Carbon Dioxide a Problem and an Opportunity

A Chemist’s View on Interacting with God’s Creation on Campus and in the Business World

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When most people have a solution they are done. But, when chemists have a solution they are all mixed up.
Westerly Road Church is a community focused on making disciples in Princeton and around the world. We are evangelical (we believe in the great news that Jesus came, died, and rose again so that we might be saved!), non-denominational, and moved by our love of God, one another, and our neighbor.
A Biblical Environmental Mandate

Therefore the Lord God sent him out from the garden of Eden to work the ground from which he was taken. (Genesis 3:23)

For every kind of beast and bird, of reptile and sea creature, can be tamed and has been tamed by mankind... (James 3:7)

The Lord God took the man and put him in the garden of Eden to work it and keep it. (Genesis 2:15)

You have lived on the earth in luxury and in self-indulgence. You have fattened your hearts in a day of slaughter. (James 5:5)

...and for destroying the destroyers of the earth. (Rev 11:18)
Humanity's Top 10 Problems for next 50 years

1. ENERGY
2. WATER (= energy)
3. FOOD (= energy)
4. ENVIRONMENT (= energy)
5. POVERTY (~ energy)
6. DISEASE
7. EDUCATION
8. TERRORISM & WAR
9. DEMOCRACY
10. POPULATION* 2003 6.5 Billion People
    2050 8-10 Billion People

David Cahen WIS
On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground

Svante Arrhenius

Philosophical Magazine and Journal of Science

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Arrhenius’s paper is the first to quantify the contribution of carbon dioxide to the greenhouse effect (Sections I-IV) and to speculate about whether variations in the atmospheric concentration of carbon dioxide have contributed to long-term variations in climate (Section V). Throughout this paper, Arrhenius refers to carbon dioxide as “carbonic acid” in accordance with the convention at the time he was writing.

Contrary to some misunderstandings, Arrhenius does not explicitly suggest in this paper that the burning of fossil fuels will cause global warming, though it is clear that he is aware that fossil fuels are a potentially significant source of carbon dioxide (page 270), and he does explicitly suggest this outcome in later work.
What is the problem?

A GigaWatt Coal Fired Power Plants...

Generate 1000 lbs of CO₂ per SECOND!
And there is more than one such plant in the U.S.
Are we meeting the stewardship mandate?

And, if not, what can be done?

Does God Encourage us to “think outside the box”? 
The Parable of the Talents (Matthew 25)

14 “For it will be like a man going on a journey, who called his servants and entrusted to them his property. 15 To one he gave five talents, to another two, to another one, to each according to his ability. Then he went away. 16 He who had received the five talents went at once and traded with them, and he made five talents more. 17 So also he who had the two talents made two talents more. 18 But he who had received the one talent went and dug in the ground and hid his master’s money. 19 Now after a long time the master of those servants came and settled accounts with them. 20 And he who had received the five talents came forward, bringing five talents more, saying, ‘Master, you delivered to me five talents; here I have made five talents more.’ 21 His master said to him, ‘Well done, good and faithful servant. You have been faithful over a little; I will set you over much. Enter into the joy of your master.’ 22 And he also who had the two talents came forward, saying, ‘Master, you delivered to me two talents; here I have made two talents more.’ 23 His master said to him, ‘Well done, good and faithful servant. You have been faithful over a little; I will set you over much. Enter into the joy of your master.’ 24 He also who had received the one talent came forward, saying, ‘Master, I knew you to be a hard man, reaping where you did not sow, and gathering where you scattered no seed, 25 so I was afraid, and I went and hid your talent in the ground. Here you have what is yours.’ 26 But his master answered him, ‘You wicked and slothful servant! You knew that I reap where I have not sowed and gather where I scattered no seed? 27 Then you ought to have invested my money with the bankers, and at my coming I should have received what was my own with interest. 28 So take the talent from him and give it to him who has the ten talents. 29 For to everyone who has will more be given, and he will have an abundance. But from the one who has not, even what he has will be take.
A Story of Three Princeton Undergrads
(a.k.a. The Tupperware ® Problem)

• **Student A:** Prof. Coates at Cornell has developed very interesting chemistry for reacting CO₂ with nature products found in lemon to make a polymer with excellent properties as a plastic. So we can make Tupperware from it!

• **Student B:** CO₂ can be reduced to elemental carbon (carbon black) and this is needed for making tires.

• **Student C:** We can do your chemistry Professor Bocarsly, and convert CO₂ into methanol, which is a fuel.

What is your answer to this problem A B or C?
On hearing this Student A responded, “No one can use that much Tupperware!”

Sequestration

CO₂ Mitigation

Fuels 93%

7%

Polymers, Solid-State Products
How About Electrochemical Conversion?

\[ \text{cathode : } CO_2 + 6H^+ + 6e^- \rightarrow CH_3OH + H_2O \]

\[ \text{anode : } 3H_2O \rightarrow 3/2O_2 + 6H^+ + 6e^- \]
Counting the Cost

If 1 Mole of CO$_2$ is converted:

- **CO$_2$ reduction kinetics**
  - 0.57 Moles CO$_2$
  - ≥170kJ/mole (1.4V)

- **H$_2$O → O$_2$ kinetics**
  - (0.4V)

According to the US DOE a gas fired power plant generates 1135 pounds of CO$_2$/MWH

- 2.82 Moles CO$_2$
  - 1.00 Moles Consumed
  - 1.82 Moles Net Formed!

- **690kJ/mole (1.2V•6e-)**

- **1.6eV photon**

- **2.25 Moles CO$_2$**

- **CO$_2$ + 2H$_2$O**

- **CH$_3$OH + 3/2O$_2$**

- **6e^-/6H^+**
The Catalyst: Pyridinium
Overview of Mechanism

CO₂ → Formic Acid (HCOOH) → Formaldehyde (HCOH) → 2HCOH

MeOH + HCOOH
$\text{CO}_2 + 6e^- + 6\text{H}^+ \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$

$pH \ 5.2, \ 10\text{mM pyridine}$

96% Faradaic Yield!
The Liquid Light Process

- Renewable Energy Source
- Water: $2H_2O \rightarrow 4H^+ + 4e^- + O_2$
- Waste CO$_2$: $CO_2 + xH^+ + xe^- \rightarrow \text{product}$
- CO$_2$ Generating Source
- Product Extraction
- Chemicals & Fuels

**Highlights**
- Abundant cathode materials
- Efficient and selective catalysts
- Low cell voltages (energy efficient)
- Stability
### Prudence and Its Counterfeits

-From Jeff Cornwall

<table>
<thead>
<tr>
<th>Good Ends</th>
<th>Ineffective Means</th>
<th>Effective Means</th>
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<tbody>
<tr>
<td>Well-intentioned</td>
<td>Prudence (flourish)</td>
<td></td>
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<tr>
<td>(moralistic)</td>
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<tr>
<td>Incompetent</td>
<td>Cunning (survival)</td>
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<tr>
<td>(broke)</td>
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Currently producing target chemicals at grams/day with product concentration streams ≥ 3% and CD > 100 mA/cm² and 1000 hr stability testing, now scaling up to kg/day over the next year.
A Three Cell Stack for Formate Production
Solar Fuel is Here!
P-GaAs: The Surface Counts

Clean GaAs (111)  
\( \text{CO}_2 \rightarrow \text{HCO}_2\text{H} \)

\( \text{GaAs (111)} + \text{Pt particles} \)  
\( \text{CO}_2 \rightarrow \text{isopropanol} \)

Dark Photocatalytic \( \text{CO}_2 \) reduction

Light+catalyst
Pt/GaAs(111)

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Light source</th>
<th>Formic acid</th>
<th>Acetic acid</th>
<th>Acetone</th>
<th>2-Propanol</th>
<th>n-Butanol</th>
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<tbody>
<tr>
<td>Pyridinium</td>
<td>HgXe</td>
<td>14</td>
<td>10</td>
<td>7</td>
<td>50</td>
<td>~20</td>
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</tbody>
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Acknowledgement
“See, I have set before you today life and good, death and evil. Therefore choose life, that you and your offspring may live, loving the Lord your God, obeying his voice and holding fast to him....” (Duet. 30:15 &20)