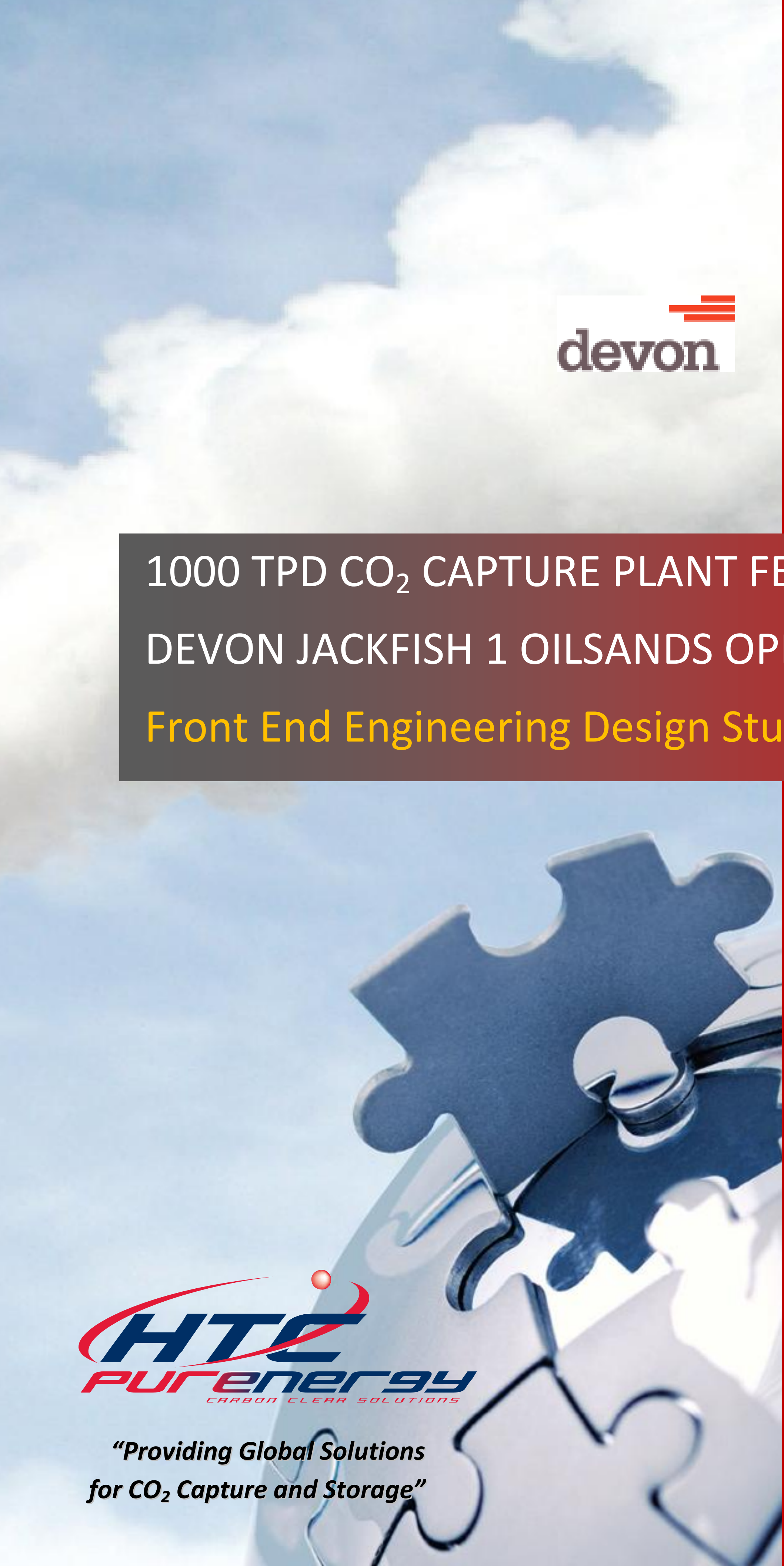

Submitted to

Climate Change and Emissions Management Corporation (CCEMC)

1000 TPD CO_2 CAPTURE PLANT FEED STUDY

DEVON JACKFISH 1 OILSANDS OPERATIONS

Front End Engineering Design Study

"Providing Global Solutions for CO_2 Capture and Storage"

Submitted by

HTC Purenergy Inc.

November 2011

1000 TPD CO_2 CAPTURE PLANT FEED STUDY

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Front End Engineering and Design Study

1	21-NOV-2011	FEED Report Issued for Publication	Salim Kadiwala/ Pawan Kundra	Allan Hart/ Mohamed Elgarni	Ahmed Aboudheir
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Contents

Executive Summary

The Alberta Carbon Capture and Storage Development Council March 2009 report showed the expected cost of CO_2 emissions reduction from SAGD operations to be $175 to $230 per tonne including the cost of capture, transportation and storage, and considering the additional CO2 produced by energy consumed in the process. This cost was shown as significantly higher than the cost from any other source indicating that a technology gap exists as a barrier to implementing CO_2 capture from thermal in-situ oil sands operations. As project Proponents, HTC Purenergy and Devon Energy applied to and received funding support from the Alberta CCEMC (Climate Change and Emissions Management Corporation) to study means to address this gap by applying the HTC Purenergy CCS® System technology that offers the following primary advantages:

- Use of the advanced HTC RS2® formulated solvent specifically designed for post-combustion capture to optimize CO_2 absorption at atmospheric pressure conditions as well as minimize process energy requirements
- Use of the patented HTC TKO® process configuration that offers energy savings compared to conventional amine processes
- Use of a standardized, modular, packaged approach for CO_2 capture, with resulting cost and schedule reductions.

A Front End Engineering and Design (FEED) study was undertaken to design an advanced CO_2 Capture Unit (CCU) to produce 1000 tonnes per day of CO_2 from the exhaust of three Once-Through Steam Generators (OTSG's) at Devon Energy's Jackfish 1 thermal in-situ operations and estimate the capital expenditure for the facilities within +/-15% accuracy.

The process utilizes HTC Purenergy Carbon Capture Technology to capture CO_2 from the OTSG exhaust gas using an aqueous chemical solvent in an absorber tower, after which the CO_2-loaded solvent is passed to a stripper tower where the CO_2 is released and the solvent regenerated. The study excludes downstream CO_2 compression, dehydration, transportation and storage.

A summary of the Process Design Performance and Utility Requirements are presented in Table 1:

Table 1 - Plant Performance Data

Plant Performance Data	Unit	
Solvent (Formulated Solvent)	-	HTC RS-2®
CO_2 Production (Dry Basis)	tonne/day	1000
CO_2 Recovery	%	90
Reboiler Duty	GJ/hr	130
Fuel Gas Consumption to Supply Reboiler Heat Duty	m^3/hr	4080
Total Cooling Duty	GJ/hr	230
Total Power Consumption	kW	2575

The CO2 capture plant is designed with a modular concept. The Main Process Building will be formed around 7 modules with a 3/3/1 arrangement to fit within the A-Frame Process building. Pumps and equipment are primarily located on the lower Modules (1&3) when pump suction requirements dictate elevation requirements. The two upper equipment modules are used to house equipment requiring head to facilitate drainage, or where adequate pressure is available. The CO2 capture process configuration is of one absorber and one stripper type. Absorber diameter is 7.62 m and stripper diameter is 3.35 m. Total CO2 Capture plant foot print for this modular design is estimated to be 8000 m2 (80m X 100m).

The total capital expenditure (CAPEX) estimated for the CCU includes project management, engineering, purchased equipment, shop fabrication cost, and material and labour cost for installation and commissioning. The estimated CAPEX for the CCU is $83.1 million (Canadian Dollars).

Based on the CAPEX estimate, using a weighted average cost of capital of 8%, and a twenty-year project life the capital component of the capture cost would be less than $37/tonne, assuming 95% plant availability and long-term average operation at 85% of design capacity. Adding an estimated operating cost of approximately $30/tonne of $CO_{2,}$ the indicated total CO_2 capture cost is under $70/tonne.

An execution schedule has been developed for the EPC Project that shows an estimated duration of 20 months, from EPC contract award through start-up to complete the plant build.

1 Introduction

HTC Purenergy is a leading provider of technology for post-combustion capture of CO_2 from industrial sources, enabling significant and economical reduction of greenhouse gas emissions. HTC's goal is to deliver practical solutions to reduce greenhouse gas emissions and help solve the challenges of energy security. HTC is a Canadian company working in conjunction with its collaborative partners - Doosan Power Systems, Petroleum Technology Research Centre (PTRC), International Performance Assessment Centre, "(IPAC-CO2)" and other international research organizations to assist in delivering these solutions

HTC Purenergy offers proprietary advanced amine technology licensed from the University of Regina and supported by over ten years of research and development. HTC utilizes the Thermal Kinetics Optimization (TKO^{TM}) process and Regina Solvent®-2 (RS-2) to provide an advanced CO_2 capture plant design that improves the CO_2 capture system performance through heat recovery, thermal balancing, optimized process flow, and specific operating protocols. The primary advantage of the TKO^{TM} process is a significant reduction in the amount of energy required for solvent regeneration, thereby significantly reducing the cost of CO_2 per tonne.

HTC Purenergy and Devon Energy, with funding support from the Alberta CCEMC (Climate Change and Emissions Management Corporation) carried out a Front-End Engineering Design (FEED) study and cost estimate for a 1000 tonne per day (tpd) CO_2 Capture Unit. The FEED study is based on CO_2 capture from the exhaust of three Once-Through Steam Generators (OTSG's) at Devon Energy's Jackfish 1 Steam-Assisted Gravity Drainage (SAGD) thermal in-situ oil sands production facilities near Conklin, Alberta.

The project was set out as six milestone events as follows:

♦ Milestone 1 – Prior to commencing engineering work, HTC and Devon jointly prepared a Design Basis memorandum that set out the Jackfish 1 operations parameters and site conditions such as flue gas flow rate, flue gas composition, temperature, pressure, product specifications, ambient conditions, available support utilities etc.

♦ Milestone 2 – Based on Design Basis developed in Milestone 1, HTC developed a Process Design Package containing the documents and data necessary for the following FEED activities. Process Design activities were focussed on developing a computer simulation model of the plant and corresponding Process Flow Diagrams (PFD's). A significant effort was put into optimizing the design to reduce the expected capital and operating costs for the proposed plant.

♦ Milestone 3 – The Front End Engineering Design (FEED) work for the shop-fabricated portions of the planned facilities was commenced with issue of the Process Design Package to Enerflex Limited. Enerflex were engaged to complete the preliminary design and layout of plant modules, obtain budget pricing for major equipment and materials, and develop a cost estimate for the supply of equipment and shop fabricated process plant and pipe rack modules for the project. The FEED activities in this milestone were centered on developing the Piping and Instrumentation Diagrams (P&ID's) and specifications for the major equipment. A primary objective of this milestone was to maximize the amount of the plant that can be fabricated in transportable modules in a climate controlled shop environment offering significant savings in labour costs compared to work on the plant site at ambient weather conditions.

♦ Milestone 4 – Module design information developed by Enerflex was issued to Cimarron Engineering Ltd., who was engaged to complete the preliminary design and cost estimate for site installation of the plant. The Cimarron scope included site preparation, foundations, equipment and module transportation and setting, mechanical installation, and electrical and control system materials and installation.

♦ Milestone 5– Following design activities, cost estimates were prepared for the shop-fabricated modules by Enerflex Ltd and for the site installation work by Cimarron Engineering Ltd. Budgetary quotations were requested for major equipment, materials and sub-contracts. In-house data was used for labour costs. The estimate components were then built up to a total installed cost.

♦ Milestone 6 –The final milestone event included preparation of the final project reports.

The Scope of the Study covers only the CO_2 Post-Combustion Capture system including exhaust gas pre-conditioning to maximize efficiency and meet specified performance requirements.

The following items are excluded from the Scope of the Study:

- CO_2 compression and dehydration
- CO_2 transportation and storage
- Utility source facilities (Fuel gas supply, De-mineralized water, Instrument air, Nitrogen etc.)
- Waste water treatment facilities (waste water to be disposed using existing facilities)

This Report contains the following Deliverables:

- Design Basis Description
- Block Flow Diagram- defining major components of the Plant and battery limits
- Process Description
- Key Performance Indicators – showing flue gas inlet & outlet composition, conditions and flow rates
- Utility Summary – including power consumption for blowers, pumps and air-cooled heat exchanger fans, and fuel gas for the Reboiler and Reclaimer
- Engineering, Fabrications and Site installation Schedule
- Installed cost estimate

2 Design Basis

The Carbon Capture Unit process design is based on the Design Basis developed by Devon Energy and HTC Purenergy. Table 2 below provides information on the exhaust gas source and target CO_2 production capacity

Table 2 – Exhaust Gas Source and Plant Performance Target

Facility Description	SAGD Thermal In-situ Oil-sands Production Facility
CO_2 Source Equipment	250 MM Btu/h OTSG Exhaust
Number of OTSG's Captured	3
CO2 Recovery Target, %	90
PCC Plant Design Capacity, tpd	1,000

Table 3 shows the exhaust gas conditions at the inlet of CO_2 capture unit and Table 4 shows CO_2 product specifications

Table 3 – CO_2 Capture Plant Feed Data

Conditions/Quantities/Compositions	
Exhaust gas flow per OTSG at CO_2 Capture Plant [1]	114,000kg/h
Number of OTSG's captured	3
Inlet Temperature, [°C]	182
Inlet Pressure [kPag]	0.0 to +0.4
Composition	
N_2 [mole%]	71.613
Ar [mole%]	0.871
O_2 [mole%]	2.595
CO_2 [mole%]	8.616
H_2O [mole%]	16.298
SO_2 [ppmv]	24
SO_3 [ppmv]	<2
NO [ppmv wet basis as NO_2]	57
NO_2 [ppmv wet basis]	3
Particulates [mg/Nm^3]	<10

Table 4 - CO2 Product Specification

Product Stream Temperature, ^{o}C	40
Product Stream Pressure, kPag	45
CO_2 Purity mole% (min, dry basis)	99
H_2O mole% (max)	Saturated – dehydration is outside battery limit
O_2 mole%	<0.010%

3 Process Design

3.1 BATTERY LIMITS AND BLOCK FLOW DIAGRAM

The Block Flow Diagram in Figure 1 shows the major unit operations within the capture plant battery limit and major utility flows to and from the capture plant The CO_2 product gas compression and dehydration are represented by a single block outside the CCU battery limits and are not a part of this study.

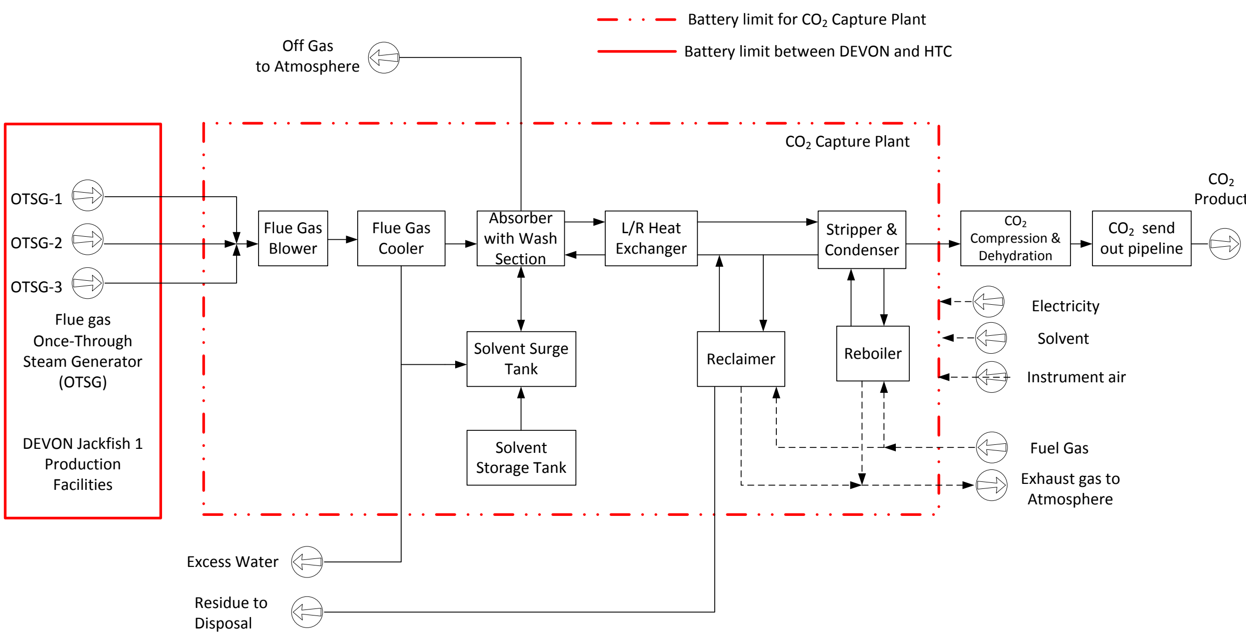

Figure 1 – Block Flow Diagram

3.2 CO_2 CAPTURE PLANT PROCESS DESCRIPTION

The HTC Purenergy CO_2 capture technology is based on the bulk removal of CO_2 from high volume exhaust gas by the use of chemical absorbents. The exhaust gas is cooled prior to absorption of CO_2 by an aqueous chemical solution in an Absorber column, and then the CO_2-rich solvent is passed to a Stripper column where the CO_2 is released by the application of heat and the solvent is thus regenerated. Ductwork from the exhaust stack tie-in redirects the exhaust of three OTSG units to the CO_2 Capture Unit (CCU). The exhaust gases at the CCU inlet are at essentially atmospheric pressure, and an inlet Flue Gas Blower is provided to overcome pressure losses through the downstream equipment before venting to atmosphere.

For optimal CO_2 capture plant performance, the exhaust gas must be cooled to a desired temperature prior to the CO_2 Absorber inlet. A cooling system, which includes a fogger to cool exhaust gas through adiabatic evaporative cooling, a heat exchanger to cool gas further below its dew point and a two-phase separator located upstream of the Absorber, is used to achieve the necessary temperature reduction. Cooling water used in the exhaust gas heat exchanger is circulated in a closed loop system and cooled by an air-cooled heat exchanger. Since the exhaust gas is cooled below its dew point, water will be condensed from the gas stream. A stream of condensed water is recycled to the fogger system, a second stream is sent to the amine surge tank as make-up water to maintain the plant water balance, and the excess water is sent to Devon's operation for on-site utilization

In the Absorber column a CO_2-lean solution exiting the Lean Amine Cooler is introduced at the top of a packed bed while the cooled exhaust gas enters the bottom of the column and flows counter currently up the packed bed where mass transfer takes place and 90% of the CO_2 in the inlet gas stream is captured by the solvent. The CO_2 laden solvent (called "rich amine") is collected at the Absorber sump and sent to the Stripper column by a Rich Amine Pump where CO_2 is stripped out of the solvent and the solvent is regenerated.

The exothermic heat of reaction from the CO_2 absorption process increases the overall Absorber section temperature, and as a result, some solvent is evaporated. Droplet entrainment is also expected due to the high volumetric flow rate of exhaust gas. To prevent significant solvent losses due to this carryover and evaporation, a wash section located above the absorption section is utilized to reduce the off-gas temperature, recover entrained solvent and maintain a plant water balance. Off-gas from the wash section, now retaining only 10% of the in-coming CO_2, is released to atmosphere.

The rich amine stream is passed through the Lean/Rich Heat Exchanger where it recovers heat from the hot lean amine stream leaving the bottom of the CO_2 Stripper column. This exchange of heat simultaneously cools the lean solvent solution, reducing the duty required from the downstream Lean Solvent Cooler.

The CO_2-rich solvent from the Lean/Rich Heat Exchanger is introduced near the top of the Stripper column and flows down through a packed bed where it is contacted by rising vapour. Heat from the vapour, which is predominantly steam generated by boiling the solvent-water solution in a Reboiler, strips the CO_2 from the rich solvent solution. The stripped CO_2 passes to the top of the column and exits as an essentially pure CO_2 stream saturated with water.

The Stripper overhead gas is partially cooled in a proprietary exchanger configuration, before flowing to an air cooled condenser where water vapour is condensed. The condensed water is separated in the Stripper Overhead Condensate Drum from the product gas and is sent back to process. The CO_2 product gas stream, approximately 97% CO_2 by volume (wet basis), is then sent across the CCU battery limit for compression and dehydration.

The regenerated lean amine solution is removed from the Stripper bottom and passes through the Lean/Rich Heat Exchanger and is cooled against the rich amine stream going to the Stripper. The lean amine solution is then sent back to the CO_2 Absorber Column via an air cooled Lean Solvent Cooler, which provides control of the temperature of the lean solvent.

In the CO_2 absorption/stripping process, the base amine components in the solvent react with O_2 and other gases such as NO_2, SO_2 and SO_3 in the flue gas to form "complex" heat stable salts that cannot be thermally regenerated. In addition, some organic degradation products can be formed through side reactions between flue gas impurities, the amine solvent and/or the heat stable salts.

Heat stable salts and degradation products, if allowed to accumulate in the solvent, will decrease the solvent CO_2 capture efficiency. Therefore, a slip stream of lean amine solvent leaving the Stripper bottom is sent to a Reclaimer to remove degradation compounds and recover amine from the heat stable salts. Fuel gas is used to provide the necessary heat required to maintain the Reclaimer operating temperature. Evaporated solvent vapour is condensed by an air cooled heat exchanger and the recovered solvent is pumped back to the Amine Surge Tank. The Reclaimer waste stream, containing the heat stable salts, degradation products, as well as a small amount of unrecovered solvent, leaves the capture plant battery limit for waste processing and/or incineration by a commercial waste management company.

3.3 KEY PERFORMANCE INDICATORS

Table 5 presents a summary of the process simulation results for the plant inlet and outlet streams.

Table 5- Process Design Conditions

Parameter	Unit	Gas Feed (From OTSG Exhaust)	Gas Feed (at Absorber Inlet)	Off Gas (Treated)	CO2 Product
Flow Rate	SCMH	2.891E+05	2.557E+05	2.361E+05	23,200
Temperature	^oC	182	35	36	35
Pressure	kPa (g)	0.2	4.4	0.2	68.5
N_2	%mol	71.6	81.0	87.7	< 50 ppmv
Ar	%mol	0.87	0.99	1.05	traces
CO_2	%mol	8.62	9.74	1.05	96.7
O_2	%mol	2.6	2.94	3.18	< 10 ppmv
H_2O	%mol	16.3	5.35	6.99	3.35

Figure 2 shows the mass flow rate and enthalpy of each stream entering and exiting battery limit and provides overall heat and mass balance for CO_2 capture plant as designed.

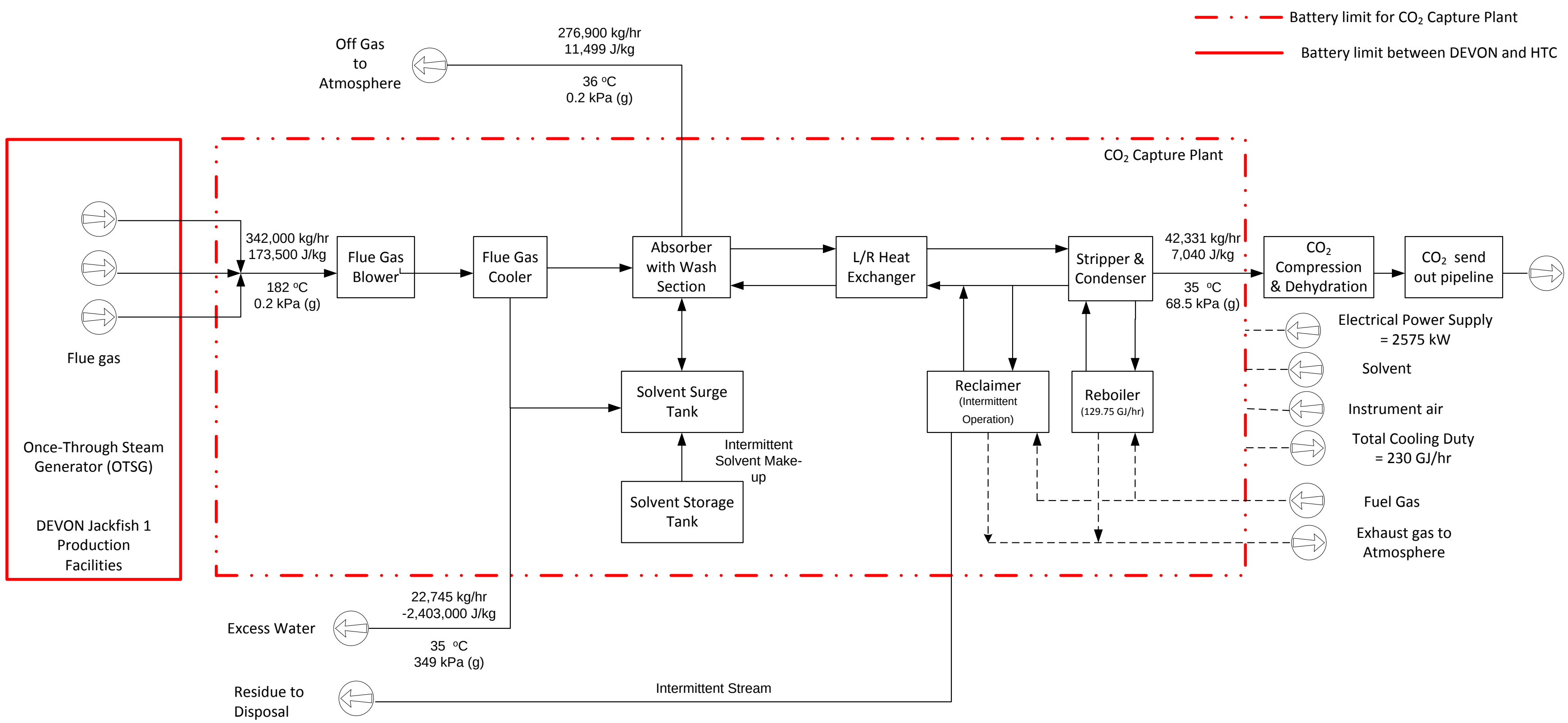

Figure 2 - Heat and Mass Balance over battery limit

The expected CO_2 capture rate is 1000 tonne per day at an expected CO_2 capture efficiency of 90% of the exhaust gas CO_2 content. Table 6 shows Greenhouse Gas (GHG) Emission of CO_2 capture process due to solvent regeneration and electrical power required for solvent pumping and exhaust gas driving force.

Table 6- Greenhouse Gas Emission of CO_2 Capture Process

CO_2 Capture, tonne per Day	**1000**
CO_2 Emission (Solvent Regeneration Duty), tonne per Day	207
CO_2 Emission (Electrical Load), tonne per Day	40
Net CO_2 Capture, tonne per Day	**753**
CO_2 Emission per Tonne of CO_2 Captured	0.247

CO_2 emission for solvent regeneration is based on a natural gas fired heater. CO_2 equivalent emission for electrical load is calculated based on an intensity number of 0.65 t/MWh.

The project design did not provide for the exhaust gas produced by the reboiler for solvent regeneration to be directed to the CO_2 Capture Unit because the desired plant capacity of 1000 tonnes per day is fully met by capture from the exhaust of three OTSG's. Capturing the reboiler exhaust would necessitate increasing the plant capture capacity by some 18% to 1180 tonnes per day, challenging the current view that 1000 tonnes per day is the maximum practical size for a modular capture plant.

3.4 UTILITY SUMMARY

Total electrical power required to operate the blower, pumps and air-cooled exchanger fans is presented in Table 6.

Table 7 - Electrical Power Consumption

Equipment Description	Operating Electrical Load (kW)
Flue Gas Blower	645
Air-cooled Exchangers (Fan Power)	1580
Pumps	310
Reclaimer Package (Intermittent operation)	40
Total Electrical Power Consumption	**2575**

The plant is designed for a natural gas-fired Reboiler and a natural gas-fired heater for the Reclaimer having fuel demand as shown in Table 7.

Table 8 - Fuel Consumption

Equipment Description	Process Heat Duty	Fuel Gas Consumption
	GJ/hr	m^3/hr
Reboiler	130	4080
Reclaimer (On-stream Factor = 0.05)	6.83	215

Note: Fuel gas consumption is calculated based on Gross Heating Value of 39.76 MJ/m3 and 80% efficiency.

3.5 PROCESS OPTIMIZATION

It was assumed for the purposes of the study that the CO_2 Capture Unit would stand-alone in terms of process heating and cooling. It is recognized that opportunities may exist for heat integration between the CO_2 plant and the SAGD facilities that would improve the thermal efficiency of the combined operations and reduce overall energy consumption. Such opportunities would be evaluated on a project specific basis.

The relatively high temperature (180^{o}C) of the exhaust gas results in a large cooling duty to cool the stream down to the required temperature at the Absorber inlet to maintain the optimum solvent loading capacity. An initial evaluation was completed to select the process configuration for the exhaust gas cooling system for the purposes of the study.

The selected system comprises a “Fogger” followed by a water cooled heat exchanger. The Fogger consists of system to spray water into the hot exhaust gas providing evaporative cooling. The water cooled exchanger then provides further cooling down to the desired Absorber inlet temperature and condensed water is separated from the cooled exhaust gas in a two-phase separator. Heat transferred to the closed loop cooling water system is rejected to atmosphere in an air-cooled exchanger.

Alternatively, flue gas cooling can be achieved by a Direct Contact Cooler (DCC) packed bed column where hot exhaust gas is directly contacted with circulating water and heat transfer takes place from gas phase to liquid phase. The hot circulating water is then cooled via air-cooled heat exchanger. The initial evaluation favoured the Fogger/exchanger system over the DCC system.

4 Capital Cost Estimate

The total installed capital cost estimate (CAPEX) for the CO_2 Capture Unit includes cost elements developed by HTC, Enerflex and Cimarron related to their respective scope in preparing the study. The CAPEX estimate is summarized in Table 8. The estimate basis for individual line items is as follows:

- Major equipment costs are derived from vendor budget proposals sourced by Enerflex.
- Shop fabrication material and labour costs are built-up from the P&ID's and 3-D modelling work completed by Enerflex.
- Site Installation costs are built-up from quantity estimates, supplier quotes, and relevant actual cost data compiled by Cimarron.
- Engineering costs are the extension of engineering man-hour estimates by HTC and Enerflex multiplied by the applicable hourly rates.
- A contingency of 20% has been added to the estimated cost of Major Equipment, Module Shop Fabrication and Engineering to allow for items not included in the design scope, but which may be expected to arise during detailed design and project implementation. A 30% contingency was added to the Site Installation estimate, to allow for additional work that may be identified during implementation.
- Project Management is estimated to be 6% of the EPC cost of the plant, consistent with industry standards.
- Technology Licence Fee is HTC's standard fee of 6% of the installed cost of the CO_2 Capture Plant and includes royalties payable to the University of Regina.

Table 9 - CAPEX Estimate

Description	Cost Estimate ($ CAD)
Major Equipment	31,580,000
Module Shop Fabrication – Materials and Labour	16,280,000
Site Installation	23,860,000
Engineering	2,230,000
Project Management	4,440,000
Technology License Fee	4,700,000
Total Installed Cost	**83,090,000**

5 Engineering, Fabrication & Site Installation Schedule

Figure 3 below shows the high level engineering, fabrication and site installation schedule for the CO_2 Capture Unit. The expected overall project duration is 20 months after EPC contract award.

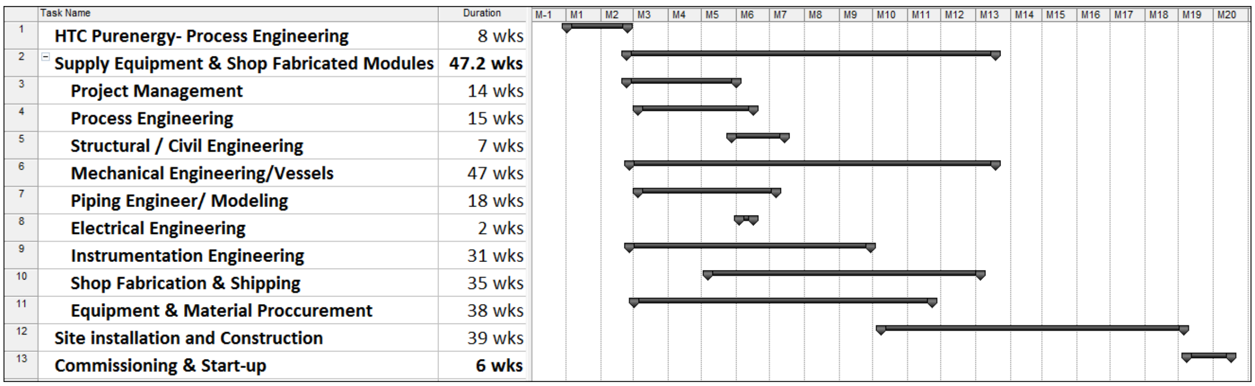

Figure 3 – EPC Execution Schedule

6 Recommendations

Additional engineering needs to be completed to definitively conclude the most cost-effective inlet exhaust gas cooling process configuration. The study must include both the cost of capital and the cost of energy required by the system.

A specific project should include a front-end study of the potential for heat integration to minimize the energy penalty for the combined production/capture operations. Potential exists to transfer high level heat from the SAGD operations to the CO_2 capture operations in exchange for low level heat available from the capture and subsequent compression operations.

7 Conclusions

- The study work has shown the technical feasibility of fabricating and installing a modular 1000 tonne per day (tpd) CO_2 capture plant.
- The indicated project execution schedule of 20 months from contract award through start-up reflects the expected advantages of HTC's approach of employing a standardized design with a modular shop-fabricated plant.
- The 1000 tpd sizing is a very good fit for "typical" SAGD developments such as Devon's Jackfish 1 that deploy 250 MMBtu/hr OTSG's, in that a 1000 tpd unit can capture the exhaust off three boilers.
- The CO2 capture process configuration is of one absorber and one stripper type. Absorber diameter is 7.62 m and stripper diameter is 3.35 m. Total CO2 Capture plant foot print for this modular design is estimated to be 8000 m2 (80m X 100m).
- The 1000 tpd modular approach will allow operators to phase-in CO_2 capture in SAGD operations in 3-boiler increments rather than considering capture from an entire facility at once.
- The estimated CAPEX for the project spread simply over 20 years of production at design rate gives an indicated CAPEX component of capture cost of about $11.98/tonne.
- Using a weighted average cost of capital of 8%, assuming a long-term average plant throughput of 85% of design rate, and assuming a plant availability of 95%, the CAPEX component of CO_2 capture cost from SAGD facilities will be under $37/tonne.
- HTC estimates the operating cost of a CO_2 capture unit to be approximately $30/tonne including fuel costs at $5/GJ ($13/tonne).
- The indicated total CO_2 capture cost at 8% cost of capital is under $70/tonne.
- It is probable that the fuel cost can be significantly reduced through project specific heat integration efforts and optimization of the inlet cooling system.
- It is recognized that the cost of emissions reduction must include, in addition to the cost of capture, consideration of additional emissions from capture operations as well as compression, transportation and drilling and injection costs. However, as the Alberta Carbon Capture and Storage Development Council report states, it is generally regarded that the cost of capture is 70 to 90% of the cost of emissions reduction.

The study results indicate that the previously published view of the expected cost of CO_2 emission reduction from SAGD operations to be from $175 to $230 per tonne is significantly overstated.