Title: Petrophysical Considerations for CO2 capture and storage

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**Abstract:** XXXXX

**One-Sentence Summary:** This paper aims to discuss the petrophysical considerations that need to be made for compliance with the CO2 Storage Resources Management System (SRMS), and highlight key differences and similarities between the SRMS and the Petroleum Resources Management System (PRMS).

# **Introduction**

Carbon Capture Utilisation and Storage (CCUS) encompasses a range of methods and technologies that involves the capture of carbon dioxide (CO2) from an emission point source and subsequent sequestration via injection into geological formations. CCUS is commonly viewed as a key technology to assist in reaching global anthropogenic climate change goals.

While the global CCUS project pipeline has been growing since the 2015 Paris agreement (COP21), required installed CCUS capacity needs an approximate 100 fold-increase by 2050 to achieve net zero targets as defined by the COP21 agreement. Between USD $655 billion and USD $1,280 billion in capital investment is required to meet these objectives [1]. Commercial scale CCUS requires an accurate understanding of the underlying subsurface for successful implementation of field development plans. The suitability of geological formations for CCUS is essentially an integration of multiple scales (**Error! Reference source not found.**), and a staged process will ensure that the data at the various length scales is properly integrated.

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**Figure 1:** Schematic illustrating the process of Data Integration

The process starts with the identification and high grade of potential storage sites. Starting with seismic interpretation (**Error! Reference source not found.** (a)), there is a need to perform depth conversion, interpret key stratigraphic horizons and faults and evaluate the stratigraphy/facies. Once a suitable site is selected, field based properties and/or a static modelling would need to be populated ((**Error! Reference source not found.** (b)) with evaluations made from petrophysical logs, routine and special core analysis (**Error! Reference source not found.**(c) to **Error! Reference source not found.**(e)), where the goal would be estimation of porosity, permeability, minerology, relative permeability and capillary pressure. At this scale as well, there should be consideration given to the geomechanical aspects of the potential storage sites, with an attempted to understand the stress regime, seal potential, geometry, and integrity. Consideration must also be given to hydrodynamism and whether faults encountered would act as conduits or seals. Reservoir engineering aspects of any CCUS project include an understanding of pressure and temperature, phase behaviour of injected CO2 fluids and the integration of data related to well tests that would have been performed in analog or offshoot wells. Geochemically, aspects related to mineral composition, rock-fluid-CO2 interactions and microbial activity should also be considered (**Error! Reference source not found.**(f)).

The integration of all the above results in the development of static and dynamic models where the volumetric evaluation of the potential storage capacity can be determined (theoretical capacity). When building the dynamic model, the efficiency of CO2 injectivity into reservoir facies would be accounted for by an “efficiency factor” (analogous to a recovery factor in oil and gas) to account for transmissibility, pore-scale trapping mechanics and connected volumes, from which an estimate of the actual storage capacity would be determined (effective capacity).

The above summarizes the multi-disciplinary challenge associated with CCUS. In this paper, we will focus on just one aspect of this process, namely the key formation evaluation considerations which need to be accounted for in any CCUS project under the CO2 Storage Resources Management System (SMRS) (**Error! Reference source not found.**(c) to **Error! Reference source not found.**(f)) [2].

This paper will also discuss how the CO2 Storage Resources Management System (SRMS), while similar in some ways to the well-established Petroleum Resource Management System (PRMS), has some fundamental differences that need to be understood. We will also share a ‘petrophysical checklist’, which we apply to a drill well off the North West Shelf in Australia, utilizing it as a case study to explain how assets can be determined as fit for CCUS applications. Finally, we will discuss the importance of data gathering and offer suggestions to help companies as they seek to de-risk future CCUS projects.

# **PRMS vs. SRMS – Similarities and Differences**

We start off by firstly discussing the similarities and differences between the PRMS and SRMS. First developed in 1962 by the Society of Petroleum Evaluation Engineers (SPEE), the PRMS provides the framework for classification and categorization of all petroleum reserves and resources [3]. Although the system encompasses the entire in-place petroleum resource and characterises projects at various levels of technical and commercial maturity, its widest application has been for estimating commercially recoverable quantities using a globally recognized system. In contrast, the SRMS is a newer classification framework first developed in 2017 by a subcommittee of the Carbon Dioxide Capture, Utilization and Storage Technical Section (CCUS). It aims to provide a consistent approach to estimating storable quantities of CO2 in the subsurface and evaluating development projects [2].

The PRMS provided the model for the development of the SRMS, by which CCUS projects can be voluntarily contrasted against. While the definitions provided within the SRMS follow standard industrial definitions for most terms and draw parallels from the definitions provided in the PRMS, there are some subtle differences in the frameworks (Figure 2). Both are similar in that they are project based, independent of implementation and detail how resources can be quantified, categorised and classified [2] . In both the PRMS and SMRS, each category (P – reserves or capacity, C – contingent resources or U – prospective resources) must consider the probability of potential outcomes. This is usually done with the in the form of probabilistic resource estimation, representing a P90 (low case referring to 90% of calculated estimates being equal to, or exceeding this estimate), P50 (best case – the median) and P10 (high case referring to 10% of calculated estimates being equal to, or exceeding this estimate), to capture geological and engineering uncertainties [3].

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**Figure 2:** Comparison of the SRMS and PRMS framework.

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**Figure 3:** Classification framework for total resources (Produced or Stored) in the PRMS and SMRS.

Both the SRMS and PRMS allow the use of volumetric estimations as an analytical procedure for determining the hydrocarbons initially in place (HCIIP) and theoretical storage resource for CO2 (mass of CO2 or MCO2 in Kilograms) (Equation 1 and Equation 2 respectively).

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| PRMS: |  | Equation 1 |
| SRMS: |  | Equation 2 |

where GRV is the Gross Rock Volume (m3); N:G is the Net to Gross (m/m); f is porosity (V/V), Sw is the water saturation (V/V), SWirr is the irreducible water saturation (V/V), is the density of CO2, FVF is the Formation Volume Factor and E is the Efficiency Factor.

Unlike the PRMS, which only concerns itself with the commercial production of hydrocarbons (reserves), the SRMS is concerned with the evaluation of accessible pore volumes to store CO2 (storable quantities) geologically, with an expectation of permanence. In other words, (1) the target geologic formation must be discovered and characterized (including containment), (2) injection can occur at commercial rates that will not breach containment and (c) the storage resource must remain trapped**Error! Reference source not found.**. Both the similarities and differences between the volumetric estimations for resources and reserves is schematically illustrated in Figure 4.

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**Figure 4:** Diagram highlighting similarities and differences for resource evaluation between SMRS and PRMS.

A challenge in the SRMS framework is the determination of Commerciality. Investment decisions are based on the entity’s view of future commercial conditions that may impact the development feasibility (commitment to develop) and injection/cash-flow schedule of storage projects [2]. Unlike petroleum, which is a sales product, the CO2 resource being injected is typically a waste product from another projects or entities; therefore, cashflows should be evaluated for the storage project alone and consider both the (rate of and total) supply as well as negotiated fiscal terms [2]. Commerciality can depend on numerous things including expected quantities of storage projected, estimated costs of injection and revenues from the stored quantities, projected storage, and revenue related taxes as well as the application of an appropriate discount rate [2].

Typically, CO2 storage is carried out via injection into virgin saline aquifers or depleted oil and gas fields or used for Enhanced oil recovery (EOR). These methods all have different project drivers, risks and commercial implications depending on what is trying to be achieved **Error! Reference source not found.**. Economic drivers for CO2 injection into saline aquifers or depleted fields is usually governed by emissions trading schemes (ETS). These are government frameworks aiming to provide economic incentives for reducing emissions (sequestering CO2). These projects typically aim for permanence of CO2 storage and the economic considerations typically depend more on the stakeholders involved. For example, if an operator owns two assets outright and is producing from Field A for injection into Field B, there is no associated issues with commerciality. However, if Field A (producer) is owned by Company A and Field B is owned by company B (Storage), then complications arise around tariff payments and from Company A to Company B for acceptance of the CO2.

On the other hand, utilization projects such as enhanced oil recovery using CO2 as a miscible gas, aims to maximise the amount of oil recovered and minimise the amount of CO2 produced per tonne of CO2 injected. While this may seem counter intuitive for a CCUS project, in principle and depending on the operating conditions, the lifecycle of a CO2 EOR project can have more net CO2 injected than is produced after final oil production [4]. With such a commercial arrangement, the operator is provided with some economic flexibility, particularly as carbon pricing increases with time. In this case, the operator can shift the emphasis from maximizing oil output to maximising CO2 storage. In the United States, assuming an oil price of $100 bbl, EOR with CO2 typically becomes economically viable at CO2 costs of $45-$60 per tonne [4].

# **Petrophysical Considerations for CCUS projects**

With the SRMS acting as a guide, the key petrophysical considerations that should be accounted for in a typical CCUS project are discussed. A caveat is that not all inputs are required all the time; it depends on the type of CO2 storage project and the stage of project maturity. What we wish to demonstrate however is that the petrophysicist can play a critical role in obtain insight into these properties. Additionally, the practicing petrophysicist is also instrumental in aiding the mitigation of risks associated with these project types, through application of careful evaluation methods.

# *CO2 migration and Trapping*

The behaviour of CO2 in the subsurface is not static, with the CO2 trapping mechanism evolving with time. In the short (injection) timescale, the primary mechanism for trapping will be geological, either under a structural high, or in stratigraphic bodies. The risk here is poor knowledge of the subsurface and reservoir, with CO2 migration via leak pathways to the surface. As part of risk management, a petrophysicist should not only evaluate the subsurface closest to the injection site, but also look at wells that can aid in delineation of the field. It will also be important for the petrophysicist to understand how the petrophysical properties change in the subsurface especially the salinity, porosity and permeability. Mapping out such properties would aid the reservoir geologist in mitigation some of the leakage risks. As much as possible, petrophysical properties should also be used for seismic calibration to determine if amplitude anomalies can potentially be flagged early.

A short to medium term process will be capillary trapping within the reservoir pore-space, as the CO2 plume migrates updip, as well as when the CO2 dissolves in brine, creating carbonic acid (H2CO3) [6]. Risks here include seal breach or seal failure, from chemical dissolution of constituent minerals brought about by acidification of the in-situ brine. Another form of failure is also “worm holing” where acidified brine dissolves a mineral forming a migration pathway. If the field is old with many abandoned legacy wells, acidified brines can interact with cement and steel left downhole, increasing corrosion and pitting, and potentially causing CO2 leak. Again, a petrophysicist can help to mitigate the risk. First, analysis of the seal properties, including mineral facies and geomechanical properties, should be undertaken. This analysis should also include capillary pressure (Pc) measurements to determine threshold pressures. If there is appetite and budget, a core analysis study on legacy core/cuttings can be undertaken to observe for interaction of CO2-brine with any seal rock. In the case of legacy wells, the petrophysicist can aid by reviewing and analysing the quality of cement bond logs (CBL).

In the long term, CO2 mineralises to form cements within the pore space of the rock. Core injection studies have shown that CO2 interactions between formation water, K-feldspar, Plagioclase and carbonate commonly cause the precipitation of silicate and carbonates. This is perhaps the most effective trapping mechanism but also the slowest occurring. However, the precipitated minerals in association with released clay particles will typically migrate through the pore throat before precipitating and reducing permeability of the formation [7]. This will result in a decrease in injectivity of CO2 into the formation and may impact the commerciality of a project. A petrophysicist can aid in the derisking of such projects by undertaking/reviewing formation damage from previous production data, or else undertaking a formation damage study.

# *Geochemical Alternations and Fines Migration*

Fines migration is a phenomenon that occurs in reservoirs when small particles of minerals and other materials present in the formation are mobilized and transported by the flow of fluids through the rock. CO2 injection into a reservoir can cause fines migration in several ways. First, because CO2-brine interaction causes a pH reduction with the formation of H2CO3, this causes dissolution of minerals in the formation, including those that bind the fines to the rock matrix, leading to its mobilization. In a related manner, pH changes from carbonic acid can cause changes to the surface properties of the rock as well and weaken the bonds to the fine clays, leading to the destabilization and mobilization of such particles. Secondly, CO2 can cause swelling of clays present in the formation, and dislodge/ break fines particles from rock surfaces, mobilizing their movement within the pore space. As pressure gradients are present with CO2 injection (which is at a higher pressure compared to the formation generally), the dislodged clays/fines move within the pore space towards areas of low pressure, where they can accumulate, reduce overall permeability, and eventually cause a blockage. As fines migration can have significant impact on project commerciality, petrophysicists must carefully evaluate the geomechanical properties of the reservoir, including sanding studies, and potentially arrange for fines migration studies prior to any injection taking place. Post-injection, petrophysicists must again monitor the efficacy of the injection process using cased hole or tracer techniques.

# *Net Effective Overburden Stress and Impact on Grain Contacts*

There are 2 competing forces in any subsurface reservoir i.e. the downward vertical stress applied by the weight of the overburden, counterbalanced by the pore pressure acting outward and radially on the internal pore walls between grains in a fluid saturated rock (Shape, arrow

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). The difference between the 2 forces is referred to as the net effective overburden stress () (Equation 3).

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|  |  | Equation 3 |

where is the total vertical stress (psi), is the Biot poro-elastic factor and is the initial reservoir pressure (pore pressure in psi).

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**Figure 5:** Schematic of Net effective overburden stress at the micro scale, with pore pressure acting outwards and total vertical stress acting downwards

has a huge impact on the life of a reservoir, with compaction, subsidence, and fracture initiation all intimately tied to this property. In a production environment, typically decreases, and compaction occurs. This can be an effective production mechanism, aiding natural pressure depletion. However, drawdown the pressure too much and there is potential failure in the form of subsidence (e.g. Ekofisk field) [5]. This is why pressure maintenance and support are important, via injection of gas or water, to increase the pore pressure to as close to virgin reservoir pressure as possible.

In the case of CO2 injection, however, where injections sites are potentially at virgin pressure already (e.g. saline aquifer), the risk here is initiation of new fractures, or reactivation of old ones. In addition, CO2 is not an inert substance. As mentioned earlier, permeance increases over time as the CO2 undergoes mineralization, but this only occurs after some amount of CO2 has dissolved in the surrounding brine, to form carbonic acid. It is possible that the chemical interaction with the acidified brine can cause a chemical weaking of the intergranular contacts, in turn resulting in a mechanical failure of the formation. A geomechanical study assisted by the analysis of log and core data for wells within the injection site is recommended to derisk this further.

# *Fresh Water vs Saline Aquifer*

Fluid/Fluid interactions and the displacement characteristics of CO2 are critical in CO2 storage within the subsurface. Salinity, electrical properties and temperature are all interrelated, and can have a major impact on the injectivity of CO2 into the formation. CO2 solubility typically decreases with an increase in salinity (Figure **6**); this results in the precipitation of salt and influences near well bore porosity and permeability [5]. Therefore, a lower salinity aquifer is preferred. However, environmental considerations with potential contamination of water resources can become a constrain when salinities are less than 30,000 ppm. A petrophysicist must therefore critically understand the aquifer characteristics and have a regional view of how the salinity varies. In the case of an injection site, the salinity calibration is very important. A petrophysicist should insist on a thorough analysis of the ionic components present in the water, and assuming there are conflicts with groundwater requirements, must be ready with secondary or even tertiary injection alternatives.

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**Figure 6:** CO2 solubility vs. salinity in freshwater (independent of pressure and temperature). Adapted from [6].

# *Effective vs Total Porosity*

Porosity is a key petrophysical input for volumetric consideration in estimate total storage potential of CO2. In traditional oil and gas exploration/development, the volumetric equation solves for a volume of hydrocarbon in the reservoir. As a result, either effective porosity (PHIE) or total porosity (PHIT) may be used as input into the equation, with the corresponding water saturation (total or effective) being used in accordance to calculate a volume of hydrocarbon (Figure ***7***). In CO2 injection projects, however, the volume of interest is only the amount of free fluid volume (FFV) that CO2 may displace after injection. Assuming CO2 injection occurs into a water saturated formation, PHIE (not PHIT) should be the input into the theoretical storage resource (Equation 2).

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**Figure *7*:**Summary of Bulk rock volume, and the various definitions of porosity.

# *Wettability*

The wettability of a rock refers to the preference of a liquid phase to be attracted to a grain’s surface. CO2 is always non-wetting to water (by definition). Therefore, wettability is not an issue in the case of injection into a depleted gas field or a saline aquifer. Wettability only becomes a concern if CO2 is being injected into a (depleted) oil field. In the case of a water-wet or mixed wet reservoir, where oil is not predominantly in contact with the grain surfaces, the dissolving of CO2 in oil or brine causes changes to both oil properties and pH respectively. In some cases, asphaltene drop out can occur, making the rock more oil-wet. A petrophysicist can assist in derisking this by conducting special core analysis studies (SCAL) with real reservoir fluids to mimic the conditions in the reservoir.

# *Trapped Residual Phase Saturation*

When CO2 is injected into a depleted oil field, residual hydrocarbon saturation (Shr) becomes an important parameter to evaluate. Shr is the fraction of hydrocarbons trapped in the reservoir that has experienced water encroachment [10]. This residual saturation occupies effective pore space which would otherwise be able to host CO2 being injected. Studies have suggested that reduction in brine mobility, density and viscosity of gas mixtures when dissolved into supercritical CO2 can cause the decrease in storage capacity. Additionally multiphase depleted gas reservoirs may also experience lower CO2 injectivity at early stages, although this may improve over time [11].

In such cases, studies into trapped residual phase saturations are valuable pieces on information. If a petrophysicist understands the fundamental reservoir properties like porosity or clay types present within the injection reservoir, then through the choice of appropriate analogs, one could obtain an early estimate of Shr (Figure ***8***). If there is higher confidence data like core measurements, than petrophysicists (working cooperatively with reservoir engineers and geomodellers) can help to design pre-injection dynamic models which can properly capture the phase behaviour of such reservoirs.

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| Increasing  Clay  Proportion |

**Figure *8*:**Plot of Residual Phase as a function of Porosity and increasing Clay Proportion. Modified from [7]

# *Capillary Pressure & SWirr Ranges:*

In injection into saline aquifers, the reservoirs of interest are typically at 100% Sw. For injection into depleted oil or gas fields, the goal is to displace any wetting phase such that all the effective pore space is filled with the non-wetting CO2. In all these cases, the focus of the evaluation is SWirr, which reflects the minimum amount of water that will not be displaced by any amount of injected CO2 volume. The assumption here is that SWirr is associated with clay and capillary bound water only. Typically, SWirr values are determined from capillary pressure (Pc) data. The Pc data can be from conventional core or mercury injection capillary porosimetry (MICP) measurements.

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|  |  | Equation 4 |
|  |  | Equation 5 |
|  |  | Equation 6 |

where is interfacial tension (dyne/cm), is the contact angle (degrees), subscript (lab) are measurements made at lab conditions and subscript (res) are measurements are reservoir conditions, x and is the wetting and non-wetting phase gradient in psi/m respectively.

A practicing petrophysicist must note a few things in evaluating SWirr. First, as Pc is converted to height above free water level (HAFWL or column height) using fluid parameters or an analogue (Equation 6), and as these values are hard to measure experimentally, a petrophysicist might consider a range of values and adopt a “low-best-high” solution for SWirr estimates. Secondly, there should be a full range of rock types available to ensure a complete characterisation of the reservoir.

Pc measurements should also be done on seal rock, if available. In the scenario where there are no data available or no reasonable analogues available nearby, an estimation of capillary seal characteristics can be made from converting pre-production hydrocarbon column heights to equivalent CO2 column heights [12]. Again, a petrophysicist should look into the sensitivities of the x or y values (Equation 6) by assuming that the density of the wetting and non-wetting phase is changing, as a function of temperature and pressure (**Error! Reference source not found.**). It is worth noting that if the structural trap is capillary limited then the sensitivities can determine the theoretical maximum CO2 column height.

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**Figure 9:** Generic pressure-temperature phase diagram (L) CO2 and (R) Water

# *Joule–Thomson cooling and Geomechanics*

The injection of high-pressure CO2 into a low pore pressure, depleted oil and gas reservoirs can lead to significant Joule–Thomson cooling (JTC). JTC is the thermodynamic process that occurs when a high-pressure fluid is allowed to expand rapidly in the reservoir, causing its temperature to decrease. JTC is particularly relevant in the context of CCUS. During injection and subsequent depressurization, JTC can cause significant changes in the geomechanical properties of the rock, which must be carefully monitored to ensure the integrity and safety of the storage reservoir.

Upon first being injected into the formation at a high pressure, the rock would become saturated with the supercritical CO2. The significant pressure gradients that develop between the under-pressured reservoir and the over-pressured CO2 could results in an adiabatic expansion of the CO2 in the pore space, causing the temperature of the fluid and the surrounding rock to decrease, potentially freezing the in-situ pore fluids as well as causing the generation of hydrates, thus severely limiting the overall injectivity of the reservoir [8]. The rapid freezing also causes micro stresses to develop at the grain-to-grain contact, brought about by the rapid freezing of the interstitial water [8].

At later timescales, as injection slows or stops, and as the CO2 fluid migrates in the reservoir, it starts to undergo expansion. In this case, Joule–Thomson expansion (JTE) can also add mechanical stress to the rock formation, via propagation of fractures or deformation of the rock. In some instances, the risk brought about by potentially increasing porosity, permeability could cause changes in the strength and stiffness of the rock. The degree of change in these properties will depend on the rock type, the magnitude of the pressure reduction, and the speed of the JTC/ JTE process.

For a practicing petrophysicists, data is key here. Part of the risk mitigation is to perform geomechanical studies on different kinds of stressed rock, and if possible, simulate rapid freezing or cooling of rock samples before subjecting them to geomechanical testing. This should be done in collaboration with a core lab or geomechanics expert. Additionally, log data should be calibrated to these studies and “what-if” scenarios modelled prior to sanctioning any form of injection process in a field, to further derisk the potential for failure.

# *Cased Hole & Production Logging*

Cased hole logging is a method used to evaluate the wellbore and the surrounding formation behind the casing of a well, while its complementary technique, production logging is a method used to evaluate the flow of fluids through a wellbore. In CO2 injection operation, monitoring for long-term effects is key, to determine formation properties over time, or to determine effectiveness of CO2 injection and storage operations.

Starting at the wellbore scale, Production Logging Tools (PLT) may prove useful to determine if fluid is entering the zones as per design, reaching target zones, or (in EOR operations) displacing oil and gas effectively. The challenge here the risk that spinners may become impacted by JTC effects. A fluid density tool, temperature and pressure measurements are useful measures as well, for efficiency of the injection and storage processes, particularly when it comes to optimizing injection rates to achieve the desired level of CO2 storage. These tools are passive and are not impacted by deleterious effects from CO2 injection. Caliper tools and magnetic casing collar locators (CCL) should be interpreted for corrosion or scale formation, which can affect the integrity of the well and the surrounding formation. In the case of case of remediation of wells, PLT tools can be used to determine if these have been adequately addressed.

For behind casing, cement bond logs (CBL) should be used to evaluate the integrity of the cement that surrounds the casing of the well. This is important for CO2 storage operations, as any leaks in the wellbore can cause CO2 to escape into the surrounding formation. Using pulsed neutron or carbon-oxygen logging, the petrophysicist can determine how the CO2 is moving in the formation via observations of fluid contact. A cased hole resistivity tool (CHRT) can serve a similar function, particularly is CO2 is being injected into a saline aquifer. The displacement of brine would cause a resistivity change, which can be used to evaluate saturation. For plume detection, CHRT applied across a series of wells in the field can be used to map resistivity changes in the field and therefore create a “pseudo-map” of Co2 movement.

# **Risk Matrix**

The above-mentioned points show the degree of risk and uncertainty there are in CO2 storage projects. It is therefore only prudent that a project risk matrix be first developed before embarking on any such injection project. For this paper, given that we focus primarily on the petrophysical considerations for storage projects, the risk matrix we have designed (

Table **1**) is a tool for project petrophysicists to document risks/uncertainties and how they rank relative to others (in terms of impact on the project) for the express purpose of better communication with project managers or subsurface members.

The risk matrix can also be used as a way of developing fit for purpose data acquisition programs. When data acquisition is tied to a project level risk or uncertainty, the purpose of data collection become a lot clearer. The value of information associated with acquiring the dataset may also be assessed – relating the likelihood of de-risking or reducing key risks and uncertainties to the financial impact that would be associated with the risk occurring. This allows the datasets which reduce the most amount of risk to a project for the least cost to be prioritized.

As opinions of risk can be subjective, we have designed the matrix with “generality” in mind. We do this using categorical “Low, Medium and High” descriptors. As illustrated by

Table **1**, and from left to right, our matrix outlines (a) key risk events which may occur, (b) impact rating, defined as how the identified risk can potentially affect the material success of the project, (c) data acquisition priority, defined as the timeliness of data collection for project derisking, (d) the impact on the project and (e) what data should be acquired.

**Table 1:** Generic risk matrix for CCUS project

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| --- | --- | --- | --- | --- | --- |
| **Risk Event** | **Impact Rating** | **Data Aq Priority** | **Impact on Project** | **Recommended Data Acquistion** | **Further Recommended Analysis on Existing Data** |
| Leakage up legacy wells | High | High | Possible migration from primary Muda aquifer storage site to secondary containment within the storage complex | Continued monitoring of production wells via cased hole logging | Well by well analysis of status and risk of leakage |
| Monitoring of seabed for surface expressions of gas expulsion |
| Drop core monitoring |
| Inaccurate storage capacity estimates | High | Medium | Not able to inject sufficient volume as expected | Additional well data | Detailed site-specific volumetrics with improved seismic mapping, refined formation tops, GRV approach, site specific reservoir parameters |
| Incorporation of regional data to understand potential aquifer size |
| Geomechanical alterations in the reservoir | High | Medium | Thermal cooling of reservoir or localised pressure build up at legacy well locations. | Lab tests on reservoir core data | Conduct prelimary geomechanical study based on existing data such as logs |
| Wellbore Collapse, subsidence |
| Active seismicity | High | Low | Possible re-activation of faults and leakage of CO2 | Seismometer deployment | Review of regional seismicity and possible impact on fault reactivation / top seal |
| Top Seal Failure | Medium | High | CO2 mobility and migration different from expectation impacting capacity and containment | Top and intraformation seal Core and SWC collection | Geomechanics study |
| Cap Pressure measurements |
| Migration of CO2 up faults | Medium | High | CO2 mobility and migration different from expectation impacting capacity and containment |  | Fault mapping (assited by coherency attributes) and correlation to overburden gas flags |
| Charge / migration / timing basin evolution study to understand fault trapping vs timing of migration and trap formation |
| Faults seal study - shale gouge, allen diagrams etc |
| Migration of CO2 beyond storage complex | Medium | High | CO2 mobility and migration different from expectation impacting capacity and containment | Tracer tests | Detailed static and dynamic modelling of reservoirs high-graded for injection and overburden. |
| Analogue studies |
| Injection into isolated channels | Medium | Medium | Lack of storage capacity and incorrect well count due to uncertainty in injectivity | Additional injection data from water disposal and / or pilot CO2 test | Detailed seismic amplitude work / spectral decomposition |
| Inversion Study / Gather conditioning to enhance signal in key reservoir areas to map rock properties and geomorphologies |
| Insufficient injection rates | Medium | Medium | Lack of storage capacity and incorrect well count due to uncertainty in injectivity | Core data taken across key injection complex | Aquifer geoceulluar reservoir modelling and matching to injection rates to understand reservoir dynamics |
| RCA / SCA |
| Geochemical alterations in the reservoir | Medium | Medium | Impaired injecvity and reduced final storage capacities. | Lab tests on core and fluid data | Geochemistry study and modelling |
| Formation of chemical compounds not anticipated impacting material selections and threatening injectivity |
| Incorrect structure | Medium | Low | Not able to inject sufficent volume as expected | Seismic processing/additional well data | Review depth conversion and velocity modelling |
| Limited ability to monitor plume through passive methods | Medium | Low | Various monitoring technologies will have to be deployed to infer CO2 remains in storage site | Installation of downhole gauges for pressure monitoring in offset wells | 4D feasibility study, fluid replacement modelling etc |
| Alternative monitoring options review: monitor wells, gravity, CSEM, microseismics |

# **SRMS Petrophysical checklist**

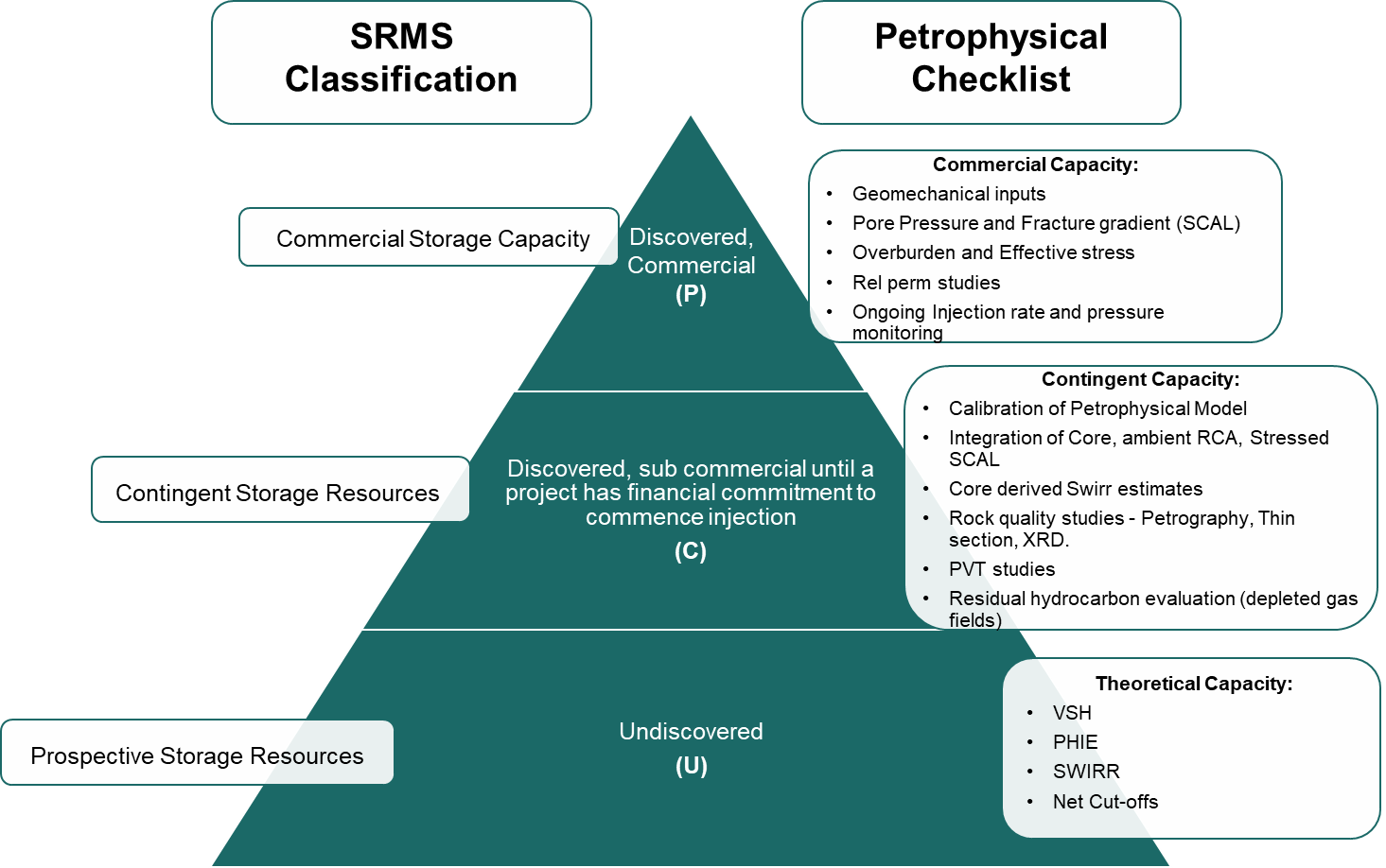
From the petrophysical considerations and risk table, we have developed a simplified checklist that can be used when conducting petrophysical evaluation of CO2 Storage potential. This checklist isn’t designed to be an all-inclusive, exhaustive list of petrophysical ‘must-dos’ in a CO2 sequestration project. Rather, it aims to provide a relatively simple guideline to follow in terms of best practices to produce a technically sound and easily auditable interpretation. The checklist is developed with consideration for the SRMS and is given in Figure 10.

How much detail required for each stage of the evaluation will depend on the geological uncertainty, the data available, as well as the timeline and scope of the project. For example, a project in a depleted gas field is likely to have a lot more data available that can be integrated into petrophysical evaluation, whereas injection into a saline aquifer is likely to carry a larger uncertainty with less data available.

We firstly start at the prospective storage resources, or the theoretical capacity as defined by SRMS (Figure **10**). The evaluation required at this stage is similar to any oil and gas petrophysical evaluation. Key differences are an assessment of PHIE and the estimation of SWirr.

As the project is matured to a Contingent Storage Resource stage, consideration must be given to formation mineralogy, permeability, core derived SWirr and residual hydrocarbon saturation (in depleted fields), formation temperature and pressure. This is account for the more detailed dynamic observations and rock-fluid and fluid-fluid interactions. This provides a more detailed understanding of the formation’s storage potential before final investment decision occurs.

Because density of CO2 is important in volumetric calculations for total storage capacity, as well as phase of the fluid being critical for the project success, the petrophysicist may be required to consider other factors or parameters which may typically fall under petroleum or reservoir engineering disciplines at both the Contingent Storage Resources and Commercial Storage Capacity phases. These include CO2 chemical composition, pore pressure and fracture gradient analysis as well as geomechanical studies on grain-grain, fluid-grain impacts as well as cased hole monitoring to evaluate injection rates and potential fines migration.

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**Figure 10:** Generic petrophysical checklist for evaluating the CO2 storage potential in line with SMRS workflow

# **Case Study - Cloverhill-1**

We will use the Cloverhill 1 well as a case study to outline the practical application of the petrophysical workflow presented in Figure 10. The well is a wildcat exploration well drilled in 2014 and is located in the southwest of exploration permit WA-268-P, in the Northwest Shelf off the cost of Western Australia (Figure **11**). Cloverhill-1 targeted the Top Mungaroo “AA” sands and the intra-Mungaroo “A-Lower” sands.

The well encountered both gas and water legs and has a modern and complete log suite, which makes it a good analog example to show a hypothetical CO2 sequestration Storage Project, either into the brine aquifer or into a (depleted) hydrocarbon bearing zone. We will start by viewing the well as you would a prospective resource (U), where the only goal is to determine some basic view about theoretical capacity. For the petrophysicsis, that means providing VSH, PHIE, SWIRR and applicable net cutoffs.

|  |
| --- |
|  |

**Figure 11:** Location map of the Cloverhill-1 well

The Triassic Mungaroo formation is characterized by upper and lower delta plain channel sandstones, swamps and restricted embayments. The system is dominantly comprised of sand and shale of variable thickness, occasionally interbedded with thin coals and pyritic nodules. The reservoirs are predominantly quartz along with some dispersed glauconite grains. The reservoir section is divided into two main intervals, the A and AA sands. In general, the A sand has poorer sand development than the overlying AA sand and is a more coal prone interval. This is reflected with a lower net to gross compared to the overlying AA sand (20% in the A sand and 80% in the AA sand). The sand quality is also poorer in the underlying A sand, with average effective porosities of 18% compared to just under 25% in the AA sands. At Cloverhill-1 the A sand and lower portion of the AA sand is water bearing, while the upper part of the AA sand is gas bearing Figure 12.

The initial steps in the generalised petrophysical workflow (Figure 10) are consistent between both hydrocarbon exploration CO2 storage projects. Both require standard formation evaluation procedures. Petrophysical analysis was undertaken, integrating wireline, LWD, mudlogs, formation pressures, cuttings, and knowledge of the depositional system. The initial evaluation covers the key inputs into the theoretical storage capacity at the prospective resources stage in Figure 10.

The storage capacity of CO2 is determined by evaluating Equation 2. Both total and effective properties were calculated in this case. From the logs and available core data, the N:G, porosity (both total and effective) and SWirr can be determined quite readily. The evaluation uses a deterministic approach for determining volume of shale, porosity, and water saturation. Both VSHGR and VSHND were calculated, with the lowest of the two being carried through the evaluation. This acted as input into the N:G calculations through the use of a VSH cutoff less than 0.5.

From here, porosity was interpreted using (a) straight Density (D) porosity (PHID), or else in combination with neutron (N) to give total porosity (PHIT). PHIT was corrected for hydrocarbon effects and invasion. For QC purposes, porosity is also evaluated using the NMR porosity with D logs (density magnetic resonance porosity or DMRP). For application to CO2 injection into a saline aquifer, however, effective porosity (PHIE) must be evaluated. To do this, we calculate the porosity of shale and remove its porosity component to determine the final PHIE value.

Water salinity was derived in the water leg penetrated in Cloverhill 1 using a Pickett plot technique. This provided an output salinity of 25,000 ppm NaCl, which is relatively fresh, thus making it a viable CO2 injection reservoir at first glance. The cementation exponent (*m\**) and saturation exponent (*n\**) were derived from a nearby analog; the final values used for this interpretation are *m\**=1.92 and *n\**=2.15. The resultant resistivity derived water saturation (SWTRES), NMR derived water saturation (SWTDMRP) and capillary pressure derived saturation from core (SWPC) show a good match. SWirr was confirmed by observing the matches between SWPC, SWTRES and saturation estimated by the array dielectric tool (SWXOADT). NMR also provides an independent measure of SWirr by summing the Clay bound water and Capillary bound water (BVW + BVI). The SWirr is equivalent to the minimum water saturation from capillary pressure curves. The integration of variable methods of evaluating porosity and water saturation gives confidence in the evaluation and the inputs into equation 2.

Chart

Description automatically generated

**Figure 12: Figure: Cloverhill 1 Log Data & Petrophysical Interpretation – 1: 1800 scale**

Post initial evaluation of the theoretical capacity, the saline aquifer in both the A and lower AA sands is a good contender for CO2 storage. To progress the evaluation through to contingent capacity (discovered and sub-commercial) the petrophysical model would need to be calibrated and updated to address some other uncertainties.

For a viable storage project, a detailed routine and special core analysis (RCA and SCAL) should be planned on the Cloverhill-1 core plugs that have been collected. This should include rock quality studies through petrography, thin sections and XRD to better understand mineralogy, pore structure as the presence of minerals such as K-feldspar, Plagioclase and carbonate that may dissolve and reprecipitate in the formation, causing a reduction of PHIE and permeability over injection time scales. Permeability should also be estimated, through porosity-permeability relationships derived from core and subsequently integrated with NMR derived estimates and mobility data available from XPT.

The AA sand may also be of interest for storage once the hydrocarbon column has been produced. Analysis would need to be undertaken on estimating column heights of CO2 that could be supported (in absence of capillary seal characteristics of the cap rock). Currently the saturation heigh function used to generate SWPC in Cloverhill-1 is based on analogue fields nearby. MICP analysis should be conducted as part of the SCAL program on a range of plugs which represent the variety of rock types encountered in the reservoir. This will provide better estimates to SWirr for input into Equation 2Equation 2. The Pressure data also confirms the free water level (FWL) which will be important to update any assumptions made around this for saturation height modelling. Having a good understanding of Swirr will be critical in the case of application to depleted field CO2 injection, as it will also aid in future modelling of any Shr post production to better understand fluid-fluid interactions after the onset of injection.

To progress to contingent storage resources (C), however, we will need to start integrating some higher level data. From Figure 10, this includes data from core analysis as it relates to SCAL and stressed RCA. Thin sections, SEM and XRD thin sections should also be analysed for mineral compotion and where possible, PVT and hydrocarbon evaluation from CO2-Brine studies should now be incorporated into the workflow.

The maturation to commercial storage capacity (P) requires even more detailed studies be undertaken, with integration of geomechanical and dynamic observation to be integrated. Relative permeability for CO2 to brine will be of interest to gauge how the CO2 plume will behave after the onset of CO2 injection. As project commerciality will now be assessed, there is less involvement from the petrophysicist. However, other subsurface experts may require petrophysical inputs and “what-if” scenario modelling as optimal injections rates as modelled, either via dynamic modelling or via material balance.

# **Data Acquisition**

Data gathering, and acquisition are critical in properly evaluating key parameters for CO2 sequestration projects.

Data types used in CO2 injection projects can be broken into three broad categories: Seismic, Logs (LWD and Wireline, WL) as well as Core. To ensure the data gathering is fit for purpose and within project scope and budget, key project risks and uncertainties should be identified early in project definition phase and the various phases of the data gathering and analysis should be outlined and understood with key stakeholders and service companies.

Typically, Seismic 2D or 3D datasets are acquired early in the project define phase, for regional interpretation, identification of traps and a range of gross rock volume which typically has the largest impact on any volumetric analysis. While the petrophysicist may be involved in the seismic providing inputs for seismic to well ties, depth conversion or fluid substitution studies, this is out of scope for the discussions of this paper.

Petrophysicists are most concerned with well based data, either from LWD or WL logging. Given the necessity to acquire core and aquifer fluid samples, oil-based muds (OBM) should be used as a preference. If there is appetite for the acquisition of both LWD and WL data, this should be encouraged, as there is natural lapsed time between an LWD and WL operation which can be used as a mini downhole “injectivity” and capillary trapping test of sorts. As an example, if OBM filtrate has invaded a depleted reservoir or saline aquifer, and a LWD pass shows a light hydrocarbon effect (LHC) in the permeable sand, then the WL pass should show a similar LHC, illustrating that capillary trapping and injectivity have taken place. In fact, the longer the time between the LWD and WL passes, the better. This is a qualitative test, of course, but adds confidence that the CO2 injection operation may be possible.

Depending on the maturity of evaluation required for the CO2 injection study, some specific log measurements may also be necessary to reduce evaluation uncertainty. This may include (but not limited to) NMR logs, which can provide an independent measure of PHIE, SWirr and FFV which can be compared with traditional evaluation methodologies outlined earlier. Formation pressure and temperature are key in predicting phase and resulting density of CO2 on injection for input into theoretical storage volume estimates. While temperature is a standard output for most wireline logging runs, it may mean acquisition of multiple pressure runs with different tool types/gauges are necessary depending on the formation’s mobility (drawdown required) and whether downhole sampling is necessary to calibrate salinity of the formation water.

Core observations are also important to calibrate log based petrophysical models. As easrly to medium time scale CO2 trapping is very much dependent on a good understanding of pore structure, conducting experiments at the microscale can allow some insight into how the system may behave at the macroscale. Table 2 highlights some of the key core analysis experiments which would be useful for CCUS evaluation depending on subsurface uncertainties in each field. This table does not consider QA/QC checks that should be conducted on the core lab facility to determine adequacy of facilities, or core preparation which should be done by default (e.g., core gamma log, photography, whole core CT etc). It is also critical as part of the update to ask the core laboratory for data showing samples have equilibrated when measurements are made. The table excludes basic measurements and only focuses on CO2 specific measurements based on objectives (which uncertainties you are attempting to reduce), experiment type and the outputs, as well as what sized samples are appropriate for testing. A last point to note is on time lapse monitoring. CO2 is a “live” fluid which changes with time and exposure to subsurface conditions. Therefore, as much as possible, these experiments should be repeated, and results should be compared to previous measured values. In this way, this “time lapse” series of experiments will show how the trapped/ injected CO2 is causing/undergoing change with time.

# **Conclusion**

**Table 2: Core based experiments for varying sized core plugs and objectives for de-risking CCUS projects.**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Objectives | Experiment | Outputs | Sample Size | | | | Sample Type | | | Notes |
| < 1"  (e.g. cuttings) | 1-1.5" | 4"  (Full  Diameter) | Composite | CCA | SWC | Percussion |
| CO2 Specific Measurements | | | | | | | | | | |
| Fluid Displacement, Diffusion Processes | X-Ray CT and mCT Capillary Pressure Imbibition and Drainage Capillary Pressure Counter Current Imbibition/ Spontaneous Imbibition | Irreducible Water Saturation Trapped gas saturation (Sgt) |  | ü |  |  | ü | ü |  | Both porous plate and centrifuge can be run Use CT to perform time lapse monitoring of CO2 migration as well as trapping mechanism Also perform a series of capillary hysteresis experiments (scanning curves) Run experiments at Swi (as an analog for gas cap behaviour) |
| Fines Migration | NMR Flow Through Experiements X-Ray mCT | (Change in)  Porosity Permeability Saturation Fines Produced in Effluent Injectability | ü | ü |  |  | ü | ü | ü | Recommended to confirm salinity before these experiments are done.  These experiments are to be done via "time-lapse" |
| Mechanical Properties | Triaxial Compression Test Uniaxial Compression Test | Strength & Elastic Properties  (Young's Modulus and Poisson's Ratio) Pore Volume Compressibility Bulk Volume Compressibility |  | ü | ü |  | ü | ü |  | Samples are required to have a 2:1 length:diameter ratio (this prevents interference between the end platens and the sample as it fails). Vertical samples preferred. Experiments should be designed to answer questions related to wellbore stability, solids production, subsidence, well operability limits, thermal fracturing and seal integrity. Also hysteresis studies are recommended |
| Seal Capacity/ Integrity | Mercury Injection | Threshold Pressure (Distribution of) Pore Sizes | ü | ü |  |  | ü | ü |  | Recommended to run |
| Salinity | Dean-Stark Standard Water Analysis (Acetate Water Analysis) | Ions present in water |  | ü |  |  | ü | ü |  | Tested on either water obtained on E-line or else water from Dean-Stark |
| Others | Interfacial Tension,  Geochemical Interactions,  CO2 Properties, CO2-HC blend for injection, salt precipitation |  | ü |  |  |  |  |  | ü | Experiments should be done on both caprock as well as on reservoir rock. Fluid samples will be required as well |

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