

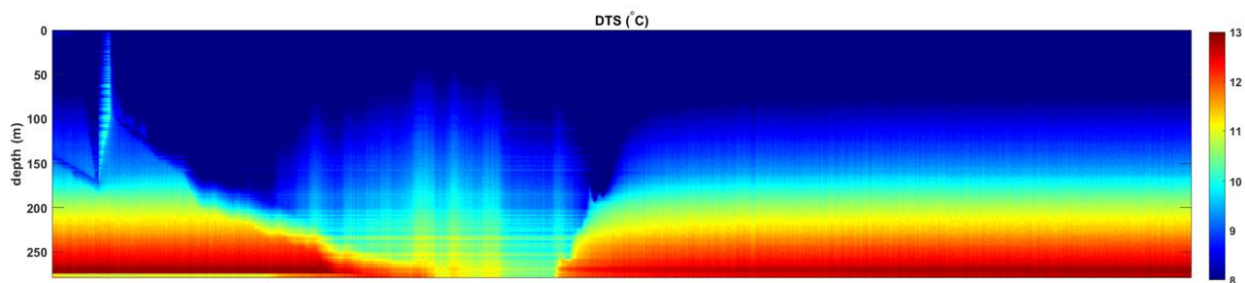
# FINAL OUTCOMES REPORT (NON-CONFIDENTIAL)

## 1.0 PROJECT INFORMATION

<b>1. ERA PROJECT ID #</b>	E0161581
<b>2. CALL / ROUND</b>	ACT-Horizon 2020
<b>3. PROJECT TITLE</b>	Reusing Depleted oil and gas fields for CO <sub>2</sub> sequestration (RETURN)
<b>4. COMPANY NAME</b>	Carbon Management Canada
<b>5. PROJECT TYPE</b> (R&D, Development, Demonstration, Implementation)	
<b>6. LOCATION</b> (primary location the project took place by address, land description, or GPS coordinates)	Calgary and the Field Research Station in Newell County (162025 Township Rd 174 (10-22-017-16W4, Newell County, AB. T0J 2M0)
<b>7. PROJECT START DATE</b>	Dec 1, 2021
<b>8. PROJECT COMPLETION DATE</b>	Nov 30, 2024
<b>9. TECHNOLOGY READINESS LEVEL (TRL) AT PROJECT INITIATION</b>	3-5
<b>10. <u>TRL AT PROJECT COMPLETION</u></b>	6-7
<b>11. JOBS CREATED</b>	
<b>12. GHG EMISSIONS REDUCED</b> (Project-level: annual, cumulatively by 2030 and by 2050)	Not applicable for this project
<b>13. TOTAL ERA FUNDING</b>	\$345,216
<b>14. TOTAL PROJECT VALUE</b>	\$690,432

<b>15. ERA PROJECT ADVISOR</b>	Ericka Rios
<b>16. SUBMISSION DATE</b>	
<b>17. KEY PROJECT CONTACT NAME AND EMAIL</b>	Dr. Donald C. Lawton Don.Lawton@cmcghg.com
<b>18. QUOTE</b> (why was ERA a pivotal funder for this project? How did ERA funding help advance on the TRL scale? Etc.)	The RETURN project increased the understanding of CO <sub>2</sub> injection strategies in depleted oil and gas reservoirs by developing tools which can properly simulate the complex processes happening both in the wellbore and the reservoir.
<b>19. NOTABLE COMMUNICATIONS</b>	Behmanesh, H., Macquet, M., & Lawton, D. C., 2024, Enhancing Geological Carbon Storage: A Detailed Study of CO <sub>2</sub> Wellbore and Reservoir Interactions: <i>17<sup>th</sup> International Conference on Greenhouse Gas Control Technologies, October 21-24, Calgary, Alberta, Available at SSRN 5071245.</i>
<b>20. IMAGE</b> (please insert or link a photo capturing the technology for ERA publications)	

*One month of profile temperature of the CO<sub>2</sub> injection well at the Carbon Management Canada Newell County Field Research Station.*



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## 5.0 EXECUTIVE SUMMARY

The RETURN Project, funded by Emissions Reduction Alberta (ERA) under the ACT-Horizon 2020 initiative, focused on enabling long-term CO<sub>2</sub> storage in depleted oil and gas reservoirs. Led by Carbon Management Canada (CMC), the project was carried out at the Field Research Station in Newell County, Alberta, and involved international collaborators.

The project developed and validated a high-resolution coupled wellbore–reservoir simulator (CALYSTO), which accurately models Joule-Thomson cooling, CO<sub>2</sub> phase changes, and thermal stresses during injection. The CALYSTO simulator, tested against real-world injection data, offers operational insights that enhance injection efficiency and maintain wellbore integrity. Field experiments confirmed the tool’s accuracy, supporting optimal injection at approximately 300 kg/day without heating CO<sub>2</sub>, thereby reducing energy demand and costs.

Although direct CO<sub>2</sub> injection at the CMC FRS is modest (~1.5 tonnes/month), RETURN facilitates future large-scale emissions reductions by unlocking depleted fields for CO<sub>2</sub> storage. These reservoirs, previously used for hydrocarbon extraction, provide vast, low-cost, and well-understood storage

capacity. By enabling infrastructure reuse and speeding up project timelines, RETURN supports provincial and global decarbonization efforts.

Key outcomes include:

- Raising TRL from 4–5 to 6–7.
- Successful development of CALYSTO and validation against CMG software.
- Integration of real-time geophysical monitoring with reservoir modeling.
- Demonstration of safe, stable CO<sub>2</sub> injection techniques.
- Providing policy-relevant evidence to include depleted fields in CCS regulations.

## 6.0 PROJECT DESCRIPTION

### 6.1 INTRODUCTION

The project is part of a larger international initiative (Project number: 327322 - CLIMIT International Calls Support for Bilateral Project), which partners from Norway, (Equinor, SINTEF, Lundin Energy), the Netherlands (TNO, University of Utrecht, Shell, EBN, Neptune), Germany (Wintershall, Freiberg University), UK (OGTC, University of Cambridge, Chrysaor, bp,), Italy (ENI), and Canada (CMC, SpectrumH2, Caledonian Midstream, COSIA). Carbon Management is contributing to Work Package 2, which focuses on coupled well-reservoir flow modelling, alongside its project partners: EBN (the Netherlands), SpetrumH2 (Canada), and Harbour Energy UK (formerly Chrysaor (UK)). Although direct CO<sub>2</sub> injection at the CMC FRS is modest (~1.5 tonnes/month), RETURN facilitates future large-scale emissions reductions by unlocking depleted fields for CO<sub>2</sub> storage. These reservoirs, previously used for hydrocarbon extraction, provide vast, low-cost, and well-understood storage capacity. By enabling infrastructure reuse and speeding up project timelines, RETURN supports provincial and global decarbonization efforts.

The project focused on unlocking the potential and strategies for injecting cold CO<sub>2</sub> in depleted oil and gas reservoirs. This will ultimately enable safe and cost-efficient re-use of depleted reservoirs for long-term CO<sub>2</sub> storage. The targeted research required to reach this goal is addressed in three main scientific work packages focusing on: (i) coupled well-reservoir flow modeling, (ii) near wellbore processes, and (iii) wellbore integrity. The work, comprising experiments, numerical modeling, and field tests, focused on understanding how CO<sub>2</sub> flows down the well and into the depleted reservoir and identifying safe operational windows for the near-well region and wellbores.

The project developed a coupled well-reservoir flow simulator that can take JT cooling and CO<sub>2</sub> phase change complexities into account (numerically and experimentally validated, tested in a case study and benchmarked towards commercially available software codes for well/reservoir flow).

### 6.2 BACKGROUND OF THE PROJECT

The use of depleted oil and gas reservoirs for CO<sub>2</sub> storage is promising, as they are well characterized from previous oil and gas activities, and they have large pressure margins for safe storage. There are, however, some technical challenges related to storage in such sites. The low pressure in the depleted reservoirs

results in strong cooling and potential freezing of the well and near-well region due to the Joule-Thomson effect and associated phase changes of the CO<sub>2</sub>. This jeopardizes not only injectivity but also near-well stability and well integrity. Large depletion can be accompanied by strong stress concentration and a hysteresis effect upon re-pressurization, in addition to thermal stress development. Today's available solutions include heating the CO<sub>2</sub> and gas-phase injection (dictating a high number of injectors); this is both expensive and emission-intensive. To address those technical challenges and unlock the depleted reservoir potential, the scientific community needs to:

- **Build new knowledge to determine safe operational windows** for CO<sub>2</sub> site injection into depleted reservoirs (this includes a better understanding of, and ability to model, injection cooling and phase transformation effects, impacts on the near-well formations and potential risks to well integrity).
- **Recommend injection strategies and infrastructure adaptations for enabling dense-phase injection of CO<sub>2</sub> into depleted reservoirs** (thus removing the need for heating prior to injection, or gas phase injection, which are today's alternatives).

### 6.3 PROJECT OBJECTIVES

The primary objective is to unlock CO<sub>2</sub> storage in depleted reservoirs potential by:

- Enabling safe and cost-effective long-term CO<sub>2</sub> storage in depleted O&G reservoirs by understanding and handling cooling and CO<sub>2</sub> phase-change during the injection.
- Enabling coupled well-reservoir flow modeling, including effects of strong cooling and phase changes of the CO<sub>2</sub> during injection. Validate the coupled flow model both experimentally and through field tests and apply the validated model to real field cases;
- Understanding how substantial temperature and pressure variations are expected during CO<sub>2</sub> injection into depleted reservoirs, which will affect the near-well region (reservoir and caprock), impact on storage capacity (depletion/re-pressurization effects) and injectivity;
- Exploring the details of how, when, where, and why well integrity can be at risk during CO<sub>2</sub> injection into depleted reservoirs, resulting from cold temperatures and substantial varying downhole pressures and temperatures.
- Assess thermodynamic well-bore effects in a CO<sub>2</sub> injection well at Carbon Management Canada's Field Research Station (CMC FRS) in Newell County, Alberta and test observations of downhole pressure and temperature against predictive modelling software.

6.4 PERFORMANCE/SUCCESS METRICS IDENTIFIED IN THE CONTRIBUTION AGREEMENT

**Table 1: Performance metrics.**

Success Metric	Project Target	Project Achievement	Explanation
<b>Optimum CO<sub>2</sub> injection at CaMI determined</b>	1 tonne CO <sub>2</sub> /month	Between 1 and 1.5 tonne CO <sub>2</sub> /month	Injection schemes were optimized through a rigorous testing process.
<b>Successful coupled well-reservoir flow simulator</b>	75%	100%	The coupled well-reservoir flow simulator accurately replicated field observations, including Distributed Temperature Sensing (DTS) profiles and pressure responses from downhole gauges. This demonstrated the model’s capability to capture key thermal and hydraulic behaviors observed during CO <sub>2</sub> injection, supporting its reliability for forecasting and optimization.
<b>Evaluation of alignment between the measured and simulated data for the pressure and temperature at the injection well</b>	+/- 20% on bottom hole pressure, temperature and flow rate	+/- 20% on bottom hole pressure, temperature and flow rate	Simulated bottom hole pressure, temperature, and flow rate were within engineering error of the measured field data at the CaMI CO <sub>2</sub> injection well, demonstrating strong alignment. In parallel, project partner EBN developed an internal software package capable of modeling coupled wellbore-reservoir behavior with fewer limitations on minimum temperature representation. Results from EBN’s simulator were

			consistent with those obtained using CMG software, further validating the modeling approach adopted across the RETURN project.
<b>Estimation of CO<sub>2</sub> storage capacity in depleted gas reservoir in Alberta (with SpectrumH2 and/or Caledonian Midstream)</b>	1 Mt/year CO <sub>2</sub> storage	1 Mt/year CO <sub>2</sub> storage (simulation based)	All reservoir simulation studies were successfully completed, incorporating both reservoir dynamic modeling and coupled wellbore-reservoir modeling using data provided by SpectrumH2. The reservoir modeling effort included detailed evaluation of flow mechanisms, plume migration and expansion, and structural trapping potential to estimate long-term CO <sub>2</sub> storage capacity. Although no field injection was carried out, the simulations provided valuable insights into storage efficiency and containment behavior.

#### 6.5 PROJECT CHANGES

Initial Milestones 6 and 9 were revised during the lifecycle of the funded Project to Milestones 6A-6B and 9A-9B due to difficulties accessing data from a commercial site in Alberta

#### 6.6 TECHNOLOGY RISKS

Accessing real field data from Alberta was challenging and the project scope focused more on history matching and simulations of CO injection at the CMC Field Research Station (FRS). Since large-scale CO<sub>2</sub> storage in depleted reservoirs is still not permitted for CO<sub>2</sub> storage hubs, there was a risk in obtaining injection field data from hubs in Alberta. Small-scale storage may be undertaken through the SSR permit scheme, but no projects were available for this study. The mitigation was to focus on field results from CMC’s injection program at the FRS.

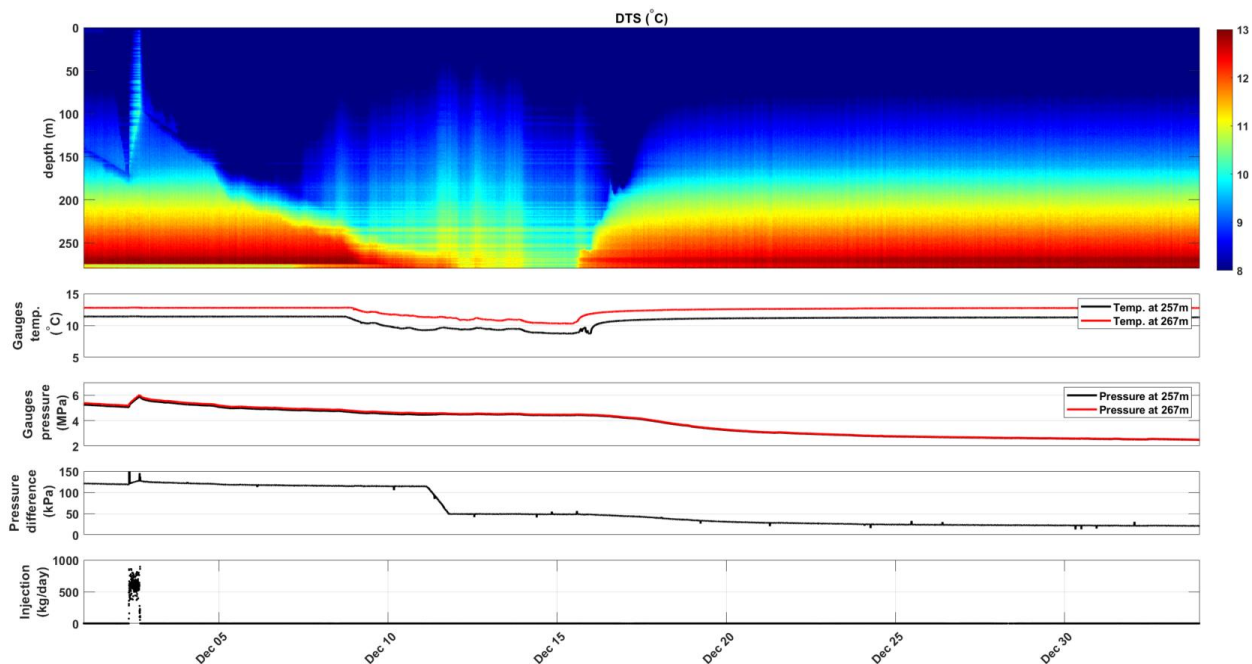
## 7.0 PROJECT WORK COMPLETED AND OUTCOMES

### 7.1 METHODOLOGY

Monthly meetings were held throughout the project to enforce collaboration with the project partners.

#### Milestone 1:

- A full assessment of CO<sub>2</sub> injection parameter data through CO<sub>2</sub> injection at the CMC FRS in 2021 has been undertaken and shared with researchers in Work Package 2 of the ACT3 RETURN project. Data includes surface and downhole pressure and temperature, Distributed Temperature Sensing (DTS) fiber data from the injection well, injection flow rates, duration, and volumes. Geophysical monitoring data (electrical and seismic) have been integrated with the CO<sub>2</sub> injection data.
  - Several meetings were held in January through March 2022 with the ACT3 RETURN collaborators including the overall Project Kick-off meeting that was held on 23-24 March and attended by Dr. Hamid Behmanesh from CMC.
- Compiled data set made available to ACT3 RETURN collaborators.
  - The extensive data set comprising injection parameters (Figure 1) was provided to ACT3 RETURN collaborators through a project SharePoint link.



**Figure 1: Injection parameters (distributed temperature sensing, borehole pressure and temperature gauges, rate) data recorded at the CMC FRS.**

- Identification and interpretation of injection data collected through 2021 from the CMC Field Research Station was undertaken. These data exhibited down-hole temperature variations considered to be caused by Joule-Thompson cooling during volumetric expansion of the CO<sub>2</sub> from liquid to gas phase in the injection well in the reservoir.

**Milestone 2:**

- CO<sub>2</sub> injection at the CMC FRS at different temperatures (controllable through an inline heater) and rate were designed and a full assessment of the injection parameter data was undertaken. It was ensured that the bottom hole pressure did not exceed the reservoir fracture pressure during these experiments.
- A static gradient field test was designed and conducted on April 8<sup>th</sup>, 2022 (Figure 2), to verify in-tubing pressure and temperatures at various depths in the wellbore. Specifically, the knowledge obtained was:
  - To obtain the temperature inside the tubing, at all depths and relate it to the existing annulus DTS readings.
  - To learn about the temperature profile in the regions above and below the gas-liquid interface.
  - To obtain liquid levels and compare to signatures of existing annulus DTS.
  - To obtain in-situ gas and liquid densities and compare to the theoretical values at the relevant wellbore pressure and temperature.
  - To learn about the temperature profile in the regions above and below the gas-liquid interface as well as the temperature profile below the fiber termination point.
  - To calibrate CMC FRS surface and downhole pressure and temperature gauges as well as the data recorded by Distributing Temperature Sensing (DTS) fibre that is strapped to the outside of the injection tubing.



**Figure 2: Aerial view of the static gradient test in CMC injection well.**

**Milestone 3:**

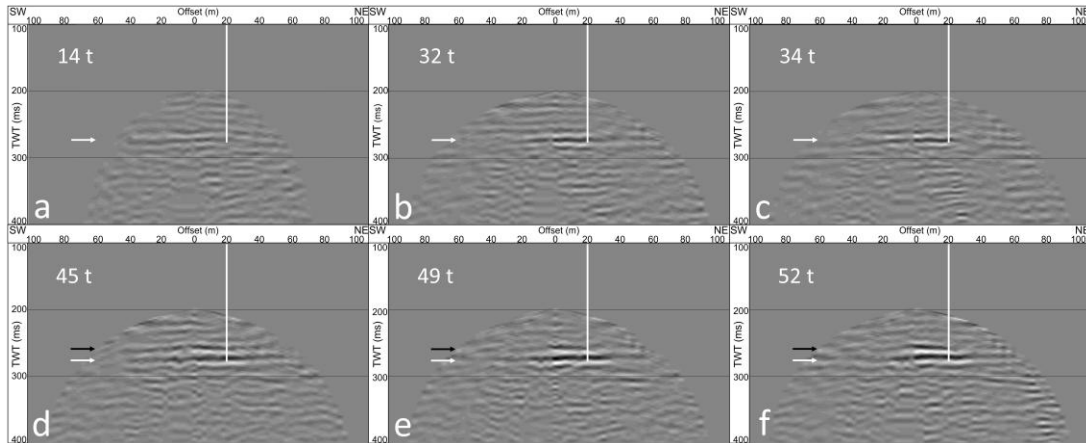
- The CO<sub>2</sub> injection and monitoring program at the Newell County Facility continued during this reporting period, apart from some shut-in time during late July and early August due to very hot weather. Data during the injection cycles were collected and also during the shut-in times that provided interesting decline data that was used for the modelling studies by ACT3 research collaborators and industry supporters.

**Milestone 5:**

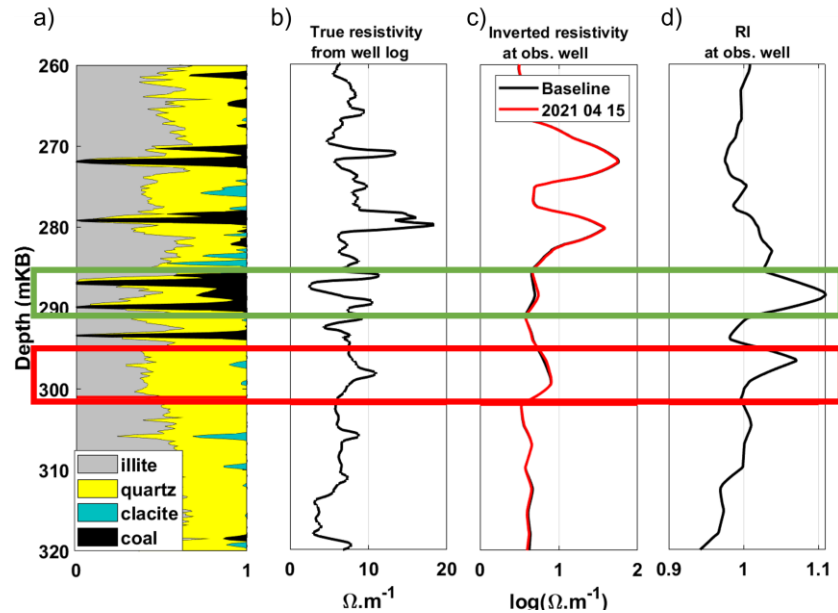
- Further experiments at the CMC FRS were conducted with CO<sub>2</sub> injection at various temperatures, which were controllable using an inline heater, and at different rates. A thorough evaluation of the injection parameter data was carried out, whilst ensuring that the bottom hole pressure remained below the reservoir fracture pressure throughout the experiments.
- The acquisition of pressure, temperature, and flow rate time series data at a rate of 1-minute recordings are part of the field of data collection and monitoring. This valuable data collection process allowed for real-time and high-resolution insights into the dynamics of the wellbore-reservoir system under observation. By capturing these key parameters at such a frequent interval, researchers and engineers gained a comprehensive understanding of how the system behaved over time, identified patterns, detected anomalies, and make informed decisions for optimizing system performance. The 1-minute recordings ensure that no critical details or transient phenomena were missed, enabling accurate analysis and precise predictions. The injection of CO<sub>2</sub> at different rates was carefully designed to guarantee that the bottomhole pressure stayed below the reservoir fracture pressure. A comprehensive report was automatically generated containing all the details of the recorded data.
- Between April 1st and July 31st, 2023, geophysical monitoring efforts encompassed continuous seismic recording on both surface and borehole geophones to collect microseismic data. Additionally, daily electrical resistivity tomography surveys were conducted using electrodes in observation well #2, allowing for the identification of resistivity changes in the subsurface resulting from CO<sub>2</sub> injection. From May 18 to May 29, 2023, a distributed strain sensing experiment in collaboration with a company (Neubrex) utilized fiber optics deployed in the two observation wells and the surface trench to analyze subsurface strain changes associated with CO<sub>2</sub> injection. Furthermore, a vertical seismic profile was acquired on June 05-06 for time-lapse Vertical Seismic Profile (VSP) monitoring, providing additional insights into the temporal evolution of the CO<sub>2</sub> plume.
- The geophysical inferences were combined with reservoir simulation results which enhanced our understanding of the behavior and evolution of the CO<sub>2</sub> plume in the storage complex. This integration of data sources enabled a more comprehensive analysis of the CO<sub>2</sub> storage dynamics and helped in making informed decisions for the project's injection program.

**Milestone 6B:**

- The CMC FRS makes extensive use of geophysical monitoring techniques to gain critical insights into the dynamics of the CO<sub>2</sub> plume, the storage efficiency of the complex, and the distribution of CO<sub>2</sub> saturation. Our interpretation of data obtained from geophysical monitoring methods, including vertical seismic profiles (VSP, Figure 3) and borehole electrical resistivity tomography (ERT, Figure 4), is integral to fine-tuning our numerical simulation results and guiding adjustments to the numerical models.



**Figure 3: VSP CDP time-lapse difference sections between a baseline acquired in May, 2017, and monitor surveys acquired in a) August 2019, b) March 1st, 2021, c) March 25th, 2021, d) September 2021, e) January 2022, and f) March 2022. The white arrow indicates the BBRS interval and the negative amplitude anomaly caused by CO<sub>2</sub> saturation. The black arrow indicates the shallower amplitude anomaly that became apparent after 46 t of CO<sub>2</sub> injection.**



**Figure 4: Lithology extracted from ELAN well logs. b) Resistivity from well log. c) Inverted resistivity for the baseline survey - September 2019 (black profile) and a monitor survey - April 2021 (red profile). d) Resistivity ratio between the monitor and the baseline.**

- In a joint effort between SpectrumH2 and CMC, a comprehensive plan was established to select fields and wells for the purpose of CO<sub>2</sub> storage in depleted reservoirs. The selection process was guided by recommendations based on ownership and technical suitability, with a focus on evaluations of capacity, injectivity, and containment assurance of the injected CO<sub>2</sub>. SpectrumH2 provided reservoir data for these endeavors, which were planned to be utilized in reservoir and CO<sub>2</sub> injection simulations conducted using CMG software. The results obtained from these simulations have yielded crucial information, including data on anticipated bottom-hole pressure and temperatures for recommended CO<sub>2</sub> flow rates.
- In parallel, CMC was engaged in building a geomodel for a depleted gas field based on the data that was provided by SpectrumH2. This endeavor involved the extraction of production data from the Alberta Energy Regulator (AER) database, as well as well-log databases sourced from SpectrumH2. SpectrumH2 had contributed valuable data, including well logs, cores information, and reservoir properties, all of which were instrumental in creating a comprehensive geomodel. The geomodel was integrated into reservoir simulation program using CMG software. This integrated approach ensured that all the reservoir and well data were effectively utilized to support CO<sub>2</sub> storage predictions and advance the understanding of the selected gas field.

**Milestone 7:**

- Updated simulation models of the CMC FRS CO<sub>2</sub> injection well were further developed and disseminated to the ACT3 RETURN WP2 research team. These models were built to address technical queries identified in Milestone 4 as well as topics raised during monthly WP2 meetings.

This milestone focused on the critical evaluation of non-isothermal coupled well-bore reservoir modeling. The primary objective was to refine injection scenarios for optimal performance, specifically targeting the reduction of Joule-Thomson cooling effects in the proximal well environment. Additionally, these updated models were instrumental in elucidating the intricate CO<sub>2</sub> phase behavior both within the wellbore and in its adjacent reservoir. This advancement was pivotal in enhancing our understanding and management of subsurface interactions during CO<sub>2</sub> injection processes. The simulation modeling processes were rigorously conducted utilizing CMG software, widely recognized as the industry standard.

- In addition to modeling using CMG software, **CARbon Low EnthalpY Storage Tool (CALYSTO)**, developed by the EBN team, represented a significant advancement in the field of reservoir simulation. This innovative tool is specifically designed to model the fully coupled dynamics of wellbores and reservoirs, overcoming many of the limitations inherent in existing models. CALYSTO employs a pressure-enthalpy formulation, with a particular focus on CO<sub>2</sub> modeling. This approach enables the tool to effectively simulate the coupled flow within both wellbores and reservoirs, providing a comprehensive understanding of the system's behavior.
- CMC, in partnership with EBN, undertook a comprehensive assessment of the modeling and simulation results of CO<sub>2</sub> injection well pressure and temperature data at the CMC FRS. Real injection data from the FRS enabled evaluation of the developed CALYSTO tool. Additionally, a comparative analysis was conducted against internal modeling efforts executed by CMC, employing the CMG reservoir modeling software. This collaborative approach aimed to ensure a robust and thorough examination of the simulation outcomes, leveraging both commercial and developed codes resources for benchmarking purposes.

#### **Milestone 8-9B:**

During this phase of the project, field experiments at the CMC FRS were refined to meet the objectives of milestone 8. This involved controlling the injection of CO<sub>2</sub> at various temperatures using an inline heater on the flow line to the well. Additionally, CO<sub>2</sub> was injected at different rates while bottomhole gauges were monitored to ensure that the bottomhole pressure stayed below the reservoir fracture pressure. Data on pressure, temperature, and flow rate were recorded at one-minute intervals. Concurrently, geophysical monitoring data were collected to observe subsurface responses to the CO<sub>2</sub> injection. All collected data were meticulously documented. This comprehensive approach ensured thorough monitoring and analysis of every aspect of the injection process.

Geophysical monitoring is routinely conducted at the site. The frequency of these monitoring activities varies depending on the specific type of monitoring technology being deployed. The monitoring program for the project was extensive and detailed. Throughout the year, daily Electrical Resistivity Tomography (ERT) surveys were conducted in Observation Well #2 to monitor subsurface changes. Continuous Distributed Temperature Sensing (DTS) was implemented in both the injection well and observation wells, with data recorded every 5 minutes and every 10 minutes, respectively. Pressure and temperature gauge monitoring were carried out continuously in both the injection well and Observation Well #1. Passive

seismic monitoring was also performed continuously throughout the year, utilizing a permanent geophone, broadband, and SADAR array to detect and analyze seismic activity.

Quarterly monitoring activities included geochemical fluid sampling in Observation Well #1, water well sampling, soil gas sampling, and surface casing vent flow analysis. These activities ensured comprehensive monitoring of the CO<sub>2</sub> storage complex, providing essential data to confirm the containment and behavior of CO<sub>2</sub> within the reservoir and provided independent evidence of the extent of the CO<sub>2</sub> plume to compare with results of simulations using CMG and CALYPTO software.

### **Milestone 10:**

This milestone provided a summary of activities and outcomes from the RETURN Project

- Different sets of experiments were conducted over a period of 10 days, involving variations in CO<sub>2</sub> injection flow rates ranging from 200 kg/day to 1000 kg/day. CO<sub>2</sub> was injected over various flow rates while ensuring that the bottom-hole pressure did not exceed the reservoir fracture pressure.
  - The experiments were performed at input gas temperatures ranging from 20°C to 60°C and bottom-hole pressures between 3 MPa and 6 MPa. CO<sub>2</sub> was injected at a range of gas temperatures, which were controlled using an inline heater installed at the FRS on the flow line to the well.
  - Reservoir performance was continuously monitored through geophysical measurements and pressure and temperature readings in two observation wells.
  - Time series data for pressure, temperature, and flow rate were collected at intervals of 1 minute.
  - Geophysical monitoring data were acquired throughout the experimental period and beyond.
  - Detailed records of all data collected were maintained to facilitate accurate reporting and analysis.
- The geophysical inferences were combined with reservoir simulation results to enhance our understanding of the behavior and evolution of the CO<sub>2</sub> plume in the storage complex. This integration of data sources has enabled a more comprehensive analysis of the CO<sub>2</sub> storage dynamics to be undertaken, and this helped in making informed decisions for the project. Vertical Seismic Profiles (VSP) provided time-lapse seismic imaging of the CO<sub>2</sub> plume. The use of ERT at the CMC site presents advantages such as the small amount of data produced, the high sensitivity to CO<sub>2</sub> saturation changes, and the high vertical resolution along the monitoring well. It has allowed us to monitor semi-continuously the subsurface, and to detect changes due to CO<sub>2</sub> accumulation very quickly.
  - Reservoir modeling for CO<sub>2</sub> injection into a depleted gas field in Alberta has been successfully completed. The data from a depleted gas field CMC has been integrated with partner-provided

datasets into a comprehensive geomodel, capturing the full complexity of reservoir characterization. This geomodel was subsequently input into CMG's reservoir simulation software to facilitate detailed analysis.

- The reservoir model was developed using these datasets to accurately represent the unique geological, petrophysical, and fluid properties of the depleted field. This approach ensures that the model provides a realistic depiction of reservoir behavior, enabling reliable simulations and performance evaluations.
- To enhance model accuracy, a history matching process was conducted to align the simulated results with historical production data (Figure 5). Key reservoir parameters, such as relative permeability and rock compressibility, were adjusted to calibrate the model effectively. This process is critical in validating the model's predictive capabilities under various development scenarios. With the calibration completed, the model is now available for partner use in evaluating CO<sub>2</sub> injection strategies and optimizing reservoir management plans.



**Figure 5: Comparison between production water rate at the field level from historical production data and the history-matched model, demonstrating the accuracy of the history matching process.**

## 7.2 TECHNOLOGY DEVELOPMENT

Data provided by CMC from its injection program at the CMC Field Research Station in Newell County has assisted CMG in further developing its reservoir simulation software for CO<sub>2</sub> injection and storage in depleted gas fields. In addition, data provided to EBN, a funding partner for CMC in the RETURN project, provided constraints and evaluations for their CALYPTO software.

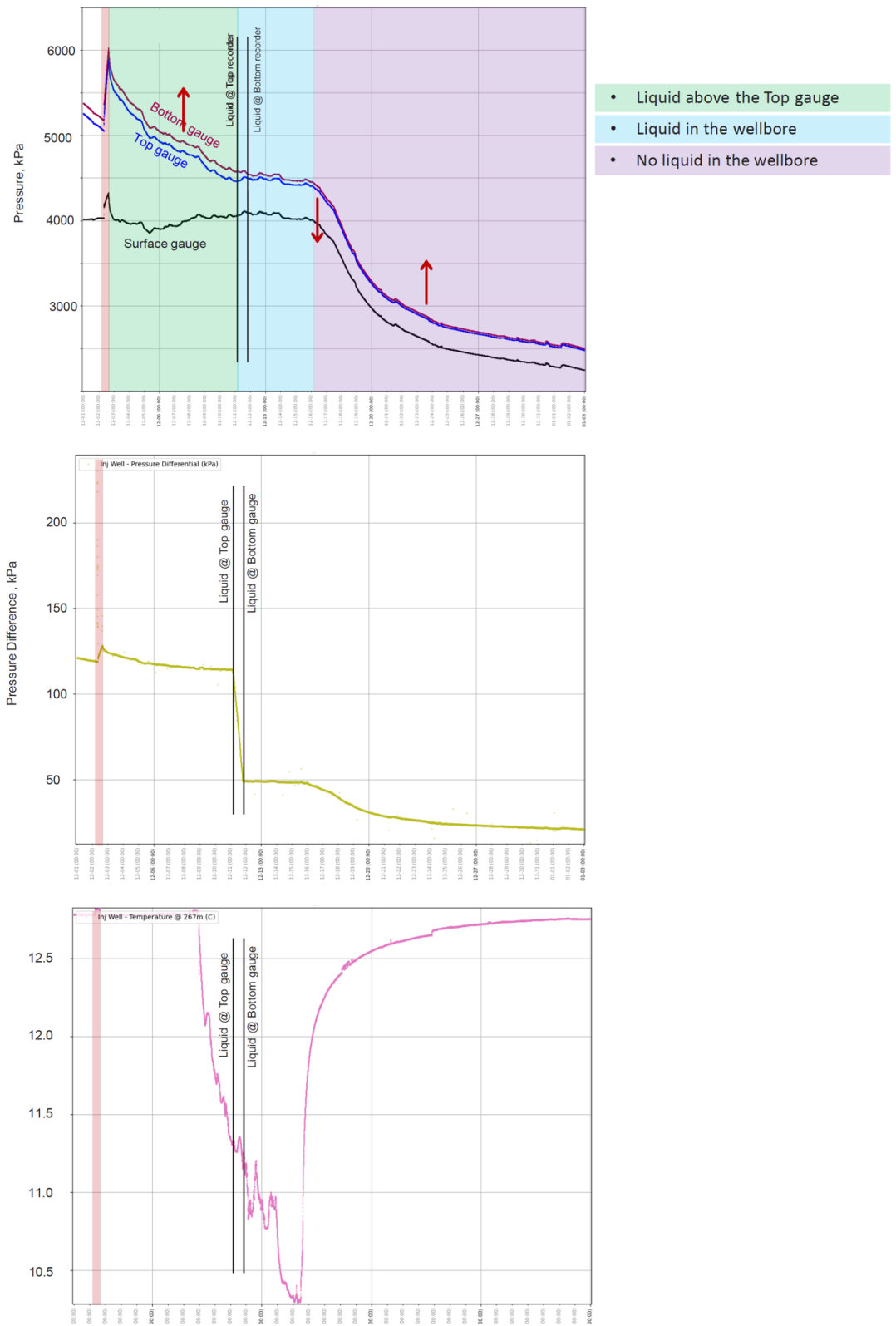
## 7.3 PROJECT ACHIEVEMENTS, RESULTS, AND ANALYSIS

### Milestone 1:

- Wellbore transient pressure and temperature and the subsequent CO<sub>2</sub> phase behavior at the CMC Field Research Station were analyzed. Results show that gas-liquid transient flow and CO<sub>2</sub> phase

changes are occurring in the wellbore during injection and the subsequent liquid/gas CO<sub>2</sub> boundary impacted the temperature profile within the liquid column of the CO<sub>2</sub>.

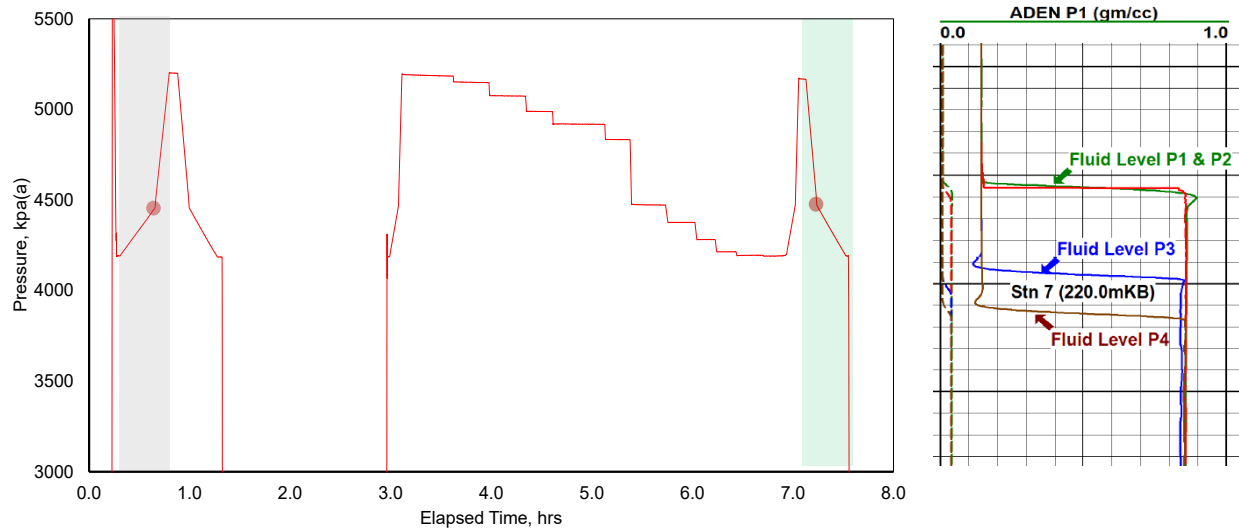
- Insight was gained on the dynamics of CO<sub>2</sub> injection falloff with the specific focus on the transient behavior of the wellbore (Figure 6). It is critically important to know the wellbore operational parameters for CO<sub>2</sub> injection into saline aquifer and depleted reservoirs.



**Figure 6: Top: Bottomhole and wellhead pressures. Middle: Bottom hole gauges pressure difference. Bottom: Bottomhole temperature.**

## Milestone 2:

- Wellbore transient pressure and temperature and the subsequent CO<sub>2</sub> phase behavior were continued to be analyzed. Results show that the CO<sub>2</sub> phase changes occurring in the wellbore during pressure fall off and the subsequent liquid head of CO<sub>2</sub> impacts the injectivity of CO<sub>2</sub> into the storage formation.
- Insight was gained about the dynamics of CO<sub>2</sub> injection pressure falloff with the specific focus on the transient behavior of the wellbore. It is critically important to determine the wellbore operational parameters for optimum CO<sub>2</sub> injection into the Basal Belly River saline aquifer for the CO<sub>2</sub> injection program at the CMC FRS.
- For a certain injection temperature, the injection rate spiked dramatically if the heater temperature was set at low values. Increasing the temperature of the CO<sub>2</sub> helped to maintain a more constant injection rate over the course of injection.
- In view of the complex wellbore dynamics associated with liquid/vapor CO<sub>2</sub> in the wellbore, the focus of the field test was on the verification of in-tubing pressure and temperatures at various depths in the wellbore. The following results were obtained:
  - The temperature gradient inside the tubing, at all depths, is generally consistent with the existing annulus DTS values, but a calibration correction was required.
  - The depth of the gas/liquid interface in the wellbore was obtained and was found to be comparable to the depth identified from the existing DTS profile from fibre strapped to the injection tubing in the annulus.
  - In-situ gas and liquid densities were measured, and the measurements were consistent with the theoretical values based on the calibrated pressure and temperature measured in the injection wellbore.
  - An improved understanding of the temperature profile in the regions above and below the gas-liquid interface was obtained. The temperature profile below the fiber termination point revealed temperature anomaly in the bottom of the injection well. The event is consistent with interpretation of geophysical monitoring data that shows some upward migration of CO<sub>2</sub> in the reservoir and a cooling anomaly interpreted to be caused by liquid CO<sub>2</sub> flashing to gas phase.
  - The surface and downhole pressure and temperature gauges needed to be precisely calibrated to properly understand the thermal behaviour of CO<sub>2</sub> in the well-bore. This calibration was obtained by a static gradient survey (Figure 7). The corrections to the pressure and temperature gauges data helped to make better sense of wellbore-reservoir interaction.



**Figure 7: The location of the liquid level is estimated from the fluid density measurements. Liquid level location in pass 1 and pass 4 are estimated from the change in the slope of pressure data, The rate of the drop of the liquid head in the wellbore is 0.83 m/hour.**

### Milestone 3:

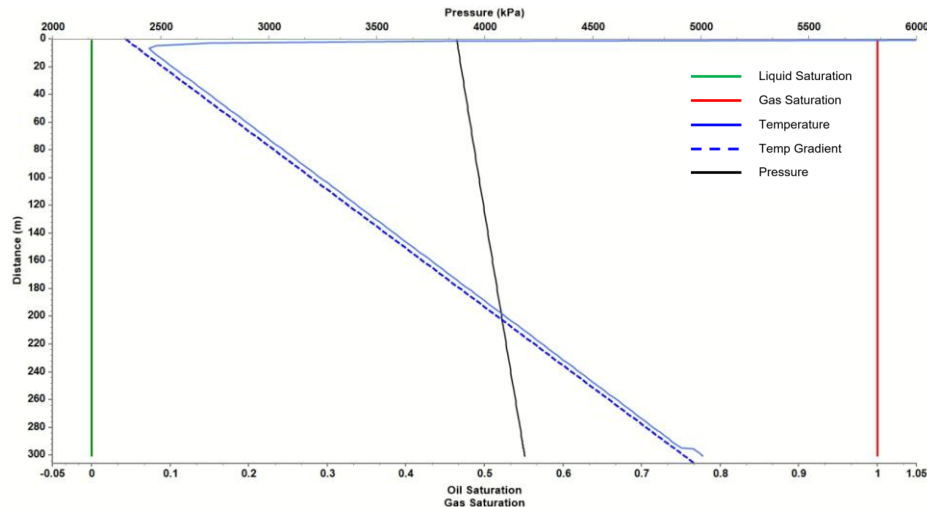
- Simulation models were prepared during July to September 2022.
- Simulation studies were undertaken by CMC and ACT3 RETURN WP2 researchers to better understanding complex wellbore dynamics associated with liquid/vapor CO<sub>2</sub> in the CaMI injection wellbore using different software packages. CMC mostly using STARS from CMG and TNO researchers presented their modeling results using OLGA software from SLB.
- WP2 researchers concluded that using current wellbore simulators alone were not adequate for properly model CMC PT data and a coupled wellbore-reservoir model needed be employed.

### Milestone 5:

- The simulations undertaken included a complete injection fall-off cycle, and a sensitivity analysis was performed to examine the influence of various parameters, including temperature of the injected gas, and injection rate.
- The simulation results indicate that generally only the first 10 meters of the well-bore is heated by the injection of hot gas (Figure 8). During the experiments conducted at the site, it was observed that the injected gas temperature had only a modest impact on the wellbore performance for the CMC injection well. This was further validated by numerical simulations.

### Milestone 6B:

- The interpretations of geophysical monitoring data were combined with reservoir simulation results to enhance our understanding of the behavior and evolution of the CO<sub>2</sub> plume in the



**Figure 8: Temperature and pressure simulation for heated CO<sub>2</sub> injection.**

storage complex. This integration of data sources enabled a more comprehensive analysis of the CO<sub>2</sub> storage dynamics to be obtained and helped in making informed decisions for the project. Vertical Seismic Profiles (VSP) provided time-lapse seismic imaging of the CO<sub>2</sub> plume. The use of electrical resistivity tomography at the CMC FRS provided advantages because of the sensitivity of the method to small changes in CO<sub>2</sub> saturation in the reservoir, and the high vertical resolution in the monitoring well. This allowed us to monitor semi-continuously the subsurface, and to detect changes due to CO<sub>2</sub> plume geometry very quickly.

- We created a reservoir model for a depleted field in Alberta, utilizing the data generously provided as an in-kind contribution by SpectrumH. The collaborative efforts between SpectrumH2 and CMC represented a crucial step in developing an effective strategy for CO<sub>2</sub> injection and storage into a depleted reservoir. By combining the technical expertise of these organizations, along with the valuable data and simulation tools, the project was well-positioned to assess the viability and potential impact of CO<sub>2</sub> storage in the selected fields and wells. The geomodeling and simulation activities are yielded critical insights that will guide future decision-making for projects incorporating CO<sub>2</sub> injection in depleted fields.

#### **Milestone 7:**

- The EBN team successfully developed an advanced well-reservoir flow simulator, designed to incorporate Joule-Thomson (JT) cooling effects and the complexities associated with CO<sub>2</sub> phase changes in the well bore and reservoir (CALYSTO). This state-of-the-art numerical code was detailed and presented during the WP2 monthly meeting held on November 24, 2023. This simulator represented a significant technological advancement in the field, offering enhanced capabilities for accurately modeling the dynamic interactions in well-reservoir systems under varying conditions.
- The code, as developed by the EBN team, is written in the Matlab programming language and is characterized by its speed and efficiency. It is a fully coupled well and reservoir model, designed specifically for layered case reservoirs with radial geometry. Each layer in the model was assigned

homogeneous petrophysical properties. The model employed a pressure-enthalpy formulation. From a computational standpoint, it is based on the finite difference method, utilizing a fully implicit mathematical scheme. This approach ensures robustness and precision in the simulation of well and reservoir dynamics, particularly in complex geological settings.

- After some testing, it was found that the CALYSTO code developed by the EBN team, despite some inherent software limitations, is exceptionally well-suited for modeling the injection data from the CMC FRS. Its robust design and computational capabilities made it an ideal tool for use as a predictive model. Specifically, it could effectively forecast pressure and temperature developments within injection wells, particularly in scenarios involving depleted gas reservoirs. This suitability stems from its precise handling of complex reservoir dynamics and its ability to accurately simulate the intricate interplay of various factors in such environments. It is our understanding the CMG software has also been further developed to better simulation coupled well-reservoir CO<sub>2</sub> injection scenarios, and tested against CMC FRS data.
- It is important to acknowledge that following the recent launch of CALYSTO, CMC maintained its collaborative efforts with the EBN team to conduct an extensive due diligence study. In this study, the CALYSTO code was applied to a practical case involving the CMC CO<sub>2</sub> injection well. This application was benchmarked against established industry-standard software codes specializing in well/reservoir flow dynamics, such as the CMG software suite. This benchmarking process was crucial to validate the reliability and precision of CALYSTO in accurately simulating complex interactions within well-reservoir systems. This includes scenarios that encompass Joule-Thomson (JT) cooling effects and the intricacies of CO<sub>2</sub> phase transitions, ensuring a comprehensive and robust assessment of the software's capabilities.

#### **Milestone 8-9B:**

An overview of the progress of the injection experiments conducted at the CMC injection well since 2018 was provided for this Milestone. The primary objective of these experiments was to analyze the behavior of reservoir and wellbore system at the CMC FRS under varying injection schedules and to understand the impact of these changes on CO<sub>2</sub> storage capacity. From 2018 to early 2024, injections were performed twice a week, with an average weekly injection amount of approximately 450 kg. During injection days, the bottomhole gauge pressure increased to nearly 6 MPa, approaching 90% of the fracture pressure. During the subsequent 2 to 3-day shut-in periods, the pressure dropped to approximately 4.0 MPa. To observe changes in reservoir and wellbore responses, different injection parameters were altered. Throughout these experiments, reservoir performance was closely monitored through pressure and temperature measurements in the injection well and observation well to analyze the impact of each input parameter on the operation results. These injection experiments have provided valuable insights into the behavior of the wellbore and reservoir systems under varying injection schedules.

- **Days of Operations:** During this period, the number of injection days per week was increased from 2 to 5. The purpose of this experiment was to maintain the bottomhole pressure at 6 MPa continuously and evaluate the impact on the potential increase in the amount of CO<sub>2</sub> injected into the storage complex. Maintaining the bottomhole pressure close to the fracture pressure did not

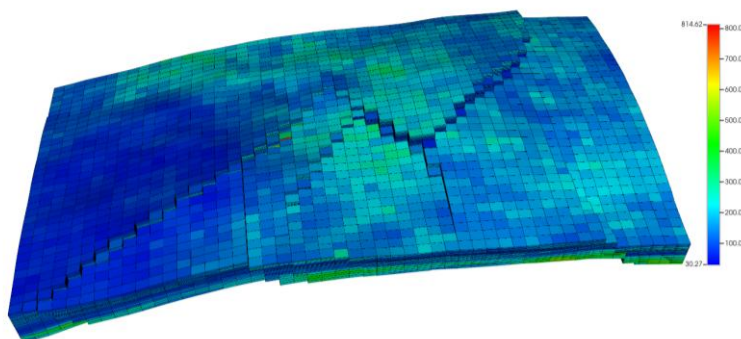
significantly enhance reservoir injectivity. Despite increasing the injection days from 2 to 5 per week, there was no significant change in the weekly injection amount from late 2023 to early 2024. This suggests that reservoir injectivity is the controlling factor for the wellbore-reservoir system.

- **Injection Gas Temperature:** The injected gas temperature, controlled by an in-line heater, ranged from 45 degrees Celsius to 80 degrees Celsius. Although no observable change in both the bottomhole gauge pressure and temperature was noticeable, the effects of varying the injection gas temperature on reservoir behavior are still being analyzed. Initial results indicate minimal impact on the overall injection rates and storage efficiency.
- **Injection Rate:** During the 2-day per week operation scheme, the injection rate was varied from 200 kg/day to 800 kg/day. The cumulative CO<sub>2</sub> injected into the wellbore for different rate profiles was kept constant. The bottomhole gauge pressure rose to the same value at the end of the injection period.

Overall, the injection experiments have provided important data on how different injection schedules and parameters affect CO<sub>2</sub> storage in the wellbore and reservoir systems.

#### Milestone 9B:

CMC integrated depleted gas field data and partner-provided datasets into a comprehensive geomodel to capture the full complexity of the reservoir (Figure 9).



**Figure 9: Permeability distribution of grid blocks in the geomodel, showing variations in permeability throughout the reservoir.**

This geomodel was then input into CMG's reservoir simulation programs. The reservoir model was built using these datasets to capture the unique geological, petrophysical, and fluid properties of the depleted fields. This ensured that the model accurately represented the reservoir characteristics, allowing for more reliable simulations and evaluations.

The constructed reservoir model was then history matched to ensure that it aligned closely with historical production data. By adjusting key parameters such as relative permeability and rock compressibility, the model was calibrated to reflect the historical performance of the reservoir. This history matching process

is crucial, as it enhances the model's reliability in predicting the future performance of the reservoir under different development scenarios. The calibrated model can subsequently be used effectively to be used by our partners to evaluate injection strategies and optimize reservoir management plans.

**Milestone 10:**

- The Carbon Low Enthalpy Storage Tool (CALYSTO), developed by the EBN team, represents a significant advancement in reservoir simulation by addressing the limitations of existing models. This innovative tool was designed specifically to model the fully coupled dynamics of wellbores and reservoirs, providing a more comprehensive and accurate representation of subsurface processes. The numerical simulation results from CALYSTO have been benchmarked against temperature profiles obtained from fiber optic data in the CMC injection well. The history-matched temperature profiles demonstrate a strong correlation, indicating promising accuracy and reliability of the model.

To achieve the maximum CO<sub>2</sub> injection capacity in the reservoir, the optimal injection flow rate at the CaMI field research station was determined to be approximately 300 kg/day. Injection rates below this threshold are practically unfeasible due to operational constraints. Maintaining this injection rate ensured the minimal effect of phase change effects and mitigates substantial cooling effects within the reservoir, enhancing the overall efficiency and stability of the injection and storage process.

**8.0 LESSONS LEARNED**

**8.1 CHALLENGES**

- Delay in starting the overall ACT3 project due to some delays in finalizing all the ACT3 contribution agreements.
- Under-expenditure for Milestone M1, due to some supply-chain issues, prevented us from obtaining all the necessary computers by March 31, 2022.
- Submission of the milestone 1 report occurred after March 31, 2021, because CMC was waiting on invoicing instructions from our project partners.
- Staff transition induced changes in the Work Package 2 lead.

**8.2 PRACTICAL LEARNINGS**

This project has successfully tested several software packages for modelling coupled wellbore-reservoir interactions during injection of CO<sub>2</sub> into depleted reservoirs, or underpressured saline aquifers. Data provided from the CMC Field Research Station has been practically useful in testing these codes against real field data.

### 8.3 ORGANIZATIONAL LEARNINGS

There were important learnings about programs like ACT. Technology transfer between countries requires research teams to share data and integrate results in an efficient manner. While there was good communication between the research groups, in this project, CMC shared large amounts of data with the WP2 team.

### 8.4 HIGHLIGHTS

- Regular meetings and strong communication are necessary for effective international team collaboration.
- Advances were made in understanding coupled wellbore-reservoir interaction during non-isothermal CO<sub>2</sub> injection into depleted reservoirs and under-pressured saline aquifers. Operational and monitoring data from the CMC Field Research Station was important in realizing this objective. As a result, this software will be able to be used for large-scale CO<sub>2</sub> injection into depleted reservoirs, helping to design injection scenarios that avoid J-T cooling and the development of hydrates in the reservoir near the injection well. In Alberta, these benefits will be realized when large-scale injection and storage is permitted.

## 9.0 GHG BENEFITS

At present, most of the CO<sub>2</sub> storage projects in Alberta are targeting deep saline aquifers. However, there is significant additional storage space in depleted hydrocarbon reservoirs that are not part of the regulation. Reusing depleted fields offers significant benefits in the effort to accelerate rapid decarbonization, including reduced development time, lower costs, and decreased uncertainty.

The RETURN project can be classified as enabling technology for CO<sub>2</sub> storage into depleted hydrocarbon reservoirs, that is currently not regulated in Alberta. The outcomes of the project should lead to policy changes so that significant greenhouse gas reductions can be achieved through CO<sub>2</sub> storage into these depleted reservoirs.

The RETURN project provides **enabling technology and validation** for large-scale GHG emissions reductions via CO<sub>2</sub> storage in Alberta’s depleted oil and gas reservoirs. While total CO<sub>2</sub> stored at the Carbon Management Canada’s site is modest, the outcomes have:

- Laid the groundwork for new regulatory frameworks.
- Delivered critical technical tools and modeling capacity.
- Opened up substantial, cost-effective CO<sub>2</sub> storage capacity in Alberta and globally.

#### 9.1 PROJECT BASELINE EMISSIONS

Not applicable for this project.

#### 9.2 PROJECT EMISSIONS

Not applicable for this project.

#### 9.3 EMISSIONS REDUCTION IMPACT

Not applicable for this project.

### 10.0 ENVIRONMENTAL, ECONOMIC, AND SOCIAL IMPACTS

#### 10.1 OTHER ENVIRONMENTAL IMPACTS

This project supports enabling technology to reduce greenhouse gas emissions through CO<sub>2</sub> sequestration in depleted hydrocarbon reservoirs.

#### 10.2 PROJECTED ECONOMIC IMPACT

Oil and gas infrastructure is already in place in Alberta. For depleted hydrocarbon reservoirs, this infrastructure can be repurposed for CO<sub>2</sub> storage into these reservoirs, leading to cost saving.

Depleted fields in Alberta are well characterized, so the benefit of re-using these fields for CO<sub>2</sub> storage is high. The RETURN project, focused on CO<sub>2</sub> injection strategies for depleted fields, will optimize storage efficiency.

#### 10.3 RESULTED INNOVATION CAPACITY

Large-scale CO<sub>2</sub> storage projects in Alberta will require close integration of monitoring data with reservoir simulations to better understand the extent and behaviour of the CO<sub>2</sub> plume and to verify containment and conformance. Innovative experiments and data from the CMC Field Research Station is instrumental in advancing these technologies. This project has results in greater confidence in modelling coupled wellbore – reservoir interactions, particularly during start-up phases of a CO<sub>2</sub> injection program.

#### 10.4 SOCIAL IMPACT AND EDI OUTCOMES

Hydrocarbon fields are depleted well below hydrostatic pressure and so have large margins for pressure increase during CO<sub>2</sub> injection, which will potentially reduce the microseismicity activities. Increasing the understanding of CO<sub>2</sub> injection in depleted reservoirs increase the public confidence in CO<sub>2</sub> storage.

## 11.0 SCIENTIFIC ACHIEVEMENTS

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Macquet M., Behmanesh H., Cooper J., Kolkman-Quinn, B., Lawton D., and Maidment G., 2023, Multi-disciplinary evidence of CO<sub>2</sub> migration at the CMC Newell County Facility: *CSEG Symposium, Calgary*

## 12.0 POST-PROJECT STEPS

### 12.1 NEXT STEPS AND FOLLOW-UP PROJECTS

The part on integrating the outcomes of geophysical monitoring into reservoir simulation will continue during the new ERA project (AMPS - FPP#E0163804). The AMPS project aims to develop a real-time, semi-continuous, cost-effective, and sustainable surveillance system for CO<sub>2</sub> storage. One component of the project is the verification that the reservoir modelling and simulation software appropriately utilizes monitoring outcomes (CO<sub>2</sub> plume delineation, saturation, pressure, and strain) to calibrate the modelling of physical processes in the reservoir and wellbore. The system will be integrated with reservoir modelling for updating the geostatic model and verification of reservoir conformance. Ongoing reservoir simulations will be improved with real data-driven predictions. This will benefit the CO<sub>2</sub>-EOR operators by helping them track storage efficiency and optimize reservoir performance.

### 12.2 PARTNERSHIPS

The experience gained and tools developed during the project will enable CMC to help industries with planning to permanently store CO<sub>2</sub> in depleted reservoir projects. The Computer Modelling Group Ltd (CMG) has reached out to pursue a collaboration on integrating the outcomes of geophysical monitoring into reservoir simulation, and to improve their historical matching capabilities by utilizing the extensive injection dataset from the CMC FRS. CMC's injection facility with pressure/rate/temperature measurements is a proxy for injecting cold CO<sub>2</sub> into a depleted reservoir. The dataset enables reservoir development groups in CCS companies to assess codes and software. This is particularly important during the start-up phase of CO<sub>2</sub> injection into a depleted (under-pressured) reservoir.

## 13.0 OVERALL CONCLUSIONS

The RETURN project is part of the ACT3 (Accelerating CCS Technologies) consortium, aimed at improving the understanding, modeling, and monitoring of CO<sub>2</sub> injection in depleted hydrocarbon reservoirs—currently underutilized in Alberta's regulatory landscape. These outcomes form the technical and operational foundation for future **cost-effective, safe and efficient CO<sub>2</sub> storage** in Alberta and internationally.

Key outcomes were:

1. Field data acquisition and reservoir simulations:
  - **Analyzed CO<sub>2</sub> wellbore behavior:** Pressure-temperature transients, CO<sub>2</sub> phase shifts (liquid/gas), and temperature gradients during injection and falloff events were characterized.
  - **Key Insights:** Transient behavior significantly impacts injection efficiency and temperature distribution— understanding the processes is essential for safe and effective CO<sub>2</sub> storage design.
  - **Result:** Field data calibration, improved data simulation fidelity, and confirmed the need for coupled wellbore-reservoir models (e.g., STARS, OLGA).
2. Injection modelling and integration of geophysical monitoring outcomes with reservoir modelling:

- **Simulations** revealed minimal impact of injected gas temperature on wellbore performance.
- **Integrated geophysics (VSP & ERT)** with simulation models to image CO<sub>2</sub> plume evolution.
- **Depleted Alberta field reservoir model** completed via partnership with SpectrumH2.
- **Result:** Improved understanding of plume migration, injectivity, and containment integrity.

### 3. Advanced modelling & operational optimization:

- **Developed CALYSTO:** A high-resolution, coupled wellbore-reservoir simulator accounting for CO<sub>2</sub> phase change and Joule-Thomson cooling effects.
- **Benchmarking** with field data demonstrated accuracy in predicting reservoir behavior and temperature profiles.
- **Operational optimization:** Identified ideal CO<sub>2</sub> injection rate at the CMC site (~300 kg/day) to reduce phase change impacts and maintain thermal stability in the reservoir.
- **Long-term injection testing (2018–2024):** Maintained pressure close to fracture limits without triggering instability or increased injectivity—proving system resilience.

Outcomes of the ENSURE project will potentially enable emissions reduction (Provincial & global scale) by:

- **Enabling policy change:** RETURN paves the way to include **depleted hydrocarbon reservoirs** in Alberta’s formal CO<sub>2</sub> storage regulations—unlocking vast underutilized capacity.
- **Infrastructure reuse:** Repurposing existing oil & gas assets could dramatically reduce deployment costs and speed up CO<sub>2</sub> storage implementation timelines.
- **Public trust:** Demonstrating the safety and predictability of CO<sub>2</sub> injection into depleted reservoirs boosts confidence and de-risks broader deployment.

A final report, integrating all work packages, was produced (<https://return-act.eu/reports>). During the projects, several meetings between the work package leaders were hosted:

- General Assembly (2022, October 17)
- General Assembly (2023, March 20-21)
- General Assembly (2024, March 19-20)
- General Assembly (2024, Oct 31-Nov 1)

Inter work package meetings were also planned and attended by Hamid Behmanesh, the project lead for CMC.

## 14.0 COMMERCIALIZATION AND TECHNOLOGY TRANSFER PLAN

### 14.1 PROJECT COMMERCIALIZATION ADVANCEMENTS

Most CO<sub>2</sub> storage projects in Alberta target deep saline aquifers, as CO<sub>2</sub> storage in depleted hydrocarbon reservoirs is not currently permitted in Alberta at large scale. RETURN outcomes can be used to support the following:

- Policy evolution and regulatory frameworks
- Recognition of depleted reservoirs as viable, safe, and efficient CO<sub>2</sub> sinks.

It would de-risk investment in CCS by using existing well-characterized depleted fields, existing infrastructure, and under-pressurized reservoirs.

Outcomes of RETURN include improvements in software for modelling CO<sub>2</sub> injection and wellbore-reservoir interactions for storage in depleted reservoirs and under-pressured saline aquifers. We understand that CMC FRS data and reports have been beneficial to CMG for advancing their software which is used by many CO<sub>2</sub> storage providers.

#### 14.1.1.1 PROJECT TECHNOLOGY ADVANCEMENTS

The RETURN project has delivered several key technological advancements in CO<sub>2</sub> storage, particularly focusing on injection into depleted hydrocarbon reservoirs. These innovations improve the safety, efficiency, and scalability of carbon capture and storage (CCS) operations in Alberta and internationally.

##### **1. Advanced coupled wellbore–reservoir simulation – CALYSTO simulator**

- Developed by EBN and CMC, CALYSTO is a fully coupled, pressure-enthalpy-based simulator for CO<sub>2</sub> flow in complex reservoir systems (Figure 10).
- Key Features:
  - Incorporates Joule-Thomson (JT) cooling effects
  - Simulates CO<sub>2</sub> phase transitions (liquid/gas)
  - Handles layered, radial reservoir geometries (Figures 11 and 12)
  - Written in Matlab using fully implicit finite-difference schemes

Impact: Enables accurate prediction of pressure, temperature, and flow dynamics in depleted fields—a significant upgrade over conventional simulators like STARS or OLGA.

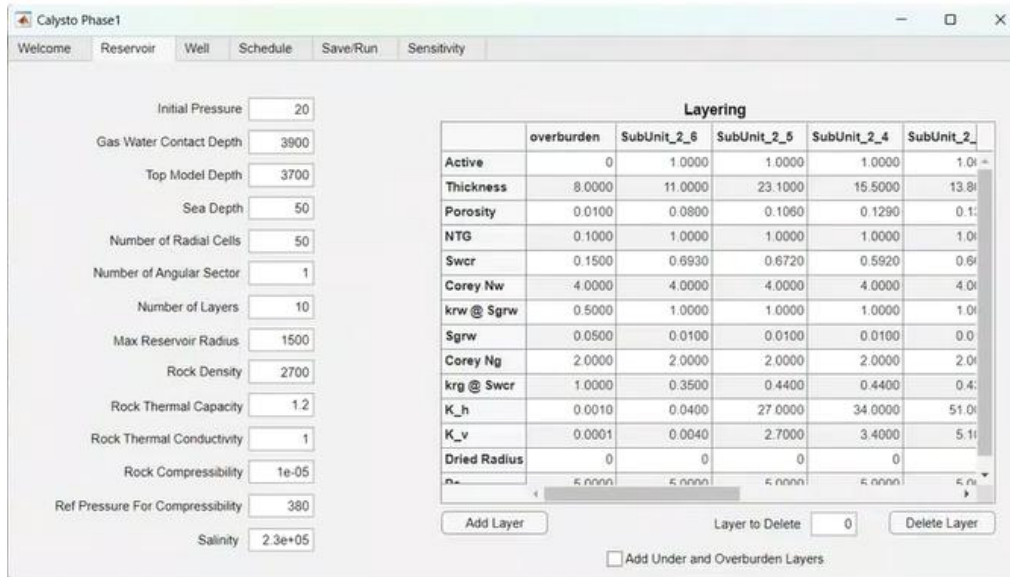


Figure 10: Matlab graphical user interface for entering reservoir and wellbore properties.

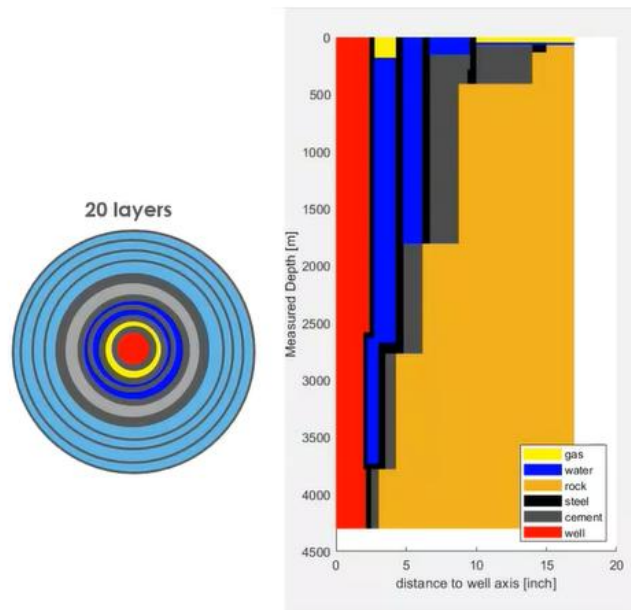


Figure 11: Top and side views of a gridded wellbore for modeling pressure and temperature gradients in the wellbore.

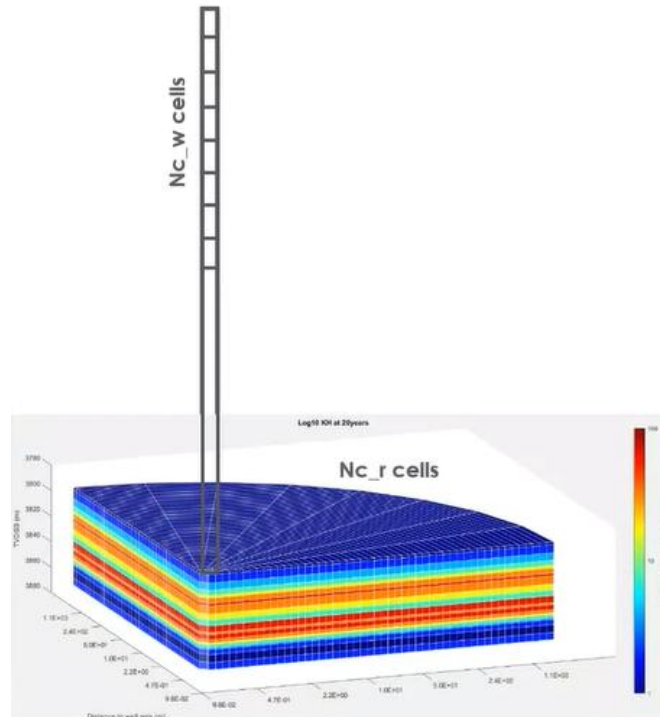


Figure 12: Diagram illustrating the connection between radial reservoir grids and wellbore grids.

## 2. High-resolution wellbore monitoring & calibration

- Calibrated surface and downhole pressure/temperature gauges to detect subtle wellbore-reservoir interactions.
- Use of Distributed Temperature Sensing (DTS) to monitor CO<sub>2</sub> plume evolution and wellbore thermodynamics in real time.
- Measured in-situ gas/liquid densities to validate theoretical models.

Impact: Enhanced ability to detect phase changes, identify liquid levels, and validate simulations with empirical data—crucial for operational safety and optimization.

## 3. Integrated field-scale experimentation

- Multi-year field trials at CMC FRS (2018–2024) included varying:
  - Injection rates (200–800 kg/day)
  - Injection temperatures (45–80°C)
  - Injection frequency (2–5 days/week)

- Assessed storage efficiency, wellbore pressure response, and injection stability under different operational regimes.

Impact: Built a rich dataset to fine-tune operational best practices for CO<sub>2</sub> injection in depleted fields, improving design for full-scale deployment.

#### 4. CO<sub>2</sub> plume imaging using geophysical monitoring

- Applied Vertical Seismic Profiling (VSP) and Electrical Resistivity Tomography (ERT) to monitor plume evolution.
- VSP provided time-lapse imaging of CO<sub>2</sub> movement.
- ERT delivered high vertical resolution and sensitivity to CO<sub>2</sub> saturation changes.

Impact: Demonstrated real-time, semi-continuous plume monitoring, providing tools to verify containment and ensure safety.

#### 5. Reservoir Characterization for Depleted Fields

- Created a static and dynamic model for a depleted hydrocarbon reservoir in Alberta using data from SpectrumH2.
- Evaluated injectivity, containment, and storage potential of depleted reservoirs vs. saline aquifers.

Impact: Showed that reused oil & gas reservoirs can be efficiently repurposed for CO<sub>2</sub> storage with lower cost, higher certainty, and faster deployment.

### 14.1.2 PROJECT TRL ADVANCEMENTS

**Table 2: TRL advancements.**

Technology Area	Starting TRL	Achieved TRL	Description
<b>Wellbore–reservoir modeling (CALYSTO)</b>	TRL 3–4	TRL 6–7	Moved from conceptual model to field-validated predictive tool
<b>CO<sub>2</sub> injection process in depleted fields</b>	TRL 3–5	TRL 6–7	Transitioned from modeling to sustained field testing at CMC FRS. The site is not a depleted reservoir but is under-pressurized, and experiment

Technology Area	Starting TRL	Achieved TRL	Description
			CO <sub>2</sub> phase change due to its shallowness
<b>Geophysical monitoring outcomes integration with reservoir modelling</b>	TRL 5	TRL 7	Validated plume tracking with integrated reservoir models
<b>Injection strategy optimization</b>	TRL 4	TRL 6–7	Derived best practices from multi-year field trials
<b>Regulatory/policy enabler</b>	TRL 2–3	TRL 5–6	Informed future storage regulations for depleted reservoirs

#### 14.2 TECHNOLOGY PROVISION AND THIRD-PARTY VENDORS

Commercial companies including CMG can use the results of RETURN to further develop their CO<sub>2</sub> simulation software. EBN has developed CALYSTO but we are uncertain whether this will be commercial externally or available publicly.

#### 14.3 COMPETITIVE SCAN

CMC is a leading-edge not-for profit company that is advancing low-cost CO<sub>2</sub> injection and storage monitoring, coupled with available reservoir simulation software. Other service providers have their own approaches, but none has the ability to test technologies in an open field setting.

#### 14.4 MARKET AND END-USERS

Carbon Management Canada has many industry partners through its Joint Industry Partnership (JIP) program. Schlumberger (SLB) and the Computer Modelling Group Ltd (CMG) are reservoir simulation developers who have shown interest in pursuing collaborative work by improving their software with CMC inputs.

Several Oil and Gas companies are also part of the JIP program, and might use our services and knowledge to develop their CO<sub>2</sub> injection projects.

#### 14.5 MARKETING

Mostly updated on LinkedIn and presentations (usually invited) at major international conferences on CCS.

#### 14.6 DISTRIBUTION

CMC provides technology outcomes to end-users through publications in refereed scientific journals and trade magazines, and also through presentations at international conferences. We also hold quarterly update meetings with members of the CMC-CaMI Joint Industry Partnership.

#### 14.7 TECHNOLOGY PROTECTION

All CMC technology outcomes become published, usually after 1 or 2 years. Specific technology may be licenced.

#### 14.8 COST OF COMMERCIALIZATION

This is the next phase of CMC's program.

#### 14.9 SHORT-TERM ACTIONS

Continued technology development in the AMPS program with CMC's collaborators and JIP members.

#### 14.10 LONG-TERM COMMERCIALIZATION

### 15.0 COMMUNICATIONS PLAN

#### 15.1 KNOWLEDGE SHARING DURING PROJECT

CMC and its partners attended and presented at different national and international conferences and workshops:

- SPE annual conference, Calgary, 2023 March 15-16
- AAPG-SPE-SEG CCUS conference – Houston, 2023 April 24-28
- AAPG-SPE-SEG CCUS conference – Houston, 2025 March 3-6
- SPE Workshop: New Perspectives in Well Performance Analysis and Production Forecasting, Colorado Springs, US, 2025
- 17<sup>th</sup> International Conference on Greenhouse Gas Control Technologies, October 21-24, Calgary, Alberta
- 16<sup>th</sup> International Conference on Greenhouse Gas Control Technologies, Lyon, France.
- SEG Geophysical Research for Gigatonnes CO<sub>2</sub> Storage, Colorado School of Mines, US
- GeoConvention conference, 2023 May 15-17

In addition, several tours of the CMC FRS were conducted, where CCS stakeholders (regulators, students, CCS professionals) were exposed to the RETURN project outcomes:

- September 2024: ConocoPhillips tour (9 participants)
- August 2024: ERA and AI (10 participants)
- August 2024: CNRL tour (17 participants)
- May 2024: CSEG Geophysics Industry Field Trip (22 participants)
- May 2024: Norwegian delegation through Canada Trade Commissioner (18 participants)

- October 2023: CSEG Doodletrain (22 participants)
- August 2023: Danish delegation through Canada Trade Commissioner (11 participants)
- August 2023: Repsol and Avalon tour (13 participants)
- May 2023: REDEVELOP tour (25 participants)
- October 2022: CSEG Doodletrain (14 participants)
- June 2022: Global Energy Show tour (15 participants)
- January 2022: Enhance tour (10 participants)



**Figure 13: Marie Macquet explaining the well temperature-pressure response to CO<sub>2</sub> injection during one of the Carbon Management Canada site tours.**

## 15.2 KNOWLEDGE SHARING POST PROJECT

Tours at the site are on-going, where the results of the project will be shared.

## 16.0 LITERATURE REVIEWED.

CMC staff are fully up to date with international literature and contribute to it.

## 17.0 DEFINITIONS