*The Unique Challenges Posed by Direct Air Capture for Chemistry and Engineering*

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Direct air capture (DAC) is engineered removal of carbon dioxide ($CO_2$) from the atmosphere. When paired with sequestration, DAC is a negative emissions technology that can reduce atmospheric $CO_2$ concentration. When paired with $CO_2$ conversion, DAC provides a feedstock for processes that seek to make carbon-neutral fuels and chemicals. Thus, direct air capture represents technology that can help us reach net carbon neutrality and potentially reverse the flow of carbon, returning it from the atmosphere to the geosphere.

Compared to other forms of engineered carbon capture, DAC presents unique challenges: (1) at 410 ppm, the concentration of $CO_2$ is 2-3 orders of magnitude lower than point sources of $CO_2$, such as combustion flue gas, and (2) the elevated concentration of oxygen, which can degrade the performance of some DAC systems. These challenges contribute to the cost and the uncertainty in the cost of the technology.

To overcome these challenges, several classes of DAC technologies have been developed. Technologies based on liquid solvents and solid sorbents are currently used at the pilot scale, using a thermal swing to regenerate the material after capture and desorb a concentrated stream of $CO_2$. Emerging approaches use a pH-, humidity-, or electro-swing for regeneration, with solvents and sorbents tailored to these processes.

The concentration of $CO_2$ presents a thermodynamic challenge, requiring capture chemistries that bind $CO_2$ strongly enough to efficiently extract it from the air, but not so strongly to impose an excessive energy penalty to reverse the reaction during the desorption/concentration step. This has led to the development of many classes of solvents and materials for absorption and adsorption. The concentration also presents a mass transport challenge, requiring systems that are engineered to contact a large volume/flow rate of gas with the separation media while minimizing the energy penalty. Finally, the challenge of high concentration of oxygen is more broadly related to the durability of the systems and degradation of the sorbents, which must be able to withstand several tens to hundreds of thousands of sorption/desorption cycles for an economically viable process.

I will give an overview of the different classes of technologies and discuss some of the materials solutions that have been developed to date. In particular, I will highlight several open challenges for both the chemistry of materials and the engineering of DAC systems. I will also provide an outlook for the future of DAC and its role in a renewably powered world.