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CCEMC Project: SkyCycle Pilot Installation

FINAL OUTCOMES REPORT: NON-CONFIDENTIAL

CCEMC Project Number: K130114
Recipient: Skyonic Corporation
CCEMC Project Advisor: Maureen Kolla, Ph.D.

Date Report Issued: May 31, 2016

Reporting Period Start Date: April 4, 2014
Reporting Period End Date: May 31, 2016

Total CCEMC Funds Received: $350,000 CAD
Total CCEMC Funds Held Back:$150,000 CAD

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- Long-term plan for commercialization of the project technology/learnings.
- Commercialization-related actions to be undertaken within two years of project completion.
- Potential partnerships under development with technology integrators, adopters, etc.

8. Communications plan:
   - Plans for communicating information about the project, project findings, and results or the underlying technology with third parties, including a description of communication tools that will be used.

LIST OF ACRONYMS AND ABBREVIATIONS

CCEMC = Climate Change and Emissions Management Corporation

CO_2 = carbon dioxide

EPC = Engineering, Procurement and Construction

HCl = hydrochloric acid

MVR = mechanical vapor recompression

PFD = process flow diagram

SCFM = standard cubic foot per minute

SwRI = Southwest Research Institute

tpy = metric tonnes per year

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1.0 EXECUTIVE SUMMARY

Introduction and Background

In April 2014, Skyonic Corporation was awarded a grant totaling $500,000 CAD from the Climate Change Emissions Management Corporation (CCEMC) under its *Innovative Carbon Use* program, to develop a SkyCycle™ Pilot demonstration module.

The impetus for developing Skyonic's carbon capture technology alongside companies like CCEMC is to help Canada's industrial manufacturing sector meet their emissions reduction goals by decreasing harmful greenhouse gases through a financially viable mechanism. This technology has the potential to positively impact the environment, generate revenue from the sale of the chemicals produced in the SkyCycle™ process, and create permanent engineering, operational and executive management jobs. There is also a competitive pricing advantage that can be applied to industrial emitters who manufacture products in locations where there is a fee charged per ton of CO_2 emissions released into the atmosphere.

SkyCycle™ is the follow-on technology to SkyMine®, a patented carbon capture and beneficial re-use process that has been developed at commercial scale in the form of Capitol SkyMine located adjacent to Capitol Aggregates, a coal-fired cement manufacturing plant located in San Antonio, Texas. The SkyMine® process is electrolytic, produces sodium bicarbonate as the mineralization product from captured CO_2, and is designed to directly capture 75k te of CO_2 annually. The SkyCycle™ process is *thermolytic* and produces calcium carbonate (Limestone) or magnesium carbonate as the CO_2 mineralization product, depending on the initial inputs. The SkyCycle™ patent describes the process as an innovative method used to sequester CO_2 by reacting a Group II halide with water to produce a Group II Base, as an intermediate. The intermediate Base is reacted with a second halide and CO_2 to form a stable, solid Group II carbonate as the CO_2 sequester agent. SkyCycle uses waste-heat from the source CO2 plant to generate the Alkali Base that will be used to capture the plant's CO2 emissions. When developed at full scale, it will be designed to be a 1M te/yr CO_2 reduction solution.

During the CCEMC Grant period of April 2014 to May 2016, significant advances in the technology have been achieved which have led to the installation of a development-scale Pilot at Southwest Research Institute (SwRI) in San Antonio, Texas. The purpose of this Pilot is to prove the intermediary equations of Skyonic's chemical engineering approach on a development-scale level. The entire representative SkyCycle™ system has been completed and is ready to move to substantive empirical Testing during Phase 2 of the project. The results of this next phase of testing will lead to process optimization and design efficiency that will be reflected by the full installation of the Pilot module at SwRI. The current equipment plan is to utilize SwRI as a controlled high bay equipment and experimental space, with all SkyCycle equipment now installed in this facility on a skidded/padded foundation. In this way, all initial test and development experiments required within Phase 1 and 2 can be run in a single space, with analytical equipment in the same facility.

2.0 PROJECT DESCRIPTION

- Technology description
- Project goals
- Work scope overview

The original SkyCycle™ CCEMC Project Description goals included the design, construction and installation of a commercial scale Pilot at Capitol SkyMine in San Antonio, Texas. The Pilot was to have the capacity to

capture 5k te/yr of CO_2 and mineralize those emissions to create marketable limestone, produce marketable hydrochloric acid (HCl) and define the energy/fuel penalty of the Pilot plant. The adjusted Scope of Work, submitted to CCEMC May 24, 2016, had changed the location of the Pilot installation to SwRI. By the end of Q1 2016, Skyonic had designed and constructed a SkyCycle™ Pilot ("The Pilot") project at Southwest Research Institute (SwRI) in San Antonio, TX for the purpose of proving the intermediary equations of Skyonic's patented chemical engineering approach, on a development-scale. During the CCEMC Grant term of April 2014 – May 2016, this Pilot had incorporated revised engineering and critical design concepts, all major equipment has been purchased and tested, is now fully installed and is ready for internal training, including all Carbon-Capture and Utilization equipment.

The Pilot has been equipped to take CO_2 from a confined source such as CO_2 tanks and to begin thermolytic decomposition of salts to produce Group II Base for Carbon Capture. The Pilot also has the Carbon-Capture section of the SkyCycle™ process equipped and ready for experiments to begin. It has repurposed Skyonic's existing bubble column from our mobile labs (located at Capitol Aggregates) and used during on-site development of SkyMine®. The bubble column represents the heart of the Carbon-Capture Section for SkyCycle™ and will offer empirical data supporting the SkyCycle™ approach. It will demonstrate the use of Group II Bases as a vehicle for Carbon-Capture, compared to our current commercial technology, SkyMine®, which uses Group I Bases successfully for such purpose.

Skyonic has continued to develop the SkyCycle™ technology in tandem with the commissioning of its parent technology, SkyMine®, a first of its kind carbon capture and beneficial re-use plant in San Antonio, TX. Due to similarities in the two technologies, significant advances in the design and engineering of SkyCycle™ have already happened and more are anticipated.

3.0 PROJECT DEVELOPMENT REVIEW AND SUMMARY

- Outcomes and Learnings (including, as appropriate)
- Literature review
- Technology development, installation and commissioning
- Experimental procedures/methodology
- Modelling details
- Results of experiments, model simulations
- Project outcomes
- Analysis of results
- Discussion
- Important lessons learned

3.1 Early stage of Project (from October 2014 submittal covering 7/14 – 9/14)

During the first period of the project, July through September 2014, the team focused on the decomposition of hydrated salt required to generate the synthetic base used for CO2 capture, and refinement to the SkyCycle™ process model. Additionally, an energy analysis was performed in order to identify ways to further reduce the process heat and electricity requirements.

Tests were conducted to help characterize the decomposition reaction/reactor (e.g. sizing, reaction kinetics) used to generate the synthetic base which is then used to capture the CO_2.

Water vapor is thought to have a high diffusivity through the Group II salt solids and to escape the vessel.

The engineering team developed a basis for selection for model inputs (flow rates, temperatures, pressures, Aspen blocks to represent unit operations, etc.) for the base case model. Trimeric Consulting Group performed an energy analysis on process heat consumers and process electricity consumers in efforts to identify areas where we could explore reducing the external process heat and electricity requirements. They compared the data to theoretical energy penalties for a 100% thermodynamically reversible process, and identified opportunities to improve the energy performance of the SkyCycle process.

As the project continued, process optimization was one of the main focal points. Between October 2014 and February 2015, additional energy analyses were performed to identify opportunities for process improvement that would reduce the process heat requirements. It became evident that the initial Aspen Block Models were of limited value in predicting thermodynamic results and an effort to find more accurate Software was enabled.

3.2 Mid-Stage of Project: October 2014 – February 2015

The Mid-Stage Project goal is based on the assumption of available gas turbine exhaust (which exits at 629ºC) to provide process heat to the following unit operations:

- A primary hot oil system, which provides indirect heating to the decomposition reactor
- A boiler used to generate superheated steam for direct steam injection into the decomposition reactor
- A secondary hot oil system, which provides indirect heating to the flash tower

The thermodynamic data (enthalpy) for concentrated solutions of Group II salt and high-level enthalpy balances were performed around three major unit operations to analyze the overall energy sensitivity. Specific areas of the process included

- Absorber Column
- Flash Tower
- Decomposition Reactor

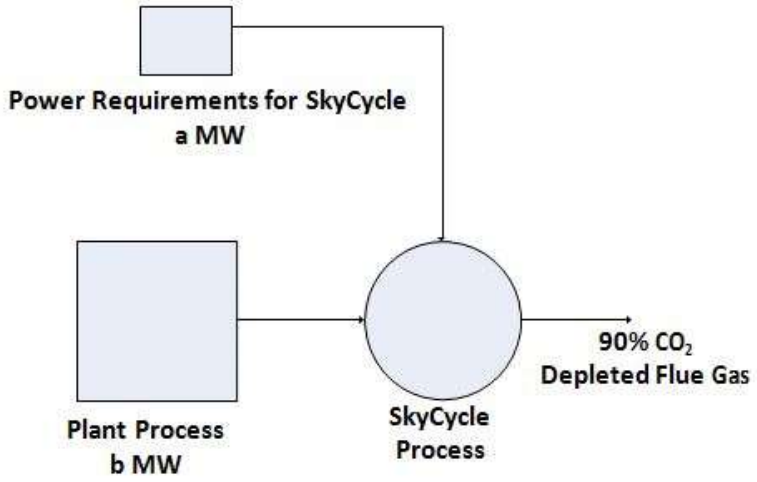
The energy analysis was conducted independent of reaction kinetics, equipment design, and electricity requirements for pumps, blowers, etc. Additional details of the analysis and the expected heat available from heat integration are segmented below:

- Overall enthalpy balances performed around all unit operations
- Energy Analysis Results – Absorption Column
- Energy Analysis Results – Water Removal
- Energy Analysis Results – Decomposition Reactor

The initial case was based on an open-cycle natural gas plant. Since there is no heat recovery steam generator (HRSG), the hot flue gas leaving the gas turbine, at a temperature of approximately ~630°C, is used to power a SkyCycle system. The results were then extrapolated to a combined cycle natural gas plant where supplemental natural gas is used instead of exhaust from the gas turbine.

Since the combusted supplemental gas is used directly after combustion for the SkyCycle process, the temperature is much hotter, namely ~1950°C, and therefore much less additional natural gas is required.

During this October 2014 – February 2015 time period, the working configuration of the CO_2 Life Cycle Analysis had an expected penalty of 15.9% as illustrated in **Figure 3.4 below**:



$$\frac{a\ MW}{a\ MW + b\ MW} = 15.9\%\ Penalty$$

For a 5000 te/yr CO2 capture the result is:
Total CO_2 present:
= 5,000 TePY + (15.9% * 5,000 TePY) = 5,9453 TePYCO2
=15.9% * 5,943 = 945.3 TePY CO2
Point CO2 emissions from SkyCycle module = 945.3 TePY

By August 2015, the project had advanced an alternative, lower-energy means for dewatering the Group II salt solution; tests were conducted at SwRI using a GEA FSD Minor spray dryer (from the institute's Microencapsulation Group). Aqueous solutions of salt were provided as the feed for the tests. Preliminary tests resulted in the formation of a solid product containing approximately 2 hydration waters.

Ongoing testing included modifications/optimization of the equipment to provide accurate parameters for modeling/scaling up the equipment as well as obtaining a consistent product through repeatability and feasibility tests. A key component of the SkyCycle process is the decomposition of Group II salt using waste heat to accelerate conversion rate to a Group II Base, based on operating parameters gleaned from literature, and by previous experimentation.
Initially, tests were performed by only heating the salt through the jacketed thermal oil system to get a baseline for future runs. Later tests included sweep air, ambient air, and hot, compressed air. The heat up rate was varied in order to reach target temperature to begin test runs. When small to moderate volumes of heat were introduced in the system, as the internal temperature reached ~113°C, the salt formed a phase of intermediate waters that were of very high density and not optimal for further processing.

Based on the results from above, prior drying steps may be attempted to remove enough waters of hydration before heat decomposition, to avoid the heavy density phase of the reaction.

By the end of August, Skyonic had decided to utilize its research partner, SwRI, to build the Pilot SkyCycle™ in

one of the available high-bay development suites at SwRI. Initial plans were to optimize the Group II salt reaction at SwRI and subsequently move the unit to the Capitol SkyMine facility. But since commissioning of the Capitol SkyMine project was not yet complete, this made it impossible to install additional equipment on the plant site, forcing a shift of direction to install the Pilot at SwRI.

The resulting completion of the process flow diagram (PFD), and process and instrumentation diagram (P&ID) for the waste heat reactor system generated a (now) standard bill of materials (BOM). A housekeeping pad was designed and installed on site for the load distribution of the steam generator and all process units. All major components of the decomposition system were received and the system installation has now been completed.

SwRI worked with all equipment vendors to setup and install all accompanying components. SwRI contracted Big State Electric for all affiliated electrical work. The piping and utilities work for the natural gas, domestic water, vent piping, drain piping, all interconnections, and heat exhaust will be performed by Mueller and Wilson Contracting Inc. To facilitate Phase 2 testing, SwRI contractors will install the process cooling water system to include the necessary water softening units and high capacity chillers. Once these tasks have been completed, training on the system can occur to establish a base operation level. . The next phase of work at SwRI will be to commission the integrated Pilot and operate the unit to start the optimization experiments.

CONCLUSIONS

Skyonic had worked with SwRI to finish the majority of the Pilot plant modifications and equipment installation by the end of December 2015. Concurrent with the installation of heat and reactors at SwRI, the Carbon Capture system that was used for initial SkyMine® experiments at Capitol Aggregates was removed and reassembled at the Pilot facility to be used in initial scale capture of CO_2. Initial experiments through the new reactors may be at a Batch level, in an effort to characterize the reaction kinetics and energy penalty for this critical step. We are confident that a continuous flow process (similar to that now in high volume production at Capitol SkyMine) will be realized in the next phase of experiments.

As a recap, Carbon Dioxide is absorbed when it is exposed to the Group II base. The Skyonic R&D team has demonstrated that aqueous solutions of varying water to base molar ratio have allowed capture of CO_2

The Mechanical Vapor Recompression (MVR) unit planned for the earlier design version, is no longer being considered. As the project advanced, alternate methods for dewatering the salt solution have emerged as better options, the main focus being on various commercial drying methods and equipment.
Once optimal conditions are elucidated, this data will be used to generate and select the equipment candidates to implement into the Pilot.

During Phase 2 of the project, each unit will be brought on-line when qualified so that commissioning of the equipment suite can occur as rapidly as possible. As commissioning is achieved, each unit will be released for testing to run setup experiments to first optimize the individual equipment and then as a full process cycle. Ultimate goal is to provide the parameters for equipment optimization necessary to attain a 5,000 te/yr CO_2 capture rate.

PRACTICAL APPLICATION:
Knowledge transfer and technology advancement via SkyMine® at commercial scale as it relates to SkyCycle™ Pilot development

During the last 6 months of this 24-month Grant period, Capitol SkyMine has served as a practical hands-on training module that is directly correlated to the advancement of new process techniques that have been and will be applied to SkyCycle™ operations. The changes in design and process engineering for the SkyCycle™ process impacted the schedule of testing and validation of the revised theories that had been developed between June 2015 and December 2015. One of the high-bay R&D suites at SwRI offered an alternative venue to install the first SkyCycle™ commercial-scale Pilot.

The potential location for a SkyCycle™ modular, skid- mounted commercial Pilot within the footprint of the Capitol SkyMine facility is indicated in Figure 3.6.

Figure 3.6 Future SkyCycle™ Commercial Pilot Plant Site at Capitol SkyMine

4. Overall Conclusions

Skyonic's goal is to be the leading provider of profitable carbon capture solutions and a supplier of carbon-negative chemicals worldwide. We have developed proprietary technology that reduces pollution and enables sustainable business practices by capturing greenhouse gases and other pollutants from power plants, industrial facilities and other stationary emitters and converting them into valuable chemicals. Our solutions are designed to address emissions reduction, carbon capture and utilization, and the global demand for chlorine- and carbonate-based products.

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Figure 3.7 – SkyCycle Mobile Laboratory with early-stage equipment design

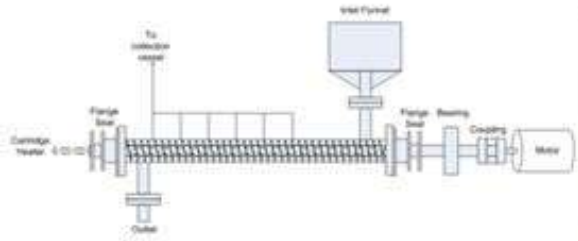
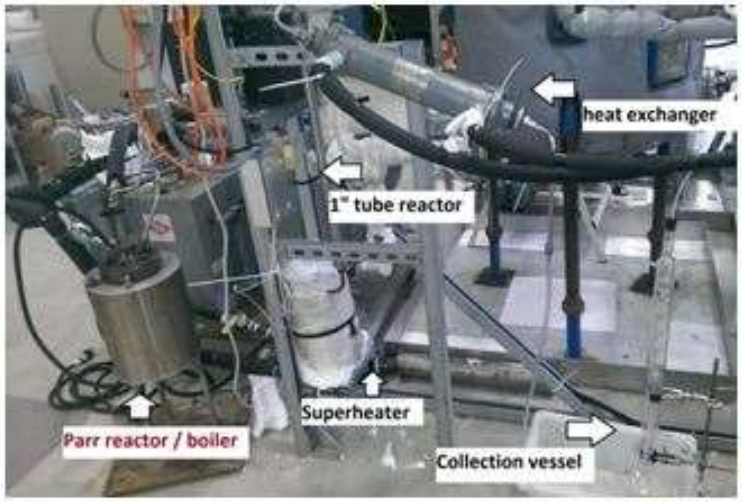


Figure 3.8– side of Mobile Lab

Figure 3.9 - 14 Meter Carbon Capture Column

Fig. 4.0 - Equipment Development in initial CCEMC SkyCycle Phase 1 experiments

Fig. 4.1 - Bench Scale Experiments



1" Pipe Reactor

- Gather data points to better understand the kinetics and mass transfer of decomposition of salt
- Address decomposition equipment challenges
- Provide parameters for effective fluidization at the bigger scale unit being constructed at SwRI

Fig. 4.2 - Beginning of SWRI SkyCycle™ Pilot Installation

Fig. 4.3 - SWRI SkyCycle™ Pilot Installation

Fig. 4.4 - SWRI SkyCycle™ Pilot Installation

Overview of project (west side)

Fig. 4.5 - SwRI SkyCycle™ Pilot Installation complete

5. Greenhouse Gas and Non-GHG Impacts

- Qualitative discussion about the GHG benefits resulting from the completed project, including immediate benefits and potential future impact
- Quantification of expected annual GHG benefits projected over a ten-year period (or further) including both direct impacts from implementation of the project and future impacts based on market adoption.
- Discussion about the immediate and potential future non-GHG benefits resulting from the competed project, including but no limited to environmental benefits, employment, economic growth/activity, training/attraction of highly –qualified personnel (HQP).

Skyonic is currently reducing greenhouse gases due to the commissioning and operation of its first SkyMine® plant in San Antonio, TX. Because of the lessons learned from this first commercial scale SkyMine® project, SkyCycle™ is expected to begin directly reducing emissions sometime in 2016. The SkyCycle™ Pilot have been designed to capture ~5k te/yr. If it is installed at Capitol SkyMine (or some other location) and functioning at capacity in early 2017, it could reduce total emissions by up to 20k te by end 2020. Skyonic's trajectory for SkyCycle scale-up and development is to have a 250k te/yr project designed and built (in parallel) by end 2020 (50x scale-up). The 1M te/yr carbon capture target for equipment designed and built is 2023. Without any expansion in our Projects except for SkyCyle™ developments, by beginning 2023, Skyonic could be capturing 330,000 te/yr of CO_2 with a cumulative emission reduction total of 530k te. With the a fully scaled and commissioned 1M te/yr SkyCycle™ in place by end 2023, those totals increase to 1.3M te/yr of CO2 reduction and a cumulative total of 1.81M te by the end of 2024.

The Greater Austin Chamber of Commerce calculated Capitol SkyMine's anticipated direct, indirect and induced impact on the Austin 5-county metropolitan area's total output to be in excess $130M on an annual basis . Over 250 direct jobs were created during the design and construction of the plant and another 200+ permanent positions added into the general U.S. economy. These positions are a high-wage mix of engineers, technicians, and managers. Based on these parameters, we anticipate that for the 250k te/yr SkyCycle™ project a similar number of jobs will be created during the design, construction and operations of that plant. And if the same parallels are able to be drawn regarding the profits made from the chemicals produced, that being a scaling of ~3X the amount of products, the financial impact could be almost $400M on an annual basis. Skyonic will conduct studies like these once a specific site and scale have been determined. We will have a more definitive understanding of the economic and social impacts a project like SkyCycle™ will have on the region once those variables and others have been defined.

Additional benefits of the SkyCycle™ technology is that it will provide Canada an alternative to paying a carbon tax on emissions. The current 2016 CO_2 tax is ~$15/te CAD with increases planned for 2017 to be $20/te CAD and $30/te CAD in 2018. For industrial emitters that produce goods or commodities sold into the marketplace, the CO_2 tax increases the price of their products. If they are able to manufacture their products without paying the CO_2 tax, they quickly become more cost competitive. Outputs of the SkyCycle™ process include white limestone and dolomites which can be sold and used for road construction. This leads to job creation, an increase in export commodities, and positive financial returns in Alberta that can be attributed to direct carbon capture and beneficial re-use.

The full expense of the equipment designed and purchased for the CCEMC SkyCycle project (minus the CCEMC contributions to date) has been borne by Skyonic. This represents Skyonic's contribution to the

project and represents our commitment to GHG reduction in Canada. A full financial report will be submitted as a separate document as part of Skyonic's obligations for this Grant.

6. Scientific Achievements

- Between 2013 and 2016, SkyCycle™ has been patented in Australia, the Eurasian Patent Organization, Japan, Mexico, New Zealand, Singapore, Taiwan, the United States, and South Africa
- Basic SkyCycle patents are 013 and 038

7. Next Steps

- Discussion about the next steps for the technology/process/innovation, including potential follow up projects
- Long term plan for commercialization of the project technology learnings
- Commercializtion related actions to be undertaken within two years of project completion
- Potential partnerships under development with technology integrators, adopters, etc

The following will be among the key experiments to determine the next course of action before moving the Pilot module to the Capitol SkyMine site which is anticipated to be between the end of 2016 and Q1 2017:

- Connect all equipment and verify operation
- Perform necessary HAZOP reviews
- Verify that the Pilot is able to generate HCl from $MgCl_2$ hexahydrate and other hydrates
- Evaluate speed of decomposition reaction
- Evaluate reaction energy penalty vs reaction speed
- Evaluate total energy penalty and commercial worthiness

In subsequent phases of the project, this system can be replicated and transferred to a suitable location in Alberta, Canada. Skyonic continues to have conversations with members of their Board of Directors and Investors at ConocoPhillips and Cenovus for potential Canadian locations for a SkyCycle™ installation. The project could either use the modular SkyCycle™ Pilot that will be installed at Capitol SkyMine or a new Pilot with a different CO_2 capture capacity developed and constructed and then shipped up to the specific site in Canada.

8. Communications Plan:

Once the final report has been submitted and accepted by CCEMC, we will begin drafting our application for the Phase 2 $3M CAD CCEMC Grant. In any event, Skyonic will continue to develop the SkyCycle™ Pilot so it will remain on its current trajectory to be at full scale capacity; we hope to reduce CO_2 by 250 kT by end of 2020 and by 1M te/yr by end 2023. We hope to partner with companies like CCEMC to take advantage of government support for innovative technology such as ours. When the report(s) becomes publicly available, we will send out a Press Release with the details of the project's outcomes, and a link to the report and describe the CCEMC program. Besides Skyonic's employees and Board of Directors, strategic recipients will include but not be limited to our DOE partners, environmental and technology publications and local media outlets.