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Global Warming Mitigation Technologies

Gregory Taylor Brooks
Georgia State University, g.taylor.brooks@outlook.com

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The history of Earth is very long when compared to the history of mankind. However, the impact which mankind has had on the Earth during its short reign is unparalleled by any other known species. Humans alone have harnessed the non-renewable resources found in carbon-based molecules; humans alone have created machines to aid us in our tasks of survival. One undeniable effect which mankind has had on the Earth pertains to the atmosphere. Since the Industrial Revolution of the late 1700s, mankind has increased the amount of greenhouse gases in the Earth's atmosphere to the point of possible climatic change (*See* Figure 1, right). Greenhouse gases are gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_20), which trap infrared heat from sunlight that has been re-radiated by the Earth's surface (USDOE Energy Information Administration). Greenhouse gases lead to the greenhouse effect. As sunlight reaches the Earth's surface, some of it is absorbed and warms the surface of the Earth, which then emits heat in the form of infrared radiation. When the infrared radiation reaches the atmosphere, the greenhouse gases absorb a portion of it. The absorbed infrared radiation is converted back to heat that stays in the atmosphere, warming the planet. This greenhouse effect happens on a global scale, hence the term 'global warming'. While global warming is one of the processes which allow life to thrive on the planet Earth by preventing a "snowball" effect, runaway global warming will make the Earth unbearably hot and therefore uninhabitable. In the short-term global warming poses significant threats to the Earth, including polar ice cap melting and sea level rising. Some of these effects have already been documented: Global average sea level rose at an average rate of 1.8 mm per year from 1961 to 2003 and new data shows that the flow rate of the outlet glaciers for the Greenlandic and Antarctic ice sheets has increased (Intergovermental Panel on Climate Change, 2007).

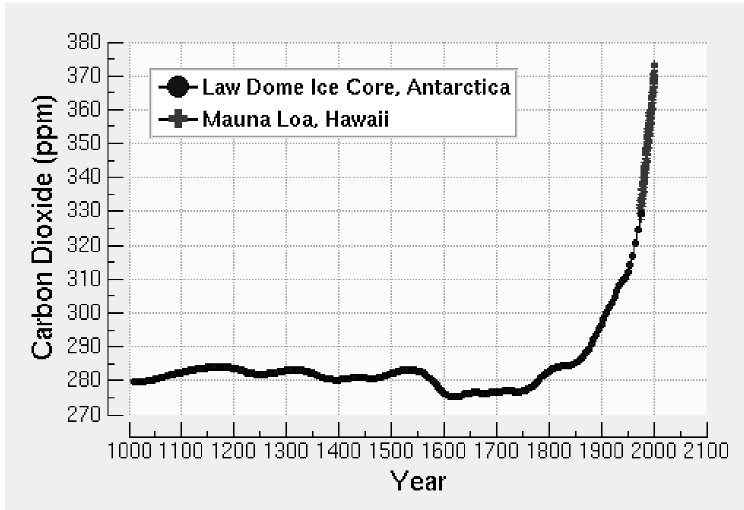

Figure 1 - Mean Concentrations of CO_2 by year since 1000 A. D, based on observations at Mauna Loa, Hawaii and from Antarctic Ice Cores
Adapted from: United States Department of Commerce. National Oceanic and Atmospheric Administration. Earth Systems Research Laboratory. Global Monitoring Division. (n.d.) [Untitled Statistical Line Graph]. Retrieved November 26, 2009 from: http://www.esrl.noaa.gov/gmd/infodata/faq_cat-3.html#9

Effects like these have caused many to realize that something must be done to mitigate the risks which global warming poses. Yet, politically and economically, to reduce CO_2 output would be infeasible. Many technologies and techniques have been developed to confront solve the issue of global warming with many focusing on reducing the amount of greenhouse gases in the atmosphere, and others focusing on increasing the reflectivity of the Earth's atmosphere. Carbon sequestration, synthetic trees and stratospheric sulfur injection are the three of these global warming mitigation technologies that seem to be the most viable and are analyzed in this paper.

Carbon Sequestration

The most abundant greenhouse gas in the Earth's atmosphere is carbon dioxide (CO_2). This gas is a waste product of many forms of human activities, burning fossil fuels to run cars and other machinery being the largest contributor of CO_2 to the atmosphere. Carbon sequestration technologies were developed to help offset the carbon output from industrial sources. The first step in the carbon sequestration process involves directly capturing the CO_2 from the emission point (i.e. the smokestack). The next step is the placement of the captured carbon dioxide into some type of storage container in a way which leaves the CO_2 permanently isolated (United States Department of Energy, National Energy Technology Laboratory [USDOE NETL] (b)). However, in order for carbon sequestration to be efficient, the costs of removing the carbon dioxide from emission sources must be less than the amount of carbon dioxide sequestered; In other words, the amount of offset CO_2 must be greater than the expenditure. There are two main approaches to carbon sequestration: geologic sequestration and terrestrial sequestration. As stated, each approach begins with the CO_2 being captured directly from the source.

Technology

The primary goal of carbon sequestration technologies is to secure permanently CO_2 molecules so that they cannot reenter the atmosphere. Direct carbon capture, which is the primary focus of carbon sequestration technologies, can be performed in three ways: post-combustion capture, pre-combustion capture, and oxy-combustion capture (United States Department of Energy, National Energy Technology Laboratory [USDOE NETL] (a)). In post-combustion capture, flue gases, a mixture of nitrogen oxides, sulfur dioxides, carbon dioxide and water, are forced through a solvent filter before exiting the flue stack (USDOE NETL (a)). The solvent absorbs the CO_2 and holds it for release at a later time. Pre-combustion is a four-step process that begins by converting the liquid fuel into gas resulting in a synthesis gas (syngas) of hydrogen (H_2) and carbon monoxide (CO) (USDOE NETL (a)). After this the syngas is processed through a water-gas-shift reactor, essentially a giant catatlytic converter, that introduces water vapor to tranform the CO into CO_2 leaving the output gas as a mixture of CO_2 and H_2 (USDOE NETL (a)). Finally the CO_2/H_2 gas mixture is placed into a tank into which chemicals called amines are being introduced. The amines bind with the CO_2 molecules and sink to the bottom, while the H_2 molecules escape out of the top of the tank. The amines and CO_2 are then seperated; the amines get recycled and the CO_2 is pressurized for transport (USDOE NETL (a)). The final capture method, oxy-combustion, commences with the fuel burning in an environment of pure oxygen. Once all of the fuel has burned the resulting vaper is a mixture of CO_2 and H_2O. The water is condensed and all that is left is pure carbon dioxide, ready to be pressurized for transport (USDOE NETL (a)). Actually capturing the CO_2 represents only the first half of the carbon sequestration technique; the second half involves stowing the carbon away indefinitely.

Geologic Sequestration. The geologic sequestration approach focuses on natural geologic formations that have the capability to segregate securely carbon dioxide, preventing its escape back into the atmosphere. Different geological formations that are being researched include oil and gas reservoirs, deep saline formations, unmineable coal seams, and basalts (USDOE NETL (b)). These types of structures are typically characterized by an upper boundary formed from a material with low permeability in the vertical direction (USDOE NETL (b)). This type of "geologic seal" is necessary to prevent carbon dioxide leaking back into the atmosphere.

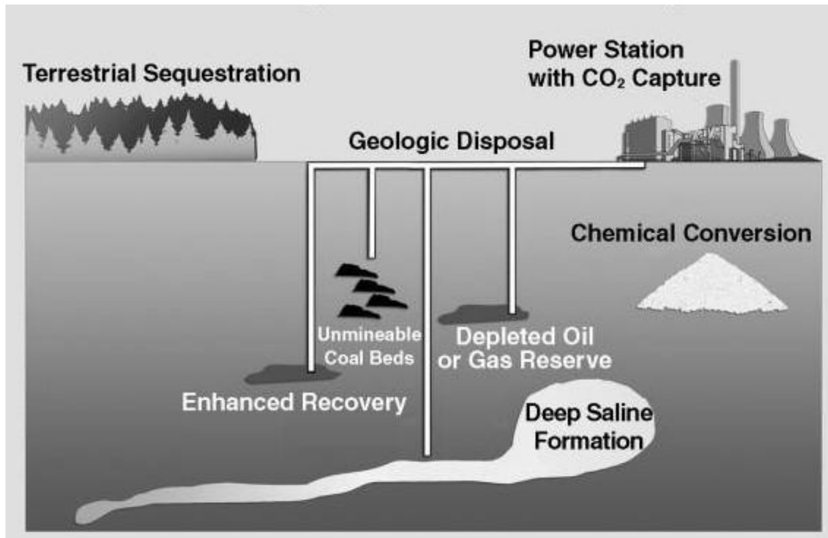

Figure 2 - Carbon Sequestration Approaches
Adapted from: United States. Executive Office of the President of the United States. Office of Management and Budget. (2006). *Carbon Sequestration Options* [Infographic]. Retrieved November 26, 2009 from: http://georgewbush-whitehouse.archives.gov/omb/budget/fy2006/energy.html

Oil and Gas Reservoirs. The most studied formations of the four are the oil and gas reservoirs, which have already been put to use as carbon sequestering mediums. In many cases, sequestering CO_2 in these reservoirs can lead to improved production of gas and/or oil from the reservoirs (United States Department of Energy, Office of Fossil Energy [USDOE OFE; USDOE NETL (b)). In effect, the incoming CO_2 pushes the oil out of the reservoir in a process called enhanced oil recovery or EOR. EOR can increase oil recovery by 10-20 percent of the original oil volume and accounts for 4 percent of oil production within the United States of America (USDOE NETL (b)). The problem with oil and gas reservoirs is that they are not geographically abundant. In other words, EOR applications are limited to locations that are close to an oil or natural gas reservoir (USDOE OFE).

Deep Saline Formations. The next type of geologic structures that holds promise for sequestration applications are deep saline formations. Saline formations are porous rock formations saturated with brine (USDOE NETL (b)). Two benefits of deep saline formations are that they are much more common than oil and gas reservoirs and offer a much greater volume in which to store CO_2 (USDOE NETL (b)). Another advantage of deep saline formations is that they are near to CO_2 source points allowing for direct injection of CO_2 from the source to the formation (USDOE NETL (b)). Deep saline formation sequestration is a relatively new idea and as such very little is known about the ability of deep saline formations to hold CO_2 safely. (USDOE NETL (b)). However, there is research currently taking place to determine the validity of saline formation sequestration, including an actual large-scale injection of CO_2 into a deep saline formation located in the North Sea by the Norwegian oil company Statoil (USDOE OFE).

Unmineable Coal Seams. The next geologic formations to hold potential for sequestration are unmineable coal seams. These coal beds are located at depths beyond conventional recovery limits (USDOE NETL (b)). Like most coal deposits, these unmineable coal seams contain large amounts of methane (CH_4) adsorbed onto the coal surface (USDOE OFE). This methane is valuable to industry and is typically procured by depressurizing the coal bed by means of pumping water out of the reservoir (USDOE OFE). However, coal absorbs CO_2 about twice as readily as CH_4 (USDOE OFE). If CO_2 were pumped into one of these coal seams, the coal would begin to adsorb it, causing the CH_4 to desorb (USDOE NETL (b)). The CH_4 can then be used for industrial purposes. Very little research has been done in regards to carbon sequestration via unmineable coal seams and many obstacles stand in the way of it becoming a viable method of carbon sequestration.

Basalts. The final geologic formations that hold promise for sequestration applications are basalts. Basalts are solidified lava formations that have a unique chemistry that transforms CO_2 into limestone in a process called mineralization (USDOE NETL (b)). This process is extremely preferable because it isolates CO_2 from the atmosphere permanently (USDOE NETL (b)). The process involves pumping water saturated with CO_2 into the basalt formation. Over time, through a chemical reaction that is not entirely understood, the CO_2 is converted to solid limestone (USDOE NETL (b)). This chemical reaction is irreversible, permanently locking the carbon dioxide into a mineral form. One potential problem with basalt formations is that as CO_2 is being pumped into the basalt it immediately begins to mineralize, impeding further flow of CO_2. Thus, while basalts offer an exciting option to sequester carbon, there is still research that must be done to make it economical viable.

Terrestrial Sequestration. The terrestrial sequestration approach focuses on the ecosystem's potential to increase CO_2 uptake and to prevent CO_2 emissions. Essentially, terrestrial sequestration involves enhancing the ability of plants and microbes to absorb CO_2 from the atmosphere or preventing net CO_2 emissions from the ecosystems into the atmosphere (USDOE OFE). Terrestrial sequestration is primarily achieved by reforestation, forest conservation and no-till farming (USDOE NETL (b)). Reforestation and forest conservation increase the amount of plants thereby increasing the amount of CO_2 a particular ecosystem can absorb. No-till farming prevents the escape of soil carbon into the atmosphere. There are many collateral benefits provided by terrestrial sequestration. These include flood protection and wildlife habitats. (USDOE NETL (b)). There are still problems with terrestrial sequestration: according to the United States Department of Energy's National Energy Technology Laboratory, it would take about 220,000 acres to offset the carbon emissions of a single, average-sized, coal power plant (USDOE NETL (b)). Terrestrial sequestration offers many advantages but in a time of increased land usage for human development in lieu of pristine environments, it may not be the method to use.

Carbon Sequestration Mitigation of Global Warming's Risks

The approaches to carbon sequestration are many and varied, but they all have one thing in common; they attempt to remove harmful greenhouse gases, the source of global warming, from the atmosphere. Carbon sequestration provides a highly site-independent method of greenhouse gas removal and storage. The technologies allow for minimal pipeline usage to carry greenhouse gases to the storage reservoir and minimize costs in the process. The potential of carbon sequestration to achieve this goal of zero net greenhouse emissions is great and as the issues surrounding the various approaches are done away with, it is undeniable that the days in the reign of CO_2 are coming to an end.

Synthetic Trees

The problem with carbon sequestration is that it only provides for the storage of CO_2 directly from the emission source; neither approach addresses the issue of 'ambient' greenhouse gases, such as those emitted from cars, trains, and planes. Many cars have a device called a catalytic converter, which converts harmful engine pollutants such as carbon monoxide (CO), and nitrogen oxide (NO, NO_2) into nitrogen gas (N_2), CO_2 and water (H_2O). The CO_2 could, in theory, be scrubbed directly from the exhaust pipe, in a similar fashion to industrial carbon sequestration. However, it would be unfeasible to attach a carbon scrubber to the exhaust pipe of all the cars, trains and planes in the world and one would need a method by which to store the scrubbed CO_2: Onboard tanks which would conceivably have to be employed as the storage medium in this case causing weight issues for planes and limiting space on all three modes of transportation. As a result of carbon sequestration's inability to collect CO_2 from mobile sources, other solutions were sought to combat these transportation-sourced greenhouse gas emissions, which are the

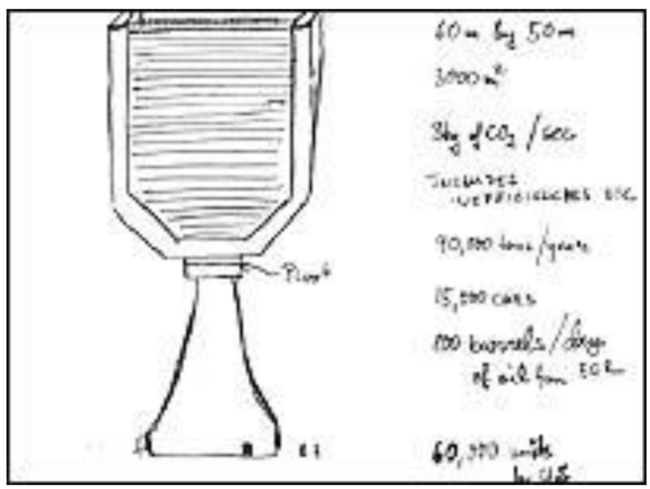

Figure 3 - Synthetic Tree Prototype Sketch
Adapted from: Lackner, Klaus. (Drawer). (2003). [Untitled Conceptual Drawing]. Retrieved November 26, 2009 form: http://news.bbc.co.uk/2/hi/science/nature/2784227.stm

largest end-use source of greenhouse gases in the United States, accounting for 29 percent of total greenhouse gas emissions (US EPA Office of Transportation and Air Quality, 2009). Thus, it is for the collection of ‘ambient’ CO_2 that synthetic trees were created.

Technology

Figure 4 - Synthetic Trees Lining Highway
Adapted from: Institution of Mechanical Engineers. (Designer). [Untitled Computer-Altered Photograph]. Retrieved November 26, 2009 from: http://blogs.discovermagazine.com/80beats/2009/08/27/fighting-global-warming-artificial-trees-and-slime-covered-buildings/

Dr. Klaus S. Lackner, a professor of geophysics, earth and environmental engineering at Columbia University, conjured up the idea for synthetic trees after his eighth-grade daughter wanted to prove that carbon dioxide could be cheaply captured from the air for a middle school science project (The Breakthrough Institute, 2008). The technology is comprised of an absorbent medium and slats (Bentley, 2003). The absorbent medium absorbs the CO_2 from the air, while the slats provide a method of increasing the surface area of the medium that is exposed to the air. In its original iteration, the absorbent would begin to mineralize the CO_2 upon exposure to the air. This layer of minerals would have had to be replaced by a worker so that the process could begin again. The absorbent medium was originally the highly alkaline chemical sodium hydroxide (NaOH), which would have forced maintenance workers to don hazmat suits in order to safely remove the mineralized CO_2 (Global Research Technolgies, LLC, 2007). After capture, the CO_2 would be used for commercial purposes such as soda carbonation or stored by some form of carbon sequestration, most likely a form of mineralization (The Breakthrough Institute, 2008).

Due to the safety issues involved with NaOH, Dr. Lackner began to look for other methods of renewing the sorbent and in 2007, the company he founded to develop synthetic tree technologies, Global Research Technologies, LLC, made a breakthrough in that area:

> GRT overcame one of the most difficult challenges in air capture when it developed for the ACCESS™ unit, a proprietary method of separating CO2 and regenerating the capture sorbent. The process developed by GRT is essentially carbon neutral, a feature of great competitive advantage because a substantial extra amount of energy had been required for CO2 capture devices previously described in the technical literature (Global Research Technolgies, LLC, 2007).

Resolving the safety issues pertaining to the maintenance of synthetic trees had been a major impediment toward commercialization of the technology; now that those issues have been settled synthetic trees seem poised to revolutionize the field of carbon dioxide mitigation technologies.

Synthetic Tree Mitigation of Global Warming's Risks

Synthetic trees supply a method of carbon capture which can be targeted to reduce greenhouse gases in areas which have a high level of carbon emissions from mobile sources such as cars, trains, and airplanes, such as along highways and near airports. Synthetic trees also have potential to lesson airborne pollution in and around cities that can lead to smog: "Synthetic trees are capable of removing one ton of CO_2 per day, [...] an amount of gas equivalent to that produced by 20 cars" (Vaknin, 2009).

Although, all of the technical hurdles concerning synthetic trees have been overcome, research is ongoing in terms of finalizing a marketable unit. The great promise of synthetic trees is that they are site- and source- independent and are the only technology currently able to remove CO_2 emissions which occurred in the past (Global Research Technologies, LLC, 2009). Synthetic trees offer mankind a method by which to fix the CO_2 emission problem that we ourselves created. Taken together, synthetic trees and carbon sequestration focus on mitigating global warming's effects by removing greenhouse gases from the atmosphere. Another technique for achieving that goal actually involves introducing additional chemicals into the atmosphere.

Stratospheric Sulfur Injection

Whereas, the previous two technologies have focused on removing greenhouse gases from the atmosphere, stratospheric sulfur injection focuses on increasing the reflectivity of the Earth. This reflectivity is called albedo. By increasing the Earth's albedo, stratospheric sulfur injection would prevent a portion of the sunlight that would be converted to infrared radiation from reaching the Earth, thereby reducing the temperature.

Technology

Stratospheric sulfur injection works by releasing sulfur dioxide molecules (SO_2) into the stratospheric layer of the atmosphere. Once the SO_2 is in the stratosphere, it is converted by "chemical and micro-physical processes […] into sub-micrometer sulfate particles" (Crutzen, 2006). These sub-micrometer particles increase the reflectivity of the stratosphere, allowing less sunlight to

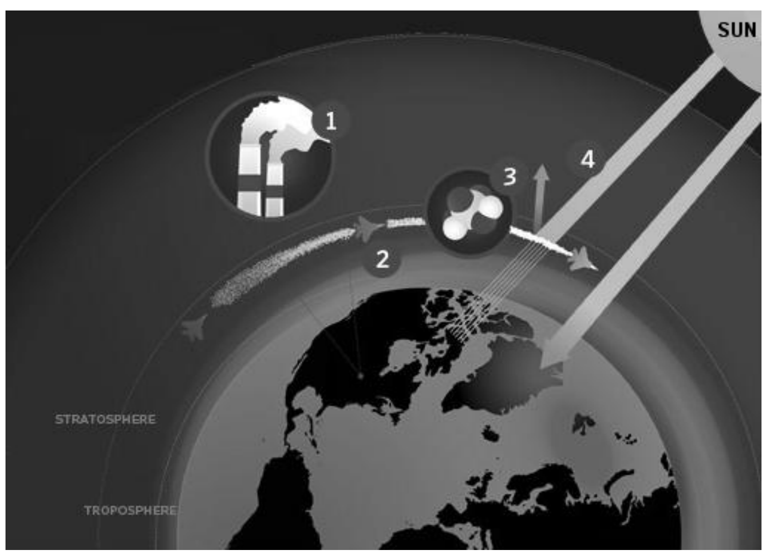

Figure 5 - Stratospheric Sulfur Injection
Adapted from: Vulk, Ryan. (Designer). (2008). *Cooling the Globe* [Infographic], Retrieved November 26, 2009 from: http://www.wired.com/science/planetearth/magazine/16-07/ff_geoengineering?currentPage=2

penetrate to the Earth's surface. The sub-micrometer particles effectively prevent incoming electromagnetic radiation from penetrating to the Earth's surface, instead causing the EM radiation to be reflected back into space. Various methods of delivering the sulfur dioxide to the stratosphere have been proposed, such as burning sulfur (S_2) floated to the stratosphere on balloons or shot into the stratosphere by artillery guns (Crutzen, 2006). The increase in albedo caused by stratospheric sulfur injection would result in a lower temperature on Earth's surface.

Stratospheric Sulfur Injection Mitigation of Global Warming's Risks

Stratospheric sulfur injection is characterized by a different approach than either carbon sequestration or synthetic trees. Global warming's primary effect of concern is the increase of temperatures on planet's surface and combating this effect is at the center of stratospheric sulfur inject, which aims to increase the albedo of Earth's stratosphere so as to cool the Earth's surface. The idea for this comes from the effect that volcanoes have on the atmosphere. (Steenhuysen, 2008). Although cooling by injecting sulfate aerosols also occurs in the troposphere, stratospheric sulfur injection offers the benefit of a long residence period of one to two years versus one week in the troposphere (Crutzen, 2006). As a result of this extended residence time, a continuous stratospheric sulfate loading of about 1.9 megatons of sulfur (S) would need to be maintained (Crutzen, 2006). Stratospheric sulfur injection may be inspired by a natural process but it effects on the root cause of global warming, namely increased concentrations of atmospheric greenhouse gases, are minimal, and little to no research has been done on potentially harmful side-effects. Even so, the relatively short period before climatic response, about six months according to Crutzen, make albedo enhancement by stratospheric sulfur injection a viable option if temperature begin to rise at an increasingly fast pace.

Global Warming and the Future

Out of these three technologies, there is no clear winner. Carbon sequestration offers an easy, affordable method of storing carbon emissions, yet is plagued by site and stability issues. Synthetic trees provide a highly mobile means of reducing greenhouse gases regardless of their source, yet are inundated with storage and maintenance concerns. Stratospheric sulfur injection is relatively maintenance-free and blocks harmful ultraviolet radiation, yet is beleaguered by the uncertainty of its long-term environmental, climatic, and health effects. Perhaps the best approach is a combination of these and other methods. However the goal is achieved, it is clear that something must be done. Global warming mitigation technologies like these offer ingenious ways of ensuring our future here on planet Earth.

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