Title
Carbon Catcher Design Report

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Table of Contents

Design Prompt

One of the most relevant problems in today's world is climate change. Year after year, the average temperature around the globe has been steadily rising. Current projections by Berkeley Earth predict that by 2060 the 'global temperature anomaly' will be 2 °C. The effects of this temperature anomaly can already be felt by several ecosystems and human settlements: global water sources are drying up, countries and cities are becoming too hot to live in, and wildfires are more common than ever before. Now is the time to address the problem and make a lasting impact; not only to stop adding greenhouse gases and other pollutants into the atmosphere, but to actually take harmful chemicals, such as carbon dioxide, out. The scope of this project aims to address the latter.

Due to human induced climate change atmospheric carbon dioxide levels, one of the most harmful and prominent pollutants, have been increasing every year since the dawn of the industrial revolution. Efforts to reduce greenhouse gas emissions by proliferating green energy are stronger and in higher demand than ever before. Yet humankind is far from limiting its aggregate global warming to 1.5 °C, as outlined by the 2016 Paris Agreement. To mitigate catastrophic environmental damage, we are proposing the design of a 'Carbon Catcher', which actively extracts and repurposes carbon dioxide from the atmosphere through utilizing a passive filtration system: membrane diffusion.

Overview

The design of the overall Carbon Catcher project can be separated into four distinct systems, each of which is assigned a specialized committee. The committee names and responsibilities are listed below:

Air Mover

The overall goal for the Air Mover committee is the design of the turbine assembly. As the overall goal of the project is to collect and separate carbon dioxide from the air, one of the most important parts is to actually get the air to pass through the carbon-catching membrane. Passive air would not give a significant enough yield rate to make the carbon dioxide collection rate impactful, thus air must be sucked through a vacuum/turbine.

Membrain

The goal of Membrain is to create a membrane that can filter out CO2 through various methods. These methods are limited, due to there being such variety, to certain techniques and membrane material types that have been decided, prior, by the committee. Most membranes will be geared towards utilizing temperature and pressure along with gaseous speed and flow rate. In addition, examining certain treatments, such as regeneration of material, and replacements will be looked into as well, to see how it fares in sustainability.

Carbon Storer

The Carbon Storer committee will design a store and transport system for fluid CO2 after it is extracted from the atmosphere. Primary considerations include geological solutions, cost-effective materials, and analysis methods to improve overall capacity and efficiency. Additionally, the committee will select an environmentally and economically sustainable method of recycling the captured CO2.

PyControl

The PyControl committee will design a series of sensors and actuators, which will primarily support the sequestration and pipeline systems present in the Carbon Storer Committee and direct air capture system in Air Mover. The design can be broken into four control layers: Input/Output, Field Controllers, Data, and Supervisory.

Goal

The overarching goal of Carbon Catcher is to design a cost-effective, scalable atmospheric carbon dioxide removal system that is capable of being deployed in a variety of urban environments and may fit a variety of different customer requirements or requests.

Objectives

The inter-committee objectives for the aforementioned scalable system are listed below, along with the names of the committees best suited to acheive each objective.

1. (AirM/PyC) Monitor air temperature and flow through systems, maintain inflow velocities for the filtration phase.
2. (CarS/PyC) Tailor User Sequence or UI to preferences of identified commercial audience.
3. (MemB/CarS) Determine a unit amount of CO2 gas through the membrane and propose a maintenance plan.
4. (MemB/AairM) Integrate components of filtration system into modular design form. Maximize flexibility of design and scope of applicability.

Project Outline

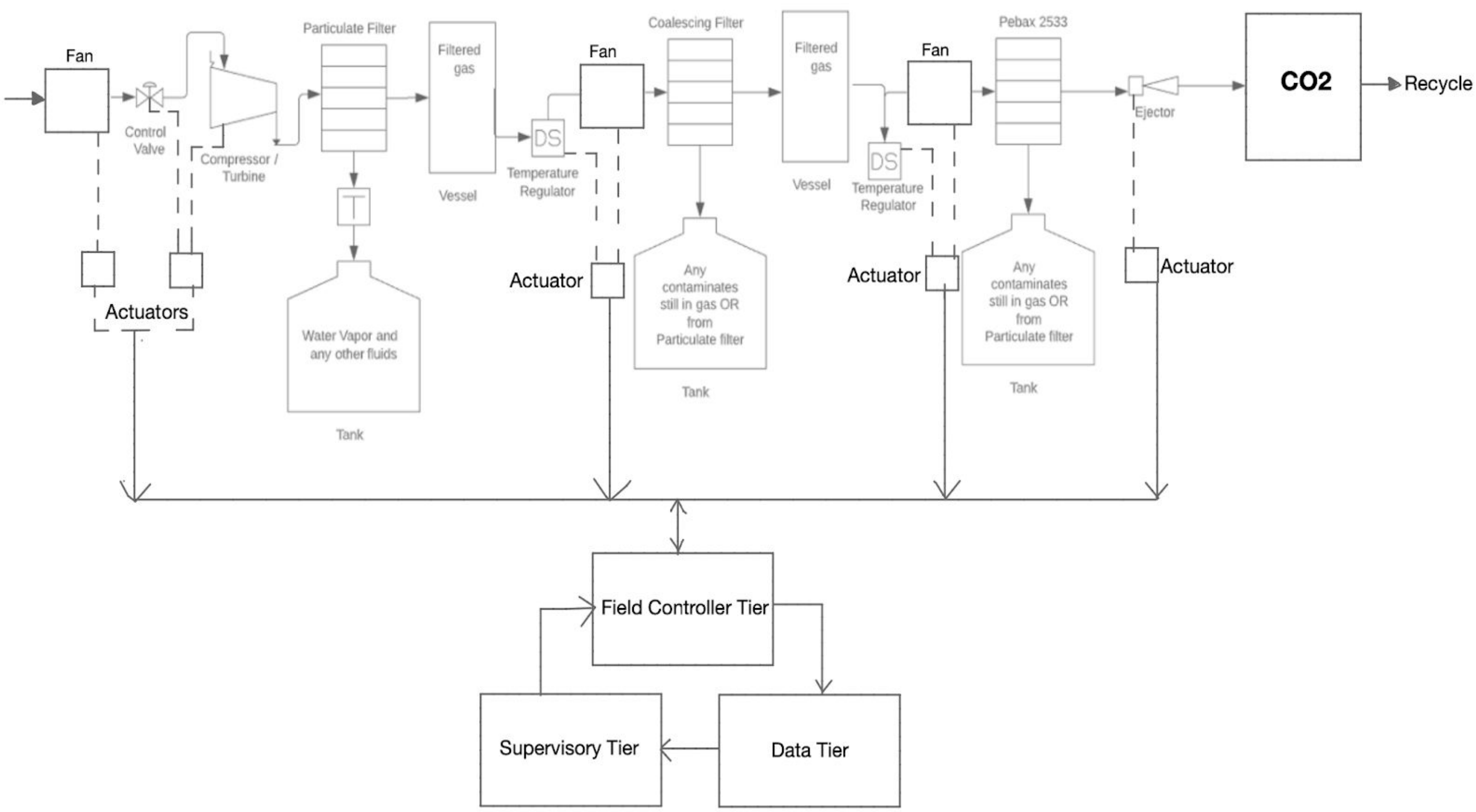

Figure 1. *Overall schematic of carbon dioxide separation process from air*

This report proposes the application of carbon capture and storage (CCS) technology to producing enhanced, carbon-injected concrete. The cement industry accounts for 3.8% of all greenhouse gas emissions and 5% of global carbon dioxide emissions (OECD). The International Energy Agency's 2008 Blue Map plan outlines safe levels of carbon emission by the years 2030 and 2050 (IEA). For the cement industry specifically, their plan requires annual carbon emissions of 2.0 Gigatons in 2007 to be reduced to 1.55 Gigatons by 2050, even though cement construction is anticipated to increase 50% during that time period. Recycling the captured CO2 into a base for sustainable concrete reduces total emissions originating from the construction industry, which has the potential to impact any area where development is present.

Figure 1 illustrates the process for separation of carbon dioxide from air by the use of fans, filters, temperature regulators, compressors, piping routing, and a field controller based on software. The air will enter the system with the help of a fan, then the compressor will adjust the pressure to feed the particulate filter. This section is composed of a filter that works as a first barrier, allowing particles that are up to 5 μm in size to pass through. Most of the water vapor and fluids will be separated on this section and then directed to a tank. Any filtered gas that passed through the particulate filter will then be adjusted to a specific temperature to improve the filtration through the coalescing device. This second filter will separate the remaining water vapor and any other contaminants that were able to pass through the particulate filter and be stored in a second tank. After regulating the temperature of the coalescing flow through, the CO_2 in the air is to be isolated using Pebax 2533 SA 01 membrane. It is also important to notice that fans will be installed to feed the last two filters and help move the gases inside the pipes. All the system is being controlled by sensors and actuators that will be controlled by a Field Controller tier that is supplemented by a Data tier and a Supervisory tier.

The extraction of CO2 from the atmosphere is made possible through a membrane filtration system based on traditional nitrogen generation. The passive filtration system autonomously separates the carbon dioxide from other air constituents, drastically reducing power/electricity input. The system's working sensors and actuators similarly employ energy-saving strategies, such as distributing cloud-computing services over multiple servers and mainframes to reduce computing power. The entire movement of air is directed by a scalable fan device, which is presented in the report as a modular design to facilitate customization of fan parts to specific size and installation requirements. As a whole, Carbon Catcher operates with high efficiency to maximize the commercial opportunity of direct air capture while saving the environment from industry-inherit damages.

Design Breakdown

Air Mover

SolidWorks was utilized for both CAD and simulation for this project. SolidWorks was chosen for simulation so that the models did not need to be exported into another program. This made the iterative design process much easier and faster.

When designing the system, the single biggest area of focus is the actual design of the propeller. The propeller, and thus the efficiency of the entire system, is heavily dependent on the propeller material choice, propeller shape, number of blades, and the angle of attack of the blades. [4]

Propellor Iterative Design Process

CFD simulation allows for the implementation of an iterative design approach with regard to the propellor. The propellor has undergone several rounds of simulations to improve upon its ability to pull air through the system. Some areas of interest that were considered were the angle of attack and the cord length of the propellor.

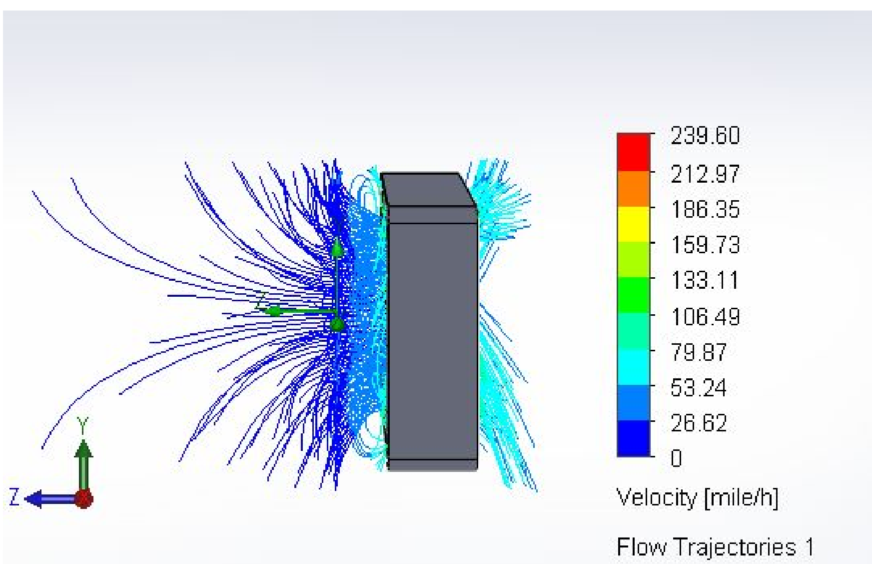

Figure 2. *Isotropic Streamlines*

Figure 2 shows the streamlines of the particles of air that will be passing through the fan. The simulation above was run with the propellor rotating at roughly 2000 RPM, which is towards the low end of typical HVAC applications. Non-overloading HVAC axial fans typically rotate at an RPM between 1500 - 3000 [9]. The streamlines at the exit have a weird pattern due to how the propellor is mounted to the front module. Unfortunately due to the size of the propellor, there is not much that can be done to make this part smaller. The air gets dispersed at undesired angles and scattered non-symmetrically however, the pipe for the intermediary modules is slighted tapered inward, which will help the flow of air to remain reasonable throughout the module. For longer devices, as per customer request, more fan modules could be inserted throughout to help the flow of air remain strong throughout the entire system.

Figure 3 shows the velocity contour lines for the surface of the actual fan module. At the tip of the propellor, the tips are travelling at 198.47 mph, which again fits in the HVAC industry standard. And as expected, the bounding box does not have a measurable velocity.

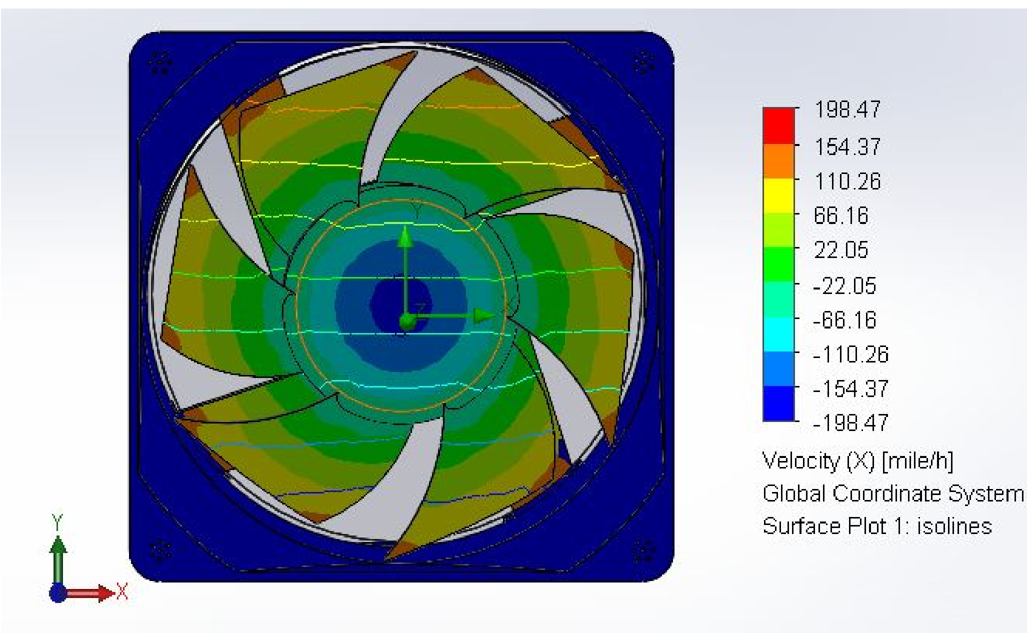

Figure 3. *Velocity Isolines Contour Map*

Mechanical CAD Breakdown

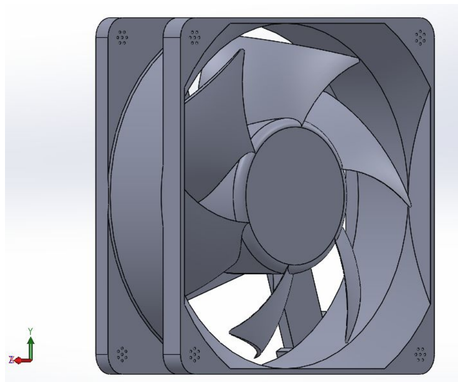

Figure 4. *In-line Structural CAD for the Fan Sub-Assembly*

The image in Figure 4 shows the fan as well as the fan housing that will be used to suck air through the membrane. The fan assembly will be housed in an outer shell -- bigger box. The bigger box provides an enclosure for all of the electrical components, piping, and the membrane. The outer shell ensures that all of the components are enclosed and relatively safe from environmental hazards.

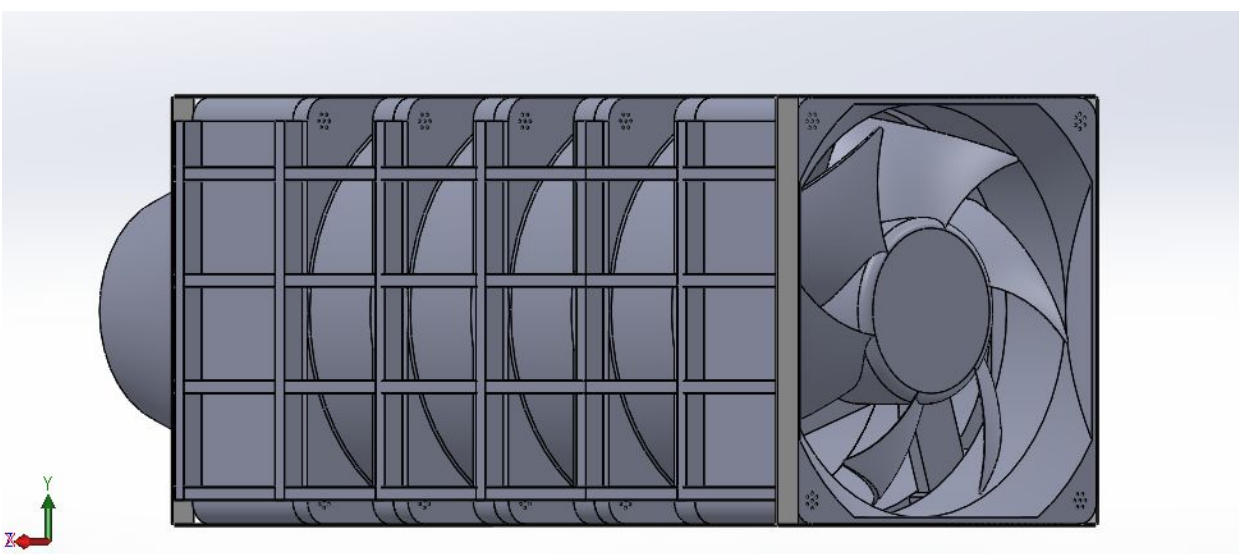

Figure 5. *Complete System Cut-out Assembly View*

Figure 5 above shows the full assembly for the fan system. The bounding box for the system shown above is 90” L x 38” W x 36” H. the entire system is made up of three different modules, as is shown in Figure 6. Image A shows an intermediate module, image B shows the exhaust module, and image C shows the fan module. This modular setup allows the system to be modified according to the customer’s needs -- whether that be low cost, high power, or high efficiency, this design can meet them all.

Note that each of the modules uses the same mounting pattern in either of the four corners. This bolt pattern allows for ever more customizability. The carbon dioxide absorbing membrane will be mounted onto a plate with the same bounding box as the modules: 36” x 36”, that contains the same bolt pattern. If more filters are needed, or even if different kinds of filters are desired, this requirement can be addressed. As well, the modularity allows for easy maintenance and cleaning. Pipes can easily be daisy chained into/out of each of these modules as well -- in case other materials are planned on being separated or filtered out.

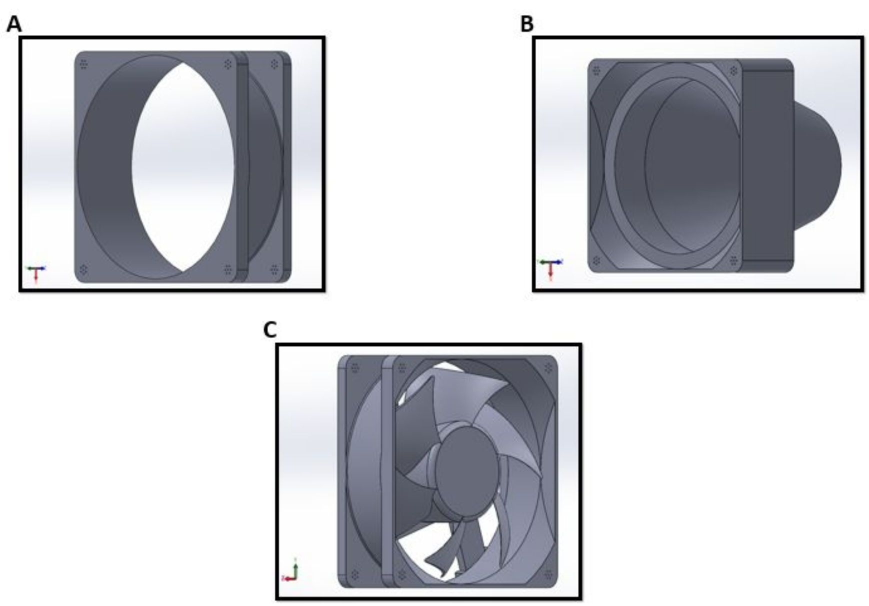

Figure 6. *System-Configurable Modules*

Figure 7 depicts a web-like structure of 1” x 2” square tubing to the left side of the system. this webbing provides storage, mounting space, and structural support for the electrical components that are required for the operation of the device. This webbing provides over 2500 cubic inches of usable components, wiring, and piping space. Pipes can be run out of the entire assembly, and be mounted and sorted using this web structure. The system can adapt to a wide variety of customer needs.

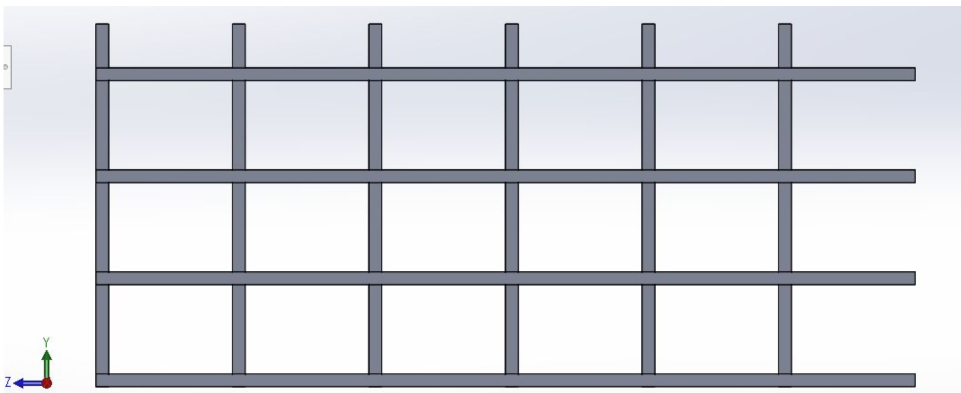

Figure 7. *Mounting Webbing*

Material Selection

As in nearly all engineering applications, the materials choice for the components plays a large role in the design process. For this project, it makes sense to utilize some kind of metal due to its strength and relatively low cost. The two metals that were considered were Chromoly steel and Aluminum. Both of these metals present high strength and good weldability. For our application, aluminum presents a better option. Aluminum is lighter weight. Although it is not as strong or as temperature resistant as steel, the system will not experience very unstable or extraneous conditions.

Now we can take a look at different alloys of aluminum. There are two main designations of alloys: wrought and cast. Wrought alloys are beaten or hammered to shape. Cast alloys are typically melted into a mold, then cooled and removed.

Since our design is meant to be modular and the same modules are meant to be continually repeated and made, it makes sense to use molds and casting for our fabrication technique. The list of castable aluminum alloys can be summarized in Table 1.

Alloy Type		Temper	Tensile Strength (min) (ksi)	Yield Strength (min) (ksi)	% Elongation
ANSI	UNS				
201.0	A02010	T7	60	50	3
204	A02040	T4	45	28	6
242	A02420	O	23	N/A	N/A
		T61	32	20	N/A
A242	A12420	T75	29	N/A	1
295	A02950	T4	29	13	6
		T6	32	20	3
		T62	36	28	N/A
		T7	29	16	3
319	A03190	F	23	13	1.5
		T5	25	N/A	N/A
		T6	31	20	1.5
328	A03280	F	25	14	1
		T6	34	21	1
355	A03550	T6	32	20	2
		T51	25	18	N/A
		T71	30	22	N/A
C355	A33550	T6	36	25	2.5
356	A03560	F	19	9.5	2
		T6	30	20	3
		T7	31	N/A	N/A
		T51	23	16	N/A
		T71	25	18	3
A356	A13560	T6	34	24	3.5
		T61	35	26	1
443	A04430	F	17	7	3
B443.0	A24430	F	17	6	3
512	A05120	F	17	10	N/A
514	A05140	F	22	9	6
520	A05200	T4	42	22	12
535	A05350	F	35	18	9
705	A07050	T5	30	17	5
707	A07070	T7	37	30	1
710	A07100	T5	32	20	2
712	A07120	T5	34	25	4
713	A07130	T5	32	22	3
771	A07710	T5	42	38	1.5
		T51	32	27	3
		T52	36	30	1.5
		T6	42	35	5
		T71	48	45	5
850	A08500	T5	16	N/A	5
851	A08510	T5	17	N/A	3
852	A08520	T5	24	18	N/A

Table 1. *Cast Aluminum Alloys* [1]

Membrain

Why this system?

The three different aspects required for air preparation are compressed air quantity (flow), air pressure, and compressed air purity. Hence, the system has two initial filtration stages prior to the membrane, such as the particulate and coalescing filtration system, has the advantage of breaking down the process into simpler components by removing impurities in the air one step at a time. This particular system was inspired by examining different systems of nitrogen membrane generators, the only difference is that the system will work towards the separation of CO_2 rather than nitrogen.

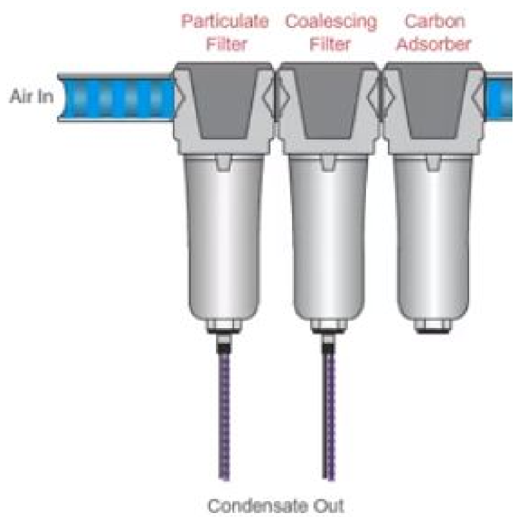

Figure 8*: Beginning section of a Membrane Nitrogen Generator, capable of producing nitrogen from air.*

Some major benefits of this is the usage of energy, because it only requires energy to operate the compressor, fan blades, and temperature to control the rate of filtration. For example, flue gas treatment and separation require the pretreatment methods, such as pre oxy-combustion, to purify the gas. Using the proposed design shown on *Figure 1* will allow for a filtration system that is based entirely of the pressure and temperature of the gas.

This system design allows for modules or pieces of equipment to be separated into different sections, allowing the modeled filtration design to be built from pre-existing equipment. It is not only convenient for installation purposes, but it can also facilitate the source for parts during maintenance. Additionally, the gas separation filters do not have moving parts, making the system reliable and last much longer compared to moving filtration systems.

Another factor to consider when separating CO_2 is that membrane separation does not require of a separating agent or regeneration, compared to absorption separation. The system is not only compact and lightweight but is able to be used in any orientation to improve the efficiency of the multistage operation.

Materials

A particulate filter is something that is crucial for obtaining the purest amounts of air. In its purest form a particulate filter is defined as a device composed of fibrous or porous materials that will remove solid particulates of various sizes, such as dust, bacteria, mold, and pollen. Capturing air is a crucial factor, but having no particulates is just as important [4].

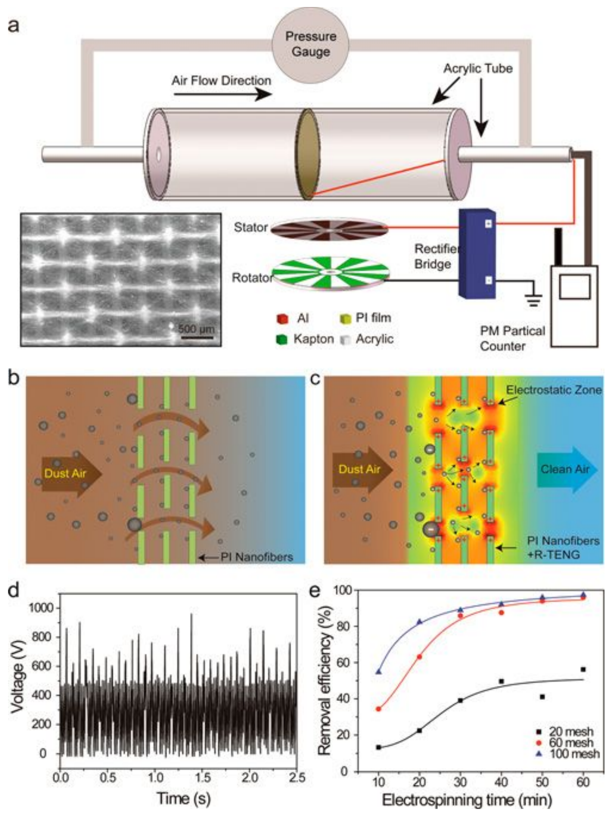

Figure 9: Diagram of how Triboelectric nanogenerator (TENG) works inside a particulate filter.

One of the most efficient ways to filter out the particulates is by using a triboelectric nanogenerator (TENG), which is an energy harvesting device that converts the external mechanical energy into electricity by a conjunction of triboelectric effect and electrostatic induction [4]. Electricity can be created through sliding or separation of two materials that have opposing tribo-polarity. In the case of this design, the motion will be done by using a rotating TENG to enhance a polyimide nanofiber to filter out particulates.

Fibrous materials, such as high efficiency particulate air filter (HEPA) and polymer films are examples of what can be used inside this rotary triboelectric nanogenerator (R-TENG) technology. For this contraption, using HEPA is both common and efficient. Sources state that the HEPA filter efficiencies range from a lower level of 99.97% at 0.3 microns to a higher level 99.9995% at 0.12 microns [4]. This measurement of efficiency is done by using the concept of MPPS (Most Penetrating Particle Size). As shown on *Figure 3*, there exists a point in which no mechanism or filter is dominant, hence it being called the area in which a filtration medium is at its medium.

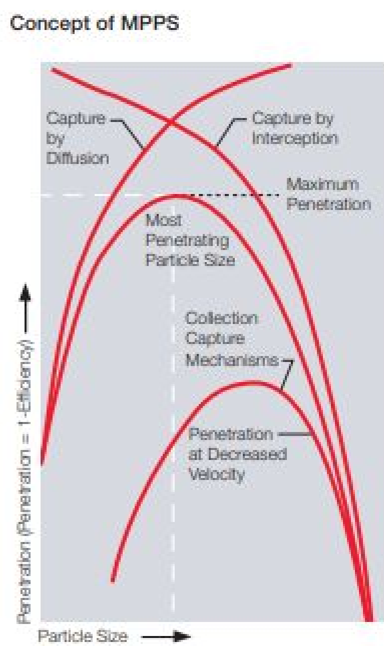

Figure 10: *How/What the MPPS is with different velocities*

If the feed of the design system were to be left unfiltered, there would be many contaminants left by the membrane section, affecting the overall performance of the system. Hence, the use of a particulate filter is able to separate the impurities that range from 0.3 to 0.12 microns at a 99% efficiency, allowing few particles to pass through together with remnants of water [5]. The purpose of adding a compressor prior to the particulate filter is to have no pressure loss, leading to lower efficiency, production time, and money wasted on maintenance.

The main purpose of the coalescing filter is to remove any remaining particulates that may have bypassed the particulate membrane due to MPPS [5]. It will also remove any liquid and particulate contaminants from compressed air. This is important because water can build up on the piping and cause corrosion, leading to problems such as clogging up valves and instrumental control lines. A basic description of how the coalescing filtration is done is through a continuous process whereby fluids run together to form a larger heavier droplet that is drained gravitationally. The main method of a coalescing filter is its centrifugal separator present inside, providing with a spinning motion of the air, where the particles will have an outward movement and will drain into the tank. This is an effective method for removing dust, dirt and water droplets that are larger than 5 microns.

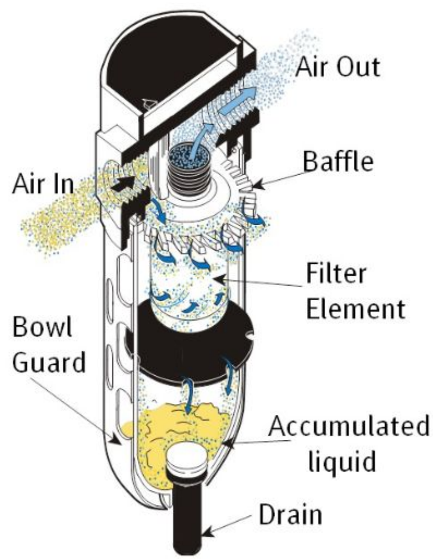

Figure 11&12. *Centrifugal rotation inside a coalescing filter (Left). Overall diagram of the coalescing filter (Right).*

Notice that inside the coalescing filter device, there is a filter element beneath the baffle. There are different types of filter elements, but in the case of our system of operation, Sintered SS Cartridges are the most optimum because it has a long shelf life. However, other filters like Microfiber Filter Cartridges or LP Cartridges are also acceptable.

Having a compressed air mechanism and a compressed air filter is crucial because when air at atmospheric pressure is compressed, water vapor is able to be easily extracted. In addition, cooling off the compressed air results in over 70% of the vapor water in the air to change phase into a liquid. In addition, having air compressed allows for control over the velocity and transfer of energy on the piping because the air being captured by the fans can vary in both velocity and concentration of CO_2.

The last section of this system is the membrane where the CO_2 is actually captured. Although there are many commercial membranes made of cellulose acetate, polysulfide, and polyimides, many of them are not used solely for CO_2 capture. A new type of membrane was developed specifically for capturing CO_2, by using zeolitic imidazolate framework (ZIF-8) as inorganic filler in PEBAX-2533 polymer matrix [8]. This new membrane-based technology has a significant increase in CO_2 permeability compared to other membranes and it provides with an economical way to separate CO_2[8] .

The raw data regarding PEBAX-2533 permeability is scarce, but a number of papers have examined and analyzed data specifically on certain PEBAX films that would exhibit high performance in CO_2 separation from other gases. These PEBAX (i.e. 1074, 6100, 1657, 3000) have been tested to determine CO_2 and nitrogen permeation. In order to determine permeability, solubility, and diffusion of these membranes, the following equations were used:

$$P = \frac{J_{st} \times d}{p_1}$$ *Equation 1*

Where the permeability coefficient P can be determined using pressure, assuming that the upstream side pressure p_1 is greater than the downstream side p_2 [3]. The constant J_{st} is the steady state flux and can be seen as the slope on *Figure 6*[3]*.* The variable d represents the thickness of the membrane.

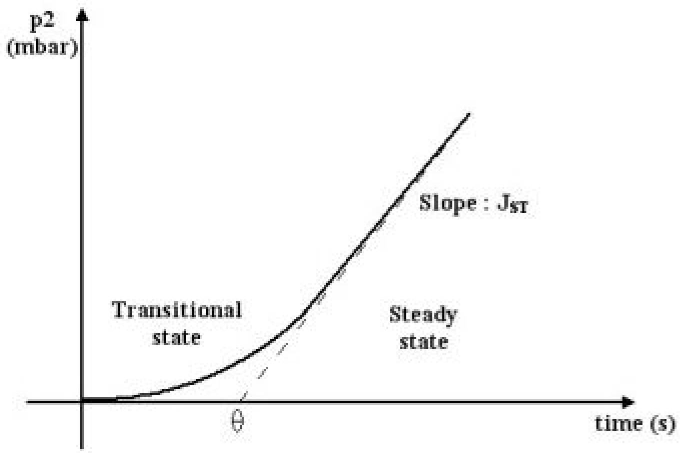

***Figure 13**: Graph relating downstream pressure and time.*

The diffusion coefficient D, shown in *Equation 2*, can be calculated by using the membrane thickness d and the θ, which is the intercept at the time axis, as shown on *Figure 6* [3].

$$D = \frac{d^2}{6\theta} \qquad \text{Equation 2}$$

The solubility coefficient S, shown on *Equation 3*, can be determined through finding the ratio between the diffusion D and permeability coefficient P [3].

$$S = \frac{P}{D} \qquad \text{Equation 3}$$

Storage of all the remnants that come from the air can be directed into tanks. In addition, drainage tubes and valves can be placed inside the tank which could lead to other areas of the factory or it could simply be released back into the atmosphere. One of the most crucial things that are required for this system are the air receiver tanks, which can be sized based on the flow rate of the compression system. For example, a receiver tank will be sized to be at around 150 cubic feet for a compressor with a rating of 25 standard cubic feet per minute at 100 psi. The meaning of standard cubic feet per minute (scfm) means the molar flow rate of a gas corrected to "standardized" conditions of temperature and pressure thus representing a fixed number of moles of gas regardless of composition and actual flow conditions. The "standardized" condition means an absolute pressure at 101,325 Pa and a temperature ranging from 60 to 70 ºF [6]. To calculate the desired air receiver tank, *Equation 4* will be used [2]:

$$V_a = \frac{(Q \times P_a)}{(P_1 + P_a)}$$ *Equation 4*

Where V_a represents the receiver size in cubic feet, Q represents the compressor output in cubic feet per minute, P_a represents the standard atmospheric pressure in psia, and P_1 represents compressed pressure in psig [2].

A variation in standard temperature can result in a variation of the receiver size. To correct for this, *Equation 5* is used to determine the standard cubic feet from the original V_a value.

$$V_s = V_a \times F_p \times F_t \times (F_{pv})^2$$ *Equation 5*

Where F_p is the pressure factor which can be calculated by dividing the absolute pressure and the standard pressure. Ft is the temperature factor which is determined by dividing absolute standard temperature and absolute line temperature. F_{pv} is the super compressibility factor (this variable can be omitted as most of the time is equal to 1).

To calculate the flow rate in terms of scfm, *Equation 6* can be used.

$$Q = \frac{V}{t}$$ Equation 6

Where Q is the volume of flow rate, V is the volume, and t is the time. With this, we are able to calculate how fast each compressed air will be moving in the system itself, not through the membrane [7].

As for the calculations of the flow speed through the membrane, it can be given depending on the diffusion happening inside the membrane. A flux can be calculated by using the steady state flux previously calculated and shown on Figure 6. For a different form of a permeability equation we can use *Equation 7* to solve for flux.

$$P = \frac{J}{(p_2 - p_1)/l}$$ Equation 7

Where P is the permeability coefficient, J represents the steady state flux, P_2 and P_1 are the feed and permeate pressures respectively. The units for this coefficient are usually in Barrer[7].

$$J = -D\frac{dC}{dx}$$ Equation 8

J is the permeation flux and the concentration gradient is dC/dx, and D represents the diffusion coefficient.[7]

As for the temperature controls on the system, setting the compressed air cool to around 104 ºF will allow for a net return of ⅔ of water inside the air [2]. Meanwhile, for the particulate filter, the R-TENG uses an aromatic polyimide (PI) nanofiber, capable of heat resistance up to 198.8 ºC [10]. The temperature is then set to 104 ºF the for the coalescing filter with the SS cartridges inside, and after the gases flows out from the coalescing filtration, it is important to make sure the temperature of the gases does not go above 130 ºF, because the thermal heat resistance for a PEBAX 2533 membrane is 136.4 F[9]. For this case, the permeability of CO_2 through the membrane is expected to be around 187.54 ± 5.65 Barrer[11].

Carbon Storer

Piping Materials

Carbon steel is employed as the main pipe material due to its resistance to carbon dioxide permeation and high factors of strength and toughness. The proposed design allows for an inlet diameter of 2 1/2 in. with extension or joints placed at intervals of 12 ft. Carbon steel pipes with a nominal (interior) diameter of 2 ½ in. have a volume capacity of .2833 gallons per foot.

Based on the internal, external, and steel transverse areas stated in the ASME/ANSI B 36.10 Welded and Seamless Wrought Steel Pipe, a cross-sectional diagram of the pipe can be presented. The internal volumetric flow for both the gas and liquid components of the fluid may be measured as well, which provides information for heat and energy analysis of the system.

Figure 17: Carbon Steel Pipe (2 ½ in. diameter)

Munkejord et. al recommends schedule 40 carbon steel for carbon fluid transport, due to the need for moderately-high corrosion-proof structures. The cost of materials reflects the necessity for high-performing materials for safety considerations and to prevent expenses related to replacing corroded joints.

Joints and welds constitute the weakest points of any piping configuration. These weak spots in the piping configuration will be supported by seals and liners composed of CPVC, a material that is flexible and resistant to corrosion. Multiple engineering companies that supply CPVC piping advise that their products undergo a maximum temperature of 200F, so the material qualifies for the conditions demanded by the carbon dioxide-water mixture.

Figure 18: CPVC union, 45° joint, 90° joint (2 ½ in. diameter)

CO2 Transport Calculations

Optimally, CO2 is transported in a supercritical condition, which can be maintained through 7.5-20 MPa and 273.15-303.15 K (Li 2008, 8). We also consider the possibility of depressurizing the pipe under failure or maintenance, which widens the required range to 0.1-20 MPa for pressure and 200-300 K for temperature.

Munkejord et. al presents a method for calculating the transport and depressurization for two-phase carbon dioxide mixtures of multiple components. The Soave-Redlich-Kwong (SRK) equation of state allows us to determine the thermodynamic and transport properties of a CO2-CH4 mixture. The pipe flow is represented using a drift-flux model, which is comprised of a system of nonlinear hyperbolic differential equations. The resulting analysis resolves the pressure and mass waves through applying the multi-stage centered scheme.

The drift-flux model reduces the two-phase flow of the pipe to a one-dimensional two-fluid model which requires fewer transport equations to be solved. This is done by relating the difference in gas (g) and liquid (l) velocity, the slip velocity, as a function of flow variables. One commonly used slip relation is given by Zuber and Findlay's equation

$$\phi = \frac{(K-1)u_g + S}{K u_l} \quad \text{Equation 9}$$

Phi represents the slip velocity, the difference between velocity in the gas and liquid phases, in terms of K and S, which are constants that depend on flow. The Zuber-Findlay slip relation has been experimentally confirmed to apply to a wide range of parameters. Values of K = 1.07 and S = .216 m/s have also been experimentally verified to serve as acceptable benchmark values to model the slip relation. The graphs below illustrate the effect of slip velocity on the pressure profile and constituent phase velocities. To assume slip velocity is 0 would neglect the changes on the internal pressure and the different velocities of the phases.

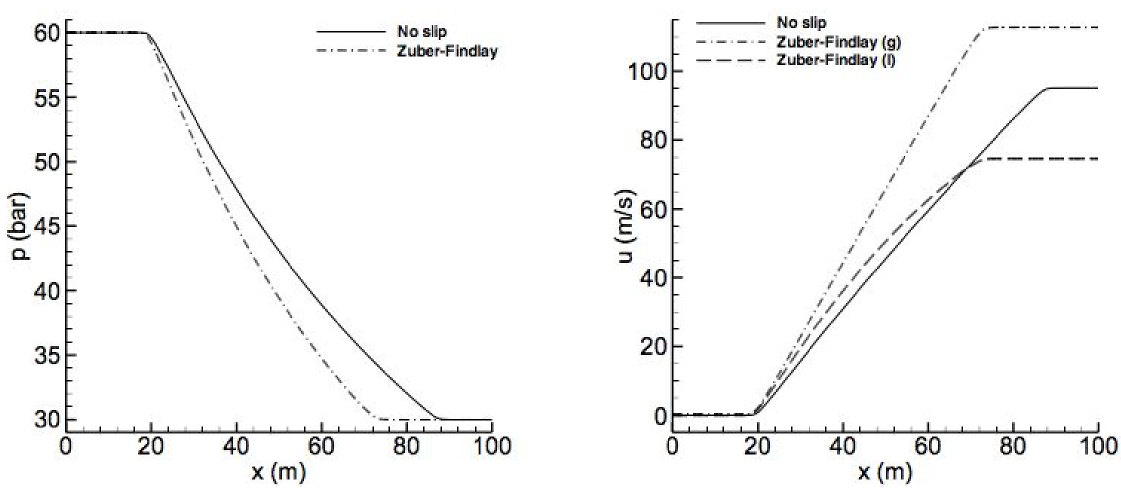

Figure 4: Zuber-Findlay Pressure vs Displacement, Slip vs Displacement models

We now calculate the heat transfer of the system to the surroundings. Under basic conditions, heat transfer can be modelled according to the following internal and external parameters.

$$Q = \frac{2(T_e - T\ )}{\frac{r}{\eta} + \frac{r^2}{\eta e r e} + \frac{r^2 ln(r_e - r)}{\lambda}} \quad \text{Equation 10}$$

where Te is the temperature of the surroundings, T is the temperature of the fluid, while r and re are the pipe's inner and outer diameters.

For the convective boiling of CO2, we take inner and outer heat transfer constants of n = 5 kW/(m^2K) and n_e = 10 W/(m^2K). We assume the exterior temperature to be 300 K and the interior temperature to be maintained at 250 K. The remaining coefficients are the inner diameter r = 2.469 in and the outer diameter r_e = 2.875 in. Carbon steel composed of 1% carbon is has a thermal conductivity of λ = 43 W/(mK). This provides the necessary terms to calculate the energy supplied by the surroundings Q = -1180.1 W/m. This figure indicates that every meter of piping experiences a heat loss of 1180.1 Watts to the surrounding environment. This information may be useful to other departments during the integration phase.

Storage: Geological Sequestration

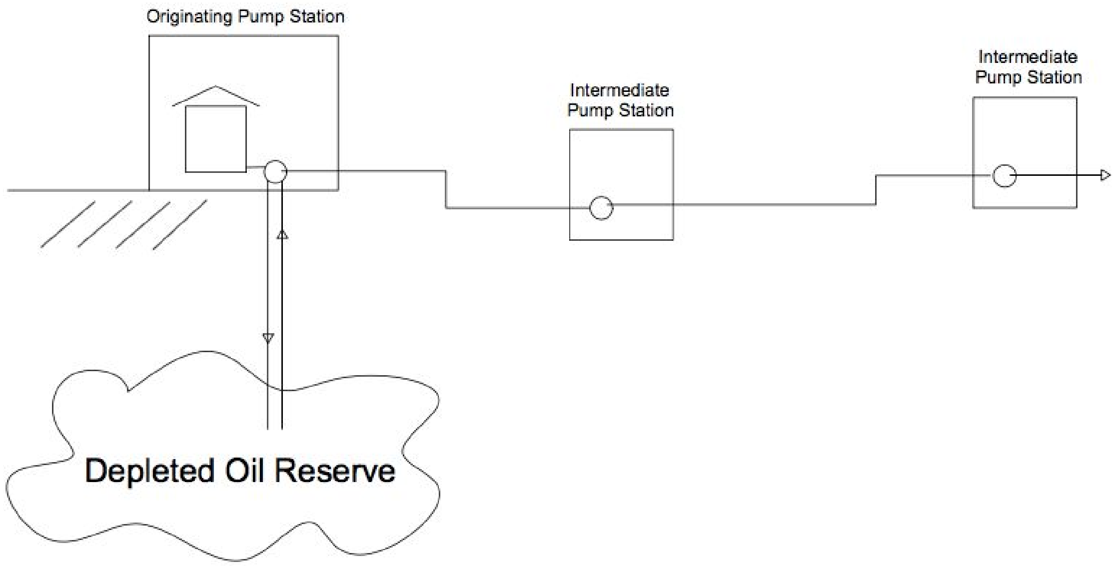

Figure 19: Oil Reserve Sequestration

Geological sequestration is the practice of storing carbon dioxide in porous and permeable rock formations. There are several methods of accomplishing this process, including enhanced oil recovery (EOR), injection into depleted gas and oil reserves, and injection into deep saline reserves. This design employs depleted oil reserve sequestration, which returns carbon dioxide into naturally occurring oil reservoirs which have previously been drilled. The reasons for the selection of this storage method are twofold: first, this method takes advantage of existing reservoirs and wells thus requiring little in part of new installations; secondly, replacing carbon dioxide to depleted oil reservoirs improves the geological health of the area, which mitigates man-made losses to the natural carbon cycle.

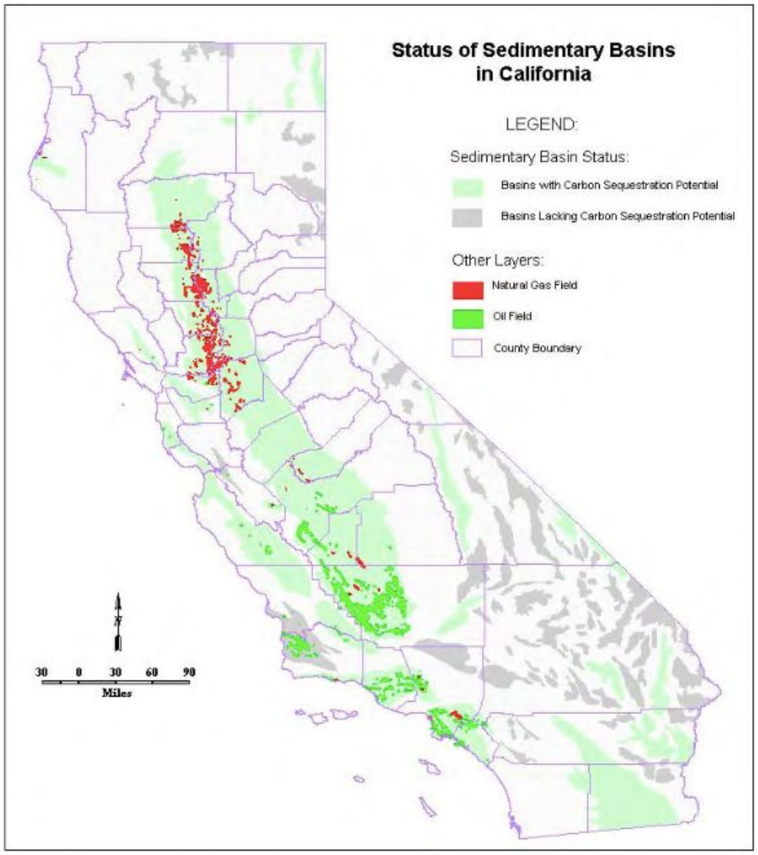

Figure 20: Geological Sequestration Potential in California (CEC)

According to the California Energy Commission (CEC, 7), the Los Angeles County and Orange County areas possess oil fields with adequate depth and geological composition to perform carbon sequestration. The Los Angeles Basin in particular is one of the most hydrocarbon-rich per unit volume in the world, making its sedimentary lining highly suitable for the storage of carbon dioxide. For the purposes of the report, however, we assume applications of this design to be centralized near Irvine, Orange County. The Huntington Beach oil fields located 10 miles west of Irvine constitute a more accessible option for storing carbon dioxide in depleted fields.

GIS data of the oil reserves in Huntington beach reveals dozens of wells that have already been installed in the area. The existing infrastructure and present ownership rights over the site make the cost of carbon sequestration dependent on partnerships or agreements with the entities in control of the depleted fields. A cost estimate of several methods of carbon dioxide sequestration performed by the MIT Laboratory for Energy and the Environment indicates that storing oil in depleted oil fields will cost $3.82 per ton of CO2 on average. This estimate is reflected in the Bill of Materials section.

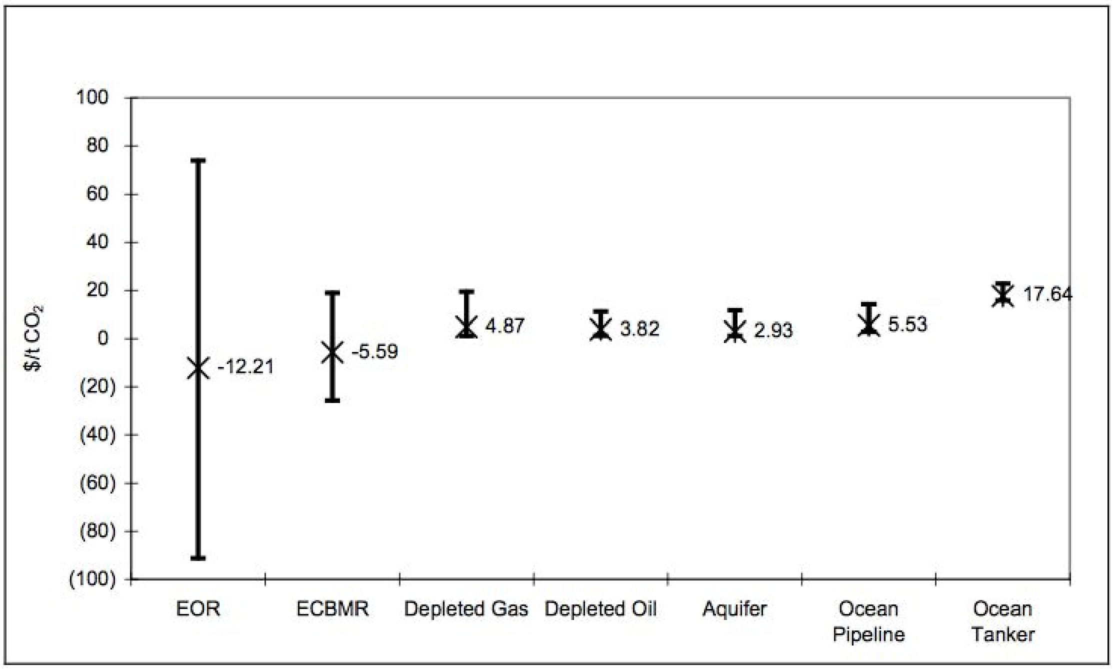

Figure 21: Cost Comparison of Sequestration Methods (MIT)

CO2-Enhanced Concrete

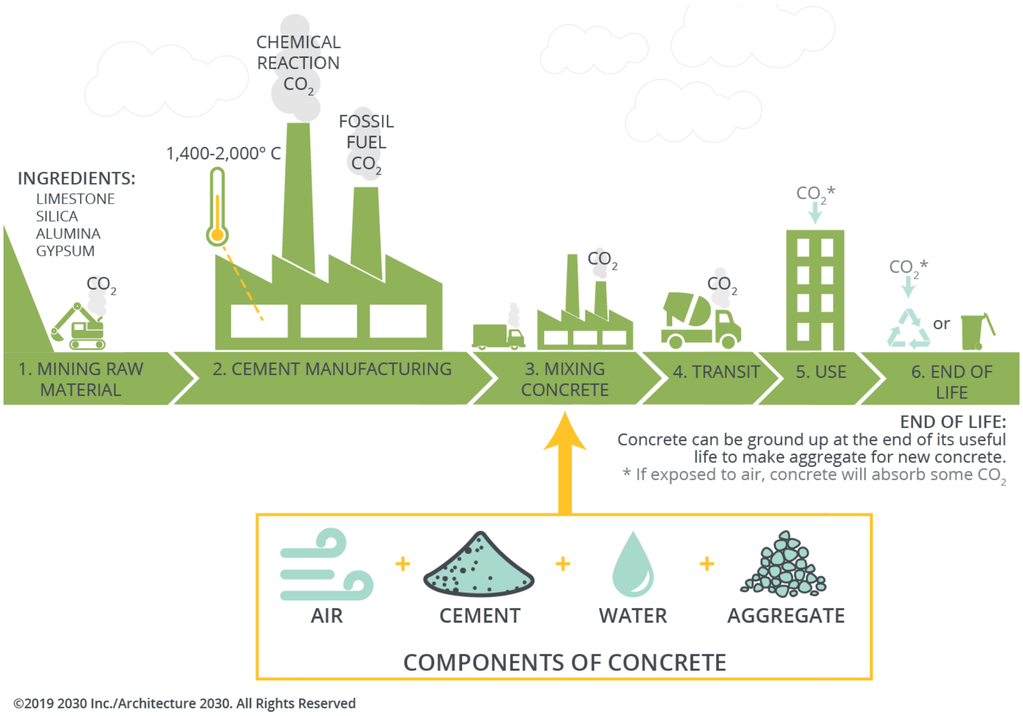

Figure 22: CO2-enhanced Carbon Process

The proposed solution is to recycle the captured carbon dioxide into a base for calcium carbonate concrete. CO2-enhanced concrete is comparable in strength to traditional Portland cement while diverting carbon dioxide emissions from the atmosphere to load-bearing structures (Sant). Construction companies like CarbonCure in Canada and research groups like CarbonUpcycling in the U.S. presently inject their own captured carbon dioxide to manufacture concrete and cement at scale. Carbicrete, a manufacturing company based in Montreal, provides construction crews with the materials and equipment they need to implement carbon-negative concrete into their own projects.

This report refers to Carbicrete's determine a mixture content for enhanced concrete. Carbicrete's manufacturing process injects 1kg or 2.2 lbs into every standard block of concrete, which will weigh 30-35 lbs. Thus, every ton of captured CO2 can be expected to produce about 14 tons of concrete. For a standard 1:3:3 ratio of cement base (hydrated lime for this mixture), sand aggregates, and large aggregates, concrete of that quantity would require 2 ton of hydrated lime, 6 tons of sand aggregate, and 6 tons of large aggregates. The costs of these constituents per ton of collected CO2 are included in the Bill of Materials. It is noteworthy that CO2 concrete has a high revenue potential, especially because the captured carbon dioxide does not need to be processed before use (Carbicrete). CO2-enhanced concrete has great profitability in the growingly environmentally-conscious construction and development industries.

Pycontrol

I/O Layer

The DAC plants sensors will monitor the air temperature, humidity, carbon dioxide (CO2) air flow and pressure within each of the DAC fan system housing. The combination of trends can be useful in estimating operations such as when filters need to be replaced. [1]

The sensor array will be coupled with Analog-to-Digital Converters (DAC) and daisy-chained to the other digital signals from neighboring fans. These daisy-chains form the field bus. Field buses are the way that the sensors communicate back to the IoT Gateway which will send the signals over the internet and receive signals back as output. The field bus that will be used is the BACnet MS/TP. These signals are passed over the field bus to the DAC plants actuators, the devices responsible for taking physical actions in order to control the plant. This is a simple I/O that uses a wired network, because they are typically faster, cost effective, and more secure than wireless. [4] The tradeoff being that wired networks are a less efficient use of space.

The sensors used in the design are:

Fan Sensor:

- Tachometer Sensor

Membrane Sensors:

- Differential Pressure Sensor
- Flow Sensor
- Humidity Sensor
- Temperature Sensor

- CO2 Sensor

C02 Pipeline Sensors:

- Temperature Sensor
- Pressure Sensor

Containerization of Field Controllers

Control systems exist to make decisions based on the I/O at the field controller layer. [3] While field controllers come in a variety of forms, this project will utilize a software based field controller. This is achieved using containers, or a standard unit of software that packages up code and all its dependencies so the application runs quickly and reliably from one computing environment to another. [5] To run manage containers at scale, the container orchestration service used is Amazon Elastic Container Service (ECS).

Using containers as an abstraction for physical field controllers provides engineers with more control over the system. For instance, a unique use case for this design is the ability to conserve power by taking the wind direction and speed into account. First the supervisor gives the container's permission to adjust based off of wind which the database will reflect in a configuration file. Then the field controller can signal actuators to turn the DAC fans in the direction of wind and reduce the power to the system. Engineers can add use cases by uploading new container images to the Amazon Elastic Container Repository (ECR). The containers will then download these images and run them without any physical changes required onsite.

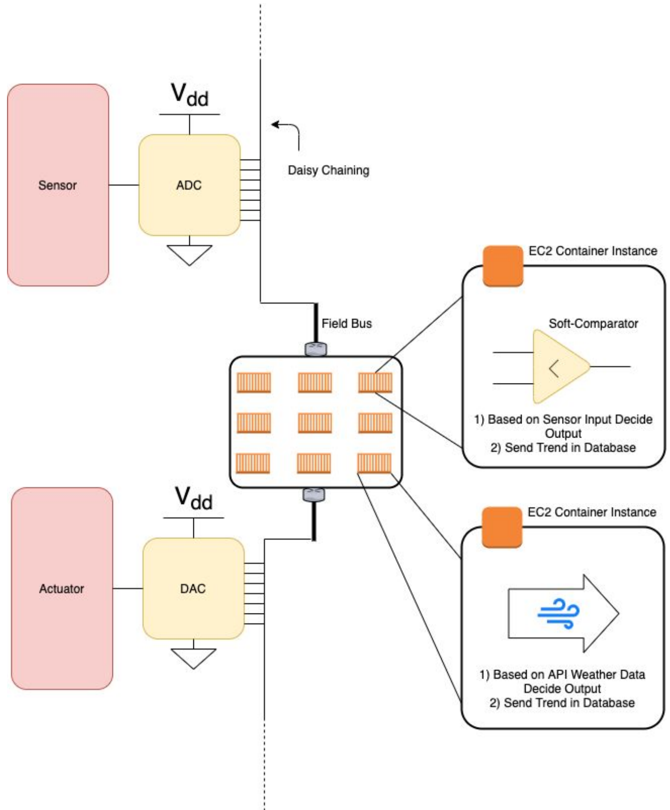

Fig. 14. Field Controller Schematic & Use Cases

Containers can be used a single task definition or as service, which will guarantee that there are tasks running at all times. These services lend themselves to be useful as field controllers as an engineer will want to configure the DAC device to run tasks such as collecting trends based on sensor input at regular intervals.

Cost and maintenance are reduced by using containers because we will not require each individual sensor and actuator in each DAC fan to have its own CPU. Field control is made through simple logic decisions that do not utilize a full CPU resources. However these logic decisions need to occur in parallel so they can react to sensor input fast. Containers reduce the amount of CPUs used by splitting its resources with an container engine. This is different from a hypervisor which is used to split CPU as virtual machines (VM). The containers do not need their own OS so they are a much more lightweight solution than VMs. A negative aspect to this decision is that it prioritizes cloud computing over edge computing, the traditional method of field controller implementation. This will result in slower response times since the actuators and the sensor input must pass through a network device before an output can be calculated.

Data Tier

Databases are a necessary component of an automated control system because they store all the trends, alarms, and sequences that the sensors recorded. They also store the configuration files that users can modify to make adjustments to the system. The most important decision in database selection is choosing to use a relational (SQL) database or a non-relational (noSQL) database. For this design, a NoSQL database, AWS DynamoDB was used. Some of the advantages of a NoSQL database are its ability to scale horizontally meaning more servers can be used as necessary. They also have a more flexible structure as their schemas behave more like key value pairs that our corresponding system will take advantage of. Some downside to noSQL databases are they don't have the ACID properties of SQL databases, instead they behave like distributed systems and follow the properties of CAP theorem. [6] Another downside is that noSQL databases are not built for complex queries. To remedy this, DynamoDB will shard its data into ElasticSearch using DynamoDB Streams. A DynamoDB stream is an ordered flow of information about changes to items in the Dynamo Table. [7]

```
{
  "DAC Plant": {
    "plant_id": "ref (DAC Plant)",
    "Fans": ["Fan_1", "Fan_2", "FAN_3"],
    "Membranes": ["Membrain_1", "Membrain_2"],
    "Pipelines": ["Pipe_1", "Pipe_2"],
    "createdAt": "Timestamp"
  },
  "Fan": {
    "fan_id": "ref (Fan)",
    "isActive": "Boolean",
    "speed": "Number",
    "direction": "Number"
  },
  "Membrane": {
    "membrane_id": "ref (Membrane)",
    "temp": "Number",
    "humd": "Number",
    "pressure": "Number",
    "co2": "Number"
  },
  "Pipeline": {
    "pipeline_id": "ref (Pipeline)",
    "temp": "Number",
    "pressure": "Number"
  }
}
```


Fig. 15. Entity Union Schema for DDB

ElasticSearch will allow our users to perform complex queries and get results instantly. The trends collected by the field controllers can be stored in ElasticSearch directly, but also backed up in DynamDB. ElasticSearch which will allow the applications search for logs based on complex queries, so that they can investigate anomalies in the DAC plant. ElasticSearch instances will be set up regionally so that users will have even faster access to their data.

Supervisory Layer

The supervisory layer provides the systems users with the tool they need to ensure the automated system is working properly. This layer is comprised of the DAC plant's Application Programming Interface (API), and the User Interface (UI). The API will provide functionality for retrieving information about the plants operation including trending, reporting, and alarming data. It will also be able to launch containers at will, giving supervisors the ability to physically control the onsite equipment externally. The API will be setup using the AWS Serverless Application Model (SAM) which simplifies the CloudFormation (Cfn) templates for serverless API. Serverless technologies are not constantly running so they reduce the cost and amount of power consumed. AWS API Gateway will be used to intercept incoming requests from users and use serverless functions. AWS Lambda functions to act as API endpoints. We will use a RESTful API structure.

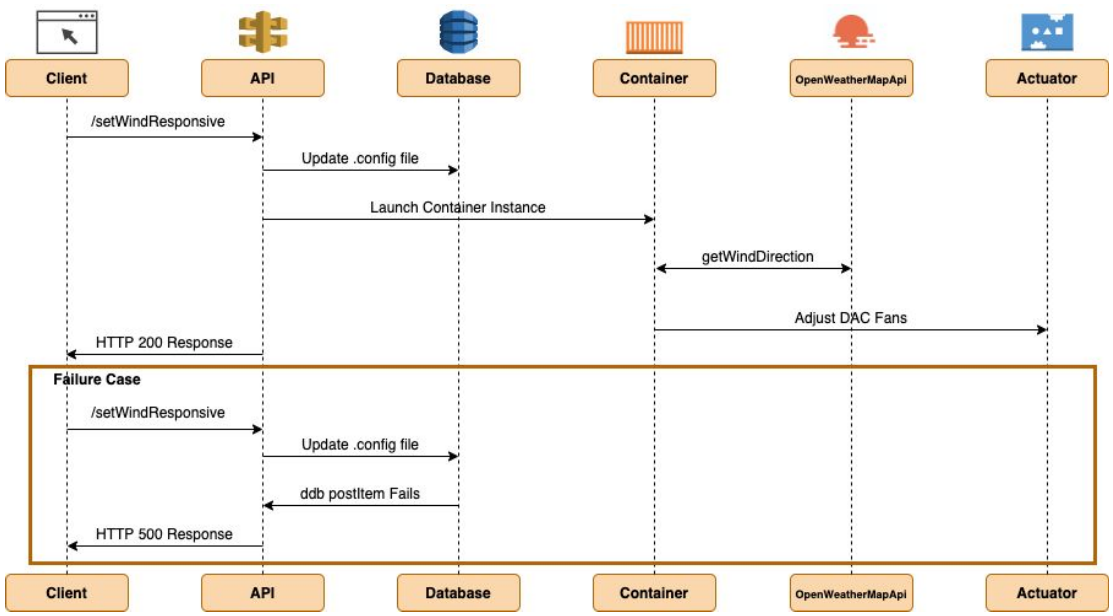

Fig. 16. User Sequence for Wind Response

The UI will be a thin-client application built using the React.js framework with the Redux design pattern and hosted on an AWS Simple Storage Service (S3). The UI will have the following functionality:

- use charts.js to graphically report trends in real time
- provide an HTML form to update .config file
- display alarms
- search bar that can filter through past log files

Bill of Materials

CARBON STORER BOM

Item	Description	Link	Manufacturer	Price per unit	Quantity	Total price
Piping Materials (per 1,000 ft)						
Carbon Steel (CS) Pipes	Main pipes for CO2 transport	Carbon Steel Pipe	Grainger	$273 / 10ft	100	$27,300
CPVC Joints	Unions and joints	Polymeric Joints	Grainger	~$0.60 / joint	100	$60
Total:						$27,360
CO2 processing (per ton CO2)						
Power/Electri-city	Pump Energy	Oil Reserve Sequestration	Huntington Beach Oil Reserves	$3.82 / ton	1	$4
Hydrated Lime	Concrete component	Hydrated Lime	Alibaba	$500 / ton	2	$1,000
Aggregates (sand)	Concrete component	Sand Aggregate	Cairo Fresh	$1/ton Note: min 15,000 ton	6	$6
Aggregate (>20mm)	Concrete component	Concrete Aggregate	Cairo Fresh	$30/ton Note: min 1,000 ton	6	$180
Total:						$1,190
Maintenance/Replacements						
Carbon Steel (CS) Pipes	Keep 3% of original quant. on hand	Carbon Steel Pipe	Grainger	$273 / unit	3	$819
CPVC Joint testing	Perform every 6 months	PVC Pressure Gauge	Grainger	$99/ unit	12	$1188
Total:						$2,007
Committee Total						**$30,557**

PYCONTROL BOM

Item	Description	Link	Manufacturer	Price per unit	Quantity	Total price
SCD30	Environmental C02 Sensor	Link	Sensirion AG	$94	10	$940
SHT30-ARP-B	Sensor Humid/Temp	Link	Sensirion AG	$3.93	50	$196.50
TE-SNW-A	Strap on surface mounted temp sensor	Link	Dwyer	$18.75	10	$187.50
102M205	Pressure Sensor	Link	PCB Piezotronics	1,321	1	1321
108-EFB0512 HHA FAH	DC Fan Tachometer	Link	Delta Electronics	$9.72	20	$194.40
DynamoDB	Managed no-sql Database	Link	AWS	$3.00	1	$3.00
AWS Lambda	Serverless Functions	Link	AWS	$0.20	1	$0.20
AWS S3	General Purpose Storage	Link	AWS	$0.23	1	$0.23
AWS ECS	Container Orchestration Platform	Link	AWS	1,260	1	1260
AWS ElasticSearch	Search Engine	Link	AWS	$157	1	$157
Dell Edge Gateway	IoT Gateway	Link	Dell	$620.70	1	$620.70
Committee Total						**$6,429.33**

AIR MOVER BOM

Item	*Description*	*Link*	*Manufacturer*	*Price per unit*	*Quantity*	*Total price*
Sheet Metal	Multipurpose 6061 Aluminum Sheet	https://www.mcmaster.com/89015k126	McMaster Carr	$88.33	10	$883.30
Welding	Pay a company for welding	N/A	N/A	$250 [3]	100	$25,000
Hardware	Various	https://www.mcmaster.com/	McMaster Carr	Various	1	$500
Front Module Cast	Includes mold price and raw material	N/A	In House	$4,000	1	$4,000
Intermediate Module Cast	Includes mold price and raw material	N/A	In House	$3,500	4	$14,000
Rear Module Cast	Includes mold price and raw material	N/A	In House	$6,500	1	$6,500
Propellor	Includes mold price and raw material	N/A	In House	$4,000	1	$4,000
Committee Total:						**$54,883.30**

MEMBRAiN BOM

Item	***Description***	***Link***	***Manufacturer***	***Price per unit***	***Quantity***	***Total price***
Pebax® 2533 SA01 MED	thermoplastic elastomer	Pebax® 2533 SA01 MEDPurchase	Arkema	$878.30	10	$8783
Sintered SS Cartridges	stainless steel sintered mesh filter cartridge.	Stainless Steel Sintered Creen Filter Tube and Cartridge 13	Boegger	150$	100	$15000
Fabco Coalescing Filters	304L or 316L stainless steel filter media with welded cartridge construction	Coalescing Filters	Fabco	5000	1	5000
30 Gallon 420cc Truck Bed Air Compressor EPA III	Contractor grade two-stage air compressor for heavy duty jobs	Compressor	Central Pneumatic	$1349.99	1	$1349.99
1,060 Gallon Air Tank Vertical with Skirt Rated for	has CNC plate rolling, CNC punching, robotic plasma cutting and welding, powder	1,060 Gallon Air Tank Vertical with Skirt Rated	CompressorWorld	6669	3	20,007

200 PSI ASME Coded | C100331	painting and other equipment for handling and fabrication of carbon and stainless steel generally under 1” in thickness.	for 200 PSI ASME Coded | C100331				
Temperature/ Steamers		Steam Boiler	Henan Yuanda Boiler Co.	30,000	2	60,000
Committee Total						**110,139.99**
GRAND TOTAL			$202,029.62			

Conclusion

A key feature of the Air Mover fan design is the separation into modular components, which allows for easy scaling of the device to fit the needs of the implementing facility. This modular design for the fan allows for easy customization to client-specific needs and requests. The airflow is kept consistent as it reaches Membrain, who employs a Nitrogen Generator system with a CO2 membrane to extract the CO2. The design utilizes passive movement, thus operating in a highly economical and efficient manner. The sensor/actuator network installed by Pycontrol allows for flexible readings of Carbon Catcher conditions, while consuming little storage space or energy through the implementation of distributed cloud computing services. The resulting CO2 is transported and processed through Carbon Storer's stabilized carbon steel piping system, finally being injected into hydrated lime-based cement mixtures to create commercially-distributed sustainable concrete.

Carbon Catcher provides a broadly applicable solution to the very real and imminent consequences of global warming. High-polluting industries often cannot reduce their emissions due to demands for production. The carbon catcher device provides the opportunity for high-polluting entities to reduce their greenhouse gas emissions without interfering with output. In the past, environmental reforms such as a carbon tax could not feasibly be passed due to the economic burden it would place on companies. Carbon Catcher is the key to scaling initiatives to incentivize ecological restoration or pollution-reduction measures.

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