ecoENERGY Innovation Initiative

Research and Development Component

Public Report

PROJECT CODE: UOSE 018

PROJECT TITLE
Submerged Combustion Vaporizer for Heating And Pressurizing Hydrocarbon Reservoirs

Contents

1 Project Snapshot

Project Title	Submerged Combustion Vaporizer for Heating And Pressurizing Hydrocarbon Reservoirs
Project Identification Number	UOSE 018
Proponent	Combustion Solutions Inc.
Number of Participating Partners	3
Total Project Cost ($000s)	$4,698
Total Contribution from Proponent and partners ($000s)	$2,451
Total ecoEII Contribution ($000s)	$2,147
Total Government Contribution ($000s)	$2,147
Project Highlights	o Designed, manufactured and operated a new burner capable of operating while fully submerged in untreated high pressure salt water for the purpose of generating steam while ensuring no hot surfaces are in contact with the water so as to prevent scaling. o Registered the "high pressure direct contact submerged combustion vaporizer" design with the applicable regulatory body. Approved as a gasifying reactor rather than a boiler eliminating the need for certified steam engineers during operation. o Produced a mixture of high pressure steam and combustion gases using saline water in a "direct contact steam generation process" that could in future be used for downhole applications.

2 Executive Summary

The ecoEnergy Innovation Initiative project UOSE-018 "Submerged Combustion Vaporizer for Heating and Pressurizing Hydrocarbon Reservoirs" was successfully completed.

Companies with nimble resources can develop breakthrough technologies assisted by the funding provided by the NRCan ecoEnergy Innovation Initiative. All barriers and challenges were overcome. Project execution increased the technological readiness level increased from 2 to 7 and is now ready to proceed to be proven in a "real world" operating environment.

During the project, the oil prices collapsed which resulted in a deviation from the planned field testing. The field test was substituted by a third party numerical simulation that predicted to increase the thermal recovery by more than 100% over a 5 year period.

3 Introduction

This report summarizes results of the initial UOSE-018 project “Submerged Combustion Vaporizer for Heating and Pressurizing Hydrocarbon Reservoirs” as well as the required add-on’s. The project was started in June 2011 and completed in September 2016. In addition to the proponent – Combustion Solutions Inc. (CSI), there were others involved including FERST Environmental Inc.and Husky Oil Operations Limited as well as collaborations with Petroleum Technology Alliance Canada (PTAC) and the Saskatchewan Research Council (SRC).

4 Project description and scope

Combustion Solutions Inc. researched and bench scale tested a high pressure submerged burner and then designed and fabricated a transportable 5 MM Btu/hour Submerged Combustion Vaporizer process package that was intended for field testing on a Husky Energy CHOPS (Cold Heavy Oil Production with Sand) well near to Lloydminster, SK.

In the process of undertaking the scope of work, it was recognized that it would be beneficial to expand the project scope in three phases:

1) Design and Manufacture a transportable SCV including add-on of annulus cooling process skid
2) Installation of the SCV at a well site
3) Testing of the SCV process including additional project scope.

The add-on project increased the scope of the project with:

a) Additional process skid for producing cooling fluids for injection into the annulus of the heavy oil and thermal Oil Sands wells,
b) Enhanced portability to facilitate testing at multiple well locations,
c) Additional instrumentation for remote monitoring and control of the equipment using a Supervisory Control and Data Acquisition system (SCADA).

5 Background

The Proponent, Combustion Solutions Inc. (CSI) is a fully integrated company that offers a complete range of products and services from front-end engineering through detailed design, fabrication, installation, commissioning and start-up of fired combustion heaters and safety & control systems. Since inception in 2004, CSI has gained a solid reputation for technical innovation and reliability, while providing exceptional quality and service to its customers. CSI has gained a reputation for developing innovative solutions for the unique problems found in refineries, offshore platforms, and gas plants.

CSI partnered with FERST Environmental Inc. to gain expertise in the application of steam generation for enhanced oil recovery related to CHOPS wells. FERST Environmental Inc. has filed a method, system and apparatus patent application on submerged combustion vaporizer for heating and pressurizing hydrocarbon reservoirs.

Genesis of the Project

The project builts on the foundation of previous work undertaken by both Combustion Solutions Inc. and FERST Environmental Inc. in the area of steam generation for thermal oil recovery. FERST Environmental Inc. developed the concept of using steam and flue gases to stimulate enhanced recovery from CHOPS wells. Of prime importance was the use of a direct contact high pressure burner to vaporize raw untreated produced oilfield water in a reactor at effectively 100% energy efficiency while providing maximum well stimulation and recovery without producing significant greenhouse gases (GHG). CSI has considerable burner and combustion experience as was therefore approached by FERST to develop the detailed design for the project. Husky Energy was approached as a potential partner for the project as they have several thousand CHOPS wells which have only realized oil recovery in the range of 4% to 6%. They foresaw that this type of technology could significantly increase their recoverable reserves and allow them to cost effectively produce more oil without incurring significant environmental impact.

In order to realize commercial operation of the SCV at a Husky Energy or similar CHOPS operator well site, the technologies and processes required further R&D and evaluation. FERST Environmental Inc. therefore submitted an expression of interest in response to NRCan's ecoEnergy Innovation Initiative invitation. FERST was selected to submit a full proposal, and upon further discussion with NRCan it was agreed that FERST's partner - CSI - would take over the role as proponent for the purpose of entering into a Contribution Agreement with NRCan.

Need for the Project

The use of thermal technologies for stimulating recovery of oil from CHOPS wells has significant potential to increase Canadas' recoverable oil reserves in the heavy oil basin around Lloydminster. Thermal technologies are therefore attractive; however, there is a concern with increasing the environmental footprint associated with the recovery of these reserves.

Steam is a typical input for conventional oil sands and heavy oil recovery processes, requiring the use of fresh water supplies, considerable fuel consumption and the associated generation of greenhouse gases. In most cases, treated fresh water (plus some recycled produced water) is used in 85% efficient gas fired boilers to produce high pressure steam. The process wastes more than 15% of the energy input while producing considerable GHG and Nitrous oxides that are released to the atmosphere. An improved method of steam production is required that reduces fresh water usage, has improved energy efficiency, provides lower emissions and has a reduced overall physical and environmental footprint. Furthermore, the use of non-condensable gases within the well has the added benefit of creating a miscible flood and keeping the well pressurized and flowing through "wormholes" in the formation akin to the benefits of fracking without the negative effects of ultra high pressures.

Innovation

This project is the first of its kind to develop, manufacture and operate a high pressure burner where the flue gases are in direct contact with raw untreated water for the purpose of effectively transferring heat for the generation of steam and combustion gases without a physical heat transfer surface. Furthermore, the steam and combustion gases are superheated to prevent subsequent condensation and associated corrosion of well string components.

The innovative design of the equipment and the proposed well stimulation process is expected to result in higher efficiency, reduced GHG emissions, lower capital and operating costs and increased water reuse when compared with existing practices applied to heavy oil production.

The R&D Project was undertaken to confirm that untreated non-potable and saline produced water can be used to make steam for the purpose of heating a heavy oil reservoir. The project aimed to assess the high pressure Submerged Combustion Vaporizer process, and confirm that the heat energy available in the combustion products combined with vaporized steam can be directly employed for the purpose of heating an oil sands or heavy oil reservoir for the recovery of hydrocarbons.

6 Objectives

The objectives of the EcoEII Project UOSE-018 and add-on are 1) to conduct research and development, 2) to design and manufacture new equipment and 3) to field test novel process technologies for use in unconventional oil production. In the process of meeting the project objectives, it was recognized that it would be beneficial to expand the project scope in three phases. The increased scope of the add-on project did not change the objectives.

The following sections describe how the three separate project phases were used to meet the specific objectives and their resulting impact on the project and the energy industry as a whole. The sections are subdivided in the three project phases.

7 Phase 1 - Design and manufacturing of a portable SCV

The primary objectives including conducting R&D as well as designing and manufacturing a transportable SCV system were successfully completed in Phase 1. Demonstration of completion of this phase resulted in renewed interest from potential investors to take the technology for the field trials prior to commercialization.

8 Phase 2 - Installation of the SCV at a well site

The third objective was the field test at a well site installation. However, this was not completed due to a substantial downturn in the oil industry. Husky Oil Operations drastically curtailed capital expenditures and decided to abandon the project even though they saw future benefits. Considerable efforts were undertaken to find a new partner but unfortunately this did not proceed beyond review of a design basis memorandum of a field trial at Cenovus' Foster Creek location. This project was also cut due to budget constraints and project prioritization. The economic downturn didn't result in cancellation of the intention to field test the SCV at a well site. Opportunities for field testing, collaboration and partnering have been actively pursued with significant interest from the Saskatchewan government.

In a best possible effort to substitute lessons learned from installation and testing of the SCV at a well site, CSI collaborated with the Petroleum Technology Association Canada (PTAC) and the Saskatchewan Research Council (SRC). The SCV process in a post-CHOPS Enhanced Oil Recovery ("EOR") application was evaluated. SRC conducted a study and numerical modelling of the SCV EOR process to evaluate potential incremental oil recovery and confirm suitability of the SCV process for application in heavy oil EOR using a non-thermally completed CHOPS well.

9 Phase 3- Testing of portable SCV including additional scope

As alternative to field testing the SCV system, the SCV was subjected to simulated field tests at CSI's shop located in Squamish, B.C. Operational tests with an NRCan representative on site were conducted to demonstrate the ability of the SCV to generate a mixture of high pressure steam and combustion gases. Further testing has continued and lessons learned have been applied to improvement of the process.

10 Results of Project

10.1 Project Achievements

The reported modifications to the objectives inevitably also resulted in deviations from the work plan in the Contribution Agreement. The deliverables of the work plan were effectively substituted. Significant challenges were encountered during execution of the work plan. The completion dates of milestones and overall project completion were significantly delayed.

The following tables provide an overview of the results of the Project, including the deliverables, major cooperation and major work elements completed.

10.1.1 Achievement – Phase 1

Tasks / Activities	Major Milestones	Completion Date	Deliverables
Phase 1 – Design and Manufacture a Portable SCV System including add-on			
1.1 - Develop Design Basis Memorandum (DBM)		Dec 20/13	Published DBM Document, including Process Flow Diagram, Material Balance, Schedule, Execution Plan
1.2 – Regulatory approvals		Mar 29/14	Formal confirmation from regulators regarding design and operational requirements
1.3 – FEED/Data sheets		Dec 20/13	Front End Engineering Design (FEED) package and Equipment Data Sheets
1.4 – Burner Design/R&D		Dec 20/13	R&D design work package for prototype SCV burners
	FEED, R&D and initial CFD Studies Completed	**Dec 20/13**	**Milestone**
1.5 - Manufacture and test bench scale burners for R&D		Dec 20/13	Prototype burners manufactured, with an interim Report on R&D testing results
	Bench scale burner tested	**Dec 31/13**	**Milestone**

Tasks / Activities	Major Milestones	Completion Date	Deliverables
1.6 – Detailed engineering		March 31/14	Detailed "Issued for Construction Engineering" Drawings
	R&D and Detailed Engineering Design completed	**March 31/14**	
1.7 - Procure long lead equipment		March 31/14	Purchase Orders issued, major equipment delivered on site for performance testing
	Equipment delivered	**March 31/14**	**Milestone**
1.8 – Manufacture full scale burner and pilot SCV vessel		March 31/14	Full scale burner manufactured and ready for shop testing
	Full scale burner manufactured	**March 31/14**	**Milestone**
1.9 - Shop test equipment		Nov 30/14	Interim Report on results of shop testing full scale burner
1.10 - Procure balance of material to build portable system		Nov 30/14	Materials delivered and on hand, Bill of Materials (BOM) signed off
	Full scale burner tested & balance of materials delivered	**Nov 30/14**	**Milestone**
1.11 - Update Documents to incorporate Add-On Project	Piping and Instrumentation Diagram (P&ID), Process Flow Diagram, and Equipment Datasheets updated	Dec. 18/14	Updated FEED documents which incorporate Add-On Project, including pressure equipment design survey tracking numbers
1.12 - Detailed Engineering of Enhanced Portable SCV System incorporating Add-On Project	Prepare and Complete Manufacturing Drawings and Bill of Materials for Add-On Project	Dec 31/14	Manufacturing Drawings
1.13 - Procurement of Materials for Add-On Project	Manufacturing Drawings, Receipt of Add-On Materials at Manufacturing Facility	April1/15	Materials for Add-On Project
1.14 - Manufacturing of Add-On Project Scope for incorporation with the Portable SCV System	Assembly and Setup of Expanded SCV System complete with Add-Ons, ready for Commissioning	Jul 01/15	Fully manufactured and assembled SCV Package incorporating Add-On components
1.15 - Testing of Add-On Components with Portable SCV System	Completion of Factory Acceptance Test	Dec 31/15	Testing Results of Portable SCV System incorporating Add-On Project Components

10.1.2 Achievement – Phase 2 Completion

Tasks / Activities	Major Milestones	Completion Date	Deliverables
Phase 2 – Numerical simulation of the SCV at well site			
2.3 - SCV Simulation		December 31/15	PTAC / SRC Simulation rest report

10.1.3 Achievement – Phase 3 Completion

Tasks / Activities	Major Milestones	Completion Date	Deliverables
Phase 3 – Shop testing of the Portable SCV with Add-On Scope			
	Completion of deficiency list.	**Jan 31/16**	**SCV ready for operation**
3.1 – Shop Test Operations (CSI)	Completion of an Operational Test Program for collection of data & lessons learned during production and injection of steam and combustion gases	August 30/16	Reporting including Data andLessons Learned.
3.2 – Data Analysis (CSI)	Analysis and interpretation completed	September 30/16	Formal documents containing recorded data and operating experience, with analysis of results and conclusions
3.3 – Final Reports (CSI)	Report Distributed to ecoEII, Partner and Collaborators	September 30/16	Formal Report including data and lessons learned for technology refinement and scale-up for commercial operation in oil sands and unconventional Enhanced Oil Recovery (EOR) projects.
	Project Completed	**September 30/16**	**Milestone**

10.2 Benefits

The main benefits of this project is in the ability to move from R&D to full scale commercialization within the next two to three years once the oil pricing environment has improved and oil companies are able to resume resource development and efficiency initiatives.

10.2.1 Benefit 1- Operational SCV process demonstration

An important achievement was operational testing of the integrated components of the SCV system in CSI's shop located in Squamish, B.C. Modifications and repairs were made to the combustion air compressor and SCV burner systems to improve operation and reliability. A significant milestone was through successful operation of the SCV at CSI's Squamish manufacturing shop which demonstrated the ability of the SCV Reactor to produce a mixture of high pressure steam and combustion gases from saline water. The impact of this achievement is that other companies have expressed an interest in assisting CSI and stakeholders in field testing of the SCV on a heavy oil well and in assisting with commercialization of the technology.

10.2.1 Benefit 2 – Registration as "Gasifying Reactor"

CSI submitted designs of fittings and pressure vessels to Technical Safety Authority of Saskatchewan (TSASK) for registration of the SCV's pressure vessels and fittings. Deliverables included design engineering documents and calculations in support of licensing pressure vessels and piping. CSI has received formal confirmation from TSASK confirming registration of the SCV as a "Gasifying Reactor", a successful and important differentiation from a "Boiler" which by definition has heat transfer surfaces for the purpose of producing steam. Operation and registration as a "Gasifying Reactor" which does not have heat transfer surfaces means that the SCV will not require full time certified steam engineers for field operation.

Registration with the pressure equipment safety authority in Alberta ("ABSA") has not been initiated due to project cost prioritization. Registration with ABSA, is awaiting developments in field testing cooperation in the province of Alberta.

10.2.2 Other benefits

The following includes benefits that will be achieved in future, once the SCV technology is field tested.

10.2.2.1 Improved energy efficiency

Direct injection of combustion gases into the saline water results in an overall equipment process efficiency close to 100% as compared with conventional water treatment and steam generation equipment that operates in the range of 80% efficiency. Commercialization of the SCV technology will therefore provide increased energy efficiency and reduced water and air emissions from oil sands and heavy oil recovery projects.

10.2.2.2 Reduced environmental impact

A benefit that will flow from this R&D Project will be availability of a thermal process technology capable of producing a mixture of superheated steam and CO2 laden combustion gas for use in the in-situ recovery of bitumen from low pressure shallow oil sand deposits. This technology will provide an alternative to surface mining for the recovery of bitumen from certain oil sand deposits, plus provide a method of recovering bitumen from stranded reserves.

10.2.2.3 Enhanced oil recovery by sequestration

This project will offer future benefits of reduced GHG and NOX emissions from oil sands and heavy oil thermal projects. The Submerged Combustion Vaporizer is capable of injecting steam plus 100% of the combustion gases into a reservoir, as compared with conventional thermal project steam generators which emit combustion gases to the atmosphere. In deep oil sands and heavy oil projects, a portion of the CO2 and other gases can be sequestered in depleted reservoirs, and in mature SAGD steam chambers which require injection of non-condensable gases to maintain pressure.

Injection of carbon dioxide gas into the well has the potential to increase the yield of depleted and high viscosity fields. Carbon dioxide and oil mix together to produce a miscible fluid with reduced viscosity. Enhanced oil recovery through carbon sequestration also provides an option to reduce the carbon foot print of Canadian oil sands towards levels that are comparable to production of other types of crude oil.

10.2.2.4 Reduced water usage

An important benefit of this project is the reduction of water usage through capture of water vapor from the flue gases which would otherwise be exhausted to the atmosphere. When gasifying water directly, the volume of water vapor is increased by ~ 10% through water formed within the combustion process. This stream is transported down the well string with the thermally generated steam.

Conventional steam generators also require a continuous blowdown of 15% to 20% by mass of the feedwater. This blowdown serves to concentrate solids which are then transported to the blowdown pond or are recycled through water treatment plant. The SCV does require blowdown of any solids; however, there are no heat transfer surfaces to protect and therefore blowdown can be minimized to a small percentage of the overall feedwater supply.

Once the SCV technology is commercialized, the results and lessons-leaned form this R&D Project will ultimately offer the benefit of increased water reuse and reduced water consumption in oil sands and thermal heavy oil recovery projects.

10.2.2.5 Reduced requirements for recycling of water

This R&D project has demonstrated that it is possible to directly gasify water (“steam”) from high pressure saturated brine thereby reducing the need for a water treatment plant within a heavy oil facility. Recycled water from the well could therefore be used directly from the free water knock out (FWKO) without any secondary or tertiary water treatment. This has significant benefits through reduced costs, land use and a smaller environmental footprint from heavy oil operations.

10.2.2.6 Portability, reduced construction and land use requirements

A benefit provided by the SCV technology is the reduction in equipment and resources required for the construction of conventional thermal projects. The small modular foot print of the SCV allows new wells to be quickly and cost effectively produced without the environmental and financial costs associated with building large central processing facilities. Furthermore existing facilities can be easily expanded and SCV assets can be redeployed in response to the increase or depletion of production from a well pad. Existing non-thermal wells (such as CHOPS) can also be reactivated for enhanced oil recovery.

10.2.2.7 Improved competitiveness

A longer term benefit of this R&D Project will be the development and ultimate commercialization of a “made in Canada” technology. Benefits to Canada include creation of new jobs in the area of manufacturing and services, new opportunities for trade and export, reduced environmental impact from oilsands and heavy oil production, and increased development of resources. Another immediate benefit of this project is that it demonstrates Canada’s commitment to protecting the environment. This project will ultimately contribute to Canada’s competitiveness by allowing increased production of bitumen and heavy oil at reduced cost and environmental impact, and will provide economic benefits due to job creation and export of a Canadian manufactured product to the international oil industry.

Technology/Knowledge Development Objectives

Figure 1 illustrates the activities from the initial R&D stages through to commercialization following successful field testing:

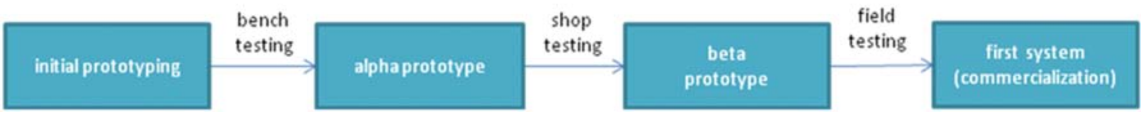

Figure 1: R&D activity process flow resulting in completion of manufacturing and shop testing of transportable beta prototype.

R&D Activities Completed

CSI undertook research activities to understand the challenges of heating untreated saline water in a high pressure / temperature environment. From the result of these activities, CSI evaluated and then selected metals suitable for operation in this severe environment without experiencing corrosion.

CSI identified needs, design requirements, and expectations from the Oil Industry in their efforts to reduce GHG emissions and fresh water use in heavy oil projects while meeting safety and operational requirements. This provided a basis from which CSI could design and manufacture a fully integrated, self-contained transportable SCV process.

During the R&D phase, CSI conducted extensive 3D modelling and Computational Fluid Dynamics (CFD) studies for the purpose of designing a prototype submerged combustion burner and vaporizer vessel. A key burner design requirement was the use of air cooling to avoid scale buildup inherent in a water cooled heat exchange surface. A second design requirement was the use combustion gases to provide circulation of water around the burner and separation of the solids, liquids and vapors in the vessel.

The 3D model and CFD studies allowed the development of construction drawings for initial, alpha and beta prototype development. The initial prototype was fabricated from quartz in order to visualize flame behaviour and confirm accuracy and applicability of CFD simulations. A second prototype was fabricated in order to verify temperature profiles of different burner parts. The alpha prototype vessel was designed and fabricated from carbon steel to the exact geometry and dimensions of the alloy vessel planned for field testing. However, it was decided that the burner would utilize corrosion resistant materials in order to ensure sufficient longevity for the test.

The alpha prototype burner and vessel were subjected to extensive testing and used for development of operating procedures. The tests were performed at reduced pressures (<1 barg) and firing rates as the carbon steel vessel was not capable of meeting full pressure and temperature design conditions. Nevertheless, important findings were revealed from this alpha prototype.

The beta prototype was constructed reusing the alpha prototype burner combined with the corrosion resistant Submerged Combustion Vaporizer vessel. The pressure retaining fittings and vessels used for the final beta prototype were designed to meet the requirements of the ASME VIII-1 code and were registered with the authority having jurisdiction in the province of Saskatchewan (TSASK) where the anticipated field trials were to be conducted. The vessel was constructed and tested in BC as an ASME VIII-1 pressure vessel.

Contribution to Technology & Knowledge Advancement

CSI has designed and constructed a high pressure Submerged Combustion Vaporizer for producing saturated and super-heated steam for use in unconventional oil recovery processes. Shop testing allowed the collection of data and analysis of the SCV process for comparison with numerical simulations. The prototype experience and technical data collected will advance Canadian knowledge in the area of reduced environmental impact enhanced oil recovery technology. Data that was collected and lessons-learned will be used for technology design refinement and scale-up for commercial operation in heavy oil projects.

The proponent has gained new knowledge regarding the design, operating and performance of a high pressure Submerged Combustion Vaporizer. Experience and lessons learned in the process of commissioning, starting, and operating a Submerged Combustion Vaporizer will confirm application of the technology to industry partners.

New knowledge has been obtained related to the process and equipment requirements for the vaporization of untreated, saline produced water. Data related to energy efficiency and water reuse will be available for comparison of this new technology with existing EOR technologies.

CSI collaborated with PTAC to evaluate use of the SCV process in post-CHOPS EOR. SRC conducted a study and numerical modelling of the reservoir subject to the SCV EOR process in order to evaluate potential incremental oil recovery and confirm suitability of the SCV for application in heavy oil EOR using a non-thermally completed CHOPS well. The overall results revealed that there was a positive effect from the injection of a mixture of steam and combustion gases on heavy oil recovery from CHOPS wells. Successful numerical modelling of the SCV operation in existing CHOPS wells has contributed to the Oil Industry's knowledge base regarding the benefits of injecting combustion gases and steam into reservoirs for the purpose of recovering heavy oil.

Impacts of Advancement in Technology & Knowledge

Impacts of advancement in technology and knowledge gained from this project will provide significant benefits to the proponent, its partners, the unconventional Oil Industry, and Canada as a whole. Advancements will provide benefits of increased confidence in the viability of the SCV technology for eventual commercialisation and an improved understanding of what further R&D is required. This R&D Project has also provided a longer term benefit from availability of a SCV Process Facility that can be utilized for ongoing development and commercialization of the technology.

A further impact of the advancements from this project is that it provides future business opportunities to the proponent and its partners through the manufacturing, sales, and operation of systems for unconventional oil recovery.

A significant impact and benefit to Canada has been achieved as a result of this project due to the development of new technology for use in unconventional oil recovery which offers improved energy efficiency, lower GHG emissions and a small environmental footprint as compared with prior art technologies. In the long term, Canadians at large will be the ultimate beneficiaries of this project once commercialization is achieved. Implementation of the technology and knowledge will have an impact by assisting Canada in achieving its GHG emission targets and meeting its international commitments and obligations.

An impact of the advancements gained from undertaking this project is that it will lead to eventual commercialization of the technology with further economic benefits due to job creation and export of a Canadian manufactured product to the international oil industry.

An impact of the advancements in technology achieved by this project is that once commercialization is achieved the advancements will benefit the oil industry by reducing its surface land disturbance, provide reduced use of potable water resources and reduced emissions of GHG and NOx compared with prior art technologies. The Industry will benefit due to availability of technology for the recovery of bitumen from shallow low pressure oil sand and carbonate reservoirs, and kerogen from oil-shale deposits. Industry will benefit from cost savings due to the reduction in the steam-oil ratio and energy requirements of thermal oil sands recovery processes by employing Submerged Combustion Vaporizer systems to produce and inject non-condensable gases into maturing steam chambers.

Challenges and Barriers

A number of barriers were encountered during execution of this R&D Project, the root cause being the downturn in the oil industry due to a collapse in the price of oil. This resulted in the unavailability of industry partners to provide a CHOPS well for field testing. The lack of field testing was mitigated by undertaking a numerical simulation of the SCV operation in an oil field reservoir.

Lessons learned

CSI developed extensive know how in operation and manufacturing of high pressure submerged burners and operation of such burners in extreme corrosive environments.

Some of the challenges encountered are detailed in the following sections:

10.2.3 Regulatory Design Registration

There were significant engineering efforts in re-execution of pressure vessel calculations and re-registration of the SCV vessels. This was caused by differences in interpretation of the ASME code requirements by representatives of BC Safety Authority after design approval by the Technical Safety Authority of Saskatchewan design surveyor. The required changes could not be facilitated by the vessel pressure design software application. The differences in interpretation of joint efficiency requirements were resolved by changing from no radiographic examination of welds to full radiographic examination.

10.2.4 Prototyping in saline environment

Upon completion of bench scale prototyping at pressures up to 6.8bar(g), testing continued at full scale at a maximum pressure of 1 bar(g) using a carbon steel vessel and alloy combustor. The transition from bench scale to full scale prototyping came with several burner design changes - such as bellows for compensation of thermal expansion.

CSI followed a mixed approach to full scale prototyping. The gasifying reactor, combustor and level column components of the SCV system were all alpha prototyped using relatively inexpensive carbon steel before proceeding with beta prototyping using expensive alloy materials. Due to significant corrosion concerns, the burner prototype was fabricated from alloy material for both alpha and beta prototype testing.

During alpha prototyping, the maximum operating pressure of the carbon steel vessel was restricted due to safety concerns. However, the testing at reduced pressure and capacity was still feasible due to the flame size being proportional to the thermal capacity of the burner and inversely proportional to operating pressure. The flame geometry was therefore of similar dimensions between the alpha and beta prototypes with only the combustion intensity changing. After installation of the burner in the alloy vessel; beta prototype testing continued without limitations in operating pressure. The pressure loss over the burner at close to full operating capacity was found to be significant higher than anticipated and resulted in malfunctioning and damage to the bellows in the burner prototype.

10.2.5 Burner design changes

The unforeseen burner malfunctions resulted in a major burner design change. The burner prototype iteration that followed resolved previous limitations, but, failed during testing due to unrelated failure of an internal non-pressure boundary weld. The burner design change and following repair resulted in significant delays caused by the use of costly corrosion resistant alloys with associated time consuming fabrication methods. The benefit of the burner design changes was an improved understanding of the burner operation through re-evaluation of the CFD studies, completion of a new CFD study as well as a tolerance stack up analysis. It also resulted in longer term benefits through the identification of options for significant burner cost reductions.

10.2.6 Equipment failures

As part of the original design basis, it was decided to utilize off the shelf components wherever possible. Unfortunately, some of these components were not as rugged or reliable as one would have hoped. Several early equipment failures occurred. After finding that one natural gas compressors ran with a significantly different knocking sound, it turned out to have an unacceptable leak out of the crank case breather. Both issues were resolved by replacement of bearings and seals.

The combustion air compressor package was found to be particularly troublesome. Upon first attempt to start the combustion air package, the controller and screen was defective and required replacing. A coolant level sensing instrument was defective and the maximum temperature switch for compressor oil failed after a few hours of operation. Cooling fan belt failures were also prevalent and there was considerably difficultly to start the engine due to unexpected pressure requirements of the air starter motor. The starting problems were further complicated by a malfunctioning engine block heater system.

The standard driver for the combustion air package provided by the vendor is typically a diesel engine. Unbeknownst to us, our requirements for a natural gas engine had transformed the off the shelf package from the vendor into a new product development. It was therefore the vendors' first encounter with this particular combination of engine and compressor. Further to this, the engine was not formally commissioned by the supplier and it was found that the fuel gas shut off valves required replacement in order to eliminate an unacceptable flow restriction that resulted in misfiring when running near full capacity.

Troubleshooting occurred with limited support from the equipment supplier as the warrantee had expired due to unrelated delays. This resulted in further delays.

10.2.7 Alloy scope changes

During detailed design, the use of exotic alloys was extended from being solely used in the gasifying reactor to the inclusion of all interconnecting feed water piping, combustion air supply spools and hoses, several high pressure fuel gas supply spools and hoses, flame scanner view ports and the air supply ring header.

There is a limited market for exotic alloy valves, piping, hoses, fittings and instrumentation. The requirement for use of a Canadian registration number (CRN) for all pressure components further narrows the number of potential suppliers. Delivery times of several items were delayed from the quoted 3-5 weeks to 5 months due to the supplier experiencing difficulties in obtaining a CRN.

The increased use of alloy materials resulted in significant cost overruns, however, the expenditures were deemed necessary for operation testing in severe saline environments. Furthermore, the materials were required for ensuring field testing readiness of SCV process equipment. The added benefit is that lessons can be learned and adaptations can be made before going to site; increasing the likely hood of positive results.

10.2.8 Droplet separator failure

Salt testing of the droplet separator and characterization of the carry-over failed due to an accumulation of salt within the cyclonic separator and excessive corrosion of separator material. The separator design is likely to function once its construction material is changed to a more exotic alloy. Salt accumulation is not expected to occur when gasifying less than saturated brines and could also be avoided by surrounding the separator with a feed water spray ring

Gender Based Analysis

During the construction and delivery phases of project the following FTEs were involved:

Phase	Male	Female	Total
1 – Design and Manufacture a Portable SCV System including add-on	2	0.4	2.4
2 – Numerical simulation of the SCV at well site	0	0	0
3 – Shop testing of the Portable SCV with Add-On Scope	3.3	1	4.3
Ongoing operations	TBD	TBD	TBD

11 Conclusion and Follow-up

Companies with nimble resources can develop breakthrough technologies assisted by ecoENERGY Innovation Initiative funding. The provision of additional funding for the project has been essential in preparation for the next phase of field testing.

CSI continues to undertake additional work with the objective of improving operation of the Burner, SCV vessel and its separator. CSI is also continuing to seek additional funding and a CHOPS well for the purpose of undertaking field testing and demonstration of the SCV technology for use in reducing the environmental impact of unconventional oil production and for enhanced heavy oil recovery.

Following up on this work, a new partnership has been formed involving CSI, FERST Environmental and an equity investor who plan on full commercialization.

Next Steps

- More funding is required to conduct a field trial in order to evaluate the SCV operation at an injection well, and to understand and validate results from injection and production cycles.
- Application of oxy-fuel Submerged Combustion Vaporization to well sites that are experiencing significant disadvantages following injection of hot nitrogen gases.
- Chops wells are just one possible application of SCV process technology. Inroads have been made for SAGD application and quotations have been provided to potential clients.
- Although currently no other applications are being actively considered; the technology could be applied to numerous other applications such as water purification by forced circulation evaporation, crystallization of industrial chemicals such as fertilizers, etc.