# Comments on the APS report on Direct Air Capture

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20 June 2011

The following slide refers to the revised final APS report dated 01 June 2011 that was edited in response to our critique of early May.

# APS Response & Revision

The APS publicly released their final report on 09 May 2011. We posted the following comments, and in response, the APS replaced the final report with a new version dated 01 June 2011. Links to both copies are on CE's website.

APS did not develop a physically-based performance model, but simply “patched” the report to minimize errors, replacing the 500Y packing with 250Y, which has half the specific surface area (pg. 37 in the new final report). This switch does substantially reconcile the pressure drop and capture fraction errors listed as discrepancies #1 and #2 in the following slides.

Despite the new packing, the revised report did not alter the cost estimate. The new 250Y packing has half the surface area of the original 500Y and is otherwise made of nearly identical stamped sheets. Our discussions with packing manufactures suggest that for large-volume orders, the cost would be roughly proportional to the surface area for stainless steel packing with similar stamping geometry. It is therefore surprizing that the APS report did not update the contactor cost estimate, because the packing comprised 55% of the capital cost of the APS contactor, that was in turn 60% of APS’s total DAC capital cost estimate.

We believe that this “patch”, taken together with the technical errors and the sub-optimal design at the core of the cost analysis, serves to highlight deficiencies in the APS’s approach to costing a nascent technology without (a) doing the underlying engineering, (b) using a transparent process to link engineering to costing, or (c) including any estimate of uncertainty.

Carbon Engineering

# Comments on the APS report on Direct Air Capture

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23 May 2011

The following slides are unchanged since 23 May 2011. They refer to the original "final" APS report dated 15 April 2001 that was released to the media on 09 May 2011.

# Preface

The APS report does a fine job explaining the physics and chemistry of air capture (AC). We are pleased that the APS assembled such an excellent and diverse group of researchers to assess this technology at such an early stage in its development.

Our view about the costs of air capture diverges substantially from that of the APS. We acknowledge our bias and self-interest as developers of AC technology, but we believe that the claims made here are independently verifiable.

The APS cost estimate for direct air capture depends on: (1) the performance of the APS reference design, (2) the choice of the reference design itself, and, (3) the validity of the cost estimating methods applied to the reference design.

We concur that the *methods* used for cost estimation conform to industry practice, and applaud the APS for describing them in a transparent manner. We find, however, that:

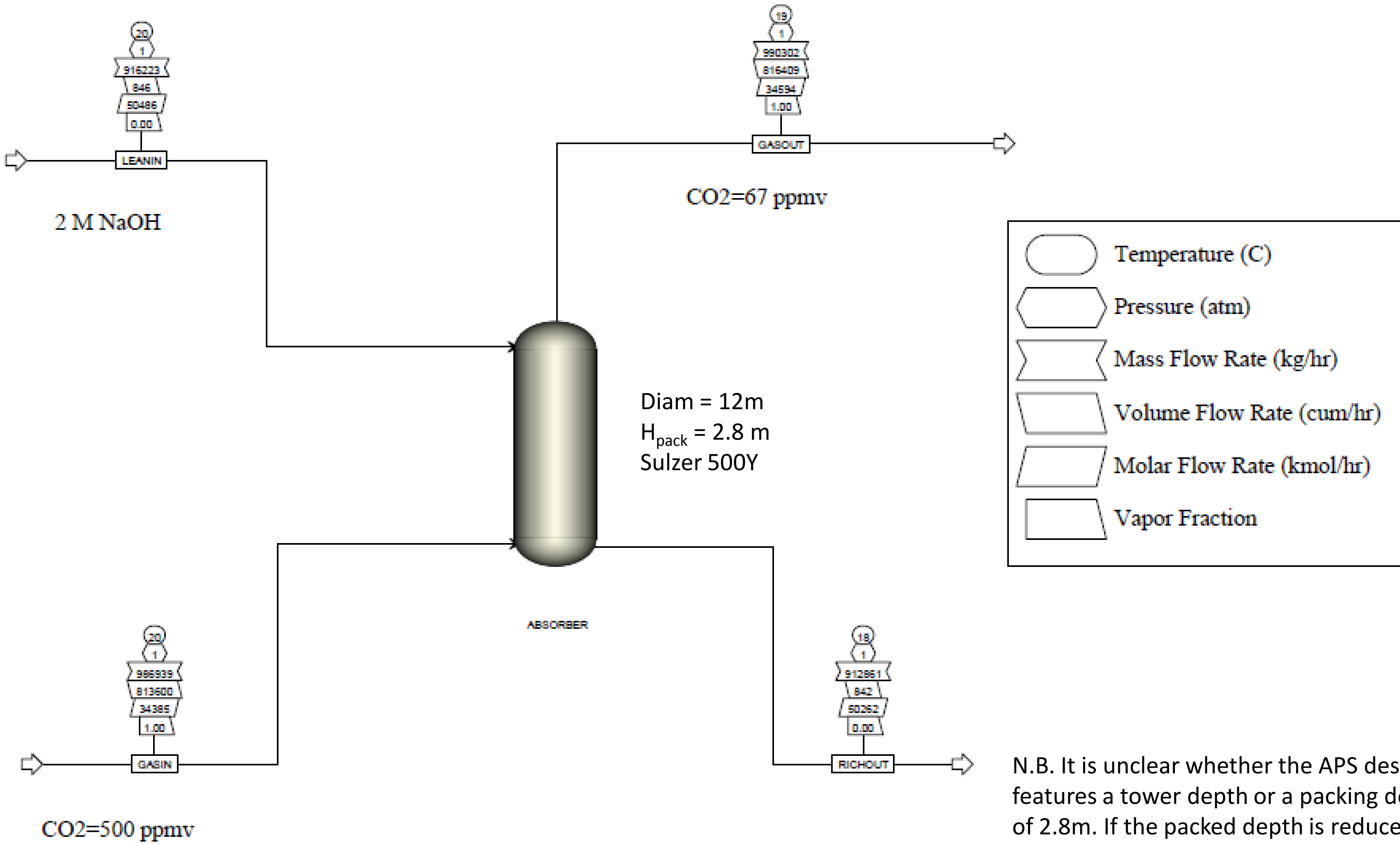
1. There are substantial technical discrepancies between APS's performance model and estimates produced by industry-standard reference sources.
2. Important capital cost estimates do not correspond to quotes from established vendors.
3. The choice of the APS's reference design results in very high costs without a clear justification in terms of the tradeoff between cost and technical risk.

# DISCREPANCIES IN TECHNICAL DETAILS OF THE APS PERFORMANCE MODEL

# Discrepancy #1: Capture Fraction

- APS predicts that their design captures **50%** of the $CO_2$ from the inlet air (pg. 53).
- This value is inconsistent with predictions made using industry-standard chemical engineering design tools and with Carbon Engineering's experience operating $CO_2$ absorber towers with Sulzer packing.
- For example, Aspen Plus, the industry-leading process design simulator, predicts a capture fraction of **86%** under the conditions specified in the APS design (see next slide for details).
- Also, an experiment performed in Professor Keith's group in 2008, with a packed $CO_2$ absorber tower using Sulzer packing, suggests that a capture fraction of **77%** would be achieved by the APS reference design.
- As an exercise to give readers a sense of the importance of this parameter, if the Aspen Plus estimate of 86% is correct this would reduce the cost of air contacting—a substantial portion of the total cost—by 40%.

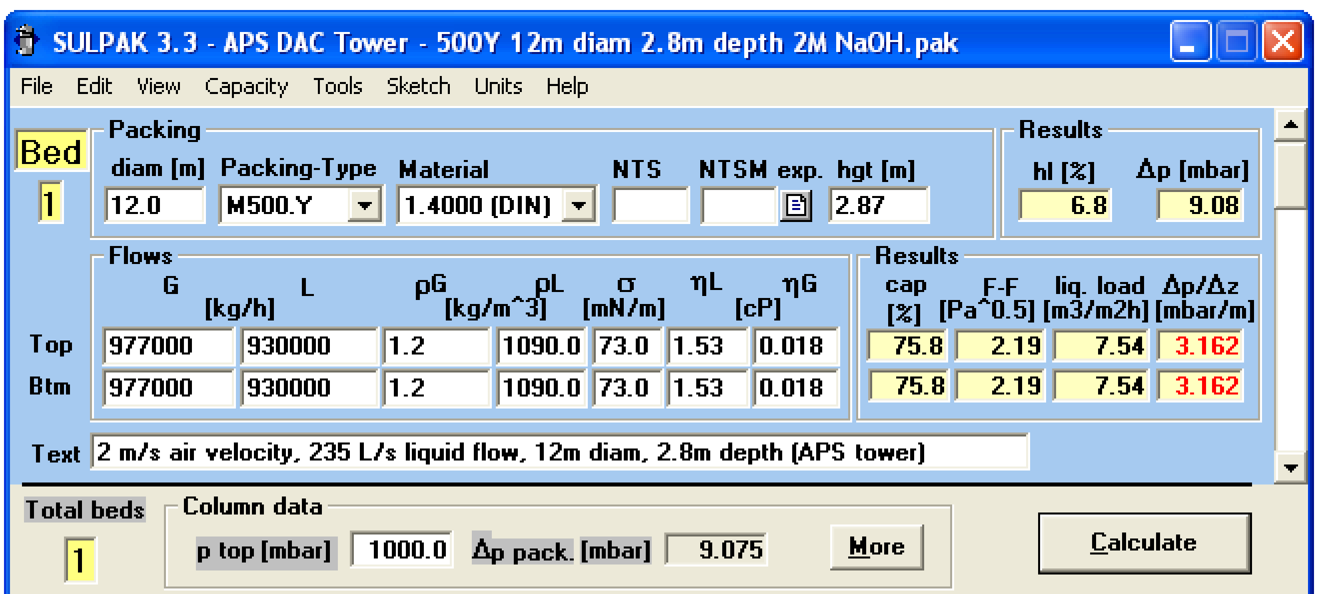
# Aspen Plus model of APS DAC tower




N.B. It is unclear whether the APS design features a tower depth or a packing depth of 2.8m. If the packed depth is reduced to 2.5m to allow room for fans and liquid handling, the predicted capture fraction is reduced by 1.5%.

# Discrepancy #2: Pressure drop in packing

- The APS predicts that the pressure drop in the specified packing (Sulzer 500Y) is **100 Pa/m** at an air velocity of 2 m/s (pg. 53).
- Like many equipment suppliers, Sulzer-Chemtech provides design tools to predict pressure drops in their packing products. These design tools are typically quite accurate as products are provided with performance guarantees.
- The Sulzer design tool SulPak3.3 predicts ~**300 Pa/m** for 500Y at an air velocity of 2m/s.
- This Sulzer value is consistent with Carbon Engineering's in-house measurements on towers and in our 'laboratory contactor' with Sulzer 500-series packing.
- Sulzer's design code is available at: http://www.sulzerchemtech.com/en/desktopdefault.aspx/tabid-145/



# Discrepancy #3: Calciner Cost Estimate

The APS estimates a calciner cost of $120 million (pg. 55-56).

CE has a quote from a leading vendor for a rotary kiln with a total products output of 1400 t/day and a major equipment cost of $19.2 million USD. The quote is dated April 28, 2010.

Using the APS's value for inlet feed of 305 t/hr (pg. 54) and assuming 90% $CaCO_3$, this results in an outlet feed of 154 t/hr CaO and 30.5 t/hr of inerts, for a total products output of 4420 t/day. Scaling our quote linearly to match this capacity requirement ($19.2M*4420/1400), we calculate a major equipment cost for the APS calciner of $60.6 million.

While APS does not give a reference for their estimate or an explanation of what constitutes *"major pieces of equipment"*, our vendor quote does include several auxiliary systems (dampers, conveyors, thermocouples) making it unlikely that the APS cost accounts for equipment which our quote does not.

Notes:

1. Both CE and APS report use very similar methods for scaling ISBL major equipment costs to full costs. If you correct this major equipment cost and use the APS factor of 4.5, the capital cost of the calciner will decrease from $540 million to $273 million.

2. APS used 90% for their $CaCO_3$ feed composition. This conflicts with paper industry operational experience that is ~95% (Tran H. *Lime Kiln Chemistry and Effects on Kiln Operations*. Tappi Kraft Recovery Short Course. St Petersburg, Florida. January 7-10, 2008).

# Comments on technical discrepancies

The central determinant of merit for DAC, the cost per ton of $CO_2$ captured, is largely determined by (a) capital cost, (b) pressure drop which determines contactor fan energy, and (c) the fraction of inlet $CO_2$ captured.

The APS's estimates for the pressure drop and the capture fraction deviate by 300% and 70% respectively from industrial performance estimates for the commercial hardware that APS specified. The APS estimate for the capital cost of a calciner is 100% higher than that provided in a quote to CE from a major vendor.

These discrepancies are not minor. They are at the heart of the performance and cost model that drives the APS cost estimate.

Note that these errors point in different directions, the under-estimate of capture fraction over-estimates the cost of air capture while the underestimate of pressure drop acts to substantially underestimate the energy component of contactor cost.

These discrepancies speak to the necessity to ensure that cost analyses are based on *a single physically self-consistent design that is in agreement with experimental data and industrial costs provided by vendors*.

Our view is that the APS cost estimate did not meet these criteria.

# THE APS'S CHOICE OF REFERENCE DESIGN

# The APS design (1)

Absent a bottom-up engineering design effort, one must cost new hardware based on adapting cost and performance estimates from some known industrial analog.

One must still do some crude optimization in order to provide a meaningful estimate of the cost. Showing that highly-sub optimal design is expensive proves nothing; one must show that a sensible design is expensive to draw a substantive conclusion.

The APS based their design choices and costing on packed towers used for gas separation in large chemical processing industries. Such towers are well adapted for (a) high performance mass transfer on gases delivered in enclosed ducts, (b) handling toxic, volatile, or flammable gases, and (c) operation at elevated temperatures.

A more cost-effective approach is to look for industrial analogs that have been designed to (a) manage massive volumes of atmospheric air at low cost, (b) manage issues of fouling, entrainment, and recirculation that arise in contacting ambient air, and (c) work at ambient temperature. Examples of such systems include forced and induced-draft cooling towers, and bio-film wastewater treatment systems.

The cost per unit inlet area of these commodity systems can be factors of 2 to 4 times less than for packed towers—even when they include high performance packing.

The following slide illustrates the role of industrial analog in shaping an air capture reference design.

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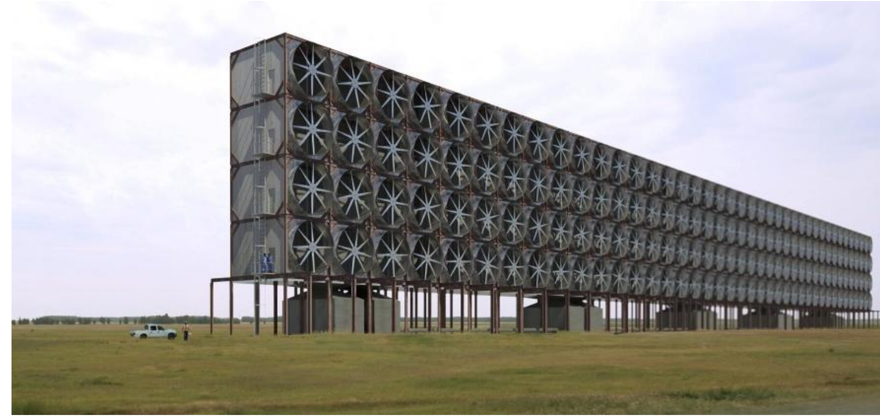
# Industrial analog

Induced-draft cooling tower

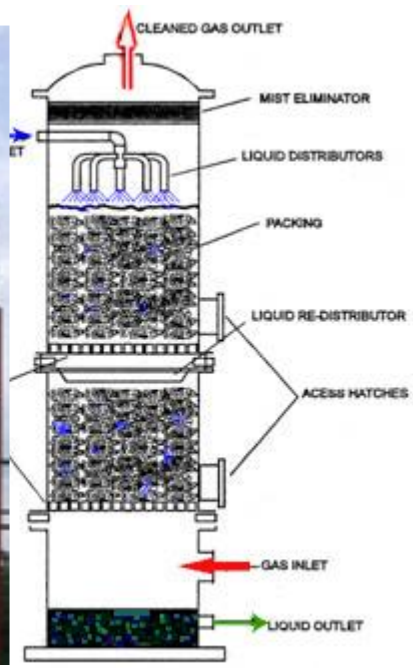
# Air capture design



CE's slab contactor design

APS Report

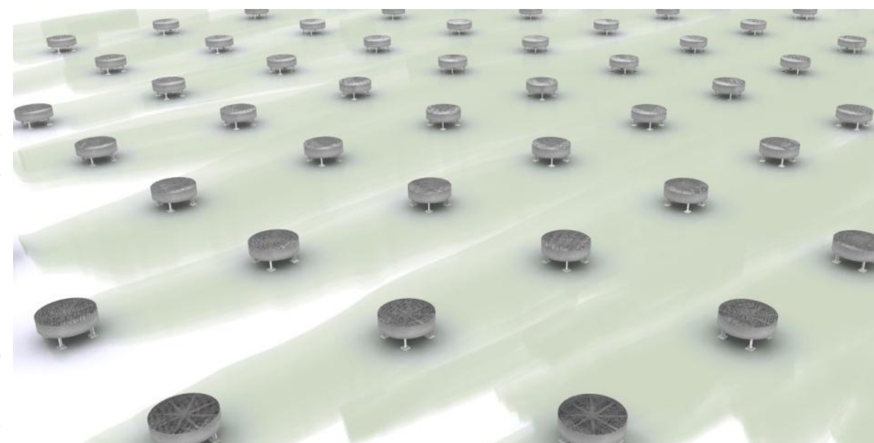
Packed scrubber tower




http://www.arb.ca.gov/cap/manuals/cntrldev/scrubber/304scrubber.htm

CE rendering of APS design. N.B., we did not draw the tower and fan assemblies because it is not clear how APS anticipates adapting pack tower designs to the low depth/high diameter design specified

Array of 330 squat scrubber towers



# The APS design (2)

The APS DAC design is costly because:

- The construction and servicing of an array of small towers is more expensive than a large integrated design.
- The cost estimating relations used by APS are, we infer, derived from chemical packed towers that meet the specific requirements of that industry.
- The design is not well adapted to ingesting and rejecting atmospheric air. In the APS design, the low-$CO_2$ outflow from one tower might be ingested into the next, substantially reducing overall performance.

For these reasons:

- No developer of air capture hardware is—to our knowledge—using a design like that proposed by APS.
- Industrial analogs that process large quantities of ambient air—air cooling or waste water treatment—do not look like the APS design.

Our central concern about the APS benchmark cost estimate is that it does not provide a strong technical argument for the choice of industrial analog that is a crucial driver of cost. An alternative choice of analog can produce a dramatically lower cost.

# What is the cost of air capture?

Careful engineering using industry-standard design and management processes, coupled with real-world testing, is the key to determining the cost and viability of air capture.

Costs claims by companies doing development—including ours—must be tested by hiring independent engineering firms to perform cost estimates. Finally, costs are not well determined by academic studies. Cost estimation is ultimately an industrial art.

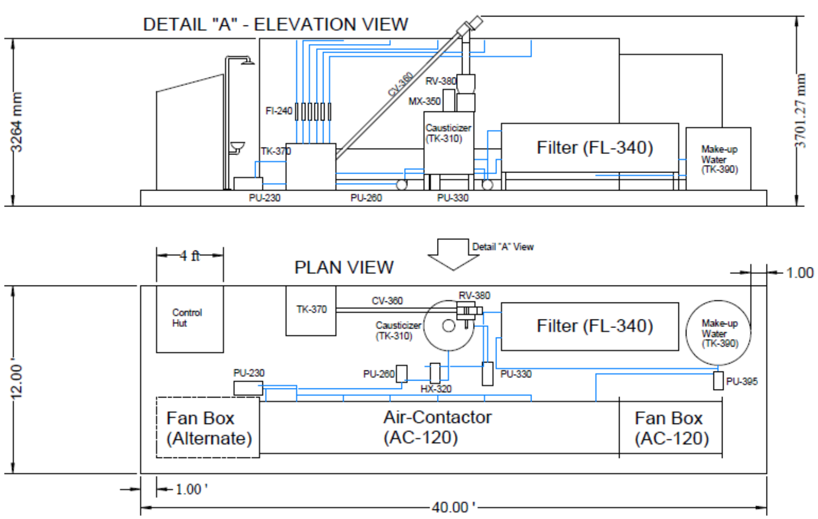
AC costs depend on design specifics, local prices of construction and energy, and on the geographic and economic niches in which AC is deployed. AC will always cost more than post-combustion CCS when both are built under the same environment of capital and operating costs at the same location. There is no single “cost of air capture”, but rather air capture presents a potent opportunity to directly manage atmospheric $CO_2$ concentrations with a *different* set of benefits and trade-offs than other emissions mitigation options. AC enables physical carbon arbitrage, which allows us to find opportunities for mitigation that arise from the differences in costs for construction, energy, and the value for $CO_2$ disposal.

Air capture should not, therefore, be solely compared to CCS, but should complete on an even playing field with all options for mitigation of net emissions.

# Rapid reduction in uncertainty is possible at low cost

The central difference between costs derived by the APS report and Carbon Engineering rest on the feasibility of using hardware derived from industrial cooling towers.

At a cost of only $1.5M, Carbon Engineering is commissioning a prototype air contactor for long-term outdoor operation this summer. The specific goal of our prototype is to identify and address technical risks in our design. If successful, it will provide confidence that these systems are viable and therefore that substantially lower costs are possible for direct air capture using today's technology.




Skid-layout (left) and a end-on shop photo of CE's air contactor prototype (right).

This is the 4th, and largest, prototype built by CE personnel, and will be the first to operate outdoors for long durations.