ecoENERGY Innovation Initiative

Research and Development Component

Completion Report

Project: Alberta CO_2 Purity Project CCSE 018

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1 Project Snapshot

Project Title	Alberta CO2 Purity Project
Project Identification Number	CCSE 018
Proponent	PTAC Petroleum Technology Alliance Canada
Number of Participating Partners	21
Total Project Cost ($000s)	$955,000
Total Contribution from Proponent and partners ($000s)	$350,000
Total ecoEII Contribution ($000s)	$525,000
Total Government Contribution ($000s)	$80,000
Project Highlights	o All project tasks were completed on time and on budget. o The key deliverables of the Alberta CO2 Purity Project, which consisted of a working techno-economic model and comprehensive report detailing the findings of the study, have been completed. The techno-economic model brings together the data from the project and allows the user to input system parameters such as capture process, pipeline length and EOR / sequestration division and understand the effect of their inputs throughout the system.
Date submitted to NRCan	July 23, 2014

2 Executive Summary

The Integrated CO2 Network (ICO2N), in partnership with PTAC Petroleum Technology Alliance Canada, and over 25 industry entities, have completed the Alberta CO2 Purity project; a project aimed at developing strong "made in Canada" purity guidelines that will inform commercial scale demonstration carbon capture and storage (CCS) projects. These guidelines will provide a foundation for accelerated CCS deployment in Canada, and develop an integrated picture of CO2 requirements from source to sink. It will also advise on the optimum purity requirements for a CCS Network, thereby addressing critical knowledge gaps for CCS technology deployment.

The Alberta CO2 Purity Project is a first of its kind project not only in Canada, but worldwide. Purity specifications have never been evaluated across the entire chain, and more importantly across an entire spectrum of impurities in combination as opposed to focusing on single impurities or processes. In determining optimal CO2 Purity, this will lead to lower costs in overall CCS implementation, ensure proper due diligence is complete before undertaking new projects, and ultimately aid in the overall reduction of GHGs through further knowledge, safety, and practicality of CC technology.

The Project developed a detailed techno-economic model populated with derived data that can analyze system scenarios to determine the effects of impurities and optimize purity levels across integrated CCS infrastructure. This work, completed in Alberta, will help establish purity recommendations that can be utilized by regulators, academia and industry in Alberta, Canada, and jurisdictions across the globe.

3 Introduction

The project was conducted between April 2011 to March 2014 through PTAC Petroleum Technology Alliance Canada. It involved 20 partners in addition to the Proponent. The Project had four phases, each with distinct objectives and discrete work programs that were carried out to produce meaningful study results. Most individual tasks occurred concurrently with other tasks, although there were several tests that require results from past tasks to be complete.
The Steering Committee made milestone decisions on individual pieces of work by allocating budget based on proposals provided by Technical Leads.

4 Background

In the area of carbon capture & storage (CCS), there are a large number of discrete carbon capture technologies, and each technology results in a unique CO2 purity and contaminant profile. CO2 purity can impact a number of CCS system operating parameters, including: the phase behaviour of CO2, conditions under which pipeline transportation can occur, as well as the technical feasibility of enhanced oil recovery (EOR) and direct CO2 storage. The technical feasibility of capture processes and overall CCS system costs are greatly affected as CO2 purity specifications become more stringent. For example, pipelines can transport various CO2 streams but the costs, operability and safety of pipelines are driven to a large extent by purity considerations. Enhanced oil recovery is negatively impacted by the presence of various impurities that affect the reservoir and impact miscibility of the CO2 and enhanced oil production. Impurities affect a storage scheme's plume extent, trapping capability, and rate of injectivity. This Project will investigate and determine the optimal balancing point with respect to purity as it pertains to each of the four components in a large scale CCS system (capture, transport, storage, and monitoring).

Understanding purity is crucial to the development of CCS in Canada. New information developed in this Project has the potential to enable the development of CO2 purity standards, which could result in lower costs, greater standardization of equipment, better CCS system effectiveness, and greater inter-operability between different CCS systems.

Overall, this one of a kind study provided opportunities for researchers and scientists to expand on traditional methodologies and learn from project experiments. The researchers whom took part in the study undertook testing that was new and exciting; this project supplied these researchers with funding so that they could test purity standards and enhance their own knowledge.

5 Objectives

The objective of this Project was to fill a crucial knowledge gap, and answer the following question: how does the presence of impurities affect an integrated CCS system? ACPP is a first- of-its-kind assessment of CO2 purity that examines all aspects of an integrated CCS system, including capture, transport via the pipeline, enhanced oil recovery, and direct CO2 storage or sequestration. The Project will develop a detailed techno-economic model populated with derived data that can analyze system scenarios to determine the effects of impurities and optimize purity levels across integrated CCS infrastructure. This work, to be completed in Alberta, will establish purity recommendations that can be utilized by regulators, academia and industry in Alberta, Canada, and jurisdictions across the globe.

The Alberta CO2 Purity Project was divided into five components/silos; Capture, Transportation, Enhanced Oil Recovery, Sequestration, and Integration/Administration.

The key deliverables of the Alberta CO2 Purity Project were to develop a working techno-economic model and comprehensive report detailing the findings of the study. The techno-economic model brings together the data from the project and allows the user to input system parameters such as capture process, pipeline length and EOR / sequestration division, and understand the effect of their inputs throughout the system. The model, data and report will be provided to each participant of the study so that inputs can be modified to reflect individual circumstances and new or regional specific data.

This one of a kind study provided opportunities for researchers and scientists to expand on traditional methodologies and learn from project experiments. The researchers whom took part in the study undertook testing that was new and exciting; this project supplied these researchers with funding so that they could test purity standards and enhance their own knowledge.

6 Results of Project

The Alberta CO2 Purity Project has been divided into five components; Capture, Transportation, Enhanced Oil Recovery, Sequestration, and Integration/Administration:

Capture:
The Dew Point program consisted of the study of dew points of various compositions of supercritical CO2, impurities and water. There are several analytical techniques for measuring solubility and dew point that generally involve combining CO2, the desired impurities and water into a closed vessel whose internal conditions can be controlled, and then looking for the point at which free water begins to form. Dew point measurements were performed at 5 equally spaced temperatures in the given range, and in turn, sufficient to map out the Pressure-Temperature (P-T) behavior. There were 6 compositions, resulting in approximately 40 dew point Measurements. For each test, an appropriate amount of the sample composition was injected into a microchip at a desired pressure and temperature. After reaching thermodynamic equilibrium, the state of the sample inside the microchip was imaged and used to determine the dew point; this is known as microfluidics technology.

Transportation:
This test was an experimental investigation into the effect of impurities on how flows capacity of CO2 transportation. Flow loop testing was undertaken to test the six compositions defined for analysis. This testing will help gain a better understanding of the effects of operating conditions in terms of ranges of pressure and temperatures on pipeline operability in the supercritical and dense regions and closeness to the respective phase envelopes.

Enhanced Oil Recovery:
EOR Laboratory Testing. The completion of this task helped in understanding the effects impurities in CO_2 have on minimum miscibility pressure (MMP). MMP was tested for in the laboratory using two different types of equipment: rising bubble apparatus (RBA), or slimtube. Using these tests, the Alberta CO_2 Purity Project will be able to estimate what the recovery impact of impurities in the CO_2 stream will be to determine the change in MMP compared to that of pure CO_2.

Sequestration:
Reactive Transport Modelling:
The purpose of this task was to establish a model which combines chemical reaction and flow behavior models to help determine chemical reactions, and permeability and porosity changes that can be expected through the system. The modeling included two related but distinct analyses: far-field and near-field. In the far-field analysis, away from the injection well, the modeling used a range of reservoir types calibrated to the autoclave geochemical experiments to test the sensitivity of each reservoir type to various CO2 purity streams. Chemical interactions of the components with minerals and other solid phases either moderated or

enhanced the change. The near-field analysis was similar but focused on the potential for sharp decrease in porosity, permeability, and injectivity which could impair wells, decrease their availability for injection (that is, more wells would be needed), and increase costs through multiple remedial workovers.

Integration/Administration:
The key deliverables of the Alberta CO2 Purity Project were to develop a working techno-economic model and comprehensive report detailing the findings of the study. The techno-economic model brings together the data from the project and allows the user to input system parameters such as capture process, pipeline length and EOR / sequestration division, and understand the effect of their inputs throughout the system. The model, data and report will be provided to each participant of the study so that inputs can be modified to reflect individual circumstances and new or regional specific data. Moreover, in collaboration with the Integrated CO2 Network (ICO2N), PTAC Petroleum Technology Alliance Canada provided project facilitation services as well as administrative support for the overall project, including contract administration where required, and acted as a liaison between the steering committee, project leads, and technical committees.

6.1 Project Achievements

- **Task 1.1** Capture industry information gathering was completed, this was important as it provided a comprehensive literature review and helped the project narrow down purity compositions of CO2 to study. The literature review findings also provide support as to why the compositions were chosen. After this a detailed work plan was developed.
- **Task 2.2** Capacity Validation the completion of this task helped with Filling a knowledge gap, the literature provided information on the capacity impacts of impurities in CO2 that can be compiled to determine the impact of mixtures of contaminants in CO2 on both pipeline capacity and compressor/pump design, this information was needed to determine what composition of CO2 was best to capture.
- **Task 2.5** Numerical Modelling, the completion of this task helped with Filling a knowledge gap, it addressed flow behaviour of CO2 rich mixtures to determine plume extent and subsurface flow characteristics. This is important as it feeds into the techno- economic model to allow the user to foresee the behaviour of C02 underground.
- **Task 2.6** Autoclave experiments the completion of this task worked to Measure changes, if any, in the mineralogy of rock samples and their likely impact on porosity and permeability this is was important to understand how CO2 would behave with certain rocks and minerals.
- **Task 2.7** Acid Species Analysis this task was completed and provided data for parameters not dealt with in laboratory experiments looking at PH and chemical reaction data specific to the pressure of acid species (HCl, SO2, NO2, and other trace gases). These tests can help to determine the rate at which wells would be lost.
- **Task 2.1** Dew Point and Corrosion Program. The purpose of this program was to

undertake a study of dew points of various compositions of supercritical CO2, impurities and water. There are several analytical techniques for measuring solubility and dew point that generally involve combining CO2, the desired impurities and water into a closed vessel whose internal conditions can be controlled, and then looking for the point at which free water begins to form. After reaching thermodynamic equilibrium, the state of the sample inside the microchip was imaged and used to determine the dew point; thus validating microfluidics technology.

- **Task 2.3** Flow Loop Testing. The purpose of this testing was to lead an experimental investigation into the effects of impurities on flow capacity of CO2 transportation. This testing will help in gaining a better understanding of the effects of operating conditions in terms of ranges of pressure and temperatures on pipeline operability in the supercritical and dense regions and closeness to the respective phase envelopes.
- **Task 2.4** EOR Laboratory Testing. The completion of this task helped in understanding the effects impurities in CO_2 have on minimum miscibility pressure (MMP). MMP was tested for in the laboratory using two different types of equipment: rising bubble apparatus (RBA), or slimtube. Using these tests, the Alberta CO_2 Purity Project will be able to estimate what the recovery impact of impurities in the CO_2 stream will be to determine the change in MMP compared to that of pure CO_2.
- **Task 2.8** Reactive Transport Modelling. The purpose of this task was to establish a model which combines chemical reaction and flow behavior models to help determine chemical reactions, and permeability and porosity changes that can be expected through the system. The modeling included two related but distinct analyses: far-field and near-field. In the far-field analysis, away from the injection well, the modeling used a range of reservoir types calibrated to the autoclave geochemical experiments to test the sensitivity of each reservoir type to various CO2 purity streams. Chemical interactions of the components with minerals and other solid phases either moderated or enhanced the change. The near-field analysis was similar but focused on the potential for sharp decrease in porosity, permeability, and injectivity which could impair wells, decrease their availability for injection (that is, more wells would be needed), and increase costs through multiple remedial workovers.
- **Task 3.1** Techno-Economic Modelling. The techno-economic model brings together the data from the project and allows the user to input system parameters such as capture process, pipeline length and EOR / sequestration division, and understand the effect of their inputs throughout the system.
- **Task 4.1** Report Writing. The key deliverables of the Alberta CO2 Purity Project are a working techno-economic model and comprehensive report detailing the findings of the study. The functional model will be provided to each participant of the study so that inputs can be modified to reflect individual circumstances and new or regional specific data.
- **Task 4.2** Administration. PTAC provided project facilitation, in collaboration with ICO2N, as well as provided administrative support for the overall project, including contract administration where required, and acted as a liaison between the steering committee, project leads, and technical committees.

6.2 Benefits

- Major stakeholders of this project include the public and non-governmental organizations. When this study is publically released the public will have viable hands on research available at their fingertips. It is anticipated that this study will help increase the public knowledge of CCS and understanding of CCS. This aids the public perception of CCS and therefor is beneficial to industry and government when they partake in public consultation.

- There are many barriers related to CCS these include monitoring, cost, CO2 behavior, unclear regulations and public perception. The Government of Canada is a key stakeholder in this project and study, and this study will act as a forum for generating and maintaining ongoing Government commitment to policies and funding mechanisms for viable CCS projects. This study will help address and understand the barriers to CCS therefore helping the Government with developing support mechanisms for CCS.

- It is understood that a tremendous amount of effort has been placed on CCS in the Alberta province by multiple parties and stakeholders over the years, this study brings together the elements of CCS and allows academics, industry, government and the public to assess the economic and non-economic effects of CCS using the same parameters and developed purity standards.

- A techno-economic model was developed which quantifies the impact of the presence of impurities on an integrated CCS system. The techno economic model was a unique undertaking for the modelling consultant. The consultant worked with all the managers from various professional backgrounds to input correct formulas and observations into the model. This opportunity has expanded the consultant's knowledge which now allows the consultant to create intricate models in a particular manner.

- The stakeholder groups involved and impacted by the ACPP are diverse and range from government, to energy producers (industry funders), and users of CO2. The funding providers range from pipeline associations to research organizations and they have been provided with detailed and sensitive data pertaining to the individual silo they have chosen to fund. The funders have continuously expressed interest in researching specific elements and methodologies in detail.

- The capture silo has found great benefit in using the microfluidics technology and the researchers work in hand with the University of Calgary, further research and potential academic opportunities have arisen from this experiment.

- The transportation silo developed a flow loop compact enough to test the various compositions of CO_2, there is currently no other flow loop that is designed with the same parameters, the funders of this silo plan to use the flow loop to conduct further tests with other chemical compositions. The transportation silo funders consist of associations which work towards providing accurate information about pipeline transportation to the public, this study will give these associations some merit when discussing the impacts of transporting CO2 the study therefore will be used to provide factual substance in internal and external conversations.

- The modeling work has prompted the senior modeler to undertake similar projects to continuously work on refining and perfecting the modeling parameters.

- The project managers have used the study results to open doors to conversations about CCS implementation and have spoken about the study at conferences and events. They also plan to disseminate the model internally which they will be able to tweak to match their companies initiatives.

- The project also allowed the transportation silo to hire a contractor who had never constructed a flow loop with the parameters the project required. This opportunity allowed the contractor group which consists of scientists and engineers to assess experiment and learn about constructing the detailed flow loop. All the managers were invited out to the flow loop to learn about the flow loop and the intense workmanship which went into its construction and operation.

- Overall, this project has active participation from a diverse and growing group of government organizations, industry representatives, companies and academic researchers who focus on advancing CCS in Canada, North America and around the world. This will ensure that the Project outcomes and knowledge are disseminated broadly.

- Lastly, the final report draws conclusions about appropriate purity standard setting and elements that must be considered when evaluating purity for integrated CCS systems.

6.3 Technology/Knowledge Development Objectives

- **Task 1.1** Capture industry information gathering was completed, this was important as it provided a comprehensive literature review and helped the project narrow down purity compositions of CO2 to study. The literature review findings also provide support as to why the compositions were chosen. After this a detailed work plan was developed.
- **Task 2.2** Capacity Validation the completion of this task helped with Filling a knowledge gap, the literature provided information on the capacity impacts of impurities in CO2 that can be compiled to determine the impact of mixtures of contaminants in CO2 on both pipeline capacity and compressor/pump design, this information was needed to determine what composition of CO2 was best to capture.
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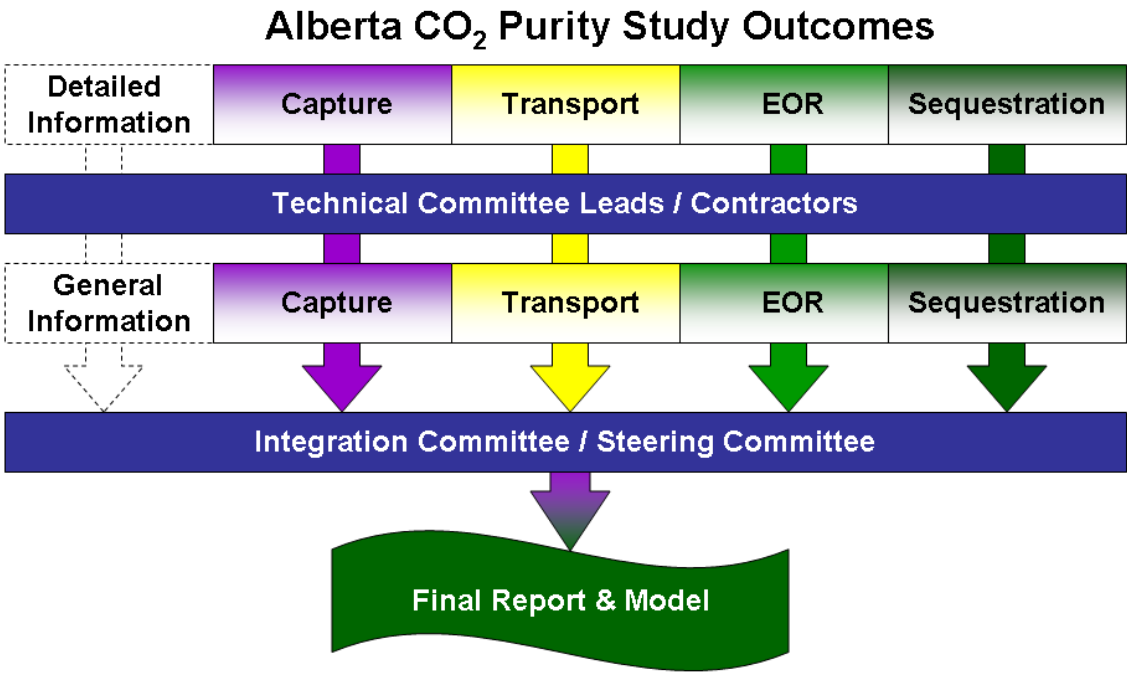
more wells would be needed), and increase costs through multiple remedial workovers.

- **Task 3.1** Techno-Economic Modelling. The techno-economic model brings together the data from the project and allows the user to input system parameters such as capture process, pipeline length and EOR / sequestration division, and understand the effect of their inputs throughout the system.

- This one of a kind study provided opportunities for researchers and scientists to expand on traditional methodologies and learn from project experiments. The researchers whom took part in the study undertook testing that was new and exciting; this project supplied these researchers with funding so that they could test purity standards and enhance their own knowledge. They have now confirmed that this project sparked their interest in the methodologies and they will be taking the studying further.

- The Alberta CO2 Purity Project is a first of its kind project not only in Canada, but worldwide. Purity specifications have never been evaluated across the entire chain, and more importantly across an entire spectrum of impurities in combination as opposed to focusing on single impurities or processes. In determining optimal CO2 Purity, this will lead to lower costs in overall CCS implementation, ensure proper due diligence is complete before undertaking new projects, and ultimately aid in the overall reduction of GHGs through further knowledge, safety, and practicality of CC technology.

- The Project will develop a detailed techno-economic model populated with derived data that can analyze system scenarios to determine the effects of impurities and optimize purity levels across integrated CCS infrastructure. This work, to be completed in Alberta, will establish purity recommendations that can be utilized by regulators, academia and industry in Alberta, Canada, and jurisdictions across the globe.



The next steps for this project are to disseminate the results of the work done through the Alberta CO2 Purity Project. All the project managers are excited to showcase and present the ACPP project. This will be done through the presentation of project findings at industry conferences, forums, and seminars, as well as through the distribution of hard copy final reports.

6.4 Challenges and Barriers

- Delayed Funding: The project received funding from NRCan one year before the expected completion date. Because of the delayed funding contracts had to amended and experiments sped up. The project had a few incidents in the lab where samples had to be re sent and the scientific equipment was no longer available for use, delaying the experiments. This delay caused a strain on the working team and also created additional work for the project managers. The ACPP team pulled through successfully.
- Technology Sourcing: During the pipeline capacity testing experiments parts to construct the pipeline were ordered from China. The price was significantly lower in China. When the parts arrived the scientists discovered that they were not up to code, they had to invest some money to bring the parts up to code. The parts ended up costing the equivalent of parts in Canada. This slightly delayed the experiments however did not have a large negative effect on the overall project. This challenge

highlighted the importance of sourcing parts locally and therefore all other parts needed in this project were sourced locally.

- Testing Technologies: During the EOR testing the scientists revealed that the RBA tests were not as accurate as the SlimTube Tests. This challenge is documented in the final report and the final report advises others on the accuracy of the technologies.
- Additional Modeling: The techno economic model was a huge undertaking. Combining the data from different scientists and 4 different silo's was a very detailed task. The project had to invest additional money into the model to complete it, this money was taken from the project contingency fund. By investing more money into completing the model accurately the project can now offer a world class tool to calculate purity costs.

7 Conclusion and Follow-up

The overarching purpose of the Alberta CO2 Purity Project was to bring industry experts and stakeholders together in advance of the critical design milestones leading to 2015. The Project has evaluated the effects of CO_2 purity and numerous contaminants on the various component parts of CCS, including capture, pipelines, EOR and sequestration. The Project also has assisted in the understanding of safety implications of CO_2 purity from an industry perspective, and will provide technical and economic information, based on the collective findings of the project, to regulators governments, and stakeholders to enhance their understanding of the purity issue. The Alberta CO_2 Purity Project will define a "made for Alberta Purity Specification".

The Project developed a detailed techno-economic model populated with derived data that can analyze system scenarios to determine the effects of impurities and optimize purity levels across integrated CCS infrastructure. This work established purity recommendations that can be utilized by regulators, academia and industry in Alberta, Canada, and jurisdictions across the globe

7.1 Next Steps

The next steps for this project are to disseminate the results of the work done through the Alberta CO2 Purity Project. All project managers are excited to showcase and present this project. This will be done through the presentation of project findings at industry conferences, forums, and seminars, as well as through the distribution of hard copy final reports.

Government of Canada is a key stakeholder in this project and study, and this study will act as a forum for generating and maintaining ongoing Government commitment to policies and funding mechanisms for viable CCS projects. This study will help address and understand the barriers to CCS therefore helping the Government with developing support mechanisms for CCS.

This study brings together the elements of CCS and allows academics, industry, government and the public to assess the economic and non-economic effects of CCS using the same parameters and developed purity standards

The techno-economic model brings together the data from the project and allows the user to input system parameters such as capture process, pipeline length and EOR / sequestration division and understand the effect of their inputs throughout the system, thus allowing for continued usage and benefit of the results of this project, throughout all industry.