.384 (Default)	5.6
0.4	4.6
0.41	4.0

Equation (4) can also be used to calculate the radial extent of a CO_2 plume in a shallower formation (Banff) under the cross-formational scenario. The volume injected is replaced by the volume leaked from the injection reservoir formation to the shallower formation through the Nisku abandoned well (Figure 2). The resulting equation is

$$r_{\max\,(Banff)} = \sqrt{\frac{\lambda_c V_{12}(t)}{\pi\varphi\lambda_w b_2}} \qquad (6)$$

Where $V_{12}(t)$ is the volume of CO_2 entering the Banff formation through the abandoned well and b_2 is the thickness of the Banff formation. $V_{12}(t)$ is given by

$$V_{12}(t) = \int_0^t Q_{12}(t')dt'$$

Where from Appendix D

$$Q_{12}(t) = \frac{k_{12}\pi r_{12}^2}{\mu D_{12}}\left[\frac{(a_1+b_1)d_2-(a_2+b_2)d_1}{(a_1b_2-a_2b_1)}\right] \qquad (7)$$

and the coefficients a_1 through d_3 are in turn functions of 4 time-dependent well functions.

Equation 3 is based on the following assumptions:

- a vertically averaged pressure within the formation;
- radial propagation of pressure (Darcy flow) in the formation;
- isotropy in the reservoir permeability tensor; and
- the injection formation is confined.

2.3 CO_2 Leakage to Surface from an Abandoned Nisku Well

The leakage component is modelled as a one-dimensional Darcy process through an abandoned well. Leakage from the injection reservoir to the surface is driven by the pressure difference between transient pressure at the base of the well in the reservoir formation and atmospheric (surface) pressure. Several well leakage paths were identified in Chapter 5 of the IPPC report (IPCC, 2005), in papers by Bachu and coworkers, such as (Gasda et. al., 2004).

Starting from the analytical solutions developed by Nordbotten et al. (2004) as detailed in Appendix B and Appendix C, the pressure $p(\bar{r}_1, t)$ at the foot of the abandoned well, located at distance $\bar{r}_1$ from the injection well can be estimated. This is then substituted into the one dimensional Darcy equation in the vertical direction to give the following expression for surface leakage flux through the plug in the first abandoned well.

$$Q_{1s}(t) = \frac{\pi r_{w1}^2 k_{1s}}{\mu D_{1s}} \left[p_s - \frac{p_{init} + \frac{\mu Q_0 W[u(\bar{r}_1, t)]}{4\pi k_1 b_1} + \frac{k_{1s} r_{w1}^2 p_s W[u(r_{w1}, \gamma t)]}{4 k_1 b_1 D_{1s}}}{\left(1 + \left\{\frac{k_{1s} r_{w1}^2 W[u(r_{w1}, \gamma t)]}{4 k_1 b_1 D_{1s}}\right\}\right)} \right] \tag{8}$$

Here k_{1s} is the permeability of the abandoned well plug between the reservoir and the surface, r_{w1} is the abandoned well radius, p_s is atmospheric pressure, $\gamma = 0.92$ is the constant from the Nordbotten et al. theory, and D_{1s} is the length of the cement plug.

Figure 5 shows the transient surface leakage during the injection period through a single abandoned well penetrating the Nisku located 1 km from the injection site. The well leakage parameters pertain to those for a fractured cement plug. Note the leakage profile is similar to the pressure profile smoothed step function shape of the transient leakage profile. Also note that the model predicts that leakage already exists prior to injection because of the pre-existing pressure difference between the atmosphere and the Nisku formation. The onset of leakage of actual CO_2 must be estimated using the two-phase plume migration model as described in Section 2.2. The time of arrival of the CO_2 plume arrival is estimated using equation (3).

Figure 5: CO_2 Leakage Rate for Single Abandoned Well Model with r=1 km, k_{1s}=10-15m^2, D_{1s}=10m and r_{1s}=0.1m

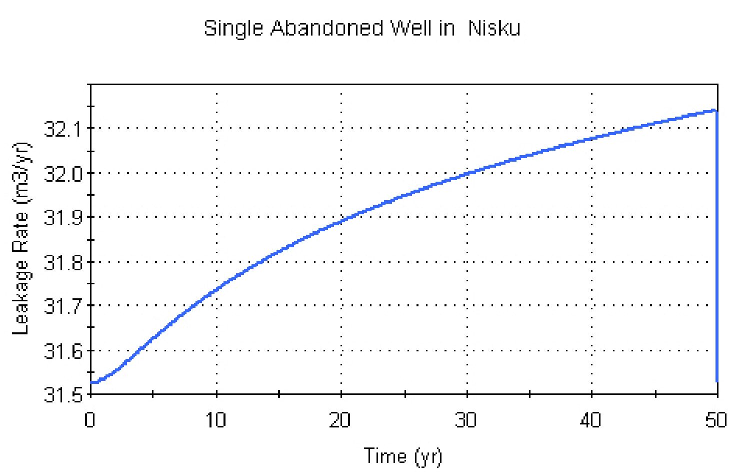
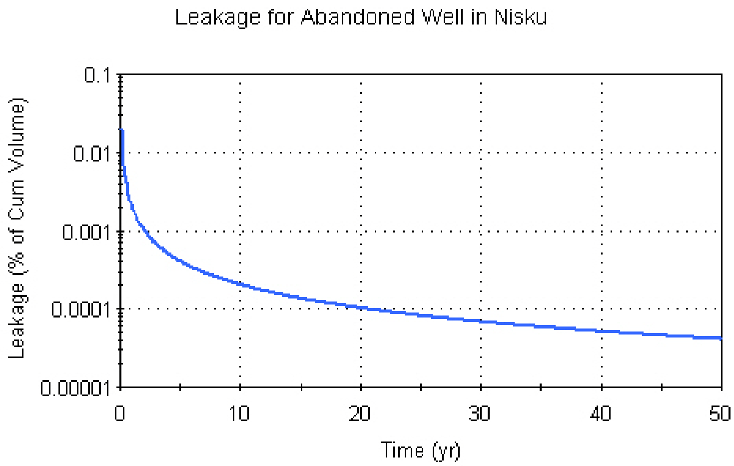


Figure 6 shows the same CO_2 leakage rate expressed as a percent of the cumulative storage volume.

Figure 6: CO_2 Leakage Rate as a Percent of Cumulative Annual Injected Rate for a Single Abandoned Well Model with $r=1$ km, $k_{1s}=10^{-15}$ m^2, $D_{1s}=20$ m and $r_{1s}=0.1$ m



2.4 CO_2 Leakage to Surface from an Abandoned Banff Well

The conceptual model for cross-formational flow from an abandoned well in the Nisku to an abandoned well in the Banff formation is shown in Figure 2. As in the previous section, the conceptual model is based on Nordbotten et al., (2004). The model makes the following assumptions:

- a vertically averaged pressure within the injection (Nisku) and overlying (Banff) formations;
- radial propagation of pressure (Darcy flow) in both formations;
- isotropy in the Nisku and Banff formation permeability tensors;
- no leakage through the underlying aquiclude and overlying (Calmar) and higher aquicludes (cap rocks);
- one dimensional Darcy flow from the Nisku formation to the Banff Formation through the first abandoned well cement plug;
- one dimensional Darcy flow from the Banff formation to the surface through the second abandoned well cement plug; and
- no leakage from the Nisku to the surface through the abandoned well.

Similar to the single abandoned well solution, the formation pressure is calculated as a function of the radial distance from the injection location within the reservoir formation. This is done by using the well pumping function (exponential integral) for single phase flow in a porous medium. The leakage component is modelled as a vertical one-dimensional Darcy process through the abandoned well which permits leakage between the Nisku and Banff formations. This process is driven by the pressure difference between CO_2 pressures in the two formations. Darcy flow is assumed in the Banff formation with the leakage flux acting as the system driver in the same way that the injection flux was the driver for radial flow in the Nisku formation. This radial flow causes a pressure increase at the bottom of abandoned wells penetrating the Banff formation which in turn causes leakage to the surface, modelled as vertical one-dimensional Darcy flow.

Tithe the next step in the modelling process is to evaluate the CO_2 pressure at the location of the abandoned well in the two formations. The pressure at the foot of the well penetrating the Banff formation is used in the one dimensional vertical Darcy equation to compute the CO_2 leakage rate through the abandoned well to the surface from the Banff formation.

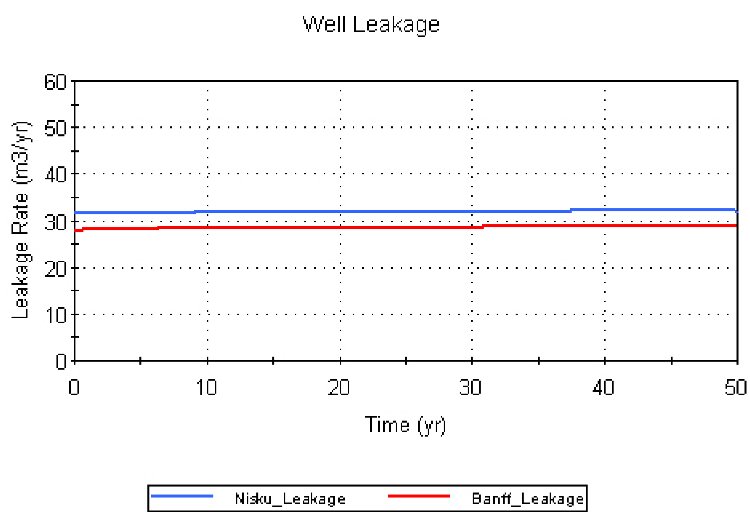
The resulting equation for leakage from the Banff formation to the surface is given by the expression

$$Q_{2s}(t) = \frac{k_{2s}\pi r_{w2}^2}{\mu D_{2s}}\left[p_s - \frac{(a_2b_3 - a_3b_2)d_1 + (b_1a_3 - a_1b_3)d_2 + (a_1b_2 - a_2b_1)d_3}{(a_1b_2 - a_2b_1)c_3}\right] \quad (9)$$

Where k_{2s} is the permeability of the (2nd) abandoned well plug between the Banff formation and the surface, r_{w2} is the radius of the 2nd abandoned well, p_s is atmospheric pressure, and D_{2s} is the length of the cement plug for the 2nd abandoned well. The set of coefficients a_1 through d_3 are defined in Appendix D. Some are dependent on the two well pumping functions which govern horizontal radial CO_2 flow from the injection well to the 1st abandoned well, and the CO_2 flow from the 1st abandoned well to the 2nd abandoned well (penetrating the Banff). Others depend on the well functions associated with vertical leakage flow from the Nisku to the Banff layers and also from the Banff to the surface.

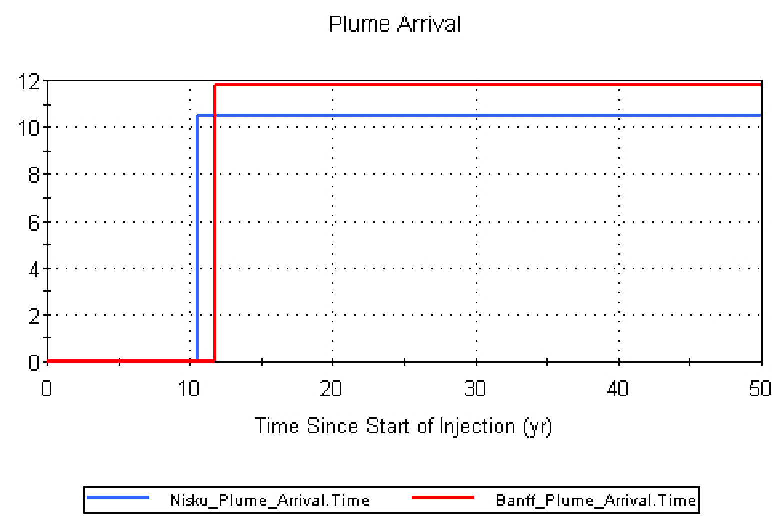
Figure 7 shows and example of the leakage flux through an abandoned well penetrating the Banff to the surface for r_1=5 km, r_2=1 km, $k_{2s}=10^{-15}$ m^2, $k_{12}=10^{-11}$ m^2, r_w=0.1 m and D_w=10 m, where w=1s, 2s, 12. The horizontal distance between the injection well and the 1st abandoned well is r_1 and the horizontal distance between the 1st and 2nd abandoned wells is r_2. The permeability of the 1st abandoned well pathway allowing leakage from the Nisku to the Banff is that of a compromised well plug ($k_{12}=10^{-11}$ m^2). Because of the relatively high permeability, the leakage rate from the well penetrating the Banff is almost equal to that from the Nisku well.

Figure 7: Leakage Rate Curve for r_1=5 km, r_2=1 km, $k_{12}=10^{-11}$ m^2, $k_{2s}=10^{-15}$ m^2 r_{w1}=0.1 m and D_{w1}=10 m



Although the leakage from the Banff formation is relatively large for the above parameters, the onset of the CO_2 leakage is delayed until the arrival of the CO_2 plume. Figure 8 shows the arrival time of the CO_2 plume at theoretical wells in the Nisku and Banff formations 5 km and 6 km respectively from the injection well. The arrival time of the plume at the abandoned well in the Nisku is the time since the onset of injection whereas the arrival time of the CO_2 plume at the abandoned well in the Banff is the time from the onset of arrival of the plume at the well in the Nisku formation (i.e., the total time for the plume to reach the well in the Banff is given by the sum of the two times which is approximately 22 years.

Figure 8: Plume Arrival Curve for r_1=5 km, r_2=1 km, $k_{12}=10^{-10}$ m^2, $k_{w1}=k_{w2}=10^{-15}$ m^2 r_w=0.1 m and D_w=10 m



3.0 SIMULATOR DEVELOPMENT

The analytical solutions presented in Section 2 were implemented using the GoldSim software package, a publically available, dynamic probabilistic simulation software platform. It is used to develop simulation platforms in a wide range of market sectors from mining to aerospace. The software uses an object-oriented programming language to develop a mathematical model that calculates changes in the specified system as a function of time. The simulation duration and time steps between calculations is specified by the user. Input parameters can be represented as deterministic or probabilistic values and the software uses the Monte Carlo method to propagate the uncertainties throughout the model calculations. The software has a library of distribution types (e.g., normal, log-normal, uniform, Weibull) that can be used to represent the probability distribution functions for uncertain inputs. Inputs and outputs can be controlled using a series of dashboards that serve as the user interface for the simulator.

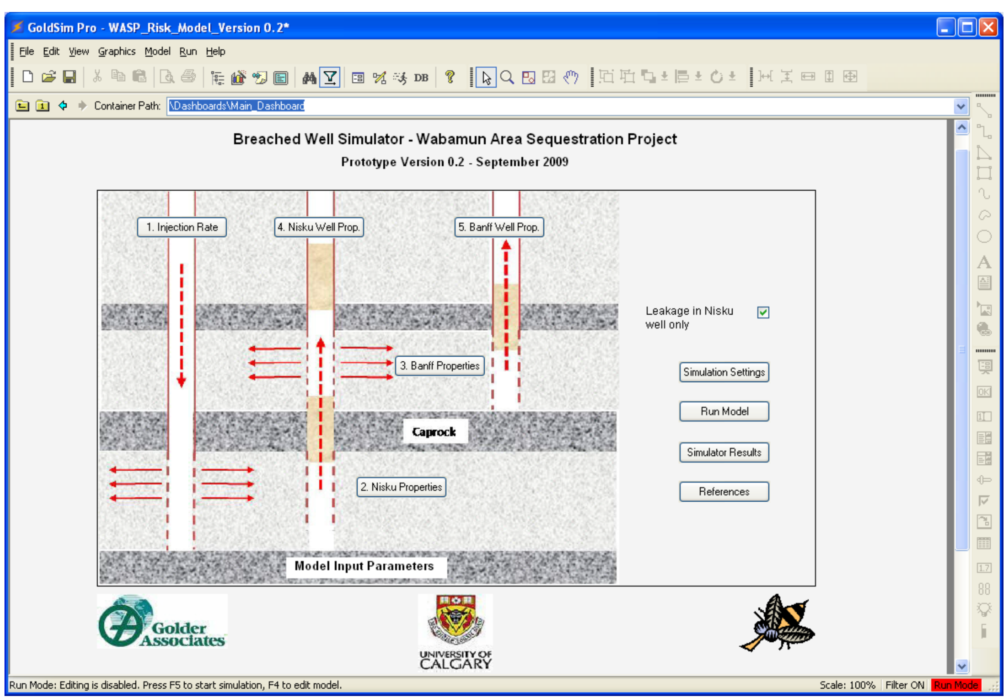
The software programming language allows for the mathematical expressions of the different components in the system (e.g., reservoir pressure, plume migration, well bore flux rate) to be developed in a modular fashion. The components are linked through the parameters and functions they have in common. This hierarchical architecture facilitates revisions and additions to the model as the complexity of the system representation is increased or the conceptual model evolves. Additional components in the model architecture are used to store the input parameters, model outputs and user interface instructions for the simulator.

3.1 User Interface

The user interface for the simulator consists of a series of dashboards to define the input parameters and assumptions in the simulation and display the results in various graphical and tabular formats. The Main dashboad is shown in Figure 9 . The Main dashboard contains links to other dashboards for entering the input parameters for the simulation, selecting different abandoned well scenarios to run (i.e., single vs. multiple wells), and generating graphical and tabular outputs of the simulation results.

The graphic of the conceptual model in the Main dashboard contains a series of five links for setting the input parameter values to be used in a simulation. The input parameter dashboards are accessed by clicking on the "buttons" shown in Figure 9.

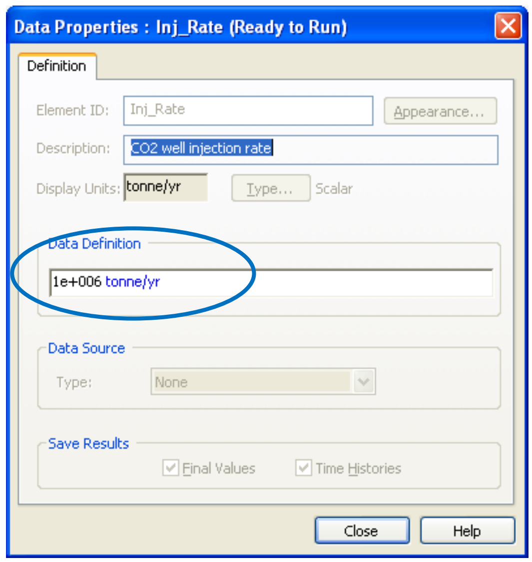
Figure 9: Simulation Model Main Dashboard



Injection Rate

The analytical expressions for calculating the formation pressure and CO_2 plume migration assume a constant CO_2 injection rate over the simulation period. The rate is set by clicking on the button labeled "Injection Rate" in the Main dashboard which produces the text box shown in Figure 10. The injection rate units are metric tonnes per year.

Figure 10: Input for CO_2 Injection Rate



Nisku Properties

The input parameters to define the properties of the Nisku formation are contained in a separate dashboard that is accessed by clicking on the "Nisku Properties" button on the Main dashboard. The Nisku formation properties dashboard is shown in Figure 11. Table 2 shows the parameters and the associated probability distribution types assumed in the model. Changes to the model are made by entering the distribution parameters in the dashboard (e.g., mean and standard deviation for a normal distribution. The probability distribution functions for the Nisku formation porosity and permeability are discrete distributions based on empirical data developed by the WASP team (Eisenger, 2009). The discrete data for these distributions is fixed, i.e., it cannot be changed by the user. Return to the Main dashboard by clicking on the button at the bottom of the screen.

Figure 11: Nisku Formation Properties Dashboard

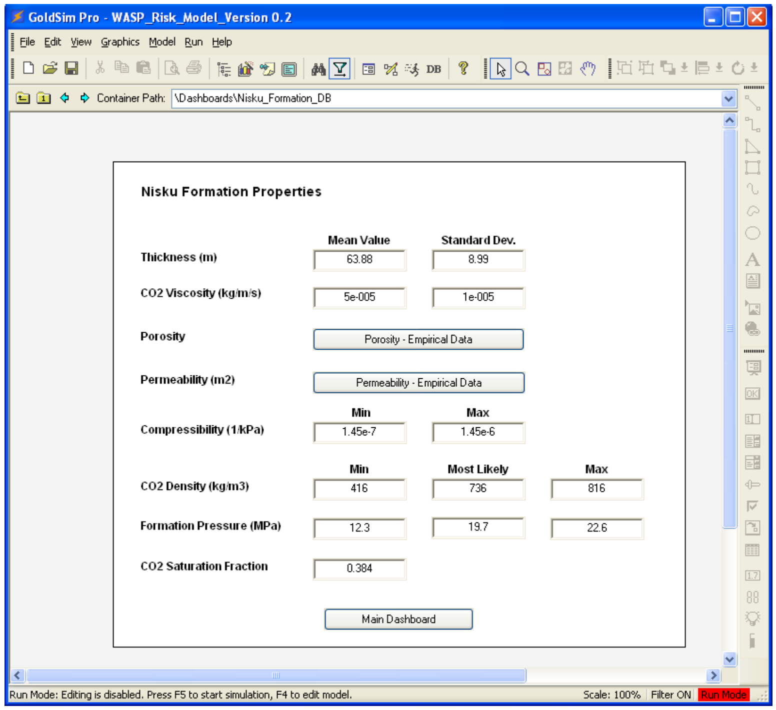


Table 2: Parameters and Distribution Types for the Nisku Formation Model Inputs

Input Parameter	Probability Distribution Function
Formation thickness	Log-normal
CO_2 viscosity	Normal
Porosity	Discrete PMF
Permeability	Discrete PDF
Formation compressibility	Uniform
CO_2 density	Triangular
Initial formation pressure	Triangular
CO_2 saturation fraction	Uniform

Banff Properties

The input parameters to define the properties of the Banff formation are contained in a separate dashboard that is accessed by clicking on the "Banff Properties" button on the Main dashboard. The Banff formation properties dashboard is shown in Figure 12. Table 3 shows the parameters and the associated probability distribution types assumed in the model. Changes to the model are made by entering the distribution parameters in the dashboard (e.g., mean and standard deviation for a normal distribution). The probability distribution functions for the Banff formation porosity is a discrete distribution based on the empirical data from the Nisku formation (Eisenger, 2009). The discrete data is fixed, i.e., it cannot be changed by the user. The user returns to the Main dashboard by clicking on the button at the bottom of the screen.

Figure 12: Banff Formation Properties Dashboard

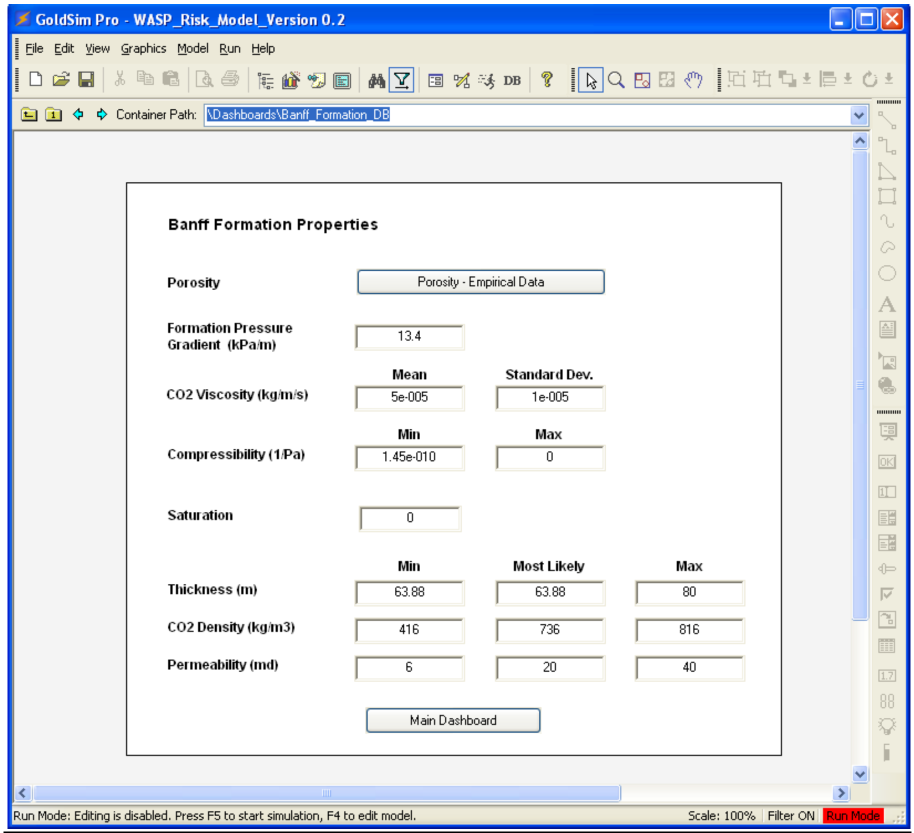


Table 3: Parameters and Distribution Types for the Banff Formation Model Inputs

Input Parameter	Probability Distribution Function
Formation thickness	Log-normal
CO_2 viscosity	Normal
Porosity	Discrete PMF
Permeability	Discrete PDF
Formation compressibility	Uniform
CO_2 density	Triangular
Initial formation pressure	Triangular
CO_2 saturation fraction	Uniform

Nisku Abandoned Well Properties

The input parameters to define the properties of the abandoned well in the Nisku formation are contained in a separate dashboard that is accessed by clicking on the “Nisku Well Prop,” button on the Main dashboard. The abandoned well properties dashboard is shown in Figure 13. Table 4 contains a list of the parameters and the associated probability distribution functions.

Figure 13: Nisku Abandoned Well Properties Dashboard

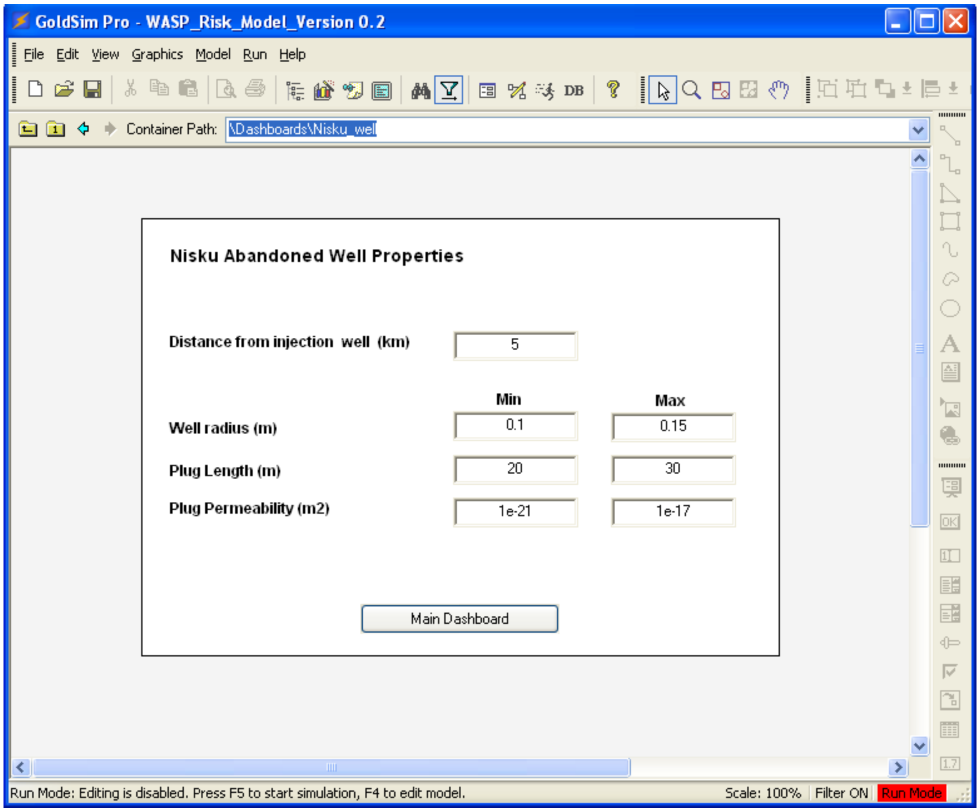


Table 4: Parameters and Distribution Types for the Nisku Abandoned Well

Input Parameter	Probability Distribution Function
Distance from injection well	Deterministic
Well radius	Uniform
Plug length	Uniform
Plug permeability	Uniform

Banff Abandoned Well Properties

The input parameters to define the properties of the abandoned well in the Banff formation are contained in a separate dashboard that is accessed by clicking on the “Banff Well Prop,” button on the Main dashboard. The Banff abandoned well properties dashboard is shown in Figure 14. Table 5 contains a list of the parameters and the associated probability distribution functions.

Figure 14: Banff Abandoned Well Properties Dashboard

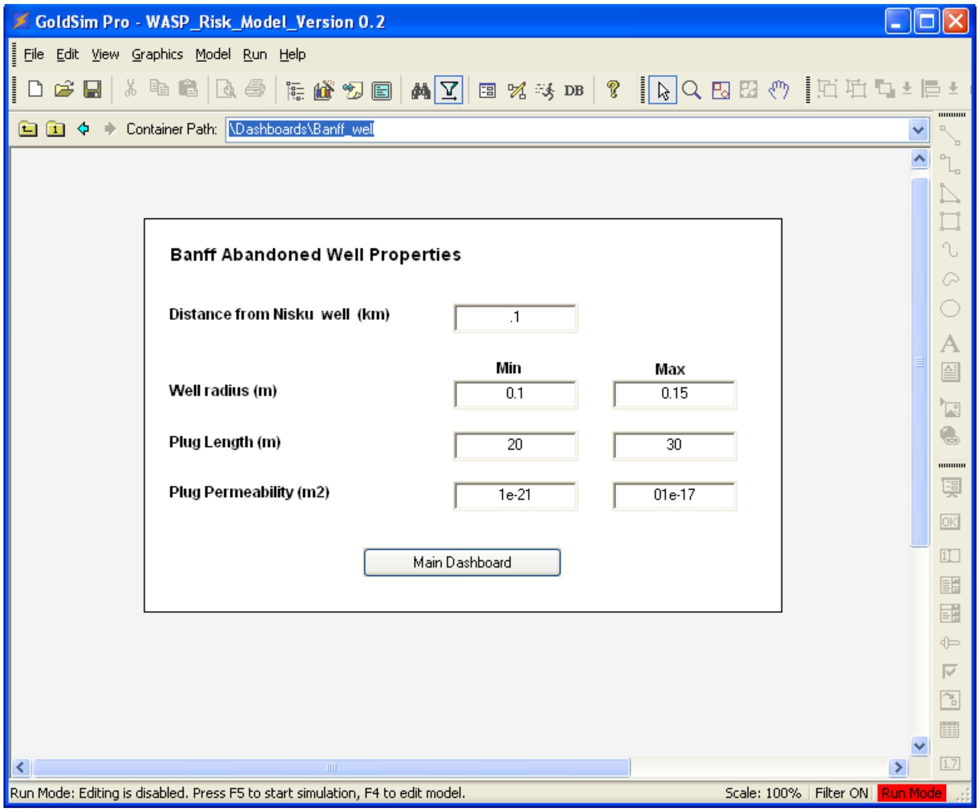


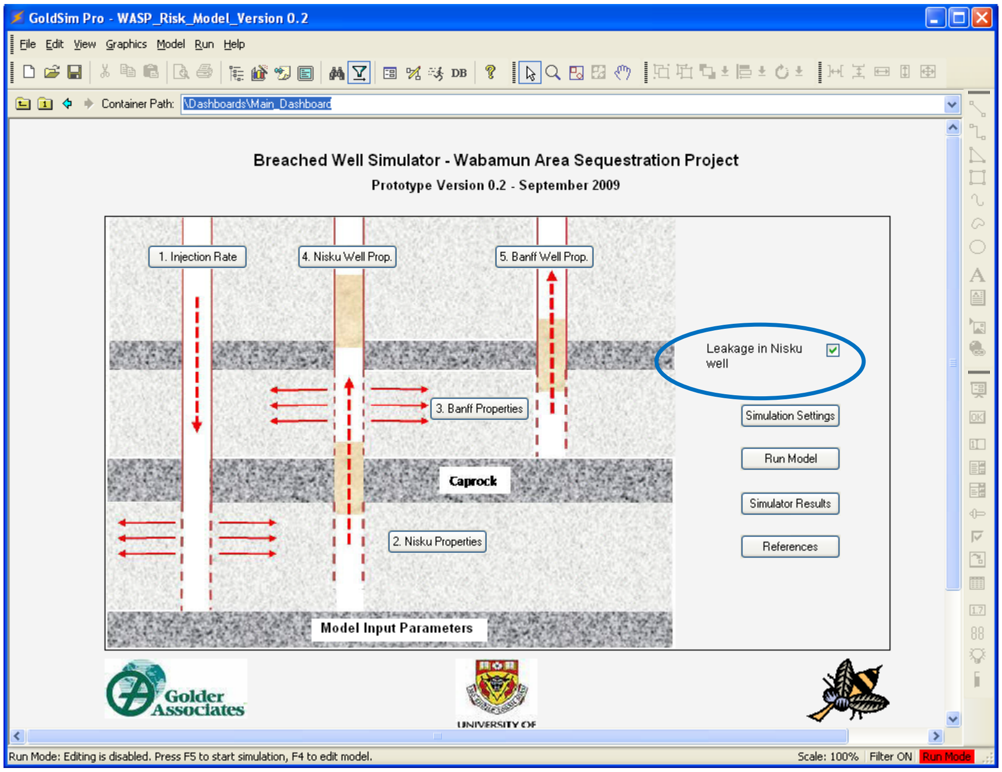
Table 5: Parameters and Distribution Types for the Banff Abandoned Well

Input Parameter	Probability Distribution Function
Distance from Nisku well	Deterministic
Well radius	Uniform
Plug length	Uniform
Plug permeability	Uniform

Abandoned Well Scenario Selection

The simulator includes two abandoned well scenarios as described in Section 2. The leakage scenario shown in Figure 1 through a single well in the Nisku formation is selected by placing a check mark in the check box to the right in the Main dashboard (Figure 15). The leakage scenario shown in Figure 2 from the Nisku, through the Nisku abandoned well into the Banff formation and then through the Banff abandoned well is selected by clearing the check box.

Figure 15: Check Box for Well Leakage Scenario Selection



Simulation Settings

The Simulation Settings button on the Main dashboard is used to set the duration of the simulation, the number of time-steps (and, therefore, the time step length), and the number of Monte Carlo realizations to run. The dialog box for the simulation settings is shown in Figure 16 (note: “Time” tab at top of box must be selected). CO_2 injection is assumed to take place over the entire duration of the simulation. Therefore the total injected mass of CO_2 is equal to the duration entered and the injection rate entered in a separate dashboard in the model. The timestep interval is determined by the number of time steps entered in the lower section of the dialog box. For example, a value of 50 time steps and a duration of 50 years results in a one-year time step intervals in the simulation. A value of 600 would result in a one-month time step.

Clicking on the “Monte Carlo” tab at the top of the dialog box produces the dialog box shown in Figure 17. The number of iterations or individual model simulations that are performed for a Monte Carlo analysis is selected using the input field at the top of the dialog box. A deterministic run (a single realization) can be selected by clicking on the radio button in the lower field of the dialog box (Figure 17).

Figure 16: Dialog Box for Simuation Duration and Number of Time Steps

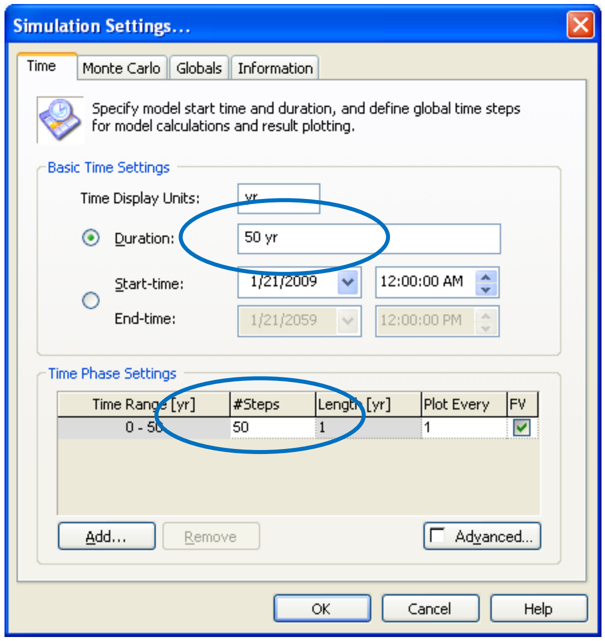
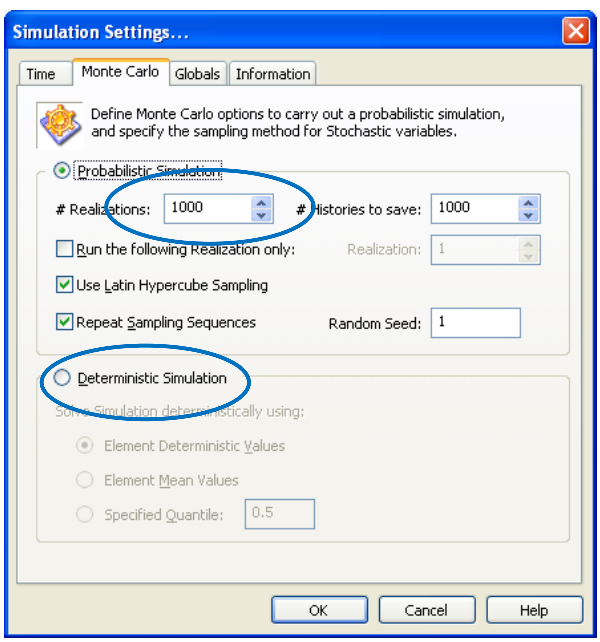


Figure 17: Dialog Box for Setting Number of Monte Carlo Realizations



Simulation Results

Simulation results can be viewed by clicking on the Simulation Results button on the Main dashboard. The Results dashboard is shown in Figure 18. Table 6 contains a description of each of the model outputs that can accessed from the dashboard.

Figure 18: Results Dashboard

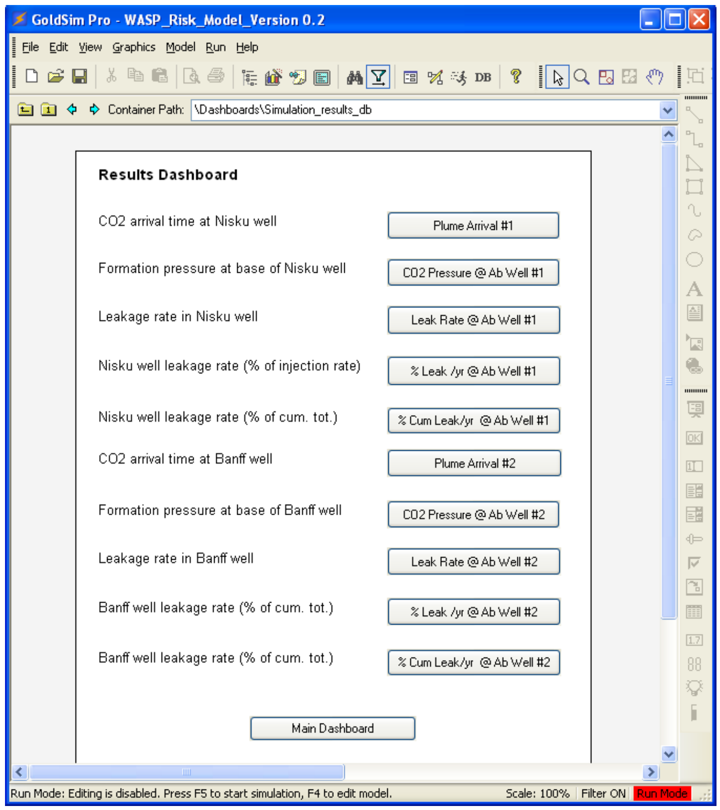


Table 6: Description of Model Outputs

Model Output	Description
Plume Arrival #1	PDF of CO_2 plume arrival at base of Nisku abandoned well
CO_2 Pressure @ Ab Well #1	PDF of formation pressure at base of Nisku abandoned well in MPa
Leak Rate @ Ab Well #1	PDF of leakage rate from Nisku abandoned well to surface in m^3/yr
% Leak/yr @ Ab Well #1	PDF of leakage rate from Nisku abandoned well to surface as a percentage of annual CO_2 volume injected
% Cum Leak/yr @ Ab Well #1	PDF of leakage rate from Nisku abandoned well to surface as a percentage of total volume injected to date
Plume Arrival #2	PDF of CO_2 plume arrival at base of Banff abandoned well in years
CO_2 Pressure @ Ab Well #2	PDF of formation pressure at base of Banff abandoned well in MPa
Leak Rate @ Ab Well #2	Leakage rate of CO_2 from the Banff abandoned well to the surface in units of m^3/yr
% Leak/yr @ Ab Well #2	Leakage rate of CO_2 from the Banff abandoned well to the surface as a percentage of the injection rate
% Cum Leak/yr @ Ab Well #2	Leakage rate of CO_2 from the Banff abandoned well to the surface as a percentage of total CO_2 volume stored

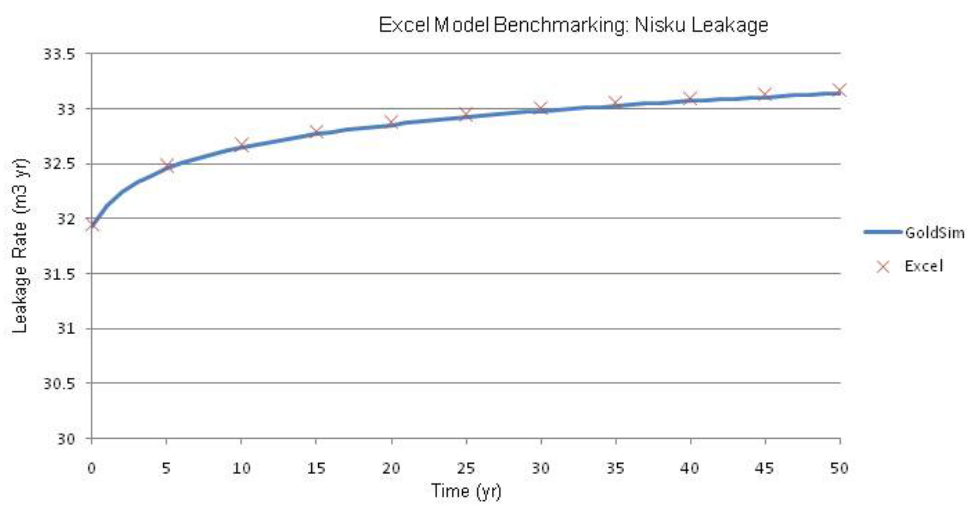
4.0 BENCHMARKING

The WASP leakage simulator was benchmarked against independent calculations that were performed by repeating the main analytical calculations in an Excel spreadsheet developed by Golder and also a spreadsheet developed by Lavoie (2009) for the plume migration calculations. A more rigorous benchmarking of the leakage model against a numerical simulator such as TOUGH2 (2009) is required to test the validity of the assumptions and the accuracy of the mathematical development. This is one of the major follow on tasks recommended in the Section 7.

4.1 CO_2 Leakage – Abandoned Nisku Well

Figure 19 shows leakage rate outputs from the Simulator and Excel models for the abandoned well in the Nisku in m^3/yr. The input parameters for the two different methods are the expected values in Table 2 with the two well plug permeabilities equal to $10^{-15}\ m^2$. Close agreement is observed for the two different models.

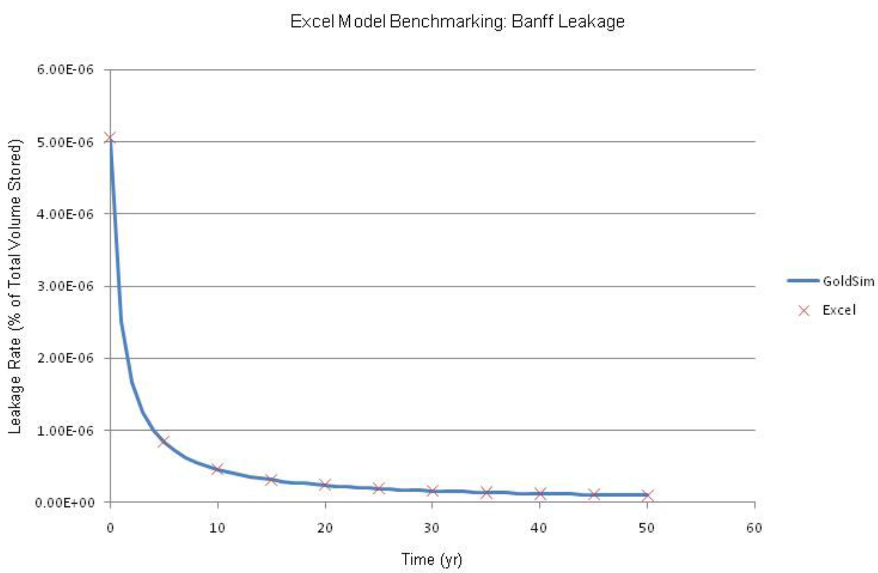
Figure 19: Transient Leakage Flux Curve in m3/s for Abandoned Well in Nisku



4.2 CO_2 Leakage – Abandoned Banff Well

Figure 20 shows leakage rate outputs from the GoldSim model and Excel model for the abandoned well in the Banff as a percentage of total volume stored. The input parameters are the deterministic parameters from Table 2 with the two well plug permeabilities equal to $10^{-15}\ m^2$. The results from the two different models are essentially the same.

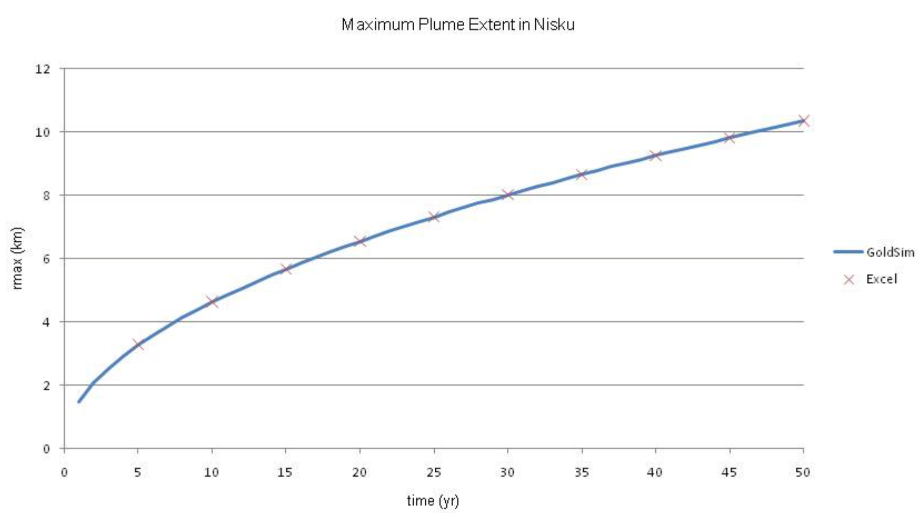
Figure 20: Transient Leakage Flux Curve as a % of Injection Rate for Abandoned Well in Banff



4.3 Plume Migration – Nisku Formation

Figure 21 shows the maximum extent of the plume for the GoldSim model and Excel model for S_{res}=0.384. The input parameters are the deterministic parameters from Table 2. The results from the two different models are almost identical.

Figure 21: Maximum CO_2 Plume Radius for the Nisku for Sres=0.3



5.0 WASP SPECIFIC DATA

This section summarizes the site specific input data for the WASP High Grade Study Area. Deterministic values were used for all input parameters during model development and testing. Probabilistic values were implemented in the simulator for the sensitivity analyses discussed in Section 6.

5.1 Probabilistic Inputs

Many of the input parameters in the model are uncertain due to limited site data, natural variability and the difficulty in characterizing hydrogeological systems. These uncertain quantities are represented in the model by probability distribution functions and are propagated in the calculations of leakage flux through the abandoned wells and plume radii using the Monte Carlo method. Parameters describing the formation characteristics were supplied by the WASP team (Eisinger, 2009) and are summarized in Table 7.

The uncertainty in the permeability and porosity of the Nisku formation are represented by discrete distributions based on the WASP Static Model (2008). Permeability is represented by a discrete cumulative distribution function (CDF) which was input directly into the simulator while the formation porosity is represented by a discrete probability mass function (PMF). The permeability, porosity and thickness distributions for the Banff formation were assumed to be the same as the Nisku.

The uncertainty in the initial pressure in the Nisku formation is represented by a triangular distribution (Lavoie, 2008). The spread of the distribution is approximately $\pm$ 25% of the mean value. The initial pressure in the Banff is based on the same distribution that is reduced based on an assumed linear relationship between formation pressure and depth (AAPG, 1996).

The uncertainty distribution for the formation compressibility is represented by a uniform distribution. The data on the thickness of the Nisku formation (Eisinger, 2009) was fit to a log normal distribution using an Anderson-Darling fit .

The leaky well parameters for the abandoned well plugs are represented by uniform distributions based on the ranges suggested by Nygaard (2009) for intact and fractured cements and an open hole.

Table 7: Probabilistic Inputs for Nisku and Banff Formation Properties

<table>
<tr><th>Name</th><th>Symbol</th><th>Value</th><th>Expected Value</th><th>Reference</th></tr>
<tr><td>Permeability of Nisku formation</td><td>k_1</td><td>CDF: Discrete<table><tr><td>$P(k_1)$</td><td>$k_1(md)$</td></tr><tr><td>0</td><td>0</td></tr><tr><td>0.05</td><td>0.01</td></tr><tr><td>0.19</td><td>0.1</td></tr><tr><td>0.3</td><td>1</td></tr><tr><td>0.3</td><td>1</td></tr><tr><td>0.59</td><td>10</td></tr><tr><td>0.81</td><td>100</td></tr><tr><td>0.975</td><td>1,000</td></tr></table></td><td>1.59×10^5 md</td><td>Eisinger, 2009</td></tr>
<tr><td>Compressibility of CO_2 rock system in Nisku</td><td>c_1</td><td>PDF: Uniform Distribution
$c \sim U(1.45\times10^{-10} - 1.45\times10^{-9})\ (Pa)^{-1}$</td><td>$7.975\times10^{-10}$ (Pa)-1</td><td>Eisinger, 2009</td></tr>
<tr><td>Compressibility of CO_2 rock system in Banff</td><td>c_2</td><td>Assumed to be the same as Nisku</td><td>7.975×10^{-10} (Pa)-1</td><td></td></tr>
</table>

Table 7: Probabilistic Inputs for Nisku and Banff Formation Properties (continued)

<table>
<tr><th>Name</th><th>Symbol</th><th>Value</th><th>Expected Value</th><th>Reference</th></tr>
<tr><td>Thickness of Nisku formation</td><td>b_1</td><td>PDF: Lognormal:
b_1~LN(63.88,8.99) m</td><td>63..88 m</td><td>Eisinger, 2009</td></tr>
<tr><td>Porosity of Nisku Formation</td><td>□</td><td>PMF: Discrete
<table>
<tr><td>p(□)</td><td>□(%)</td><td>p(□)</td><td>□(%)</td></tr>
<tr><td>0.014</td><td>1e-006</td><td>0.004</td><td>0.13</td></tr>
<tr><td>0.146</td><td>0.01</td><td>0.003</td><td>0.14</td></tr>
<tr><td>0.274</td><td>0.02</td><td>0.002</td><td>0.15</td></tr>
<tr><td>0.22</td><td>0.03</td><td>0.002</td><td>0.16</td></tr>
<tr><td>0.114</td><td>0.04</td><td>0.002</td><td>0.17</td></tr>
<tr><td>0.07</td><td>0.05</td><td>0.002</td><td>0.18</td></tr>
<tr><td>0.04</td><td>0.06</td><td>0.002</td><td>0.19</td></tr>
<tr><td>0.038</td><td>0.07</td><td>0.002</td><td>0.2</td></tr>
<tr><td>0.018</td><td>0.08</td><td>0.002</td><td>0.21</td></tr>
<tr><td>0.014</td><td>0.09</td><td>0.002</td><td>0.22</td></tr>
<tr><td>0.011</td><td>0.1</td><td>0.002</td><td>0.23</td></tr>
<tr><td>0.009</td><td>0.11</td><td>0.001</td><td>0.24</td></tr>
<tr><td>0.006</td><td>0.12</td><td></td><td></td></tr>
</table></td><td>0.04</td><td>Eisinger, 2009</td></tr>
<tr><td>Porosity of Banff Formation</td><td>□□</td><td>Assume same as Nisku</td><td>0.04</td><td></td></tr>
<tr><td>Initial pressure in Nisku</td><td>p_1^{init}</td><td>p_1^{init}~tri(12.3, 19.7, 22.6) MPa</td><td>18.2 MPa</td><td>Eisinger, 2009</td></tr>
<tr><td>Initial pressure in Banff</td><td>p_2^{init}</td><td>$p_2^{init} \sim p_1^{init} - 4.08\ MPa.$ ~tri(10,13,16) MPa
Use same as Nisku, except correct for pressure change with decreased depth</td><td>15.2</td><td>(Lavoie, 2008) and (AAPG, 1996)</td></tr>
<tr><td>Permeability of Banff formation</td><td>k_2</td><td>~Assumed same as Nisku.</td><td>18.7 md</td><td></td></tr>
<tr><td>Thickness of Nisku formation</td><td>b_2</td><td>~Assumed same as Nisku</td><td>63.88 m</td><td></td></tr>
<tr><td>CO_2 viscosity in Nisku formation</td><td>c_l</td><td>Kolmogorov-Smirnov fit to WASP measured data
□~N(5×10^{-5}, 1×10^{-5}) Pa·s</td><td>5×10^5 Pa-s</td><td>Data: (Eisinger, 2009)</td></tr>
<tr><td>CO_2 density in Nisku formation</td><td>□</td><td>Kolmogorov-Smirnov fit to WASP measured data
□~tri(416, 736, 816) kg</td><td>565 kg/m^3</td><td>Data: (Eisinger, 2009)</td></tr>
<tr><td>CO_2 viscosity in Banff formation</td><td>□$_2$</td><td>Assume same as Nisku</td><td>5×10^5 Pa-s</td><td>Data: (Eisinger, 2009)</td></tr>
<tr><td>CO_2 density in Banff formation</td><td>□$_2$</td><td>Assume same as Nisku</td><td>5×10^5 Pa-s</td><td>Data: (Eisinger, 2009)</td></tr>
</table>

Table 8: Probabilistic Inputs for Abandoned Wells Parameters

Name	Symbol	Value	Expected Value	Reference
Permeability of well plug in 1st abandoned well between Nisku and surface	k_{1s}	These will depend on well completion state. The following distributions will be used: $k_w \sim U(10^{-21}-10^{-17})\ m^2$: Open Hole $k_w \sim U(10^{-16}-10^{-14})\ m^2$: Fractured cement $k_w \sim U(10^{-12}-10^{-10})\ m^2$: Intact cement	$5{\times}10^{-18} m^2$	Data from Nygaard, 2009
Permeability of well plug in 2nd abandoned well between Banff and surface	k_{2s}		$5{\times}10^{-18} m^2$	
Permeability of well plug in 1st abandoned well between Nisku and Banff	k_{12}		$5{\times}10^{-18} m^2$	
Length of well plug in 1st abandoned well between Nisku and surface	D_{1s}	These will depend on well completion state. The following distributions will be used: $D_w \sim U(0.1\text{-}10)\ m$: Open Hole $D_w \sim U(10\text{-}20)\ m$: Fractured cement $D_w \sim U(20, 30)\ m$: Intact cement		
Length of well plug in 2nd abandoned well between Banff and surface	D_{2s}		*25 m*	
Length of well plug in 1st abandoned well between Nisku and Banff	D_{12}		*25 m*	
Radius of 1st abandoned well between Nisku and surface	r_{1s}	These will depend on well completion state. The following distributions will be used: $r_w \sim U(0.19\text{-}0.22)\ m$: Open Hole $r_w \sim U(0.15\text{-}0.2)\ m$: Fractured cement $r_w \sim U(0.1\text{-}0.15)\ m$: Intact cement		
Radius of 1st abandoned well between Banff and surface	r_{2s}		*0.125 m*	
Radius of 1st abandoned well between Nisku and Banff	r_{12}		*0.125 m*	

6.0 SENSITIVITY ANALYSIS

Sensitivity analysis is used to identify the input parameters which most strongly influence a specific output from the model. The model outputs used to evaluate the simulator sensitivity are the two leakage rates for the abandoned wells penetrating the Nisku and Banff formations and the maximum extent of the CO_2 plume migration. Each sensitivity analysis is a series of simulations in which selected independent variables are varied, one variable at a time, through a range of values while the other values are assigned their expected value. A lower bound, central, and upper bound value are assigned to each independent variable. Simulations are run at the three different values for the first dependent variable while the other independent variables are assigned their central value. The process is repeated for each independent variable. The central, lower and upper bound values in the sensitivity analysis are based on the 50^{th}, 5^{th} and 95^{th} percentile values respectively from the probability distribution functions in Tables 2 and 3 in Section 5.

The results of a sensitivity analysis can be illustrated using a Tornado diagram, a graphical representation of the degree to which a model output is sensitive to the specified independent variables. The x-axis of a Tornado chart represents the values of the result for different values of the independent variables. Each bar represents the range of result values produced when each independent variable is set to lower bound, central, and upper bound values (with the other variables being held constant). A light blue bar indicates that the value was produced by the lower bound value (Low), and a dark blue bar indicates that the value was produced by the upper bound value (High). The variables are organized from top to bottom according to the total range of results produced. That is, the variable that produces the largest range of the result between the lower and upper bound values is at the top of the chart. Hence, bars become smaller toward the bottom of the chart, and the overall effect is to take on the appearance of a “tornado”. The solid vertical line represents the value of the result when the central values are used for all independent variables. Figure 25 in the next section is an example of a Tornado chart.

The X-Y function chart is another type of sensitivity analysis that provides a graphical representation of the degree to which the result is sensitive to the specified independent variables. Similar to the method used for the Tornado plots, a series of deterministic simulations are performed, varying one independent variable at a time through its range of values. In addition to the lower bound, central and upper bound values, simulations are performed at other intermediate values. The charts in the figures include 11 points or values. There is one line for each variable. Each line illustrates how the result changes when that independent variable is varied from its lower bound to its upper bound (with the other variables being held constant). Because the variables sometimes have different units and a different range, the x-axis does not represent actual values; rather it represents normalized values (and hence they all range from 0 to 1). Figure 22 in Section 6.1 is an example of an X-Y function chart.

The results from the sensitivity analyses for the four outputs are described below.

6.1 Leakage in Nisku Abandoned Well

The parameters identified as potentially having a strong influence on the leakage in the Nisku abandoned well are:

- plug permeability in the abandoned well;
- plug length;
- abandoned well radius;
- density of CO_2 in the Nisku formation;
- CO_2 viscosity in the Nisku;

- permeability of the Nisku formation;
- initial pressure in the Nisku; and
- Nisku thickness.

The results of the sensitivity analyses for the leakage through an abandoned well in the Nisku formation are shown in Figures 22 and 23. The parameter with the strongest influence on well leakage is plug permeability with a linear relationship between permeability and the leakage rate. The CO_2 viscosity and abandoned well radius are the next to parameters with the greatest influence on the leakage rate. The CO_2 viscosity relationship is nonlinear at the lower range of the distribution included in the sensitivity analysis. The sensitivity of well leakage to CO_2 density, formation pressure and plug length are similar with a slightly nonlinear relationship for all three parameters. The leakage rate is largely insensitive to the permeability and thickness of the Nisku formation.

Figure 22: Tornado Plot of the Sensitivity Analysis Results for Leakage Through Abandoned Nisku Well

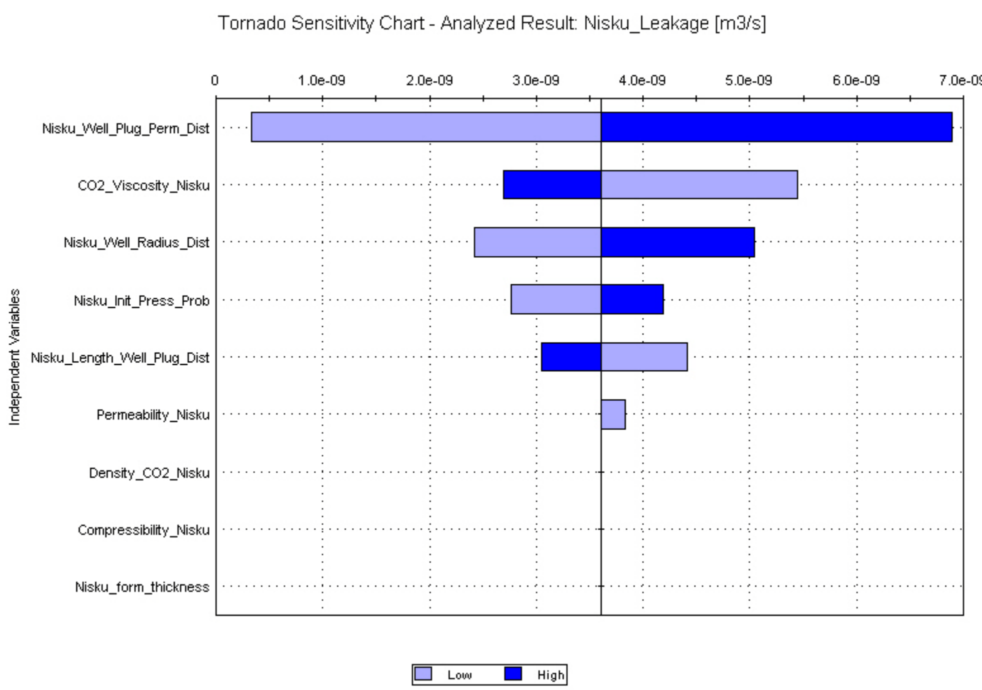
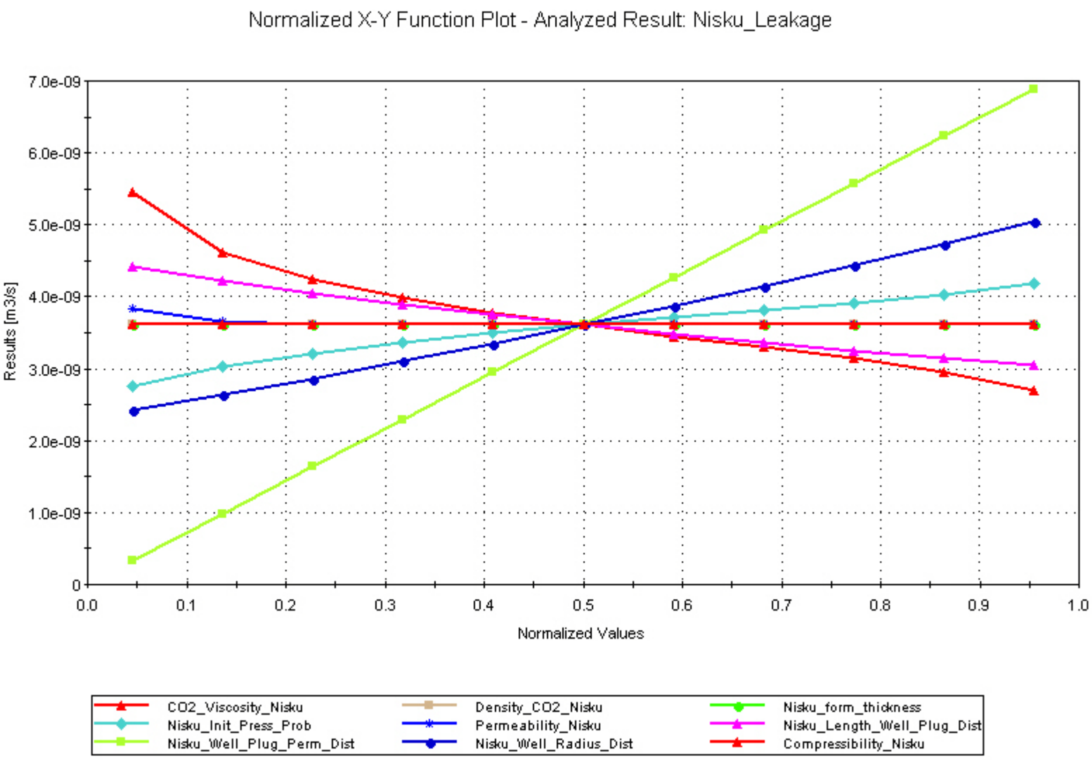


Figure 23: X-Y Function Chart of Sensitivity Results for Leakage through Abandoned Nisku Well



6.2 Leakage in Banff Abandoned Well

The parameters identified as potentially having a strong influence on the leakage in the Banff abandoned well are:

- the abandoned well parameters associated with leakage through the plug between the Banff and the surface;
- the Banff formation hydrogeological parameters;
- the abandoned well parameters associated with leakage through the conduit plug between the Nisku and Banff formations; and
- the Nisku formation hydrogeological parameters.

The results of the sensitivity analyses for the leakage through an abandoned well in the Banff formation are shown in Figures 24 and 25. The results are similar to the leakage in the Nisku abandoned well (Section 6.1). The parameter with the strongest influence on well leakage is plug permeability with a linear relationship between permeability and the leakage rate. The CO_2 viscosity and abandoned well radius are the next to parameters with the greatest influence on the leakage rate. The CO_2 viscosity relationship is nonlinear at the lower range of the distribution included in the sensitivity analysis. The sensitivity of well leakage to CO_2 density, formation pressure and plug length are similar with a slightly nonlinear relationship for all three parameters. The leakage rate is largely insensitive to the permeability and thickness of the Nisku formation.

Figure 24: Tornado Plot of the Sensitivity Analysis Results for Leakage Through Abandoned Banff Well

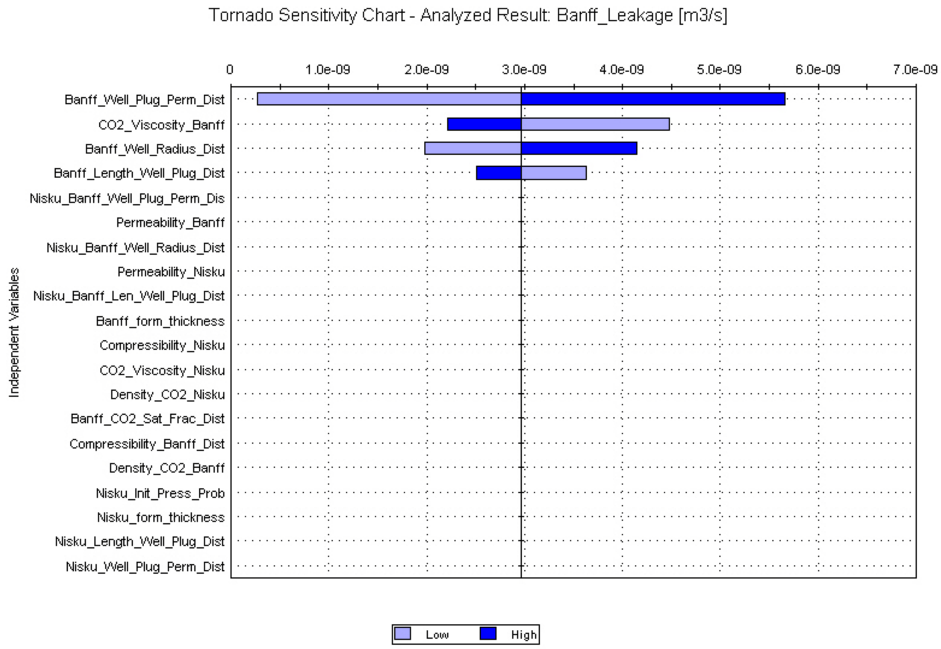
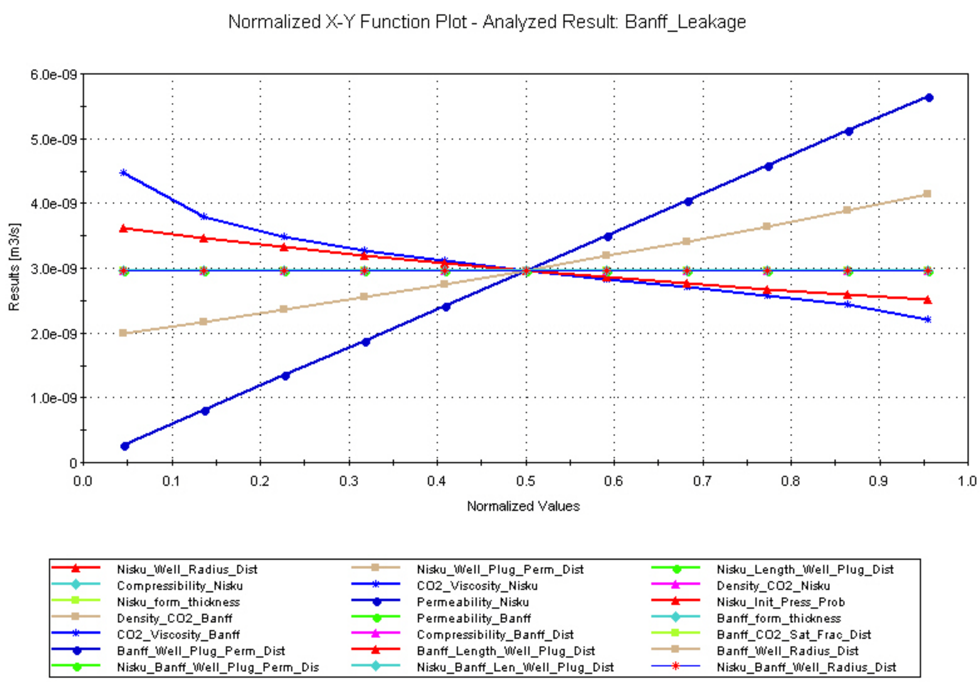


Figure 25: X-Y Function Chart of Sensitivity Results for Leakage through Abandoned Banff Well



6.3 CO_2 Plume Migration in the Nisku

The parameters identified as potentially having a strong influence on the maximum radial extent of the plume and plume arrival time in the Nisku abandoned well are:

- the saturation fraction of CO_2 in the Nisku;
- the porosity of the Nisku; and
- the CO_2 density in the Nisku.

The results of the sensitivity analyses for the leakage through an abandoned well in the Banff formation are shown in Figures 26 and 27. The parameter with the strongest influence on plume radius is the CO_2 saturation ratio with a highly nonlinear relationship between the ratio and plume radius. The Nisku porosity is the next parameter with the greatest influence on the plume migration but has a significantly smaller influence than the CO_2 saturation ratio. The sensitivity of the plume radius to CO_2 density is relatively small.

Figure 26: Tornado Plot of the Sensitivity Analysis Results for Plume Migration in the Nisku

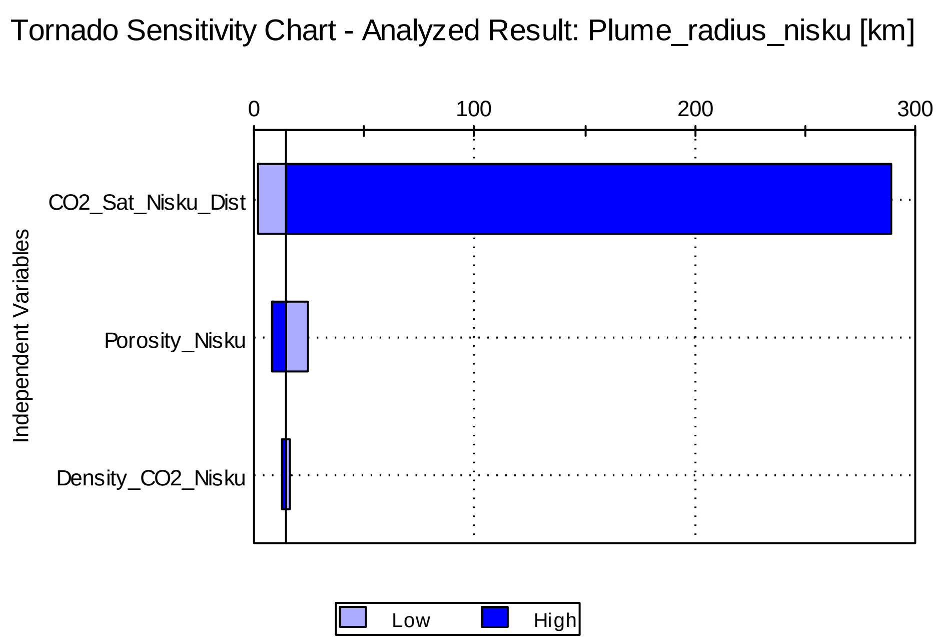
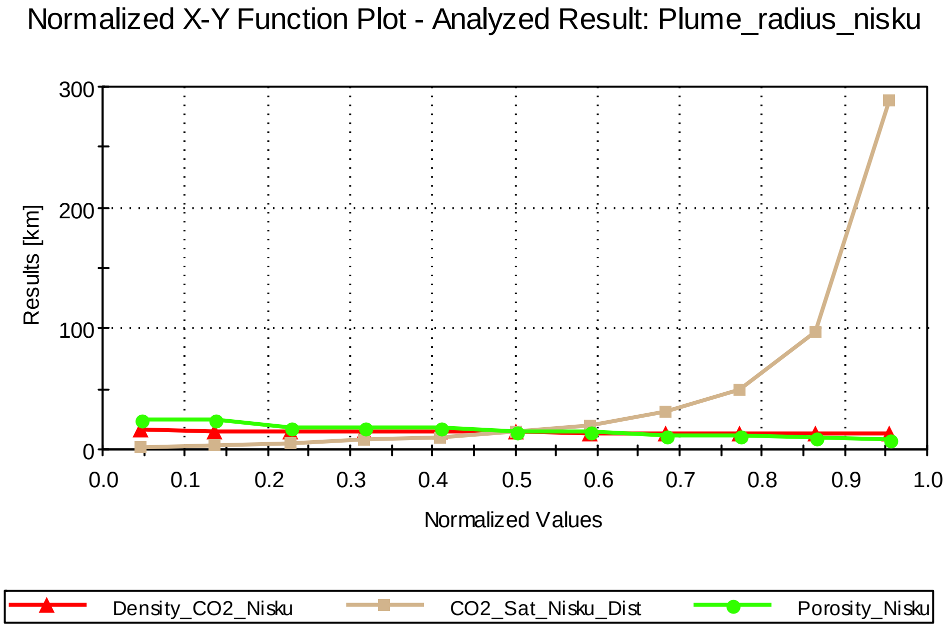


Figure 27: X-Y Function Chart of Sensitivity Results for Leakage Plume Migration in the Nisku



7.0 SUMMARY AND RECOMMENDATIONS

Golder Associates have developed a probabilistic analytical simulator capable of evaluating alternative leakage scenarios associated with legacy wells in multiple formations. The simulator can be used to evaluate the simplest scenario of leakage to the surface via a single abandoned well in the Nisku formation and the more complicated scenario of leakage through a combination of wells in the Nisku and Banff formations. The mathematical models are based to a large extent on the analytical solutions developed by Nordbotten et al., (2004, 2005). The use of analytical expressions in the simulator allows the uncertainty in the input parameters to be explicitly represented and propagated in the model calculations using the Monte Carlo simulation method. The simulator is scalable and can be expanded to represent CO_2 release through additional leakage pathways such as faults, fracture networks and spill points.

The simulator includes a user interface for defining the input parameters and describing different release scenarios (i.e., 'what if' analysis) that are fundamental in CO_2 sequestration risk analysis and useful for developing a diagnostic understanding of the different leakage scenarios. The interface contains a number of predefined model outputs including time histories of formation pressure, CO_2 plume migration within the injection formation, and CO_2 flux rates through the abandoned wells. The preliminary set of input parameters in the simulator that describe Nisku and Banff formation properties and the characteristics of the potential leakage pathways up the abandoned wells were developed by members of the WASP research team.

The reference input parameters were used to perform sensitivity analyses to identify those that most strongly influence the projected CO_2 plume migration and potential leakage through abandoned wells. The results from the sensitivity analysis can be used to prioritize site characterization data needs for reducing the overall uncertainty in the performance of a potential CCS site.

The conceptual model that forms the basis for the simulator can be expanded to include other potential pathways (e.g., faults and spill points) and multiphase flow. These features can be accommodated by adding additional modules to the existing model. Prior to further development or using the simulator for guiding site characterization activities, Golder recommends the current version of the simulator be thoroughly tested by the WASP research team in order that any errors or omissions are addressed. Furthermore, while the simulator has been benchmarked against independent calculations, the large number of input parameters and calculations as well as the imbedded logic in the simulator calls for additional testing. For example, the simulator could be more thoroughly benchmarked using an established reservoir simulator such as TOUGH2 (Preuss, 2009). For these reasons, the simulator should be considered a prototype until this testing has taken place and the model has been revised as appropriate.

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APPENDIX A

Conversion from Hydraulic Head to Pressure

The following relationships hold linking hydraulic head h to pressure p , transmissivity T to hydraulic conductivity K, hydraulic conductivity to permeability k and storability S to compressibility c :

$$h = \frac{p}{\rho g} \qquad (A1)$$

$$T = Kb \qquad (A2)$$

$$K = \frac{\rho g}{\mu} k \qquad (A3)$$

$$S = \rho g b c \qquad (A4)$$

Therefore the standard well pumping equation (Nordbotten et al., 2004)

$$h(r,t) - h_{init} = \frac{Q_w}{4\pi T} W(u) \qquad (A5)$$

where $W(u)=E_1(u)$ becomes

$$p(r,t) - p_{init} = \frac{\mu Q_w}{4\pi k b} W(u) \qquad (A6)$$

where

$$u = \frac{c \mu r^2}{4kt} \qquad (A7)$$

and the well pumping function $E_1(u)$ is the exponential integral function:

$$E_1(u) = -\gamma - \ln(u) - \sum_{n=1}^{\infty} \frac{(-1)^n u^n}{n \cdot n!} \qquad (A8)$$

Where γ=0.557 is Euler's constant.

The starting point for the mathematical model of leakage is equation (2) from Nordbotten et al. (2004) which is (A6). This is the pressure equation for single injection into the storage formation (CO_2 reservoir), without leakage outwards:

$$h(r,t) - h_{init} = \frac{Q_w}{4\pi T} W(u) \qquad (A9)$$

here h denotes hydraulic head (as defined in Darcy′s equation for flow in a porous medium)

r denotes the distance between the injection well;

t denotes time since start of injection;

h_{init} is the hydraulic head of the target formation prior to injection; and

Q_w denotes volumetric flow rate (injection rate for an injection well and later, leakage rate for an abandoned well), which is assumed to be constant; and u is given by (A7).

APPENDIX B

Nordbotten et al. Equations for Multiple Wells and Multiple Layers

The Nordbotten et al. equations for M multiple active and *N* abandoned wells, where the abandoned wells penetrate *L* multiple formation layers, are given by equation (7) of (Nordbotten et al., 2004) where the substitutions (A1) to (A3) have been made, the weight of the CO_2 has been included as was the case in (Nordbotten et al., 2005b), and the partial derivative replaced as per the discussion in 2.3 of (Nordbotten et al., 2004). They are a set of L coupled algebraic equations:

$$p_l(r,t) - p_l^{init} = \frac{\mu}{4\pi k_l b_l}\sum_{i=1}^{M} Q_{l,i}\, W(r - r_i, t) + \frac{\mu}{4\pi k_l b_l}\sum_{j=M+1}^{M+N} Q_{l,j}^{+} W(r - r_j, \gamma t)] - \frac{\mu}{4\pi k_l b_l}\sum_{j=M+1}^{M+N} Q_{l,j}^{-} W(r - r_j, \gamma t)]$$

$A(12)$

where

$$Q_{l,j}^{+}(t) = \frac{\pi r_{wj}^2 k_{wj}\left[p_{top} - p_l(r,t)\right]}{\mu D_{wj}} \qquad (A13)$$

is the vertical leakage flux (out) of the l^{th} layer to a top layer above (could be the adjacent layer or the surface),D_{wj} is the length of porous material in the well bore through which leakage can occur, L_{wj} is the distance between the storage formation and the top layer and

$$Q_{l,j}^{-}(t) = \frac{\pi r_{wj}^2 k_w [p_l(r,t) - p_{l-1}(r,t)]}{\mu D_{wj}} \qquad (A14)$$

is the leakage in to the l^{th} layer from the adjacent $(l\text{-}1)^{th}$ layer below and $\gamma=0.92$. Note γ is not the same here as the Euler constant.

For N abandoned wells, the pressure is evaluated at a total of N times at the appropriate radial distance from each abandoned well. This results in NL equations in NL unknowns in block tri-diagonal form which can be solved by standard linear equation solving techniques, as discussed earlier in this document.

APPENDIX C

Leakage Flux for One Injection Well and One Abandoned Well with One Aquifer Penetration

For the case of 1 injection well and 1 abandoned well, we have $M=1$ and $N=1$ which reduces (A12) down to one equation in 1 unknown for evaluating the pressure at the abandoned well location. Note that the second term and third terms in equation (A12) are singular if we evaluate them at the middle of the injection well. Therefore we evaluate the expression with an offset equal to the abandoned well radius $\bar{r}_1=r_1+r_{w1}$ which results in a finite W-value. Since we are interested in leakage from the storage formation through the wellbore directly to the surface only, we have

$$p(\bar{r}_1,t)-p_{init}=\frac{\mu}{4\pi k_1 b_1}Q_0 W[u(\bar{r}_1-r_0,t)]+\frac{k_{1s}r_{w1}^2}{4k_1 b_1 D_{1s}}[p_s-p(\bar{r}_1,t)]\,W[u(\bar{r}_1,\gamma t)] \qquad (A15)$$

where, in general,

$$\bar{r}_1=r_1+r_{w1} \qquad (A16)$$

and D_{1s} Is the vertical length associated with the porous material between the storage formation, L_{1s} is the distance from the storage formation to the surface, ρ is the density of CO_2 in the reservoir, k_{1s} is the permeability of porous material between the storage formation and the surface along the wellbore, and p_s is the pressure at the surface (atmospheric pressure).

Rearranging (A15), and using (6), the following two equations are obtained for estimating surface leakage through a single abandoned well:

$$Q_{1s}(t)=\frac{\pi r_{w1}^2 k_{1s}[p_s-p(\bar{r}_1,t)]}{\mu D_{1s}} \qquad (A17)$$

where

$$p(\bar{r}_1,t)=\frac{p_{init}+\frac{\mu Q_0 W[u(\bar{r}_1,t)]}{4\pi k_1 b_1}+\frac{k_{1s}r_{w1}^2 p_s W[u(r_{w1},\gamma t)]}{4k_1 b_1 D_{1s}}}{\left(1+\left\{\frac{k_{1s}r_{w1}^2 W[u(r_{w1},\gamma t)]}{4k_{1s}k_1 b_1 D_{1s}}\right\}\right)} \qquad (A18)$$

Note that for wells in 'good condition', the cement permeability k_{1s} is low (of the order of 10^{-11} m^2 or less) and the cement plug length is high (larger than 10m), hence the denominator term is close to unity. We can then approximate (A18) with

$$p(\bar{r}_1,t)\simeq p_{init}+\frac{\mu Q_0 W[u(\bar{r}_1,t)]}{4\pi k_1 b_1}+\frac{k_{1s}r_{w1}^2 p_s W[u(r_{w1},\gamma t)]}{4k_1 b_1 D_{1s}} \qquad (A19)$$

APPENDIX D

Leakage Flux for One Injection Well and Two Abandoned Wells with Two Aquifer Penetrations

The starting point for the single injection well and 2 abandoned well penetrations, with 1 penetration in the storage formation, and one penetration in a less deep formation close to the storage formation, is equation (A12). This situation corresponds to a single injection into the Nisku formation and 1 abandoned well penetration in and Nisku formation and a second well penetration in the Banff formation. We assume negligible leakage occurs between the Nisku and the surface.

We evaluate this equation for each layer and at each abandoned each well location, offset by well distance r_{wj} so that the W-values are non-singular. Given that we know the pressure at the surface, we have 3 equations in 3 unknowns.

In the Nisku layer, the pressure at the foot of the first abandoned well is a sum of the initial pressure prior to injection, the pressure flow due injection and the loss of pressure through a pathway in the first abandoned well. The injection pressure can be calculated by applying the Theis equation which accounts for the vertically averaged radial flow in the Nisku formation from the foot of the injection well to the foot of the first abandoned well. The pressure lost through the abandoned well is calculated using the Theis type equation, except with injection replaced by the vertical flux from the Nisku to the Banff layers. Here the well function is evaluated at a distance equal to the well radius which accounts for pressure loss through the cement in the well casing.

Similarly, the pressure in the Banff formation at 1st abandoned well is the sum of the initial formation pressure prior to injection, the pressure gained from leakage through the 1st abandoned well and the pressure lost through leakage through the 2nd abandoned well. The well leakage pressure is computed by multiplying the leakage fluxes by an appropriate well function.

In conceptual terms we have a summation of four different well functions times three vertical fluxes

$$p_1(\bar{r}_1) = p_1^{init} + W_{inj\ well \rightarrow well1}^{rad\ flow} \cdot Q_{inj} + W_{1\rightarrow 2}^{well1} \cdot Q_{1\rightarrow 2}^{vert\ flux}$$

$$p_1(\bar{r}_2) = p_2^{init} - W_{1\rightarrow 2}^{ab\ well1} \cdot Q_{1\rightarrow 2}^{vert\ flux}$$

$$p_2(\bar{r}_2) = p_2^{init} - W_{well1 \rightarrow well2}^{rad\ flow} \cdot Q_{1\rightarrow 2}^{vert\ flux} + W_{2\rightarrow s}^{well} \cdot Q_{2\rightarrow s}^{vert\ flux}$$

Which in our standard mathematical notation becomes:

$$p_1(\bar{r}_1) = p_1^{init} + \frac{\mu Q_0}{4\pi k_1 b_1} W[u_1(\bar{r}_1), t] + \frac{k_{12} r_{12}^2}{4 b_1 k_1 D_{12}} [p_2(\bar{r}_1) - p_1(\bar{r}_1)] \cdot W[u_1(r_{w1}, \gamma t)] \qquad (A19)$$

$$p_2(\bar{r}_1) = p_2^{init} - \frac{k_{12} r_{12}^2}{4 b_2 k_2 D_{12}} [p_2(\bar{r}_1) - p_1(\bar{r}_1)] \cdot W[u_2(r_{w1}, \gamma t)] \qquad (A20)$$

$$p_2(\bar{r}_2) = p_2^{init} - \frac{k_{12} r_{12}^2}{4 b_2 k_2 D_{12}} [p_2(\bar{r}_1) - p_1(\bar{r}_1)] \cdot W[u_2(\bar{r}_2), \gamma t] + \frac{k_{2s}\, r_{2s}^2}{4 b_2 k_2 D_{2s}} [p_s - p_2(\bar{r}_2)] \cdot W[u_2(r_{w2}, \gamma t)] \qquad (A21)$$

where

$$u_i(r, t) = \frac{c \mu_l r^2}{4 k_l t} \qquad (A22)$$

And *l=1* or *2*.

These equations (A19) to (A21) can be arranged into the following matrix equation where the dot (·) denotes matrix multiplication. The matrix formulation will be used in the next section for solving the pressure for *N* wells and *L* layers.

$$\begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{bmatrix} \cdot \begin{bmatrix} p_1(r_1) \\ p_2(r_1) \\ p_2(r_2) \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} \tag{A23}$$

Where the matrix coefficients are given by:

$$a_1 = 1 + \frac{k_{12} r_{12}^2 W[u_1(r_{w1}, \gamma t)]}{4 b_1 k_1 D_{12}} \tag{A24}$$

$$b_1 = -\frac{k_{12} r_{12}^2 W[u_2(r_{w1}, \gamma t)]}{4 b_1 k_1 D_{12}} \tag{A25}$$

$$c_1 = 0 \tag{A26}$$

$$a_2 = -\frac{k_{12} r_{12}^2 W[u_1(r_{w1}, \gamma t)]}{4 b_2 k_2 D_{12}} \tag{A27}$$

$$b_2 = 1 + \frac{k_{12} r_{12}^2 W[u_2(r_{w1}, \gamma t)]}{4 b_2 k_2 D_{12}} \tag{A28}$$

$$c_2 = 0 \tag{A29}$$

$$a_3 = -\frac{k_{12} r_{12}^2 W[u_2(\bar{r}_2), \gamma t)]}{4 b_2 k_1 D_{12}} \tag{A30}$$

$$b_3 = \frac{k_{12} r_{12}^2 W[u_2(\bar{r}_2, \gamma t)]}{4 b_2 k_2 D_{12}} \tag{A31}$$

$$c_3 = 1 + \frac{k_{2s} r_{2s}^2 W[u_2(r_{w2}, \gamma t)]}{4 b_2 k_2 D_{2s}} \tag{A32}$$

And the d-vector elements are:

$$d_1 = p_1^{init} + \frac{\mu Q_0 W[u_1(\bar{r}_1), t)]}{4 \pi k_1 b_1} \tag{A33}$$

$$d_2 = p_2^{init} \tag{A34}$$

$$d_3 = p_2^{init} + \frac{k_{2s} r_{2s}^2 W[u_2(r_{w2}, \gamma t)]}{4 b_2 k_2 D_{2s}} p_s \tag{A35}$$

The matrix equation can easily be solved using Cramer's rule from matrix algebra (Anton, 1984) to give

$$p_1(\bar{r}_1) = \frac{(b_2 d_1 - b_1 d_2)}{(a_1 b_2 - a_2 b_1)} \tag{A36}$$

$$p_2(\bar{r}_1) = \frac{(a_1 d_2 - a_2 d_1)}{(a_1 b_2 - a_2 b_1)} \tag{A37}$$

$$p_2(\bar{r}_2) = \frac{(a_2 b_3 - a_3 b_2) d_1 + (b_1 a_3 - a_1 b_3) d_2 + (a_1 b_2 - a_2 b_1) d_3}{(a_1 b_2 - a_2 b_1) c_3} \tag{A38}$$

for the three pressure terms.

The leakage rate of CO_2 to the surface is given by Darcy's equation through the abandoned well is given by:

$$Q_{2s}(t) = \frac{k_{2s}\pi r_{w2}^2}{\mu D_{2s}}\left[p_s - \frac{(a_2b_3 - a_3b_2)d_1 + (b_1a_3 - a_1b_3)d_2 + (a_1b_2 - a_2b_1)d_3}{(a_1b_2 - a_2b_1)c_3}\right] \quad (A39)$$

and the flux between the two formations through the abandoned well is given by

$$Q_{12}(t) = \frac{\pi r_{12}^2 k_{12}[p_2(\bar{r}_1) - p_1(\bar{r}_1)]}{\mu D_{12}} \quad (A40)$$

which substituting for the two pressure terms becomes

$$Q_{12}(t) = \frac{k_{12}\pi r_{12}^2}{\mu D_{12}}\left[\frac{(a_1 + b_1)d_2 - (a_2 + b_2)d_1}{(a_1b_2 - a_2b_1)}\right] \quad (A41)$$

These equations will be implemented in the simulation model to provide estimates of CO_2 surface through the abandoned wells.

Note that the pressure equations reduce to a simpler form by making some approximations. First the determinant det(A) can be closely approximated by unity when the well plug permeability terms are low (k_{wi}< 10^{11} m^2)

$$\det(A) = (a_1b_2 - a_2b_1)c_3 \simeq 1$$

because the first term resulting from the multiplication of all three diagonal terms (each in turn close to unity) of matrix A dominates the determinant.

Second we note that the terms c_1 and c_2 are identically zero

$$c_1 = c_2 = 0$$

Finally, we note that the diagonal terms of the A-matrix are close to unity for abandoned wells in a state of good completion:

$a_1 \simeq 1$,

$b_2 \simeq 1$ and

$c_3 \simeq 1$

so that

$$p_1(\bar{r}_1) \simeq p_1^{init} + \frac{\mu Q_0}{4\pi k_1 b_1} W[u(\bar{r}_1 - r_0), t] + b_1 d_2 \quad (A42)$$

where the sum of the first two terms are equal to the pressure in the reservoir after injection and the third term accounts for leakage from the reservoir to the surface since it depends on leakage flux from the first to the second formation multiplied by leakage flux from the second formation to the surface. Note that the third term in the equation is negative.

$$p_2(\bar{r}_1) \simeq p_2^{init} - a_2 \quad (A43)$$

and

$$p_2(\bar{r}_2) \simeq p_2^{init} - a_3 d_1 + b_3(p_s - d_1) \quad (A44)$$

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