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A Practical Workflow of Stochastic Simulations for Fast-Track CCS Development

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Abstract

To secure a CO2 sequestration license under strict regulations in Australia, a clear demonstration of CO2 containment is mandatory. The key objective of this paper is to provide practical demonstration how uncertainty study can be used to accelerate evaluation of CO2 storage resources of G-7-AP and progress towards obtaining a storage license by achieving the following key milestones:

- Capture various CO2 plume outcome for all static and dynamic permutations.
- Test robustness of injection concepts.
- Demonstrate CO2 containment within constraint boundaries; and
- Assist in project's MMV plans.

The scope of the study commenced by gathering and combining static and dynamic reservoir parameters. A tornado is created to understand the influence and ranking of each parameter on CO2 plume dynamic behavior phenomena and overall spatial migration. Two hundred realizations with individual grids were stochastically built to assess well locations and the respective CO2 plume generated against project parameters and constraints.

The key results of 200 stochastic simulations provides a clear demonstration the likelihood of CO2 plume migration pathway under the project development concepts and range of subsurface outcomes. A CO2 plume migration probability map is created to allow contouring of P90, P50 and P10 plume migration pathways. This probability map provides clarity and justification of CO2 containment within the intended storage complex.

The CO_2 probability map allows the quantification of the probability of CO_2 plume migration within the storage complex due to elements of subsurface parameters and project design (e.g. reservoir architecture, well locations and injection rates/duration). Extreme cases are identified with common subsurface parameters distilled and examined to understand the true merits of these cases. Appraisal data are then planned accordingly to derisk identified key uncertainties. Meanwhile, remaining uncertainties are incorporated into the project's Risk Management Plan, including MMV plan and remediations.

Introduction

Australia has suitable basins for geological large-scale storage of CO_2 along the margins of the Australian continent. The Bonaparte Basin (including the Petrel Sub-basin) offshore northern Australia is considered by Geoscience Australia (GA) and the Commonwealth Scientific and Industrial Research Organization (CSIRO) as one of the most promising settings in Australia for large-scale CO_2 storage[1].

The Bonaparte CCS Assessment Joint Venture - with INPEX (as Operator), TotalEnergies and Woodside Energy - was awarded the greenhouse gas assessment permit (G-7-AP block) in the Petrel Sub-basin in 2022. A comprehensive work program was approved and will be completed in 2025 to demonstrate the suitability of the saline aquifers for large scale CO_2 injection targeted around year 2030[1].

The purpose of this paper is to demonstrate how subsurface risk and uncertainties are captured and managed prior to obtaining data from a planned appraisal program. Thus, allowing the JVP to assess the likely robustness of the project from its early stage.

Theory and/or Methods

Figure 1 is an overview of how static and dynamic workflows are combined to ultimately create unique realizations that capture a broad range of technically credible reservoir/subsurface scenarios. The static workflow is created to integrate seismic interpretation, various geological concepts and uncertainties in petrophysical parameters. Meanwhile, the dynamic workflow is created to capture facility, wellbore and fluid uncertainties. A Best Technical Case (BTC) is created by underpinning most likely subsurface datasets. The BTC then becomes the basis for the Uncertainty Study.

In the Uncertainty Study, there are 167 parameters declared either Uncertainty or Expression. Latin Hypercube stochastic method was used to create 200 realizations for the first ensemble. This first ensemble is conducted with only the first injector with the aim of understanding how far the CO_2 plume migrate over time for each realization. Thus, it provides an insight into the general CO_2 plume migration philosophy with time due to various unique combinations of static and dynamic parameters. For each realization, its unique combination of static and dynamic parameters is preserved to run the second ensemble. The second ensemble is run with the notional Field Development Plan (FDP) containing notional injectors and the planned injection profile.

All 200 realizations are run in parallel within the Cloud Virtual Environment which are later retrieved upon completion. Multiple post-processing workflows are created to retrieve simulation results to create CO_2 net map, CO_2 plume probabilistic map and CO_2 plume stabilization profile for the Uncertainty Study.

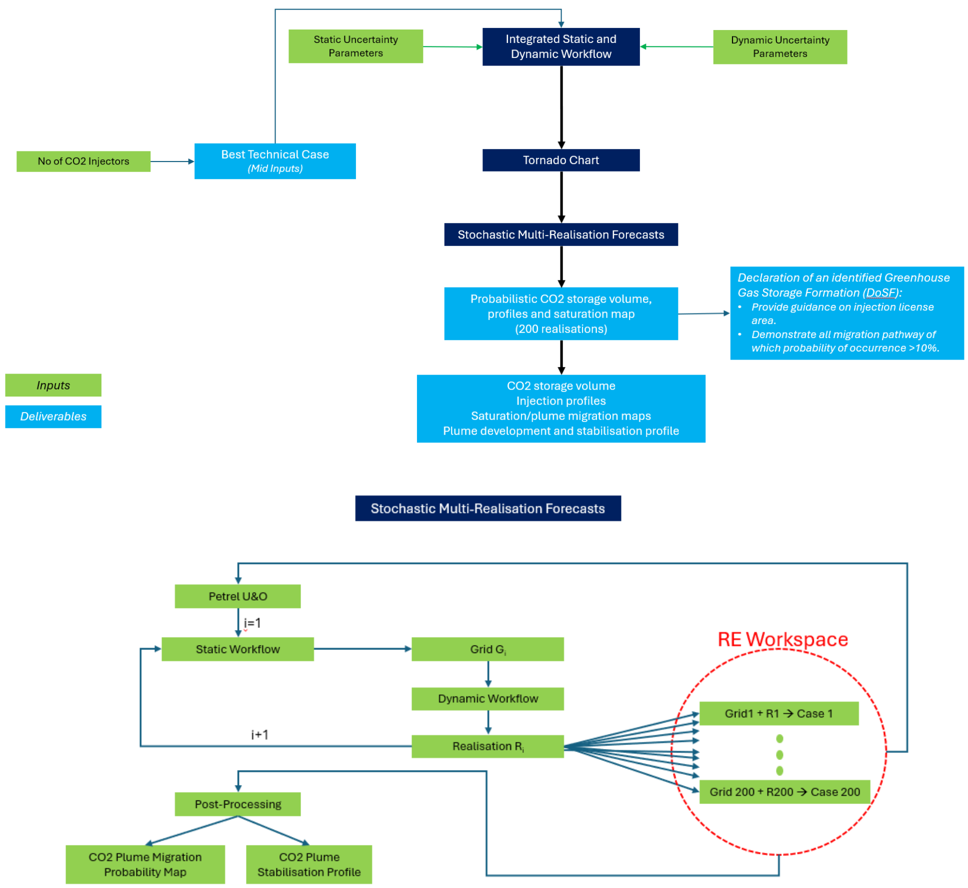

Figure 1. Uncertainty Study Workflow Combining Static and Dynamic Uncertainties.

Results

The initial result is a construction of the probabilistic S-curve to measure CO2 plume migration extent from a single injection perspective (Figure 2). The 200 realizations are ranked based on their respective CO2 plume length at the end of the simulation time-step.

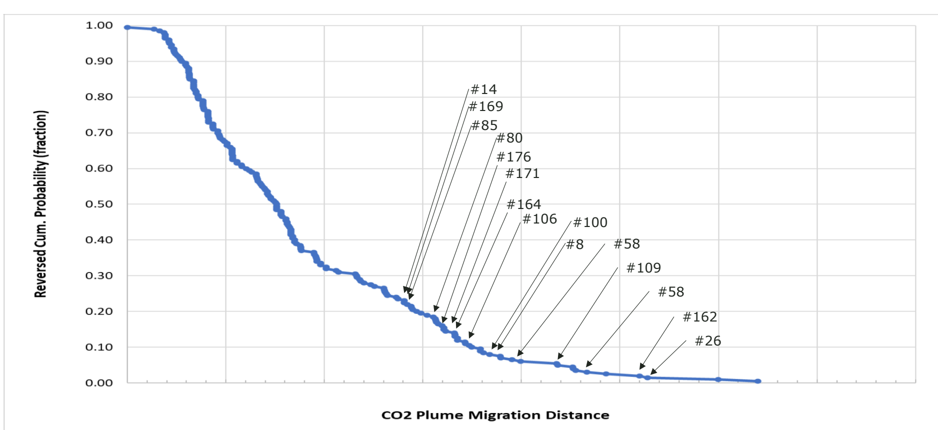

Figure 2. Probabilistic S-Curve From 1st Ensemble With 1 Injector Only.

The 200 realizations from the second ensemble are then combined to yield a probabilistic CO2 plume migration profile as shown in Figure 3. The purpose of this probabilistic CO2 plume migration map is to capture all possible CO2 migration footprints as a function of injection well count, injection distribution, injection profile and reservoir properties. Thus, the probabilistic map demonstrates the level of confidence of CO2 migration and stabilization over time for the notional FDP. In this case, the P50 and the conservative P10 contours provide a high degree of confidence that the injected CO2 will remain within the identified storage complex. The map also indicates that the initial injection spacing assumption is sufficient to provide displacement area between injectors to minimize different CO2 plume fronts from merging and thus, resulting in longer CO2 plume lateral extents.

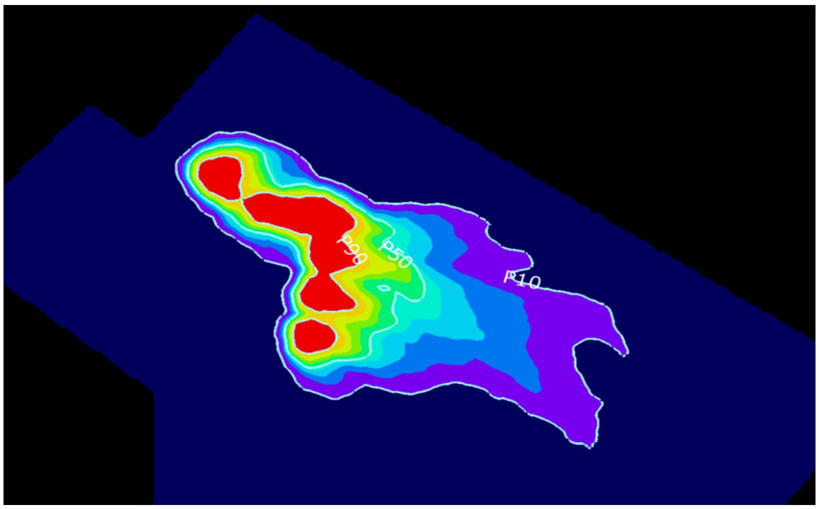

Figure 3. CO2 Plume Migration Probabilistic Map.

For the notional FDP, extreme cases contributing to the P1 contour are also examined in the uncertainty study to understand the circumstances whereby the CO2 plume migration may have extreme lateral migration relative to the injectors and boundary permit. The key objectives of this investigation are to (1). Quantify the extreme extent of CO2 migration; and (2). Capture the circumstances these extreme cases may occur. A workflow was built to sieve through the ensemble's gas saturation net map to identify these extreme cases. The identified cases are regrouped to deduce the common combination of static and dynamic parameters that yield cases that do not meet CO2 migration criteria. Table 1 summarizes the combinations of static and dynamic parameters for extreme cases. Extreme cases are also identified within the S-curves as shown in Figure 2.

Constraint Boundary	Static Parameters	Dynamic Parameters
Criteria 1	• High reservoir properties of formations above with lowest shale content. There is also permeability contrast between channels and Inter-distributary bay and delta plain)	• Mid-High Kv/Kh • High CO2 relperm. • Low-Mid reservoir temperature • Conservative CO2 solubility.
Criteria 2	• Seismically interpreted ridges, (present in all current realisations). • Conceptual modelling of high quality distributary channels within top formation.	• High CO2 relperm. • Conservative CO2 solubility.

Table 1. Identified Common Combination of Static And Dynamic Parameters in Extreme Cases.

The identification of these static and dynamic parameters was imperative as it provides guidance on the objectives of the appraisal program in terms of location of appraisal wells and their respective coring, logging and well test objectives. Upon a successful delivery of all appraisal datasets, essential reservoir and fluid data will be evaluated to narrow the initial estimated ranges applied to key parameters.

The CO2 plume lateral extent over each time step was also measured at each time step. The purpose of this is to understand how the plume lateral extent changes over time and ultimately, defining the time required for each realization CO2 plume to stabilize. In Figure 4, the probabilistic plume migration distance versus time is constructed to demonstrate the range of plume migration distance and stabilization with time.

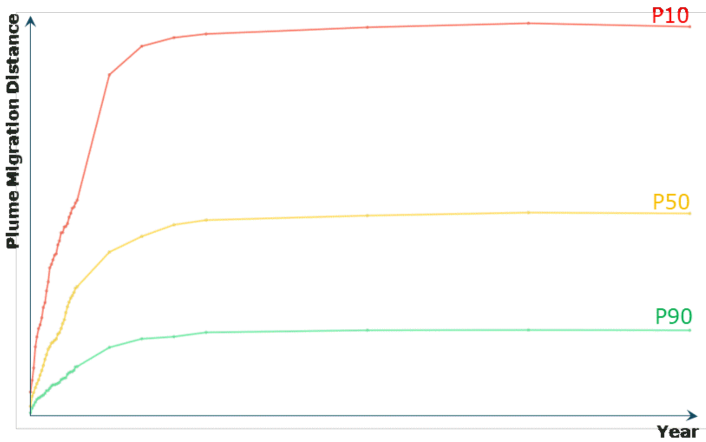

Figure 4. CO2 Plume Stabilization Versus Time

Discussion

The two wells appraisal campaign conducted in the block included significant coring, fluid sampling and MDT test programs for each well. Additionally, an injectivity test was conducted to prove injectivity expected in the vicinity of the notional placement of injectors. Initial results of the appraisal wells are mostly within expectation or better. Moreover, a high injectivity index was proven. These results will allow uncertainty ranges to be calibrated and, in some cases narrowed, providing the basis of adjusting the initially assumed uniform distributions for some of the uncertainty parameters. Consequently, a proportion of the extreme cases will likely be removed which is key to derisking the project uncertainties.

The MMV plan under evaluation will be designed to appropriately monitor CO2 containment through targeted, fit-for-purpose monitoring and management strategies. Monitoring may include 4D seismic or other remote geophysical technologies which would aim to track the development and actual migration of the CO2 plume. Surveillance will enable direct validation of simulation predictions against observed plume behavior.

The monitoring system will incorporate an iterative update process of refining the stochastic simulations based on surveillance data. This approach enhances the accuracy of CO2 movement forecasts and enables dynamic adjustment of operational parameters as needed.
The integration of monitoring data with predictive models enables adaptive management throughout the storage operation.

Conclusions

Stochastic simulation allows capturing of all outcomes due to uncertainty in reservoir parameters. This approach was essential in providing an initial perspective on the level of risk associated with the notional field development plan and storage location prior to the appraisal program. As key reservoir and fluid parameters are identified through the uncertainty study, the appraisal program and subsequent studies are tailored accordingly to confirm all initial assumptions. With a focused appraisal program, extreme cases may be removed which further derisk subsurface uncertainties and in turn, derisking the planned injection/storage capacities. Refinement of the remaining realisations will also enable optimisation of the MMV program.

References

1. Inpex, Bonaparte Carbon Capture and Storage.pdf, < https://www.inpex.com.au/projects/ccs-activities> [6 January 2025].