

SANDIA REPORT

SAND2010-7112

Unlimited Release

Printed September 2010

Thermokinetic/Mass-transfer Analysis of Carbon Capture for Reuse/Sequestration

Chad L. Staiger, Patrick V. Brady, Anay Luketa and Ellen B. Stechel

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>



SAND2010-7112
Unlimited Release
Printed September 2010

Thermokinetic/Mass-transfer Analysis of Carbon Capture for Reuse/Sequestration

Chad L. Staiger
Materials, Devices, and Energy Technologies Department

Patrick V. Brady
Geoscience Research & Applications Group

Anay Luketa
Fire & Aerosol Sciences Department

Ellen B. Stechel
Energy, Climate & Atmosphere Management Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0734

ABSTRACT

Effective capture of atmospheric carbon is a key bottleneck preventing non bio-based, carbon-neutral production of synthetic liquid hydrocarbon fuels using CO₂ as the carbon feedstock. Here we outline the boundary conditions of atmospheric carbon capture for recycle to liquid hydrocarbon fuels production and re-use options and we also identify the technical advances that must be made for such a process to become technically and commercially viable at scale. While conversion of atmospheric CO₂ into a pure feedstock for hydrocarbon fuels synthesis is presently feasible at the bench-scale – albeit at high cost energetically and economically- the methods and materials needed to concentrate large amounts of CO₂ at low cost and high efficiency remain technically immature. Industrial-scale capture must entail: (1) Processing of large volumes of air through an effective CO₂ capture media and (2) Efficient separation of CO₂ from the processed air flow into a pure stream of CO₂.

ACKNOWLEDGMENTS

This work was performed at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The authors wish to express their appreciation to the Laboratory Directed Research and Development (LDRD) office at Sandia National Laboratories and the U.S. Department of Energy (DOE) for funding this project. We would also like to thank George (Geo) Richards at the National Energy Technology Laboratory for helpful discussions.

CONTENTS

Abstract.....	3
Acknowledgments.....	4
Nomenclature.....	6
1. Introduction.....	7
1.1. Rationale.....	7
2. Results & Discussion.....	8
2.1. Air Processing.....	8
2.2. CO ₂ Selective Sorbents.....	10
2.2.1. Liquid Sorbents.....	10
2.2.2. Solid Sorbents.....	11
2.2.3. Integrating CO ₂ Sorbents and Processed Air Flows.....	13
4. Conclusions.....	14
5. References.....	15
Distribution.....	17

FIGURES

Figure 1. Concept for carbon neutral fuel production.....	7
Figure 2. Collector area needed to remove one gigatonne of CO ₂ per year at various capture efficiencies.....	8
Figure 3. Solar chimney at Manzanares, Spain.....	9
Figure 4. Temperature contours and velocity vectors for vortex based air movement. CO ₂ capture media would be placed in the tangential entry points at the base of the vortex.....	10

TABLES

Table 1. Theoretical CO ₂ capacity and regeneration energy of metal oxides.[12].....	12
---	----

NOMENCLATURE

GJ	gigajoule
n	moles
R	ideal gas constant
K	Kelvin
T	temperature
tonne	metric ton
ΔG_{unmix}	Gibbs Free Energy of unmixing
χ	mole fraction

1. INTRODUCTION

1.1. Rationale

Distributed recycling of atmospheric CO₂ into hydrocarbon fuels from stand-alone facilities operating on solar and wind energy would: (1) Contribute to US energy security by adding a new feedstock for domestic liquid fuel production; and (2) Increase the tooth to tail ratio^a of our armed forces by potentially enabling fuel production closer to where it is needed; while (3) avoiding further increases in the concentration of atmospheric CO₂. For a carbon neutral liquid hydrocarbon fuels process, the CO₂ feedstock must come from a bio-refinery or from the atmosphere using energy not derived from fossil fuels. Capturing CO₂ from point sources such as power plants would allow the CO₂ to be recycled into a liquid fuel only once and mitigate some, but not all, CO₂ emissions. Note that distributed CO₂ capture would also allow on-site utilization of CO₂ to enhance and simplify algal biofuel production, enhanced oil recovery, and potentially the production of fertilizers, and solvents, and polycarbonate plastics.

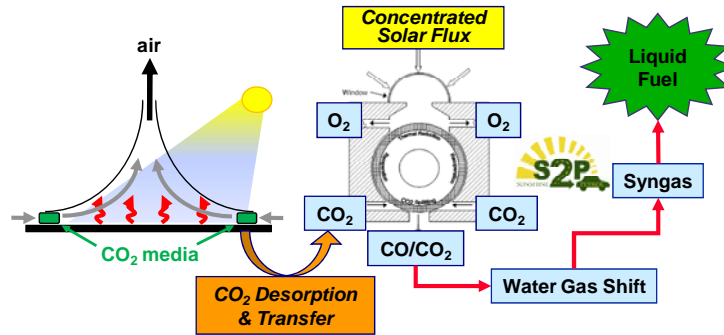


Figure 1. A concept for carbon neutral fuel production.

The burning of fossil fuels consumes roughly 10 to 15 GJ of energy for every tonne of CO₂ that is produced and released to the atmosphere.[1] The Gibbs free energy of un-mixing 100% of the CO₂ from the atmosphere is much less, at 0.5 GJ/tonne CO₂.^b In comparison the energy required to separate 100% of the CO₂ from flue gas (12% CO₂) is marginally less energy intensive on an absolute basis at 0.2 GJ/tonne CO₂. Despite small theoretical absolute energy difference, the key technical features of low cost, high efficiency, large-scale atmospheric carbon capture remain unresolved. The primary technical obstacles involved fall into three categories: (1) Air processing, (2) Designing better CO₂ sorbents, (3) Efficient integration to maximize efficiencies. The critical success metrics are: (1) efficiency (theoretical energy/actual energy,) (2) cost, (3) scalability or sustainability, and (4) durability.

^a Tooth to tail ratio (T3R) is a comparison of combat to non-combat (overhead and logistic support) elements in the armed forces.

^b Using $\Delta G_{\text{unmix}} = -nRT(\chi_{\text{CO}_2} \ln \chi_{\text{CO}_2} + \chi_{\text{atm}} \ln \chi_{\text{atm}})$ whereby $n = 5.98 \times 10^7$ mol air/tonne CO₂, $R = 8.314$ J/K·mol, $T = 288$ K, $\chi_{\text{CO}_2} = 3.85 \times 10^{-4}$ and $\chi_{\text{atm}} = 1 - \chi_{\text{CO}_2}$.

2. RESULTS & DISCUSSION

2.1. Air Processing

Since CO₂ is a trace component of the atmosphere (385 ppm by volume), the capture of industrially useful volumes of CO₂ will require processing exceedingly large volumes of air. CO₂ capture rates increase and scale linearly, with increases in the capture effectiveness of CO₂, air flux, and collector area. This relationship is:

$$\text{Captured CO}_2 \text{ (kg/yr)} \propto (\text{Capture Effectiveness, \%})(\text{Air Flux, m/sec})(\text{Collector Area, m}^2)([\text{CO}_2]_{\text{air}}, \text{kg/m}^3)$$

Using the ideal gas law and conditions of 15 °C and 1 atm, the density of CO₂ in dry air is calculated to be 0.0007 kg CO₂/m³ air. This means that a 1 m² collector operating at 10% capture percentage with an air speed of 3.6 km/h could remove 2.2 tonnes CO₂/yr. Figure 2 shows the collector area needed to remove one gigatonne of CO₂ per year, roughly 1/7 of annual CO₂ emissions for the US, as a function of capture percentage and air speed. Lower capture effective sorbents will require greater collector areas and vice versa. Higher air speeds, natural or engineered, would allow a smaller collector footprint (Figure 2).

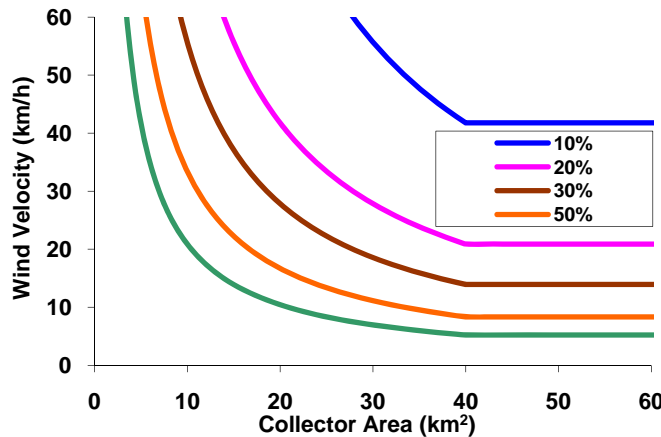


Figure 2. Collector area needed to remove one gigatonne of CO₂ per year at various capture effectivenesses.

The collector areas required to capture large amounts of CO₂ are relatively small, and may be a reasonable source for limited fuel production (i.e. forward military operations). However maintaining a constant air flow to prevent plant start/stop events and/or overcoming back pressures associated with moving air through CO₂ capture media is potentially more problematic. Natural wind requires no external energy input, but wind velocities vary diurnally and seasonally with solar radiation inputs and the alternative, controlling air flows with motorized fans, could be prohibitively energy intensive. The challenge to air processing appears to be to take advantage of passive or concentrating solar power to generate high, sustained and directed air velocities.

Solar chimneys (Figure 3) are one type of device identified for passive wind generation and potential integration with CO₂ adsorbent materials. Solar chimneys rely on a temperature gradient, created by passive or concentrated solar energy, to generate fluxes of air (wind) which turn a turbine to produce electricity. Coupling the solar chimney with the capture of CO₂ from

air would result in a “negative-carbon” energy source, if the CO₂ is later sequestered or carbon neutral if the CO₂ is used as a feedstock for hydrocarbon fuels. The solar chimney would generate power with turbines AND provide the necessary fluxes of air to be passed over/through sorbents to remove CO₂ from the atmosphere. Both thermal and electrical energy generated from the chimney could be utilized for the CO₂ capture and release mechanism (thermal swing, pressure swing, etc...) and/or be delivered to the grid, assuming the availability of transmission lines.

How to best interface air fluxes to sorbent media; determining the effects and interactions amongst the critical operating parameters (temperature, air speed, chimney height, chimney design, and collector footprint) are elements that still need to be understood for a CO₂ capture form air device.



Figure 3. Solar chimney at Manzanares, Spain.

One method investigated to move large amounts of air would entail generating a vortex through the combination of buoyancy and shear forces. This concept is similar to a solar chimney, however air would enter tangential to the chimney. The size of the vortex is yet to be determined, but it is anticipated that the diameter would be on the order of 10s of meters and height on the order of 100s of meters, up to kilometers. The vortex can be created by either introducing air at a higher temperature than the surroundings in tangential entries in a circular base structure that anchors the vortex, or by heating a surface in the center of the base structure resulting in entrainment through the tangential ports. The circular base structure only needs to extend roughly a diameter in height since it is necessary only to allow the vortex to become established. The ability to generate such a vortex has been demonstrated at a relatively small scale (~1 m dia., ~7 m height).[2] Questions remain, however, regarding atmospheric interaction, energy supply requirements, and air intake potential. Thus, the outstanding research questions for development pertain to efficiency and stability for prototypic scales. Efficiency for the objectives of this research pertains to the ratio of intake air to the heating requirements both in terms of power.

An initial evaluation has been performed using the Computational Fluid Dynamics (CFD) code Vulcan in order to determine the potential to utilize small temperature differentials to create a vortex. A simulation of a 10 m diameter base structure with a height of about 10 m and a heated plate of about 5 m in diameter at the bottom of the base structure was performed. The plate was specified at a temperature 30 K above ambient. Figure 4 showing temperature

contours and velocity vectors indicate that even at this low temperature differential a vortex five diameters in height can be created. The intake velocities are approximately 1.5 m/s, providing a volumetric air intake of about 60 m³/s through the ports in the base structure. Note that this volumetric air intake is several orders of magnitude below what is required for the objective of this project (~ 2 x 10⁵ m³/s). However, it is anticipated that future simulations would reveal much higher intake capacities at prototypic scales, particularly for optimized base structures that could be designed using CFD.

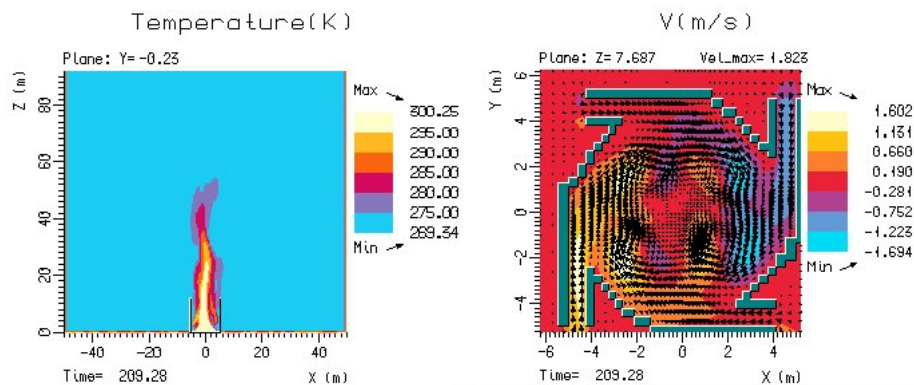


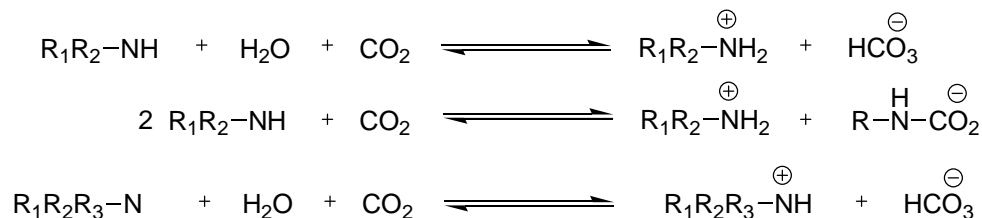
Figure 4. Temperature contours and velocity vectors for vortex based air movement. CO₂ capture media would be placed in the tangential entry points at the base of the vortex.

2.2. CO₂ Selective Sorbents

Given sufficient air fluxes, sorbents are needed that can efficiently, cost-effectively, and reliably catch and later release CO₂ with minimal energy inputs. There are commercial processes that remove CO₂ from concentrated streams associated with flue gas and hydrogen production. Metal oxide and hydroxide chemistries to capture CO₂ from flue gas have also been proposed. However, chemistries/materials to remove CO₂ from air have been less well studied. A notable exception are small scale systems developed for use in space life support.[3] The following discussion highlights technologies that might be adapted to separate CO₂ from air. The separation can take place in a liquid or solid media.

2.2.1. Liquid Sorbents

Aqueous amine solvents, such as monoethanolamine (MEA), Econamine (Fluor) and KS-1 (Mitsubishi), are commercially available to remove CO₂ from flue gas. Aqueous solutions of amine compounds react with CO₂ from flue gas at near atmospheric pressure to produce ammonium salts.[4] The ammonium salts are subsequently heated to recover CO₂ and regenerate the amine:



High energy demands are largely due to CO₂ release from the large volumes of water; dilution by water, for example, is required to mitigate the corrosive power of the amine on pipes, pumps, etc. The dilution increases the energy required in the regeneration step since a substantially larger volume of solvent, that doesn't participate in CO₂ capture, must be heated. Solvent losses due to evaporation during operation add to costs. The volume of aqueous amine required for CO₂ flue gas capture can be reduced by using a membrane contactor[5], however dilute amine solutions are still needed. Ionic liquids[6] show promise as they eliminate evaporative loss encountered with amine systems, but are usually considered for physical absorption (i.e., at high pressure in fuel gas). Material costs of ionic liquids are currently high and further development is needed to make these solvents suitable for low-pressure applications.

Other aqueous CO₂ sorbents contain alkalis, such as NH₄OH, NaOH, or KOH, and rely on the very high solubility of CO₂ in high pH solutions (> 100 g/L at pH 11 and 25 °C). CO₂ is then released by either: (1) (for ammonia-based solutions) raising the temperature and relying on temperature-dependent ammonium acid-base equilibria to lower the solution pH (ammonium acidity is unique in being peculiarly sensitive to temperature), or (2) using lime to convert the dissolved CO₂ to calcium carbonate that is subsequently calcined to recover the CO₂. Ammonia-based approaches require energy inputs associated for shifting the temperature. Also, ammonia is hazardous and caution must be taken so that ammonia is not released in the process. The calcination step in the second process occurs at ~700°C and requires high energy inputs. In addition, all liquid sorbents must overcome kinetic resistance to the hydration/dehydration of CO₂ as it crosses the gas-liquid interface. In biologic systems the enzyme carbonic anhydrase dramatically accelerates CO₂ equilibration. Carbonic anhydrase has been suggested as a potentially important enabler for achieving the same effect in atmospheric carbon capture schemes, though no pilot scale testing has been done.[7]

2.2.2. Solid Sorbents

Many of the candidate solid sorbents have been borrowed from what has been proposed or commercialized for CO₂ capture from flue gases.[8-9] These rely on metal oxide sorbents and amine functionalized mesoporous sorbents. The metal oxide and mesoporous sorbents capture CO₂ and are later regenerated producing a pure stream of CO₂ through a thermal, pressure, and/or electrothermal swing process.

Metal oxide materials have been extensively investigated for removing CO₂ from air. Other potential adsorbents include alkali carbonates and minerals containing metal oxides or hydroxides of calcium or magnesium.[10-11] A metal oxide reacts with carbon dioxide from the air to form a carbonate. The carbonate is then heated to regenerate the metal oxide and a pure stream of CO₂.



Table 1 shows the CO₂ capacity and regeneration energy for various metal oxides.[12] Calcium oxide has been studied the most since converting calcium carbonate to calcium oxide is a commercial process used by the paper and pulp industry. Silver and zinc oxides have been evaluated on a smaller scale to scrub CO₂ from air in submarine and space applications. While magnesium oxide appears to be the best candidate for CO₂ adsorption from air based on CO₂ capacity and regeneration energy, other processing parameters including humidity of the air to be

scrubbed, available heat/energy for oxide regeneration and carbonate forming/decomposition characteristics must also be considered as additional critical metrics.

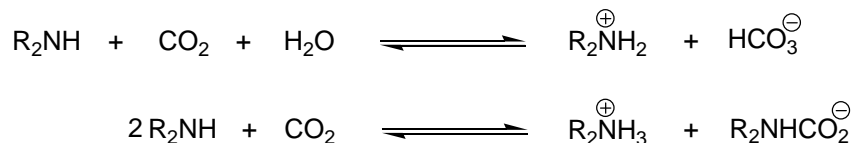
Table 1. Theoretical CO₂ capacity and regeneration energy of metal oxides.[12]

Metal Oxide	Density (g/cm ³)	CO ₂ Capacity (g CO ₂ /g oxide)	CO ₂ Capacity (g CO ₂ /cm ³ oxide)	Regeneration Energy (kJ/g CO ₂)
Ag ₂ O	7.14	0.189	1.349	1.865
BaO	5.72	0.287	1.642	6.081
CaO	2.62	0.785	2.057	4.042
Cs ₂ O	4.36	0.156	0.680	9.279
K ₂ O	2.32	0.468	1.086	8.895
Li ₂ O	2.01	1.471	2.957	5.146
MgO	3.65	1.092	3.986	2.261
Na ₂ O	2.27	0.709	1.609	7.309
Rb ₂ O	3.72	0.235	0.874	9.172
SrO	4.70	0.425	1.998	5.249
ZnO	5.47	0.540	2.954	1.616

The main advantage of metal oxides is their low cost, abundance and relatively benign environmental impact. Carbon dioxide can be stored indefinitely within these materials or regenerated on a continuous basis. Regeneration of the oxides can be problematic though. High temperatures, 200 to 1000 °C depending on the oxide, must be used and ideally regeneration of the oxide should occur in a vacuum or atmosphere of carbon dioxide to produce a pure CO₂ stream. This is contrary to how an industrial kiln operates in which the hot gases from combustion are in direct contact with the oxide/carbonate materials. Most envisioned CO₂ capture plants have an oxygen fueled kiln to do the oxide regeneration, thus requiring an oxygen separation plant.[13-14] Another issue associated with metal oxides is a loss in capacity after repeated cycles of carbonation/decarbonation.[12] The loss in capacity is due in part from an intractable build up of oxide crystallites which effectively decreases the reactive surface area for CO₂. [15]

Solid amine-sorbents work in much the same way as aqueous amine systems, but with much lower water and hence potentially lower energy requirements. A number of amine-modified materials have been examined for reversible CO₂ adsorption/desorption behavior, however, the bulk of them suffer from low CO₂ capacities, instability during cycling, high temperature requirements, and are prohibitively expensive for more general use. This has focused research onto improved sorbents.

A number of amine functionalized mesoporous sorbents have also been proposed for use in capturing CO₂. These sorbents include carbon[16] and silica[17] based sorbents and zeolites[16]. The sorbents are typically activated (by heat) or functionalized with amines to increase carbon dioxide selectivity. Sorption can occur via chemi- or physisorption at ambient temperatures and pressures. The high CO₂ capacity sorbents are functionalized with amines and work in a similar manner to the solvent based amine system. In such a system, CO₂ can react in two different ways. In the first pathway, CO₂ reacts in the presence of water and an amine to form a bicarbonate and ammonium species. Two amines may also react with CO₂ form a carbamate and ammonium species. Both reactions are reversible upon heating to temperatures up to 100 °C.



The amine functionalized sorbents are attractive because of their specificity for CO₂. However improvements must be made in sorbent CO₂ capacities, stability during cycling, and synthesis costs for an effective and economical process to capture CO₂ from air.

2.2.3. Integrating CO₂ Sorbents and Processed Air Flows

Efficiently integrating a carbon dioxide selective sorbent and air processing unit will be critical for success. There have been several laboratory/bench scale analyses that suggest what a CO₂ processing plant would look like. Keith *et al* has proposed using “spray tower” technology to remove CO₂ from air.[18] In this scheme, air is passed using a motorized fan through a mist of aqueous sodium hydroxide to remove the CO₂. The sodium bicarbonate generated from this process is then geologically sequestered; no effort was made to consider recovering the CO₂ as a gas for use in fuels production or reuse for algae production, industrial, or enhanced oil recovery purposes. Researchers at Columbia University use sheets of a basic ion exchange resin to capture CO₂ from air.[19] Hydroxide anions bound to the resin react with CO₂ to form a bound bicarbonate and one equivalent of water. Carbon dioxide catch and release can be performed by simply changing the water content of the ion exchange resin. Few details of this proprietary system have been revealed (i.e., how air is moved through the resin, overall efficiencies). A process that uses calcium oxide to capture CO₂ and thermal energy from concentrating solar power to produce a pure stream of CO₂ has also been described, but the scalability, economics, and mechanism for air flow have not been reported for this process.[20]

4. CONCLUSIONS

Our analysis suggests the following technical challenges must be met before capture of atmospheric CO₂ for conversion and recycle to hydrocarbon fuels or for re-use options can be considered plausible at the industrial scale.

1. Low-energy input air processing approaches must be pioneered to assure regular and effective air flows through CO₂ sorbent media to ensure high production rates. Ideally these will take advantage of, or be engineered enhancements of, natural wind-generating thermal gradients. Air flows must be over-pressured to compensate for pressure drops or deflection that will naturally occur during passage through or around the media.
2. For aqueous CO₂ sorbents, air-water CO₂ transfer may be the step that limits overall process success. Using carbonic anhydrase or a similarly effective CO₂ hydration/dehydration catalytic agent is a potential enabler for an industrial scale CO₂ capture process.
3. Less expensive solid CO₂ sorbents must be developed that are stable over very many catch and release cycles, have higher CO₂ capacities, and lower non-recuperable swing energies. Media and/or its support must be designed to minimize the pressure drop associated with the air processing.
4. Atmospheric CO₂ capture systems must be objectively evaluated first at the bench scale and later at the pilot scale. A host of bench and pilot-testing has built confidence in flue gas capture approaches and driven significant progress. No such track record exists to benchmark and accelerate the development of atmospheric CO₂ capture approaches.

5. REFERENCES

- [1] "Documentation for Emissions of Greenhouse Gases in the U.S. 2005," Energy Information Administration, Department of Energy 2007.
- [2] L. M. Michaud. "Atmospheric Vortex Engine", <http://vortexengine.ca/index.shtml>, (accessed September 2010).
- [3] S. Satyapal, T. Filburn, J. Trela, and J. Strange, "Performance and Properties of a Solid Amine Sorbent for Carbon Dioxide Removal in Space Life Support Applications," *Energy Fuels*, **15**, 2001, pp. 250-255.
- [4] D. E. Penny and T. J. Ritter, "Kinetic Study of the Reaction between Carbon Dioxide and Primary Amines," *J. Chem. Soc., Faraday Trans. 1*, **79**, 1983, pp. 2103-2109.
- [5] P. H. M. Feron and A. E. Jansen, "CO₂ separation with polyolefin membrane contactors and dedicated absorption liquids: performances and prospects," *Sep. Purif. Technol.*, **27**, 2002, pp. 231-242.
- [6] J. L. Anthony, S. N. V. K. Aki, E. J. Maginn, and J. F. Brennecke, "Feasibility of using ionic liquids for carbon dioxide capture," *Int. J. Environ. Technol. Manage.*, **4**, 2004, pp. 105-115.
- [7] P. Mirjafari, K. Asghari, and N. Mahinpey, "Investigating the Application of Enzyme Carbonic Anhydrase for CO₂ Sequestration Purposes," *Ind. Eng. Chem. Res.*, **46**, 2007, pp. 921-926.
- [8] D. Aaron and C. Tsouris, "Separation of CO₂ from Flue Gas: A Review," *Sep. Sci. Technol.*, **40**, 2005, pp. 321-348.
- [9] W. Hermann, P. Bosshard, E. Hung, R. Hunt, and A. J. Simon, "An Assessment of Carbon Capture Technology and Research Opportunities," Stanford University, Global Climate and Energy Project, Palo Alto 2005.
- [10] K. S. Lackner, C. H. Wendt, D. P. Butt, J. E. L. Joyce, and D. H. Sharp, "Carbon Dioxide Disposal in Carbonate Minerals," *Energy*, **20**, 1995, pp. 1153-1170.
- [11] J. L. Soares, R. Moreira, H. J. Jose, C. A. Grande, and A. E. Rodrigues, "Hydrotalcite Materials for Carbon Dioxide Adsorption at High Temperatures: Characterization and Diffusivity Measurements," *Sep. Sci. Technol.*, **39**, 2004, pp. 1989-2010.
- [12] B. Feng, H. An, and E. Tan, "Screening of CO₂ Adsorbing Materials for Zero Emission Power Generation Systems," *Energy Fuels*, **21**, 2007, pp. 426-434.
- [13] R. Baciocchi, G. Storti, and M. Mazzotti, "Process design and energy requirements for the capture of carbon dioxide from air," *Chem. Eng. Process.*, **45**, 2006, pp. 1047-1058.

- [14] F. Zeman, "Energy and Material Balance of CO₂ Capture from Ambient Air," *Environ. Sci. Technol.*, **41**, 2007, pp. 7558-7563.
- [15] B. Feng, W. Liu, X. Li, and H. An, "Overcoming the Problem of Loss-in-Capacity of Calcium Oxide in CO₂ Capture," *Energy Fuels*, **20**, 2006, pp. 2417-2420.
- [16] Z. Yong, V. Mata, and A. E. Rodrigues, "Adsorption of Carbon Dioxide at High Temperature - A Review," *Sep. Purif. Technol.*, **26**, 2002, pp. 195-205.
- [17] M. L. Gray, Y. Soon, K. J. Champagne, H. Pennline, J. P. Baltrus, R. W. Stevens Jr., R. Khatri, S. S. C. Chuang, and T. Filburn, "Improved Immobilized Carbon Dioxide Capture Sorbents," *Fuel. Process. Technol.*, **86**, 2005, pp. 1449-1455.
- [18] J. K. Stolaroff, D. W. Keith, and G. V. Lowry, "Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray," *Environ. Sci. Technol.*, **42**, 2008, pp. 2728-2735.
- [19] A. B. Wright, K. S. Lackner, E. Leon-Guerrero, U. Ginster, T. Catterson, K. Madison, R. Ishikawa, G. Grimm, M. Malcomson, and P. Liu, "Capture of carbon dioxide from air," 2008.
- [20] V. Nikulshina, C. Gebald, and A. Steinfeld, "CO₂ capture from atmospheric air via consecutive CaO-carbonation and CaCO₃-calcination cycles in a fluidized-bed solar reactor," *Chem. Eng. J.*, **146**, 2009, pp. 244-248.

DISTRIBUTION

1	MS0359	D. Chavez, LDRD Office	1911
1	MS0734	Chad L Staiger	6364
1	MS0734	Ellen B Stechel	6383 and 6364
1	MS0754	Patrick V Brady	6370
1	MS0821	Anay Luketa	1532
1	MS0899	Technical Library	9536 (electronic copy)



Sandia National Laboratories