Black Oil Modelling of CO_2 Sequestration and the impact of Simulation Grid dimensions in the SW Hub Phase 2 Modelling

A Report by ODIN Reservoir Consultants

DMIRS/2018/5

ODIN
Reservoir Consultants

December 2017

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Government of **Western Australia**
Department of **Mines, Industry Regulation and Safety**

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Declaration

ODIN Reservoir Consultants was commissioned to undertake to provide a reservoir modelling study for the SW Hub CO_2 Sequestration Project on behalf of the Department of Mines, Industry Regulation and Safety (DMIRS)

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Neither ODIN Reservoir Consultants nor its employees have any pecuniary interest or other interest in the assets evaluated other than to the extent of the professional fees receivable for the preparation of this report.

Note:

ODIN has conducted the attached independent technical evaluation with the following internationally recognised specialists:

***David Lim** is a member of the Society of Petroleum Engineers (SPE). He has over 30 years of international reservoir engineering experience in Europe, North and South America, North and West Africa, Middle East, Asia and Australasia. David is an internationally recognised reservoir simulation and reservoir engineering expert and has specialist expertise in field development planning, reservoir engineering, reserves reviews and simulation. David has been the Reservoir Simulation and Reservoir Engineering Advisor to NOCs, major and independent operators in Australia and SE Asia. David has also chaired SPE committees and forums on reservoir simulation, well testing and field development planning.*

1. EXECUTIVE SUMMARY

Two issues were raised during the Peer Review of the Phase 1 study in 2016 and further investigations are required:

1. Investigate the feasibility of Black Oil modelling of the SW Hub to establish if a quicker turn-around of reservoir simulation runs could be achieved

2. Investigate the impact of grid dimensions in the lateral direction on CO_2 solubility.

In this study, the compositional model of the Reference Case from Phase 1 of the SW Hub was converted to a Black Oil model. The results from the Black Oil version of the Reference Case model of the SW Hub shows that:

- The results of the Black Oil model are consistent with the compositional model in that the injected CO_2 remains in the Wonnerup reservoir

- The predicted shape and CO_2 plume movement in the Black Oil model are similar to the compositional model. However, the Black Oil model is optimistic as it predicts more CO_2 dissolution in the liquid phase than the compositional model.

The use of a Black Oil model allows reservoir uncertainties and development sensitivities to be evaluated relatively quickly compared to compositional modelling. The Black Oil model is more optimistic than the compositional model and it is recommended that selected cases in the full field modelling study are checked against a fully compositional model.

The results of the grid sensitivity studies show that the dimensions of the grid in the lateral direction have a significant impact on the shape of the plume of injected gas but the solubility of the gas in the liquid phase varies only by about 10% between the models. It is concluded that the solubility of the injected gas can be reasonably calculated using the coarse scale model with cell dimensions of 250x250 metres. A finer grid size, 100x100 metres or 50x50 metres could be used if it is important to have an understanding of the shape of the injected gas plume.

2. INTRODUCTION

Dynamic Modelling or Simulation is a key step within the modelling workflow (Figure 2.1) which is the study of fluid flow within the Static 3D Geological Model. The results are analysed and compared to expected reality. The findings of the simulation study may be fed back into building another version of the 3D geological model to either refine the results or assist with defining the uncertainties/sensitivities of the reservoir.

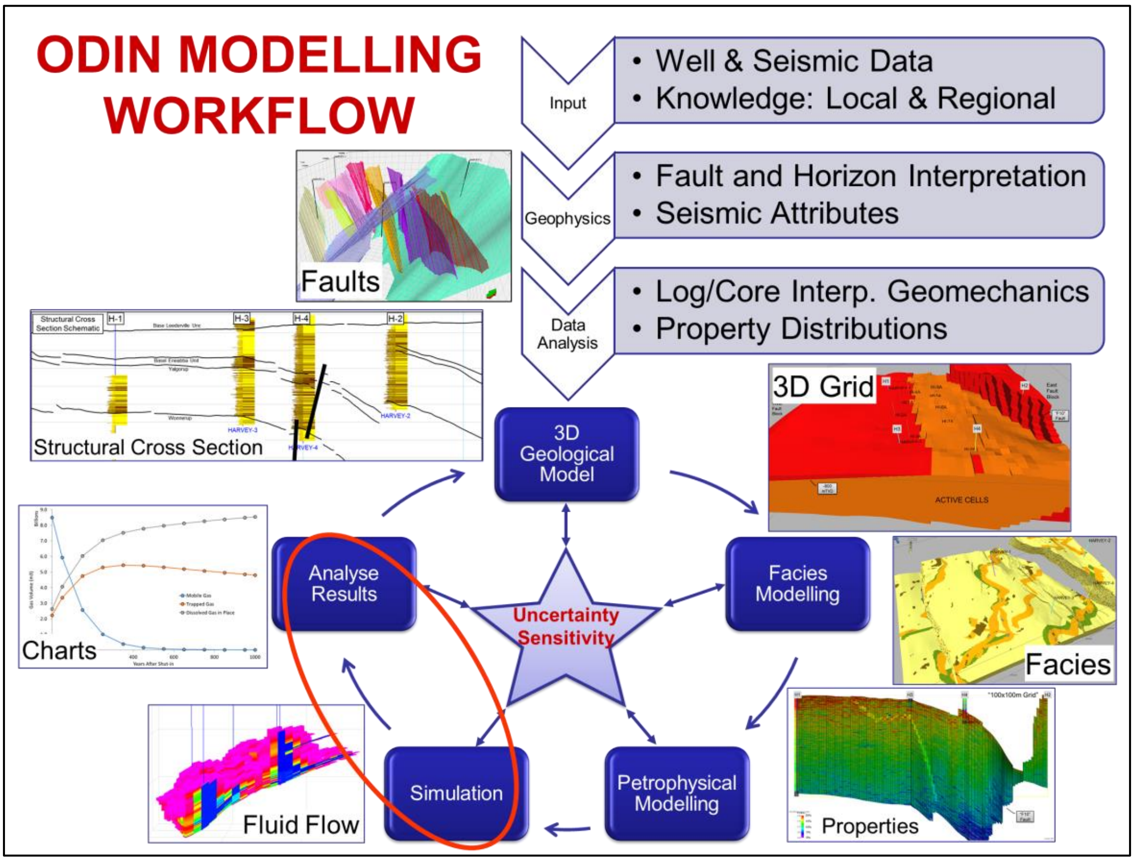

Figure 2.1: ODIN Modelling Workflow

In the 2016 phase of the SW Hub studies, CO_2 sequestration was modelled using the compositional simulator, GEM™ from CMG (Reference 1).

In the 2016 study (Reference 1), detailed grid sensitivity studies were conducted to demonstrate whether the static model of the Wonnerup reservoir could be upscaled for dynamic modelling from a vertical resolution of 1 metre to 4 metres. To make the model practical for studies, upscaling was also applied in lateral direction (i.e. I- and J-directions) to increase the dimensions of the cells from 25x25 metres to 250x250 metres. This reduced the model to a practical size of about 2 million cells (Reference 1). No dynamic models were run to test if the upscaling in the I- and J-directions was appropriate. Despite the significant reduction in grid cells in the dynamic model, a single run of the model using parallel processing and 8 CPU cores could take 72 to 160 hours of CPU time on an Intel Xeon workstation.

During the Peer Review of Phase 1 of the SW Hub studies, the long turn-around time for simulation studies was identified as an area which could limit the number of subsurface and development sensitivities that could be evaluated. In addition to the concerns with the time of turn-around for simulation runs, it was commented that the gas solubility could be overestimated as the Reference Case model had cell sizes of 250x250 in the I- and J-directions.

Two issues were raised during the Peer Review of the Phase 1 study:

1. Investigate the feasibility of Black Oil modelling of the SW Hub to establish if a quicker turn-around of reservoir simulation runs could be achieved.
2. Investigate the impact of grid dimensions in the lateral direction on CO_2 solubility.

3. CONVERSION OF COMPOSITIONAL TO BLACK OIL

For this study, the Black Oil version of the reservoir simulation package from Schlumberger, Eclipse™, was selected. Direct conversion of the compositional model to black oil was possible for the following items:

- Model rock properties.
- Grid geometry and dimensions.
- Imbibition and drainage relative permeability.
- Well production and injection constraints.

Items which are specific to compositional modelling could not be converted directly:

- Temperature gradient (black oil models are isothermal).
- CO_2 and water properties - these are calculated by equations of state.

3.1 Modelling Temperature

Black oil models are isothermal and reservoir temperature is not required. Fluid properties are calculated at a single temperature and input as a table. The PVT data for the Black Oil model of the Reference Case was calculated at 55°C, which is the reservoir temperature at a depth of about 1600mTVDss. This depth is the mid-point of the Pore Volume of the model (i.e. 50% of the pore volume of the model is shallower than 1600 mTVDss and 50% is deeper).

3.2 CO_2 and Water Properties

In Black Oil simulation of CO_2 sequestration in aquifers the oil is assigned the properties of the water phase and gas are assigned the properties of CO_2. The input to the Black Oil model was generated using software created by CSIRO (Reference). In Eclipse, the properties of the brine and CO_2 are represented by live oil tables (Figure 3-1) and dry gas (Figure 3-2). The solubility of CO_2 in the 44,600ppm brine was represented by the solution gas ratio as a function of pressure.

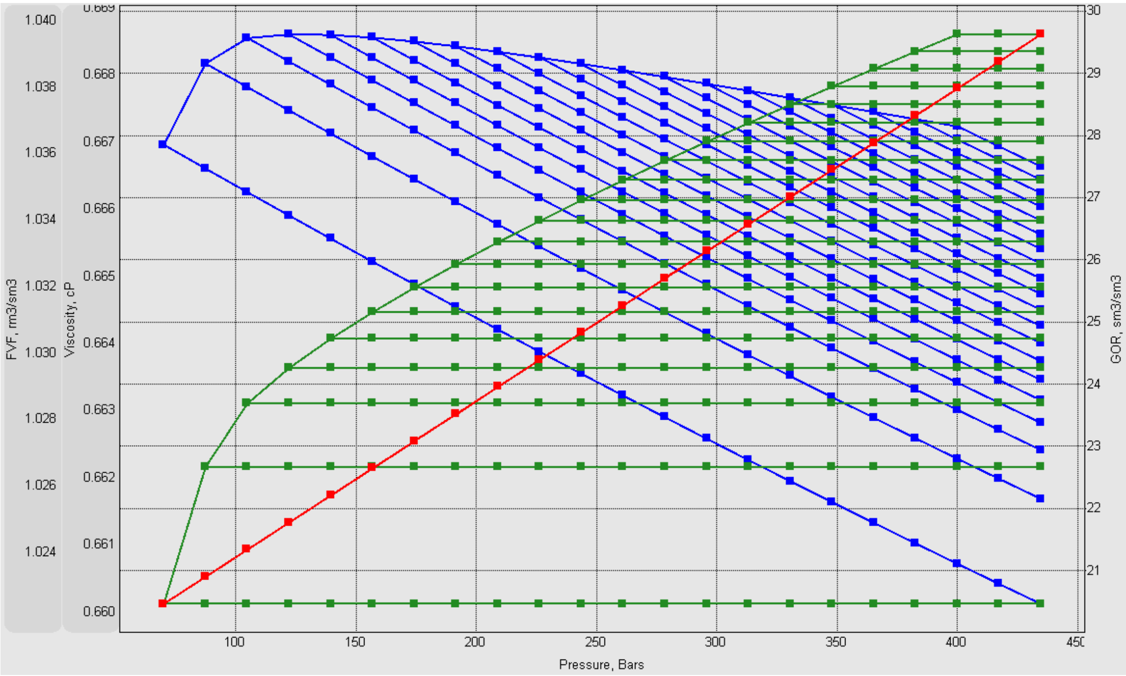

Figure 3-1 PVT Properties – Oil (PVTO)

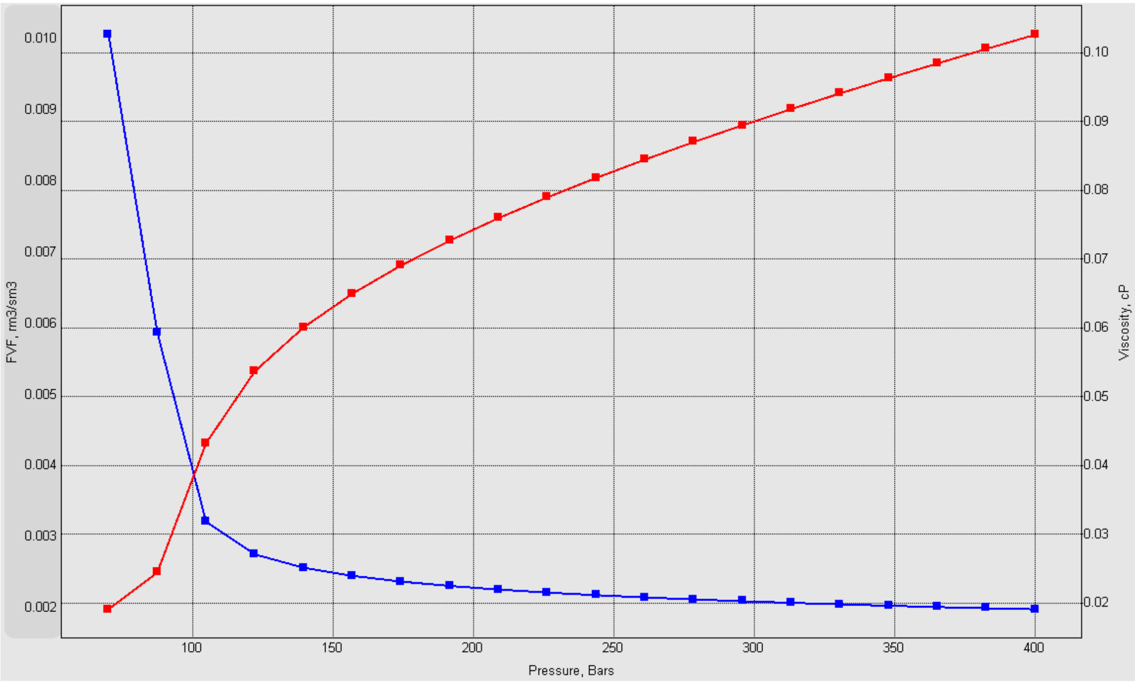

Figure 3-2 Dry Gas PVT Properties (PVTG)

4. MODEL DESCRIPTION

The details of the compositional model used in the Phase 1 of the SW Hub studies are documented in Reference 1. A brief description of the model is presented below.

4.1 Grid Dimensions

The model was constructed with grid blocks of 250x250 metres in the I- and J-directions with the resolution of the layers in the Yalgorup retained at the geological model scale of 1 metre. In the Wonnerup, the 4 metre layers were used (Figure 4-1). To further reduce the number of cells in the full field model, all cells with a depth shallower than 800m TVDss was made void. Migration of CO_2 shallower than 800mTVDss is considered a breach of containment as the CO_2 changes from a supercritical state to a gaseous state at depths shallower than 800mTVDss.

The dimensions of the model are summarised below:

- 51 cells in the I-direction
- 37 cells in the J-direction
- 1050 cells in the K-direction
- Total number of cells = 1, 981, 350
- Number of active cells = 1, 024, 382
- Cell sizes of 250mx250m x 1m in the Yalgorup
- Cell sizes of 250mx250m x 4m in the Wonnerup
- The Yalgorup is modelled in Layers 1 to 700
- The Wonnerup is modelled in Layers 701-1050

4.2 Initialisation Parameters

The full field model was initialised with the following parameters:

- Initial Pressure
  - Initial pressure based on the RCI data from GSWA Harvey 1.
  - Reference pressure of 19,327kpa at 1900m.
- The model was initialised as completely oil saturated with the initial solution gas-oil ratio, Rsi, set to zero.

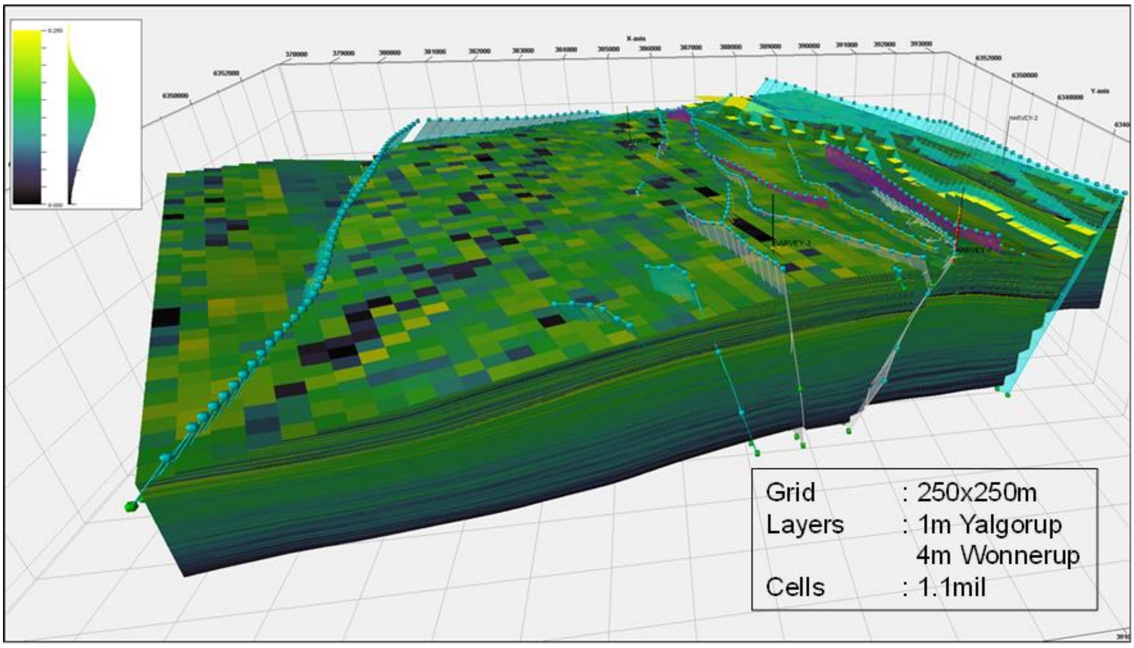

Figure 4-1 Model Showing Porosity Distribution

4.3 Aquifer Extent

The full field model of the Harvey area by no means captures the full extent of the Wonnerup and Yalgorup aquifers. Figure 4-2 shows that the Yalgorup and Wonnerup (Reference 2) are unconstrained at least 50km to the north and 25km to the south of the area of interest. To model the likely extent of the aquifer the pore volume of the columns at the end of the model were increased (Figure 4-3) using multipliers.

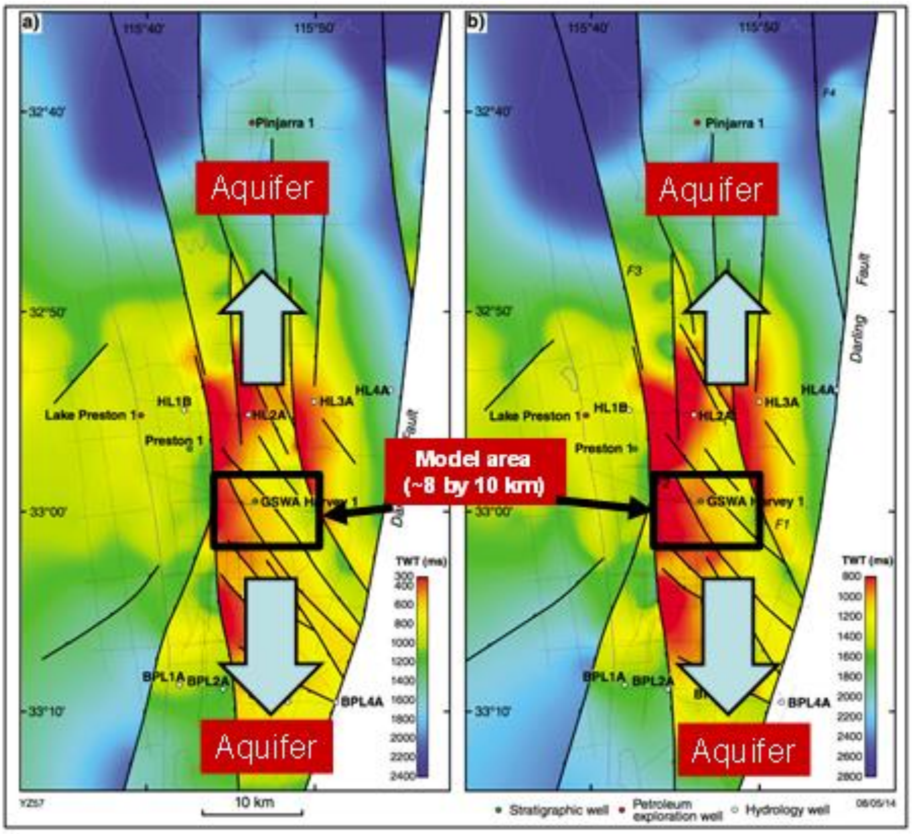

Figure 4-2 Time Structure maps of the: a) top Yalgorup Member; b) top Wonnerup Member (After Reference 2)

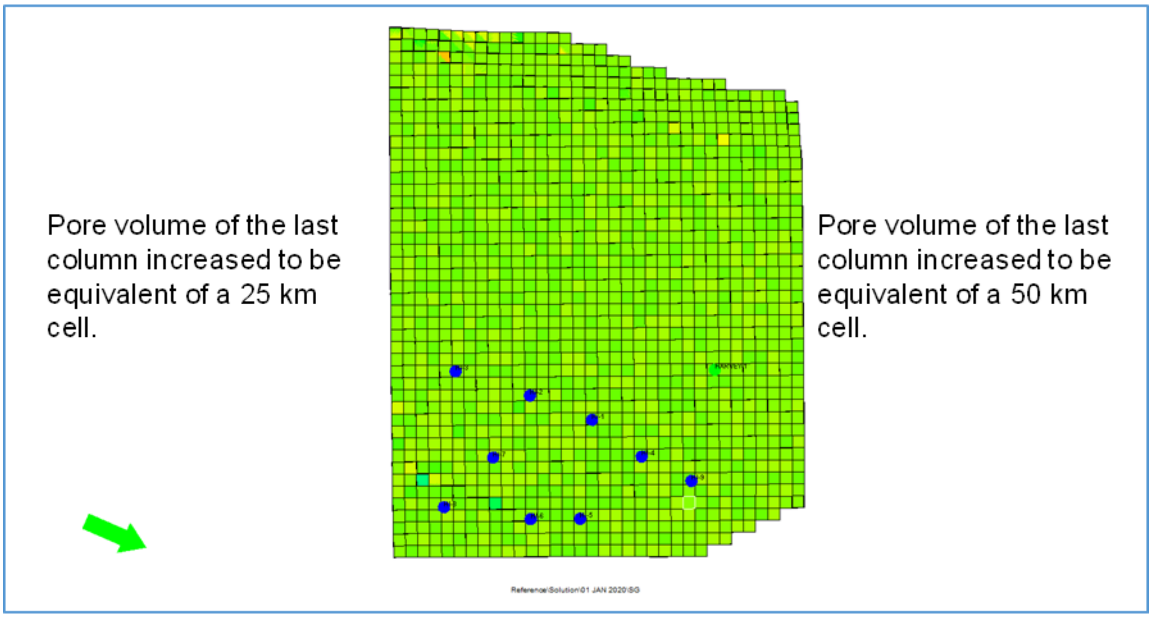

Figure 4-3 Modelling the Extent of the Wonnerup and Yalgorup Aquifers

5. REFERENCE CASE DEFINITION

The conceptual development plan for the Harvey area envisages injection of 800,000 tonnes of CO_2 per year for 30 years. At the end of the 30 year injection period, the wells are shut-in and the CO_2 is allowed to dissipate through the aquifer. In this work, it was assumed that 9 wells laid out in a staggered line-drive configuration would be used to inject CO_2 into the Wonnerup reservoir (Figure 5-1). All of the wells are completed in the bottom 250 metres of the Wonnerup.

The Reference Case for the study is defined as follows:

- Reservoir
  - All faults are assumed to be not sealing
  - Wonnerup and Yalgorup are assumed to be in communication
- Model built in Eclipse™ Black Oil format
- PVT Properties
  - Oil properties calculated using a salinity of 46 g/L H_2O
  - Temperature of 55°C.
- Rock-Fluid
  - Hysteresis of the gas phase is assumed
  - Trapped gas saturation, Sg_T = 0.19
  - No hysteresis of the water phase
- Injection
  - Dry gas ("CO_2") is injected at rate of 1.2 million m^3/day
  - Injection begins on an arbitrary date of 1/1/2020 and ends on 10/1/2050
  - Bottom hole pressure constraint = 360 bars (pore pressure + 35 bars) based on mid-point injection depth of 3250 mTVDss.]
- In the simulation model, relative permeability curves were generated using the following Corey exponents and end points:
  - Nw= 4.0
  - Ng= 4.5
  - Krw @ (Sw=1) = 0.37
  - Krg @ (Swmin=0.49) = 0.12
  - Carlson's Hysteresis Model chosen as default

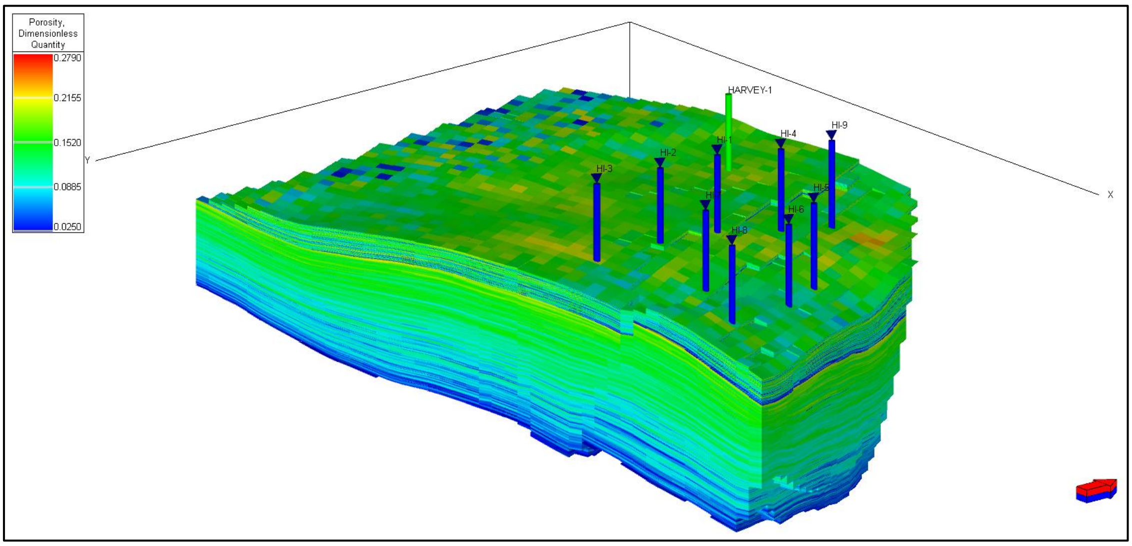

Figure 5-1 Porosity Grid Showing Well Locations in the Model

5.1 Injection Profile

Figure 5-2 show the injection profile for the Reference Case. The injection profile in the Black Oil model is identical to the injection profile in the compositional model (Figure 31, Reference 1).

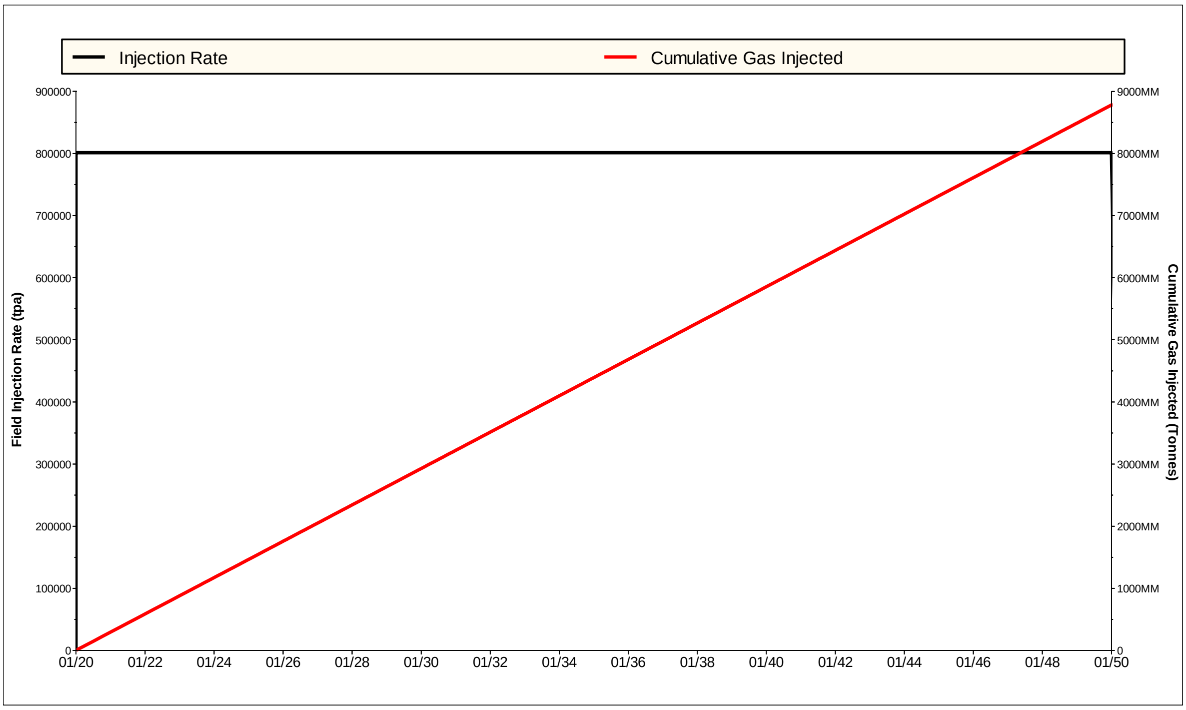

Figure 5-2 Injection Profile - Reference Case (Black Oil)

5.2 Comparisons between Compositional and Black Oil Model

Figure 5-3 compares the gas saturation profile along a cross section of the model through wells HI-2 and HI-6. The figure shows that the gas saturation profile in the Black Oil and compositional models are similar. The main differences are:

- The injected gas is less widely spread in the Black Oil compared to the compositional model
- The solubility of the gas in the Black Oil model is higher

In line with the compositional model, no gas breached the Wonnerup.

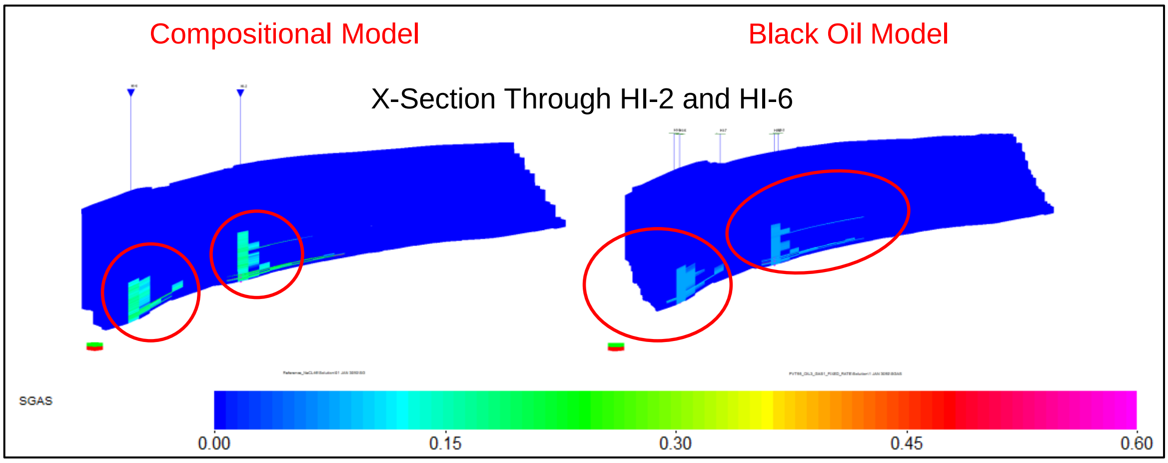

Figure 5-3 Gas Saturation Profile – Comparison between Compositional and Black Oil Model

Figure 5-4 and Figure 5-5 show the plume of injected gas after 1000 years of shut-in. In the Black Oil model, the plume is represented by the gas oil ratio (Rs). The shape and aerial extent of the plumes are similar. Figure 5-6 and Figure 5-7 compare the plume of the injected gas in the Black Oil and compositional model. The shape and extent of the plume in the vertical direction are almost identical. These results show that the Black Oil model provides a fair representation of CO_2 injection in the aquifer. **Error! Reference source not found.** is a comparison of the material balance of CO_2 in the compositional and Black Oil model. The table shows that the proportion of the injected gas dissolved in the Black Oil model is optimistic when compared to the compositional model. Nevertheless, the results of the Black Oil model of the SW Hub shows that Black Oil modelling is a suitable alternative to compositional modelling of CO_2 sequestration in the Harvey area.

- The results of the Black Oil model are consistent with the compositional model in that the injected CO_2 remains in the Wonnerup reservoir.
- The predicted shape and CO_2 plume movement in the Black Oil model are similar to the compositional model. However, the Black Oil model is optimistic as it predicts more CO_2 dissolution in the liquid phase than the compositional model.

The use of a Black Oil model would allow reservoir uncertainties and development sensitivities to be evaluated relatively quickly compared to compositional modelling. As the Black Oil model is more optimistic than the compositional model it is recommended that selected cases in the full field modelling study are checked against a fully compositional model.

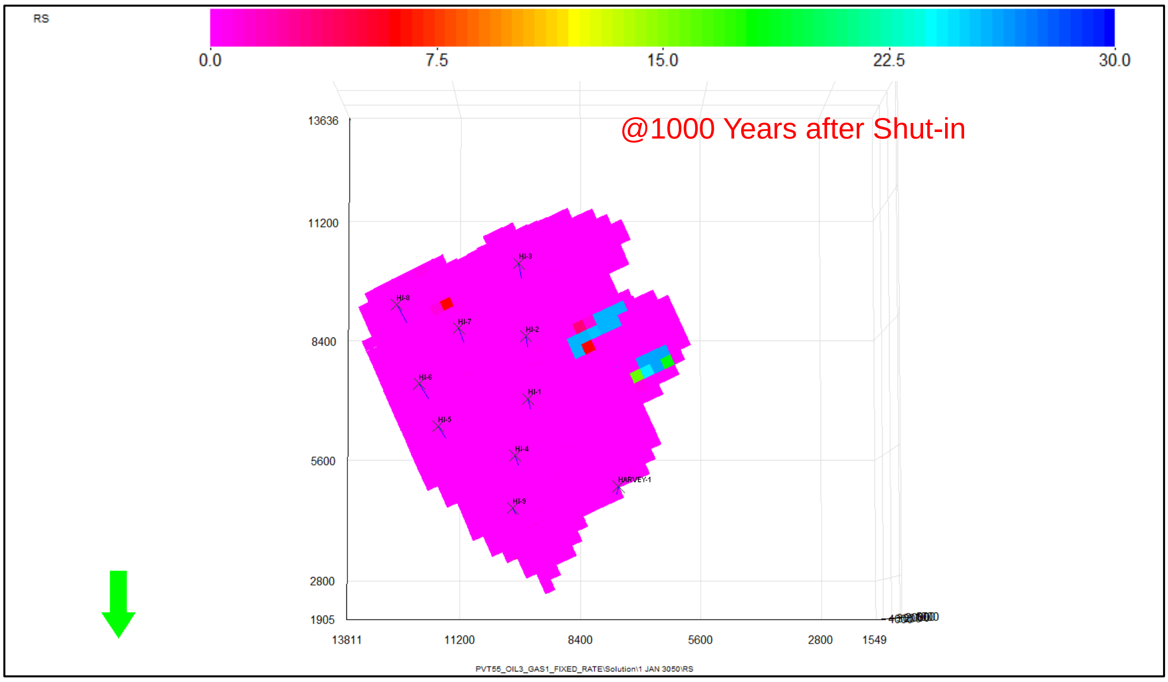

Figure 5-4 CO_2 Plume – Aerial View (Black Oil Model)

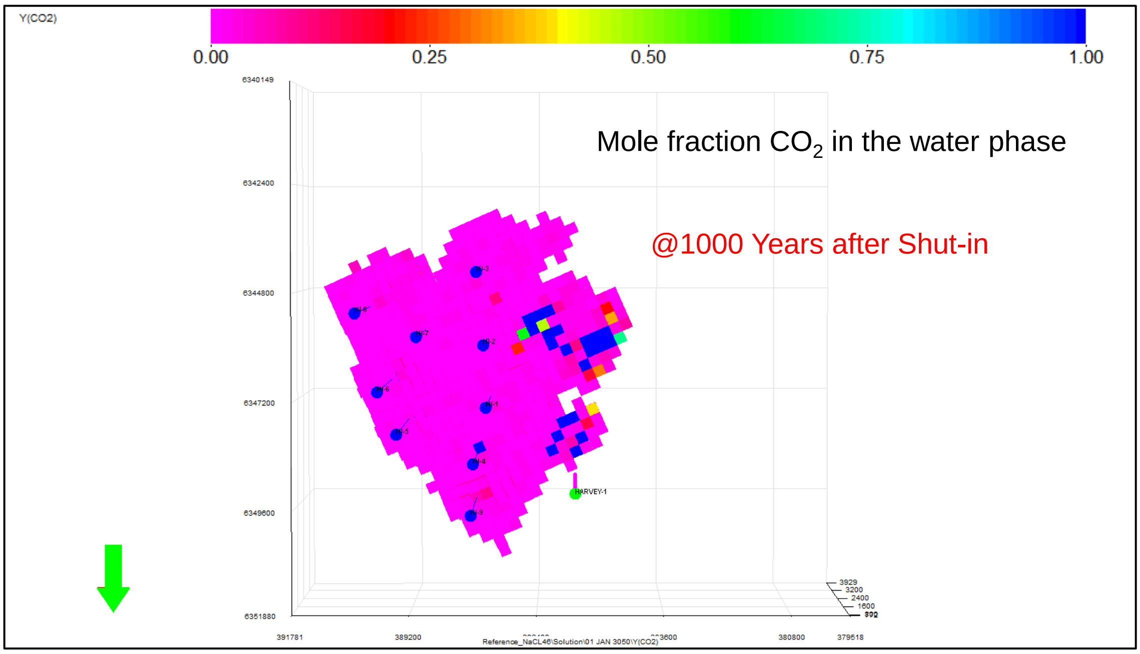

Figure 5-5 CO_2 Plume – Aerial View (Compositional Model)

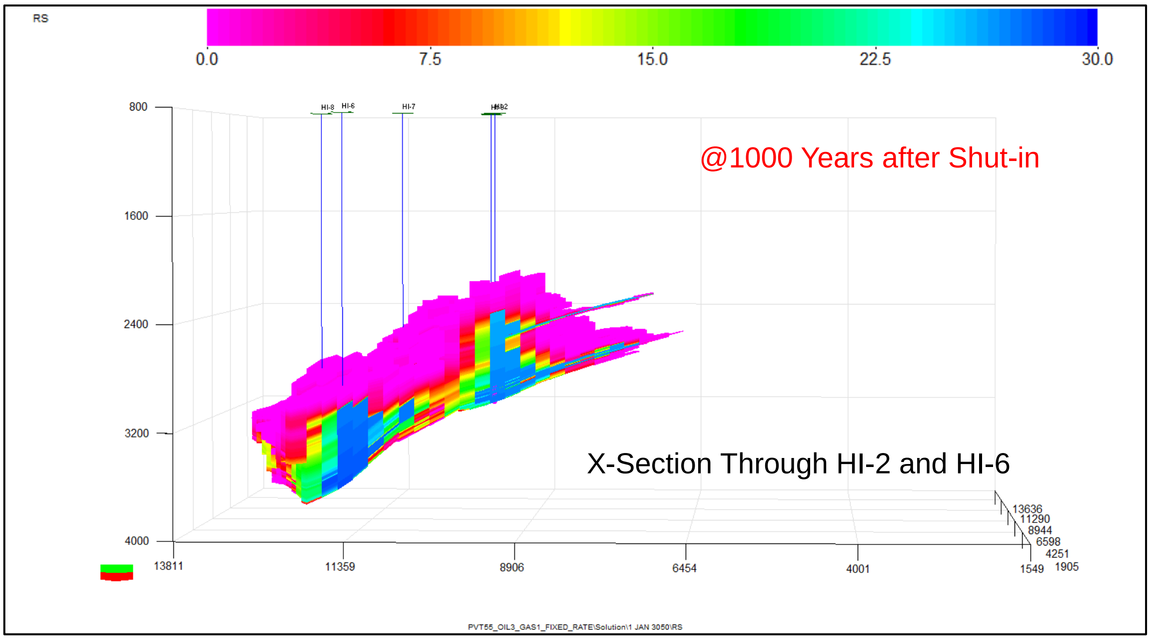

Figure 5-6 CO_2 Plume – Cross Section through HI-2 and HI-6 (Black Oil Model)

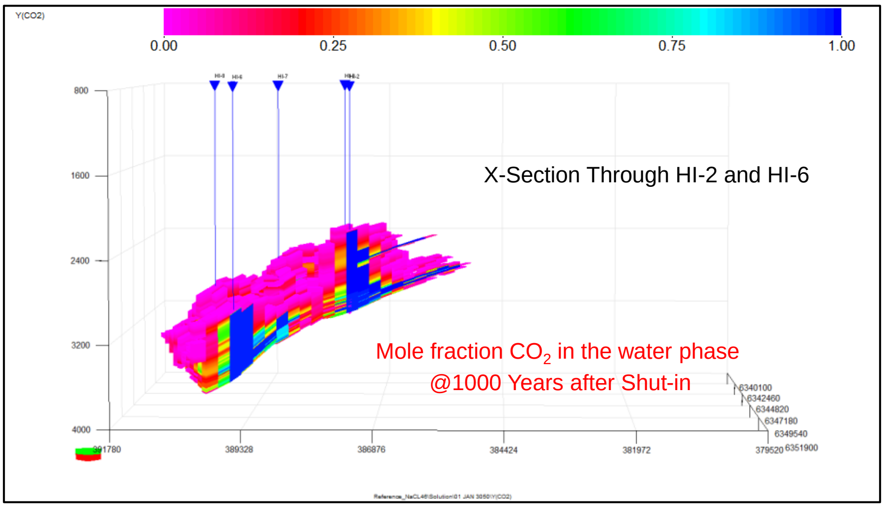

Figure 5-7 CO_2 Plume – Cross Section through HI-2 and HI-6 (Black Oil Model)

Table 5-1 CO_2 Material Balance (After 1000 Years of Shut-in) – Comparison between Compositional and Black Oil Model

Compositional Model

	Supercritical CO2			
	Trapped Gas (Sm3)	Mobile Free Gas (Sm3)	Total CO2 Dissolved (Sm3)	Total CO2 (Sm3)
Gas Material Balance	5.7E+09	1.2E+08	7.6E+09	1.3E+10
% of Injected	42.8%	0.9%	56.4%	100.0%

Black Oil Model

	Supercritical CO2			
	Trapped Gas (Sm3)	Mobile Free Gas (Sm3)	Total CO2 Dissolved (Sm3)	Total CO2 (Sm3)
Gas Material Balance	3.5E+09	8.4E+07	9.8E+09	1.3E+10
% of Injected	26.3%	0.6%	73.1%	100.0%

5.3 Processing Time

The simulation run of the Black Oil model of the Reference Case took about 3 hours to complete on a 12 core Xeon(R) CPU E5-2680 v3 with 64 GB RAM and an NVIDIA GeFORCE GTX1080 Ti graphics card. This is a significant improvement on the processing time required for the full compositional model.

6. IMPACT OF GRID DIMENSIONS ON CALCULATIONS OF CO_2 SOLUBILITY

The impact of lateral upscaling on the modelling results were conducted using the Black Oil model described in Sections Error! Reference source not found. and 4. Three full field models upscaled to different levels of coarseness were investigated. All of the models have the same PVT, SCAL, well controls and differ only in the level of coarsening.

- **Coarse scale model (1.98 million cells, 0.76 million active cells)**
  - Yalgorup
    - 250x250x1 metre cells in the I- and J-direction
  - Wonnerup
    - 250x250x4 metre cells in the I- and J-direction

- **Mid-scale model (12.9 million cells, 2.8 million active cells).**
  - Yalgorup
    - 100x100x1 metre cells in the I- and J-direction.
  - Wonnerup
    - 100x100x4 metre cells in the I- and J-direction.

- **Fine Scale model (15.4 million cells, 11.4 million active cells).**
  - Yalgorup
    - The Yalgorup was not modelled in the fine scale model.
  - Wonnerup
    - 50x50x4 metre cells in the I- and J-direction.

Figure 5-6, Figure 6-2 and Figure 6-3 show the plume of injected gas in a cross section through HI-2 and HI-6. The figures show that the shape of the plume in the 250x250 metre grid is very different from the 100x100 metre and 50x50 metre models. The profile of the plume in the 50x50 metre and 100x100 metre model are similar. In all three grids the gas plume is deeper than 2000mTVDss.

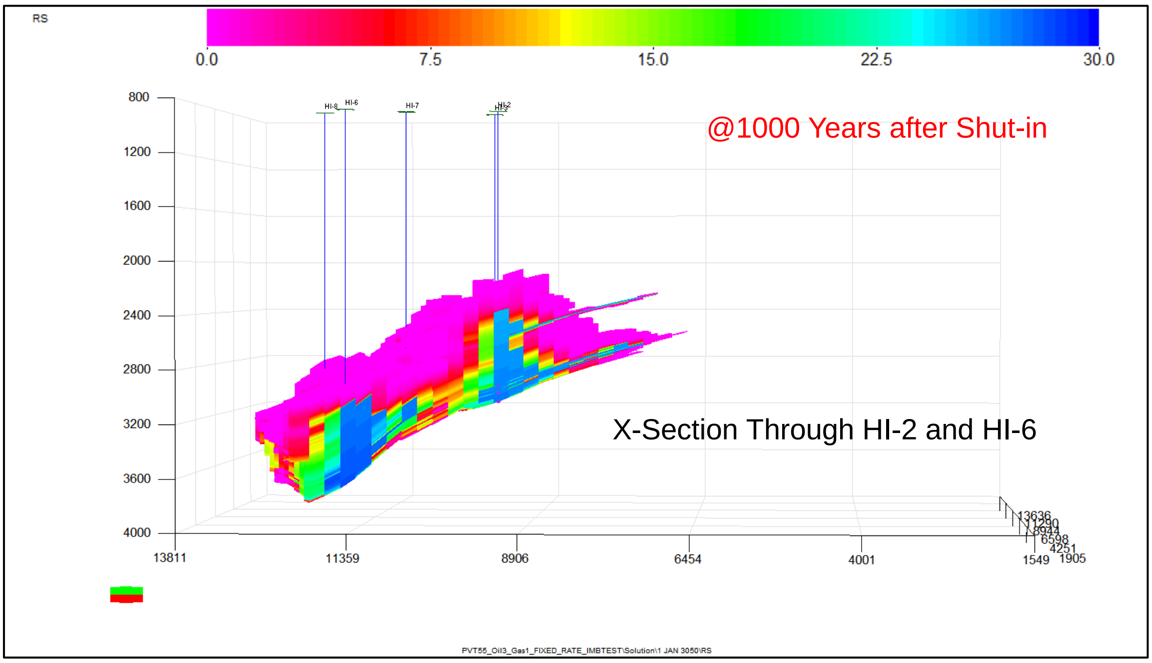

Figure 6-1 CO_2 Plume – Cross Section through HI-2 and HI-6 (Coarse Model)

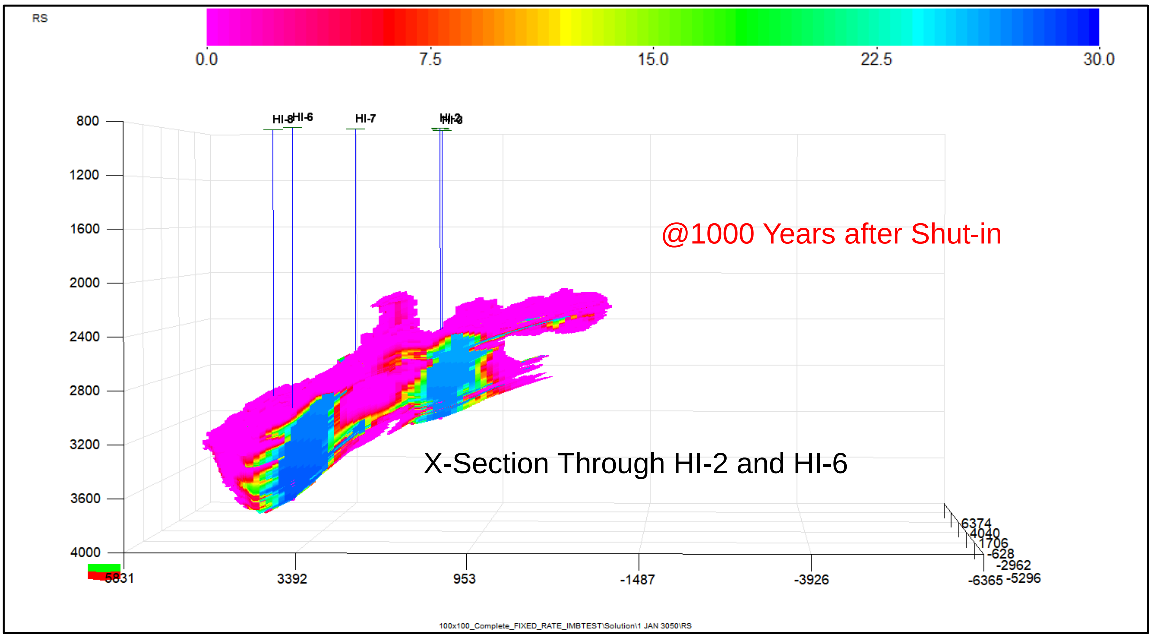

Figure 6-2 CO_2 Plume – Cross Section through HI-2 and HI-6 (Mid-Scale Model)

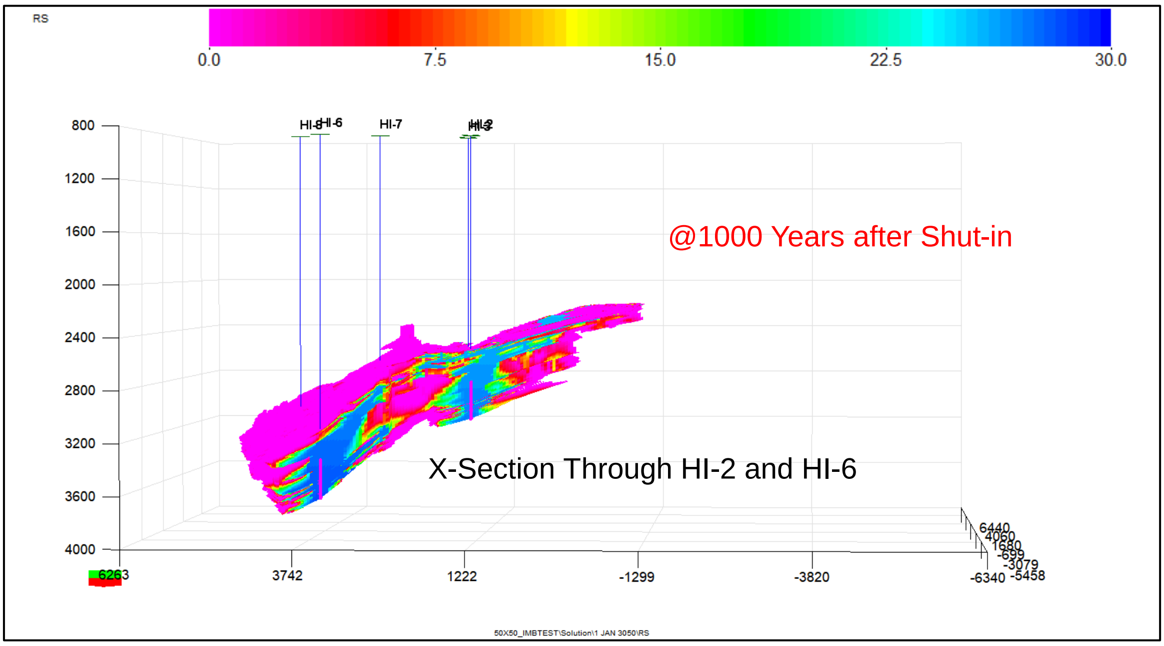

Figure 6-3 CO_2 Plume – Cross Section through HI-2 and HI-6 (Fine Scale Model)

Figure 6-4, Figure 6-5 and Figure 6-6 compare the plume profile for the injected gas in the coarse, mid-scale and fine scale grids respectively. The areal distribution of the plume in the 250x250 metre model is different from the 100x100 metre and the 50x50 metre model. As expected there is more resolution in the plume in the 100x100 metre and 50x50 metre models compared to the 250x250 metre model. The profile of the plumes in the 100x100 metre and 50x50 metre models are similar.

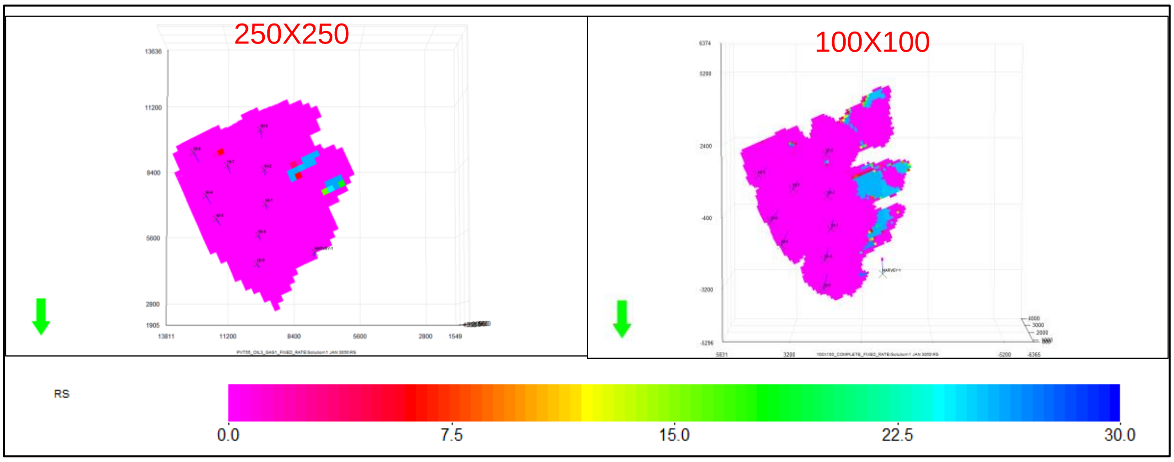

Figure 6-4 CO_2 Plume – Aerial View Comparing the Coarse and Mid-Scale Model

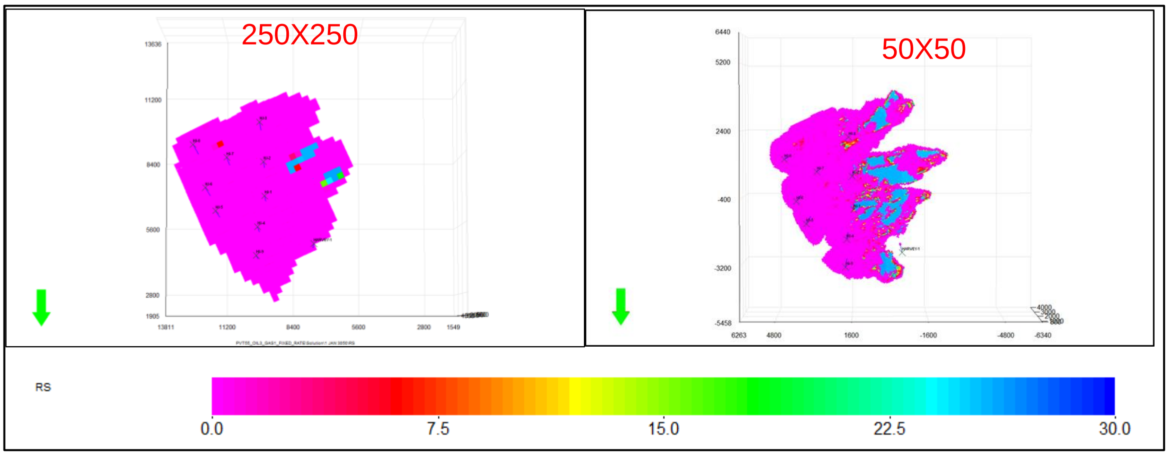

Figure 6-5 CO_2 Plume – Aerial View Comparing the Coarse and Fine Scale Model

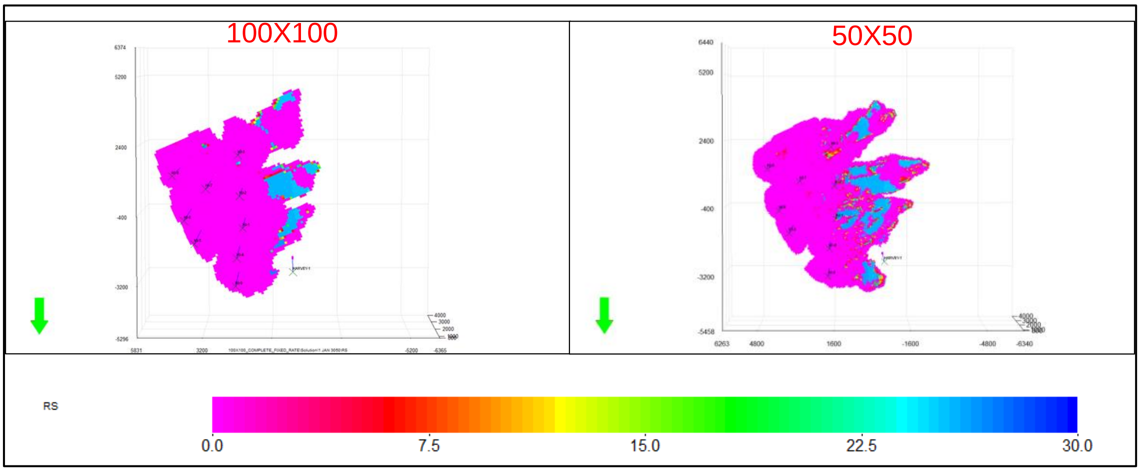

Figure 6-6 CO_2 Plume – Aerial View Comparing the Mid-Scale and Fine Scale Model

Error! Reference source not found. shows the material balance accounts for the three models. The highlights are:

- The proportion of gas dissolved in the liquid decreased when the size of the grid blocks were reduced from 250x250 metre to 100x100 metre and 50x50 metre, the decrease was not consistent
- Mobile free gas in the supercritical state increased as the resolution of the model increased
- There was about a 10% difference in the volume of gas dissolved in the liquid phase

Table 6-1 Material Balance Accounting – Coarse, Mid-Scale and Fine Grid full field models

250X250	Supercritical CO2			
	Trapped Gas (m3)	Mobile Free Gas (m3)	Total CO2 Dissolved (Sm3)	Total CO2 (Sm3)
Gas Material Balance	3.5E+09	8.4E+07	9.8E+09	1.3E+10
% of Injected	26%	1%	73%	100%

100X100	Supercritical CO2			
	Trapped Gas (m3)	Mobile Free Gas (m3)	Total CO2 Dissolved (Sm3)	Total CO2 (Sm3)
Gas Material Balance	4.5E+09	1.9E+08	8.6E+09	1.3E+10
% of Injected	34.0%	1.4%	64.6%	100.0%

50X50	Supercritical CO2			
	Trapped Gas (m3)	Mobile Free Gas (m3)	Total CO2 Dissolved (Sm3)	Total CO2 (Sm3)
Gas Material Balance	4.0E+09	4.3E+08	8.9E+09	1.3E+10
% of Injected	30.2%	3.2%	66.6%	100.0%

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6.1 Very Fine Scale Model

It is impractical to construct a full field model of the Harvey area at a grid resolution of 25x25x4 metres. A model at that grid resolution and covering only the Wonnerup would have over 160 million cells. To evaluate the impact of grid size on plume migration An element of the Harvey model encompassing the wells HI-2 and HI-6 and covering only the Wonnerup was built at a resolution of 25x25x4 metres (Figure 6-7). The model consisted of approximately 23 million cells with about 7 million of those cells active. This model was built to investigate if the movement and shape of the injected gas plume is significantly different from the coarser grids evaluated in the study. An element model of the same region were also built for the 250x250x4 metre model. Figure 6-8 compares the injected gas plume in the 250x250 metre and 25x25 metre element models. The plots show that there is significant difference in the plume profile between the 250x250 metre and 25x25 metre models there is little difference in the material balance (**Error! Reference source not found.**). This result indicates that although the plume profile is affected by grid resolution, the impact of grid resolution on the solubility of the injected gas is not significant.

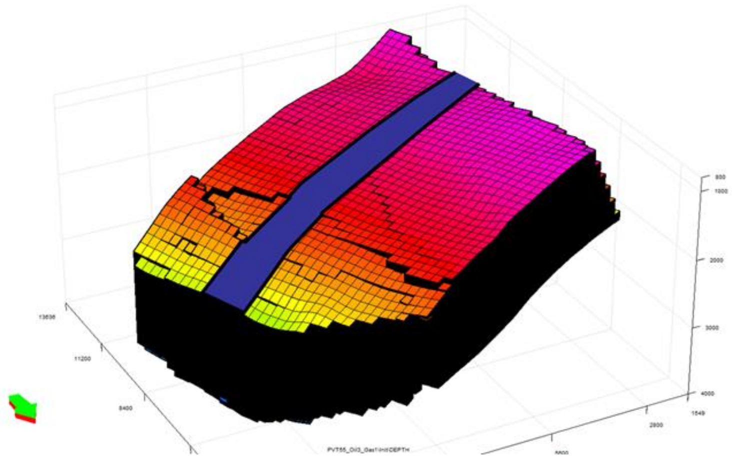

Figure 6-7 Harvey Model showing the area used in the element models

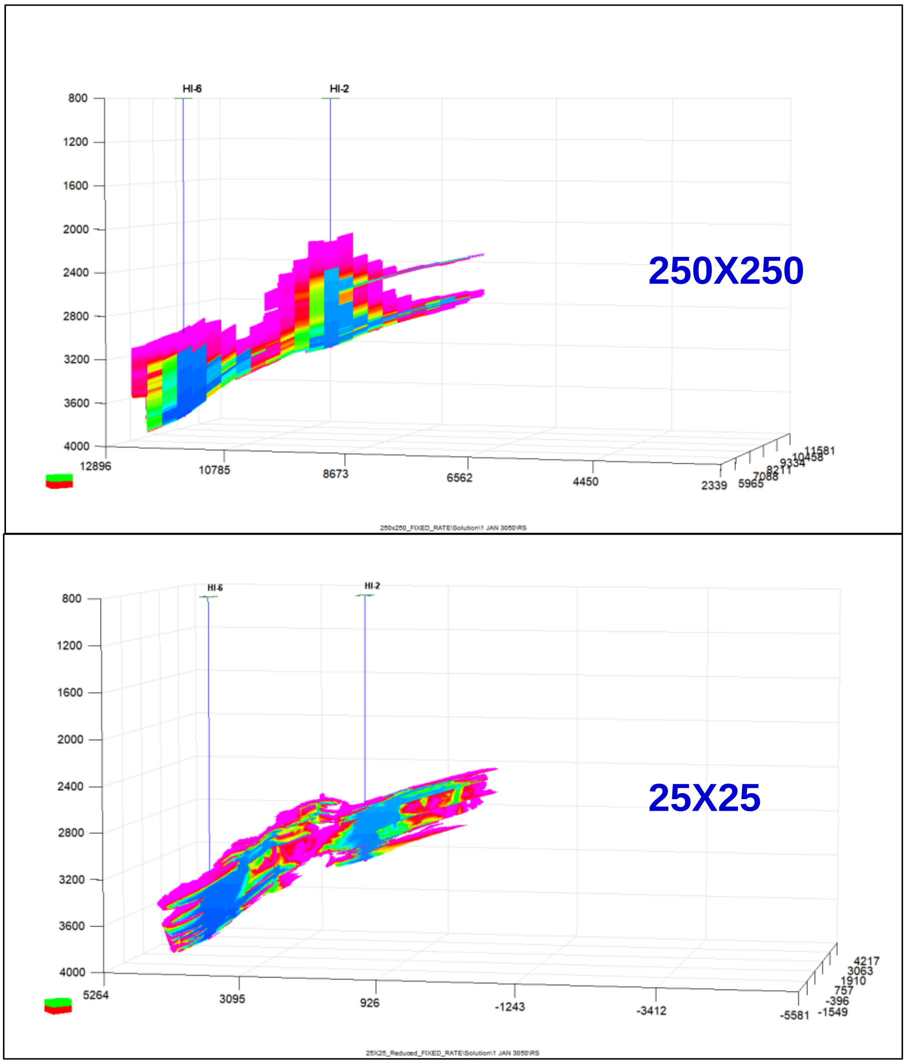

Figure 6-8 CO_2 Plume – Cross Section through HI-2 and HI-6 (Comparison of 250x250 and 25x25 models)

Table 6-2 Material Balance Accounting – 250x250 and 25x25 Element models.

250X250

	Supercritical CO2			
	Trapped Gas (m3)	Mobile Free Gas (m3)	Total CO2 Dissolved (Sm3)	Total CO2 (Sm3)
Gas Material Balance	6.5E+08	1.5E+07	2.3E+09	3.0E+09
% of Injected	21.9%	0.5%	77.6%	100.0%

25X25

	Supercritical CO2			
	Trapped Gas (m3)	Mobile Free Gas (m3)	Total CO2 Dissolved (Sm3)	Total CO2 (Sm3)
Gas Material Balance	7.5E+08	3.8E+07	2.2E+09	3.0E+09
% of Injected	25.4%	1.3%	73.3%	100.0%

7. REFERENCES

1. "Dynamic Modelling of CO_2 Sequestration in the Harvey Area", Report for Department of Mines and Petroleum, WA, DMP/2016/5, July 2016.

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3. J. Ennis-King 2017, personal communication, 22 September 2017