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Process design and costing of an air-contactor for air-capture

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Abstract

Carbon Engineering (CE) has developed an air-contactor design, specifically optimized to the challenge of efficiently removing CO_2 from atmospheric air. CE's air-contactor design is based on the wet-scrubbing method, where air is brought into contact with an alkali hydroxide CO_2-absorbing liquid solution. This is a similar process to that carried out in absorption or reactor towers commonly used in the chemical processing industry, but unique constraints posed by the challenge of removing CO_2 from atmospheric air have led CE to a number of original, innovative, and proprietary design modifications to these existing technologies. These key differences have led CE to depart from traditional chemical industry practice involving packed reactor towers, and to develop an intermittently-wetted air-contactor with cross-flow slab geometry. This design has as much in common with induced draft cooling towers as with chemical reactor towers. Design has been tested in a 5m tall packed tower prototype and detailed tests of packing performance have been performed in a laboratory system that enables us to control CO_2, air velocity, relative humidity while accurately measuring packing performance. In addition to CE's on-going in-house engineering and experimental evaluations, the structural design and cost estimation of the air-contactor system was performed by an independent Engineering, Procurement and Construction (EPC) firm (SolTech Projects Inc., Calgary, Alberta). The cost estimate produced by this EPC firm forms a conservative upper bound on the cost of the air-contactor because it is based on 2008/09 Alberta, Canada construction and labour costs, which were among the highest in the world. The EPC firm collected quotes from vendors for major equipment and components, and the total system cost was estimated using standard engineering cost-evaluation procedures. The total estimated cost of the air-contacting system, evaluated using conservative labour and energy rates as mention equates to \$80/tonne-CO_2 and CE has identified specific areas of research to decrease this cost to \$49/tonne-CO_2.

Keywords: Air-Capture;Air-Contactor;Costing

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1. **Introduction**

This paper aims to give readers an overview of Carbon Engineering Ltd's (CE) approach to air-contactor design and testing The air-contactor as designed by CE is based on the use of structured packing to remove CO_2 from a gas stream using a hydroxide solution. The design and development of CE's air-contactor is based on the performance and cost of a number of key equipment components. These are the basic pieces of equipment which allow the gas-liquid contacting to occur and the equipment performance in turn contributes to the determination of the CO_2-uptake performance of the air-contactor. Small-scale ancillary equipment, such as specific liquid distribution nozzles, are not discussed here. We will present a cost breakdown including a description of the costing methodology and equipment selection justification. The reader should note that neither the included performance data nor the capital costs represent a fully optimized design, and CE will continue to develop its design over the next few years to lower the cost of capturing CO_2.

2. Packing Selection

Packing materials are used to spread a film of alkali solution over a large surface area as a major factor in uptake rate is the area available for the mass transfer. The air-contactor packing materials must have the following criteria:

1. resistance to the hydroxide solutions used for CO_2 absorption
2. a service life of 20 years or more
3. a low air side pressure drop
4. good CO_2 uptake performance
5. be inexpensive, and
6. resistant to fouling

Packing materials in the chemical processing industry for similar applications are commonly made of stainless steel, and those in the cooling tower applications are commonly made from plastics. Both types of packings meet criteria 1 and 2 [1, 2] and the following section will show that plastic packings are the preferred choice once all 6 criteria are considered. Literature and experiments performed by CE show that pressure drop across a packing is only affected by the structure of the packing and not the material of construction. The pressure drop is a function of velocity (V), liquid loading (Q_l), and length of packing the air must travel through (ATD). For example, the presure drop through XF12560 packing [3], produced by Brentwood Industries Inc., is given by the following equation:

$$\Delta P = (7.4\,V^{2.14} + 4.3\,Q_l V^{0.4})ATD^{0.95} \quad (1)$$

V	m/s
Q_l	L/s per m^2 of packing footprint
ATD	m

Since the energy to move a volume of gas across this pressure drop is linearly proportional to the pressure drop through it, moving the air through the packing at a high velocity implies high energy cost. In general air velocities must be below ~4m/s to achieve acceptable pressure drops.

It is generally known that the surface energy of plastic materials is lower than that of the metals; hence one would expect lower wettability of the plastic packing, leading to lower CO_2 uptake. In cooling tower operation these plastic packing's develop a surface film of carbonate salts which renders the plastic packing surfaces hydrophilic, a process referred as "conditioning" in the cooling tower industry, thereby making the plastic packings wettable. This process occurs naturally in our application and only needs to be carried out once in the packing's 20 year lifetime. Carbon Engineering has shown that once conditioning is complete PVC packing materials and steel packings have similar CO_2 uptake, see Figure 1. The cost of steel packing falls between \$1000 - \$2000/m^3, whereas a PVC packing with identical flow pattern cost around ~\$200/m^3. Finally, the packing manufacturers who work with conditions and design constraints most similar to that of a DAC system are Brentwood Industries and their competitors, companies which produce packing for the chemical processing industry have no practical experience with the design considerations which arise from DAC such as fouling due to material ingestion. For those reasons the solutions to the contacting problem devised by Brentwood Industries are the most applicable approach. Further improvements in these packings are being undertaken at CE to optimize them for air-capture.

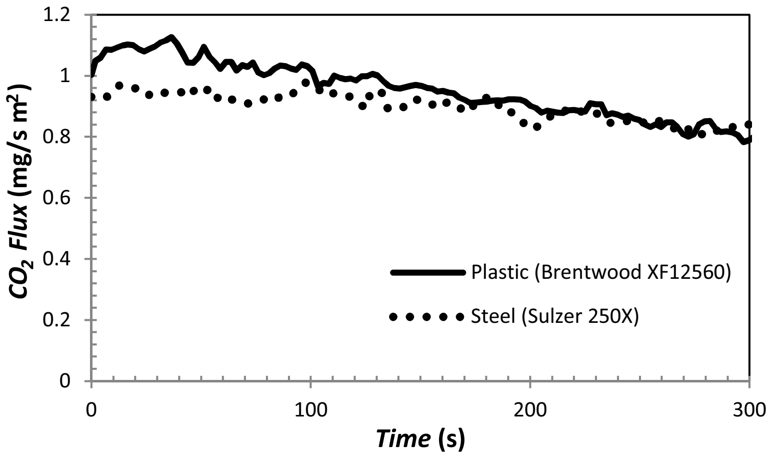

Figure 1: The graph above compares packing's with similar geometries but different materials of construction. The 'Y' axis is the CO_2 flux normalized the packing area (manufactures specs). Fluid is 2.9 M NaOH at 20 C, and flow is turned off as time '0'. Short period variations come from noise in the CO_2 servo loop and measuring instrument. The data were gathered during the summer of 2010 using an experimental apparatus developed by CE. In this case, the plastic packing and steel packing have similar CO_2 uptake under identical operating conditions.

3. Intermittent Wetting

In a standard gas liquid absorber the energy consumed to pump the liquid around the system makes up a significant portion of the total energy requirements. These standard systems are usually quite short by design because the energy required to pump the liquid is directly proportional to the height the liquid must be pumped. The caustic solution used in the air-contactor can absorb ~50,000 times more CO_2 per volume than is present in the air. This low liquid to gas ratio allows us to wet the packing material intermittently. Intermittent operation if gas and liquid phase reactants are in similar mass flow rates. Intermittent operation can be exploited to manage fouling and drift. Our system shows minimal decrease in CO_2 capture rate over time periods as long as 600 seconds (as shown in Figure 2) and the performance is stable over numerous cycles. Allowing CE to take advantage of the significant energy and cost savings associated with intermittent wetting operation.

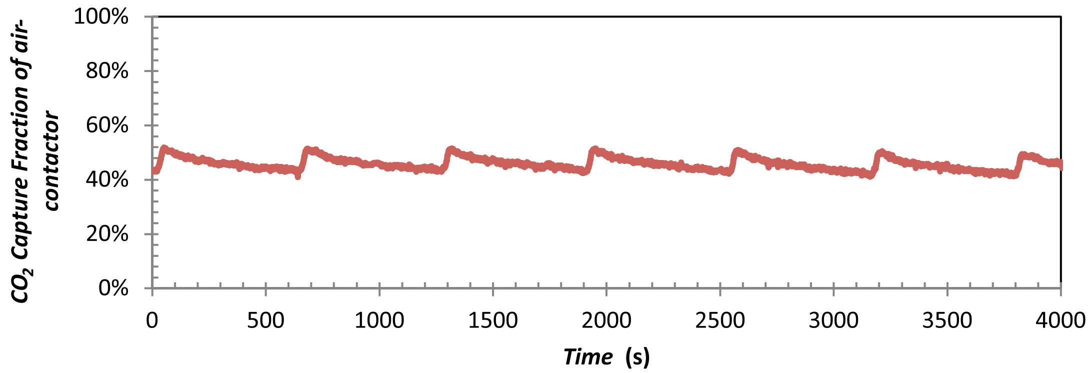

Figure 2: CO_2 capture fraction over time, associated with intermittent wetting. The data was collected during experiments performed by CE in 2008, using and experimental apparatus measuring 6m tall by 1.2m in diameter, built to explore and quantify the CO_2 absorption performance of a packed tower air-contactor. In the three tests shown the pump was run for 30 seconds out of every 630 seconds.

The intermittent wetting operation leads to a drastic reduction in the cost of fluid pumping, to the point where it is no longer an important factor driving system configuration. With this constraint removed CE is free to build an air-contactor of any height that is cost-effective from a standpoint of structural engineering and construction.

4. CO_2 Uptake

CE has conducted numerous experimental tests at varying operating conditions, inlet air conditions, and with numerous solutions to estimate the performance of our system and improve the design of the major components. Over the course of these experiments CE conducted tests at 2 scales, the first proof of concept tests were conducted in a pilot scale device with an inlet area of ~1m^2; due to the size, liquid handling, and other operational constraints only a limited number of tests were conducted with this device. Later CE developed a small laboratory scale apparatus in which a many more tests were carried out to isolate specific effects.

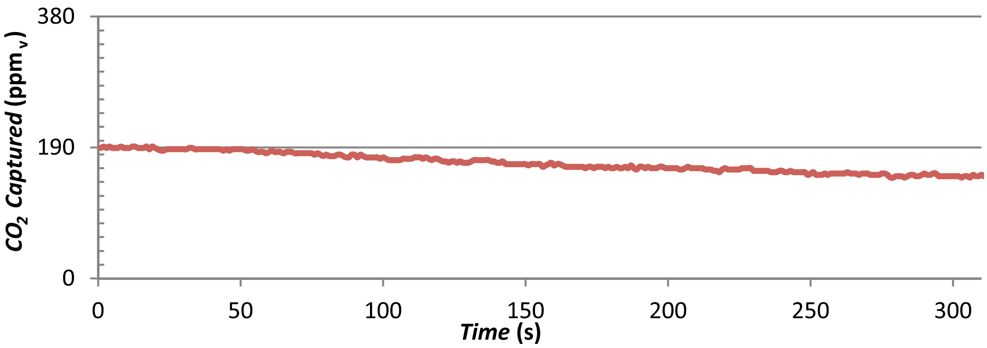

Figure 3: The figure to the left shows the amount of CO_2 captured as air is pushed through 1.6m of packing at 1.1 m/s in the CE pilot scale test apparatus. In the above image the pump is supplying fluid to the packing for the first 30 seconds and the inlet CO_2 concentration was 380ppm (the top of the graph).

The uptake of CO_2 in the CE air-contactor may be approximated by the function:

$$[CO_{2\,captured}] = [CO_{2\,in}] \quad \left(1 - e^{-SSA \cdot ATD \cdot V_{p,eff}/V}\right) \tag{2}$$

$[CO_2]$	kg/m^3 of air
SSA	Surface area per m^3 of packing
ATD	m of packing air must travel through
$V_{p,\,eff}$	m/s

Where SSA is the specific surface area of the packing, ATD is air travel distance, and $V_{p,\,eff}$ is the effective piston velocity of the CO_2 into the liquid film. The flux of CO_2 into a high molarity OH fluid can be solved as a reaction diffusion equation which, to a good approximation, is controlled by the diffusivity of CO_2 in the liquid and the pseudo first order reaction rate of CO_2 and OH^-, which in turn depends on the activity coefficients of at a given molarity [4]. Since the flux is always proportional to the amount of CO_2 it can be represented as a piston velocity times the local CO_2 concentration. Effective piston velocity used here is corrected for the packing efficiency and the ratio of the actual wetted surface area to the manufactured surface area. In practice, the effective piston velocity is a complex function of operating conditions and material properties and can only truly be determined through experimentation. To reduce scale-up risks, this equation will be applied to the pilot data in Figure 3 which results in a piston velocity of 0.0017 m/s. This equation and the pressure drop formula from section 2. form the basis of a cost optimization which determines the optimal air velocity and ATD. CE continues to improve liquid side chemistry to improve the CO_2 uptake rate, for example using KOH instead of NaOH increases the piston velocity by ~50%.

5. Economies of Scale:

Packed towers which are similar to the CE's air-contactor are operated world-wide in chemical processing facilities, each with ~50m^2 of inlet area. The most technically-conservative design would be to build 300 of these traditional packed towers in a large array. One limitation of this approach is that these devices would have to be widely spaced otherwise they may ingest the exhausted air of an adjacent air-contactor. Since the uptake rate is linearly proportional to the inlet CO_2 concentration these systems would suffer drastic reductions in uptake rate which would increase the cost per tonne of capture CO_2. Second, standard engineering experience shows that the cost of equipment scales with physical size to the factor 0.6 (\$ = Cap$^{0.6}$) [5], or applied to the previous example, one large air-contacting unit would cost ~1/10th that of 300 smaller packed tower units. A single large system will minimize land use, land preparation, electrical connections, and piping. Based on the analysis performed by Soltech Project Inc. Located in Calgary, Alberta Canada, the cost of these items is a significant driver of total project costs [6].

6. Simplified Cost Optimization to Determine Velocity and Depth

Working upwards in scale from packing to structure, we need to estimate the operating air velocity and packing depth in order to determine a suitable structural configuration. High velocities mean high operating costs (fan energy) whereas low velocities mean higher amortized capital cost since the capture rate per unit of contactor structure is low. An approximate velocity and packing depth may be determined from the following set of equations.

$\Delta P = (7.4\,V^{2.14} + 4.3\,Q_l V^{0.4}) ATD^{0.95}$			(1)
$[CO_{2\,captured}] = [CO_{2\,in}] \left(1 - e^{-SSA \cdot ATD \cdot V_{p,eff}/V}\right)$			(2)
$C_{Energy} = C_{elec}\left(\frac{\Delta P * V}{\eta_{fan}}\right)$	η_{fan}	Fan efficiency, 60%	(3)
	C_{elec}	Cost of electricity, \$1.9x10^{-8}/J	
$Capital = C_A + C_{pack} ATD$	C_A	Capital cost per frontal area, 2900 to 4100 \$/m^2	(4)
	C_{pack}	Cost per m^3 of packing, \$212/m^3	
$Capex = \frac{Capital \quad CCF}{t_y}$	CCF	Capital Charge Factor, 15%	(5)
	t_y	Seconds in a year	
$Opex = \frac{Capital \quad M\&O}{t_y}$	M&O	Maintenance and Operation, 6%	(6)
$\dot{m}_{CO2} = [CO_{2\,captured}]\, V$	$\dot{m}_{CO2}$	CO_2 capture rate, kg/s	(7)
$\min\limits_{V,ATD} C_{CO_2} = \frac{Opex + Capex}{\dot{m}_{CO2}}$	C_{CO_2}	Cost of CO_2, \$/kg	(8)

Here we assume a cost of electricity (\$0.07/kWhr [7]). In the full design electricity for the contactor is generated by the caustic recovery system and the two systems must be optimized jointly. This simplified analysis ignores the cost of liquid pumping as intermittent wetting reduces this cost to an insignificant amount (see 8. Operating Costs). The capital cost per frontal is a representative value, see next section. The capital charge factor and M&O factor are industry standard values. The equations can be minimized to find an optimal air velocity and ATD. CE has determined that an air-contactor cannot rely on a source as inconsistent as the wind to move air through it. In fact, analysis performed by an independent Engineering, Procurement and Construction (EPC) firm SolTech (SolTech Projects Inc., Calgary, Alberta), using current CE air-contactor design parameters, showed that the optimal air velocity for CE's design is ~1.5m/s and the optimal ATD is 5.5m. These parameters have led to CE to the air-contactor design pictured below in Figure 4.

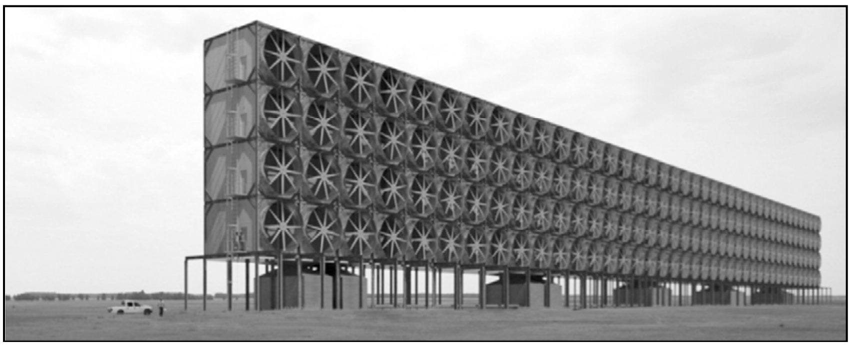

Figure 4: An artist's rendering of the CE air-contactor design. Each such unit will be able to capture 50-100k-tonne of CO_2/year from air. Many such units along with a centralized regeneration and processing facility will comprise a full 1 Mt-CO_2/yr capture facility.

7. Capital Cost

Before contracting Soltech Project Inc. CE had created an air-contactor design, but no structural engineering had been done. Soltech's first task was to develop and verify a civil engineering design which would form the backbone of the air-contactor. The height and width of CE's air-contactor are determined by an engineering optimization, which balances the costs associated with land use and site preparation (incurred by a "short, long" air-contactor) with the structural, labour, and maintenance costs of building tall structures (associated with a "tall, narrow" air-contactor). By utilizing the structural design and cost-analysis work conducted by SolTech, CE has arrived at an optimized air-contactor design that is roughly 20 m tall, 7 m deep, and 200 m long. They ran simulations of wind loading on a fully loaded structural design to ensure it could withstand a wind speed which would only be seen once every 100 years. Next, Soltech estimated the installed cost of structures of various heights using a combination of vendor quotes for the material cost and past engineering experience to estimate the cost of the necessary labour. These structures were compared to determine the most cost effective height to construct.

The capital expense of constructing the air-contactor contributes towards overall cost to capture CO_2 and thus to the viability and competitiveness of an air capture facility. The estimated cost of the air-contactor is based on two different methodologies. The primary method of evaluating the cost of the air-contactor is a bottom-up cost estimate in which actual costs of key equipment are determined and the costs of installation and necessary ancillary equipment are estimated using standard engineering estimation factors. This was done for every major piece of equipment and produced a nearly complete cost estimate that accounted for all the equipment and labour needed to create a fully operating air-contactor. Any piece of equipment not covered by the above cost evaluation is accounted for by using standard industrial-estimation techniques which can estimate the cost of a piece of equipment based on what type of equipment it is and the cost of the equipment it interfaces with.

The following cost breakdown is the product of the work performed by Solech. All of the cost estimation is based on 2008/09 Alberta pricing and labour rates, which can be up to 75% higher than US Gulf Coast costs because of the demand for workers in the petroleum industry. Efforts are currently underway to explore the cost savings associated with a modular, shop-built air-contactor design, based on units with $5m^2$ inlet areas which would be constructed off-site, then shipped and assembled at the air capture facility. According to CE's industrial contacts, this could decrease construction costs because in-field construction labour is on average four times more expensive than in-shop labour. CE has estimated modular construction to reduce the overall labour costs by 30% as not all the labour can be moved into the shop and in shop construction will increase the delivery cost of the equipment. The cost breakdown by equipment type is shown in the table below and no ranges are given as this data represents the numbers directly developed by the EPC. The final total cost is given as a range with higher cost being a firm upper bound on the cost and the lower value being an estimate of the final cost once the above advancements are implemented. Excluding the cost of the packing, these costs can also be expressed as 2900 to 4100 $\$/m^2$ of inlet area (C_A) [6], which is a useful measurement when optimizing the operating conditions for the air-contactor.

Table 1: The above data is derived from an itemized list of hundreds of equipment and cost categories which was developed by Soltech Projects Inc. and used to estimate the cost of the air-contactor. For this paper CE has grouped the items into categories by their association with the major pieces of equipment.

Item	Labour	Materials	Percent of Cost	Capital Cost (million CAD$)
Project Management	7%		7%	23
Fans	9%	10%	19%	62
Packing	2%	14%	16%	52
Pumps	2%	2%	4%	13
Structure	24%	6%	30%	97
Overhead/Contingency			24%	78
Total	**44%**	**32%**	**100%**	**247 - 325**

8. Operating Costs

Before the complete cost to capture a tonne of CO_2 can be estimated and effort must be made to determine the energy use and operating cost of the air-contactor. The energy use of the air-contactor has 2 components the energy needed to drive the fans and the energy needed to pump the liquid. The CE air-contactor relies on liquid distribution systems from the cooling tower industry and these systems are designed so that the pump only needs to lift the fluid to the top of the packing as they have extremely small losses in the piping and nozzles. The design of the air-contactor incorporates a packing which requires 4.7 liters/sec of flow for every m^2 of packing footprint, taking into account the size of the CE design if all these systems were active at once the total flow would be $88m^3/s$, but since the CE design is intermittently wetted the required flow decreases to $10m^3/s$. Knowing this and the air-contactor is 20m tall it is possible to determine that the pump must supply the fluid with energy at a rate of 2.2 MW. Based on performance data from pump vendors a pump is 63% efficient and the air-contactor will require 3.5 MW of power to move the fluid. To determine the energy required by the fans to drive the air through the air-contactor, performance data from the vendors of fans and structured packing was used. The fans incorporated in CE's air-contactor design are Swifter CTX-5181's and are commonly used in forced-draft cooling towers. These two applications are very similar in terms of required volumetric air flow-rate, air velocity, and duration of run-time. With a packing depth of 5.5m, an air velocity of 1.5m/s, and using the liquid flowrate derived below the packing will induce a pressure drop of ~100Pa. The entire air-contactor system will be processing ~100, 000 m^3-air/s which requires that the fans put energy into the air at a rate of 10MW. Vendor dats gives the fan total efficiency as 60%, therefore the air-contactor will consume 16 MW to move the air necessary to capture 1Mt-CO_2/year.

During operation the CE air-contactor will lose water to the atmosphere and this cost must be included in the total cost. Processing modelling using ASPEN Plus estimates this water loss at 5kg H_2O/kg CO_2 for current operating conditions which, based on a conservative estimate of the cost of water, adds \$0.2/tonne CO_2 to the total capture cost. This amount of loss is through evaporation and does not represent the loss of hydroxide. Any hydroxide loss must be in the form of droplets carried out of the contactor and this type of loss must be addressed from both a cost and safety standpoint. CE's design controls this loss by using a commercial demister section at each face of the packing. Based on vendor specifications [8] and based on the liquid flow through the contactor the calculated drift losses from a contactor would be less than 0.08% of the OH^- flow through the system with a concentration at the outlet face that will be <3% of the OSHA Permissible Exposure Limit (PEL) [9]. This rate of hydroxide loss has such a small cost that it can be completely ignored in all cost estimating and optimization analysis.

9. Optimized Costs

In this section we present a simple approach to calculate per unit CO2 capture cost by rolling in capital and operating costs. The capital cost of the system has a yearly cost of 37 to 49 million based on a 15% annual capital charge factor which includes the interest, depreciation, taxes, and other minor charges. The annual cost of operating personnel and regular maintenance is estimated annually as 6% of the system capital cost or in our case 15 - 20 million dollars per year. The loss of water through evaporation adds \$1 to the cost of every tonne of captured CO_2. The final cost to be added to the cost per tonne of CO_2 captured is the cost of the electricity to drive the fans and the pump. These pieces of equipment consume 19.5MW of electricity to capture 36 kg of CO_2 per second or 150 kWhr per tonne of- CO_2. Assuming produces power at a cost similar to the national average of \$0.07 per kWhr the total cost for the electricity is approximately \$10 per tonne of captured CO_2. To arrive at the final values for the cost ranges the upper bounds are left as prescribed by Soltech and all of the lower bounds take into account the increased uptake of KOH.

Table 2: Summation of the costs to build an air-contactor facility and the related costs per tonne of captured CO_2.

Item	Estimated Value	\$/tonne CO_2
Capital Cost	\$247 – 325 million	29 - 49
Operating Cost		
Operators etc.	\$15 – 20 million/yr	12 - 20
Water Use	5kg H_2O/kg CO_2	0.8 - 1
Fans – energy cost	16 MW	6 - 8
Pumps – energy cost	3.5 MW	1.5 - 2
Total Cost		**49 - 80**

CE considers the current cost estimate of \$80/tonne-CO_2 to be a conservative upper bound on the cost of the air-contactor. The lower bound of \$49/tonne-CO_2 is an estimate which does not assume some undetermined advancement which should decrease the cost but is based on the expected outcomes of identified research paths.

10. Concluding Remarks

During the summer of 2011 CE will commission a second pilot air-contactor to reduce technical risk, gain experience in operation, improve performance and cost estimates, and study the effects of ingested material. This contactor is designed for extended (six months) outdoor operation under varying environmental conditions. It will enable us to test various packings at a depth a similar to that in the full-scale design, and with height sufficient to minimize the effects of the distribution system.

Results of this long-duration outdoor contactor study combined with additional laboratory work and packing design will feed into a second-order full contactor design in collaboration with than EPC firm as well as into the design of an integrated industrial pilot facility for CO_2 capture from air.

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