

Kolodji Corporation (Brian Kolodji)

Landfill Methane Regulations only reference methane emission recovery/separation technologies that concentrate the methane at a very high and uneconomical cost. Landfill Methane Regulations do not reference recently patented innovations (Inventor Kolodji, Black Swan, US Patent No. 12,465,884 B2, Issued November 11, 2025) that most economically convert methane emissions from landfills into a high heating value fuel by way of membrane oxygen enrichment. The mature (60 year+) science and commercial practice of Oxygen Enrichment has used concentrated oxygen to locally increase the heating value of fuel streams such as refinery sulfur recovery and steel production for decades and can also be used for dilute methane as produced from landfills. This proven science and technology has been around for over 50 years as summarized and promoted by USDOE, see USDOE Process Heating Energy Tip Sheet #3, Oxygen Enriched Combustion; DOE/GO-102005-2178, September 2005. The practice of separating and producing concentrated nitrogen (from 79% to 90+%) and also producing concentrated oxygen (from 21% to 60 %O₂) directly produced from air has been most economically produced and commercially practiced gas separation with membranes for 50+ years. Generon (largest manufacturer in California), Membrane Technology and Research Incorporated (also in California), and other manufacturers (Air Products in Missouri is world's largest air separation manufacturer in the world, and Honeywell/UOP, the world's largest membrane manufacturer for gas separation, and Schlumberger's Cynara, the next largest competitor, both with membrane manufacturing operations in California) have been commercially manufacturing these systems in a circa \$100 million dollar industry. California's membrane manufacturer, Generon, has most economically performed membrane air separation with Black Swan's recently patented device that reduces membrane costs and energy consumption by up to 50%, with an up to 10% higher performance than conventional membranes for the past almost five years. I strongly encourage CARB to consider regulations that allow this most economic methane emission conversion to fuel innovation that enables a profit to be made out of methane emission reductions from landfills by making a profit from converting methane emissions into a valuable fuel.



US012465884B2

(12) **United States Patent**
Kolodji

(10) **Patent No.:** **US 12,465,884 B2**

(45) **Date of Patent:** **Nov. 11, 2025**

(54) **APPARATUS AND METHOD FOR OXYGEN AND CARBON DIOXIDE ENRICHMENT OF ATMOSPHERIC AIR**

(71) Applicant: **Brian Kolodji**, Bakersfield, CA (US)

(72) Inventor: **Brian Kolodji**, Bakersfield, CA (US)

(73) Assignee: **Black Swan, LLC**, Bakersfield, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1012 days.

(21) Appl. No.: **17/121,560**

(22) **Filed:** **Dec. 14, 2020**

(65) **Prior Publication Data**

US 2021/0178318 A1 Jun. 17, 2021

Related U.S. Application Data

(60) Provisional application No. 63/039,846, filed on Jun. 16, 2020, provisional application No. 62/947,488, filed on Dec. 12, 2019.

(51) **Int. Cl.**
B01D 53/22 (2006.01)
B01D 53/26 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC **B01D 53/226** (2013.01); **B01D 53/261** (2013.01); **B01D 53/265** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC .. B01D 53/226; B01D 53/261; B01D 53/265;
B01D 53/62; B01D 53/85; B01D 63/043;
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,073,089 A * 2/1978 Maginnes A01G 9/18 47/17
5,034,126 A * 7/1991 Reddy B01D 63/103 210/321.74

(Continued)

FOREIGN PATENT DOCUMENTS

CN 108430611 A * 8/2018 B01D 69/1216
CN 108883378 A * 11/2018 B01D 71/32
(Continued)

OTHER PUBLICATIONS

Google translation of WO-2012153809-A1 (Year: 2012).*
(Continued)

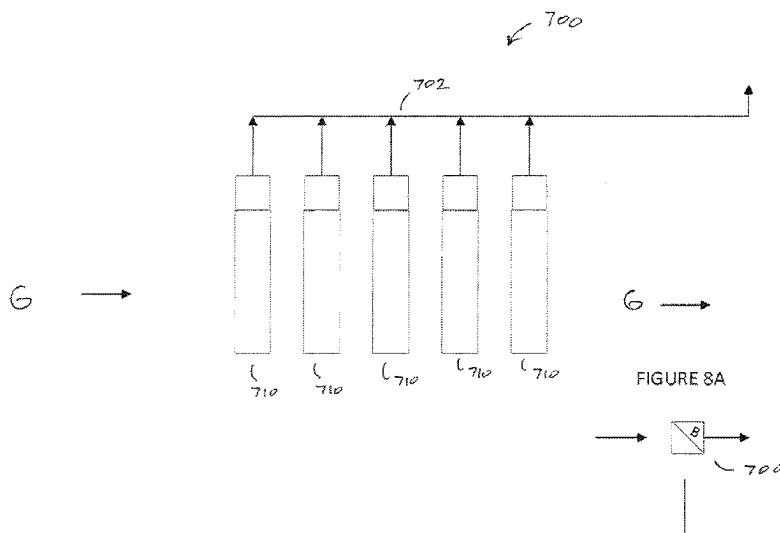
Primary Examiner — Stephen Hobson

(74) *Attorney, Agent, or Firm* — James M. Duncan;
Young Wooldridge LLP

(57) **ABSTRACT**

An apparatus utilizes a membrane unit to capture components from atmospheric air, including oxygen and carbon dioxide, resulting in a permeate stream having an enriched concentration of oxygen and carbon dioxide. Alternatively, the membrane unit may be utilized to form a permeate stream having a permeate of enriched fast gas components. The permeate stream is thereafter directed to a permeate processing facility which may include a second stage of permeate enrichment, a flue gas generator, or a carbon dioxide sequestration facility for processing of an enriched stream of carbon dioxide. Among other carbon dioxide sequestration facilities, the carbon dioxide may be biologically sequestered by a facility of photosynthetic organisms, such as trees in an orchard, crops, or the like. The membrane unit may be shell-less and utilize a vacuum or positive pressure to facilitate the flow of fast gas components through a selective barrier of the membrane.

19 Claims, 27 Drawing Sheets



- (51) **Int. Cl.**
B01D 53/62 (2006.01)
B01D 53/85 (2006.01)
B01D 63/04 (2006.01)
B01D 63/10 (2006.01)
- (52) **U.S. Cl.**
CPC **B01D 53/62** (2013.01); **B01D 53/85** (2013.01); **B01D 63/043** (2013.01); **B01D 63/107** (2022.08); **B01D 2053/224** (2013.01); **B01D 2251/95** (2013.01); **B01D 2257/504** (2013.01); **B01D 2313/24** (2013.01); **B01D 2317/02** (2013.01)
- (58) **Field of Classification Search**
CPC B01D 2053/224; B01D 2251/95; B01D 2257/504; B01D 2313/24; B01D 2317/02; B01D 53/225; B01D 2256/12; B01D 2257/102; B01D 2258/06; B01D 53/228; B01D 63/02; B01D 63/10; B01D 63/12
See application file for complete search history.
- (56) **References Cited**
- U.S. PATENT DOCUMENTS
- 5,071,451 A * 12/1991 Wijmans B01D 53/225 95/52
5,682,709 A * 11/1997 Erickson A01G 7/02 47/1.4
6,108,967 A * 8/2000 Erickson A01G 7/02 47/1.01 R
6,237,284 B1 5/2001 Erickson
6,745,580 B1 * 6/2004 Brown F24F 13/222 62/272
7,842,264 B2 * 11/2010 Cooper B01D 53/62 423/220
8,002,875 B1 * 8/2011 Bossard C01B 3/501 95/55
8,137,527 B1 * 3/2012 Woods B01D 53/965 205/555
8,197,857 B2 * 6/2012 Dressler A01G 33/00 210/600
8,252,091 B2 * 8/2012 Anand C10K 1/26 95/177
8,595,020 B2 * 11/2013 Marino G01N 21/3504 705/1.1
8,617,292 B2 * 12/2013 Hasse B01D 71/64 62/928
8,852,319 B2 * 10/2014 Wijmans F23J 15/02 423/220
8,889,400 B2 * 11/2014 Martin C12N 13/00 435/257.1
8,999,038 B2 * 4/2015 Ungerank B01D 53/225 95/47
9,266,057 B1 * 2/2016 Jones B01D 53/1425
9,359,750 B1 * 6/2016 Perez F15D 1/02
9,433,887 B2 9/2016 Wijmans et al.
9,433,896 B2 * 9/2016 Eisenberger B01D 53/0462
9,514,493 B2 12/2016 Marino
10,687,477 B1 * 6/2020 Kolodji A01G 9/02
10,897,851 B1 * 1/2021 Kolodji A01G 7/02
10,898,846 B1 * 1/2021 Kolodji B01D 53/84
11,383,199 B1 * 7/2022 Kolodji B01D 53/229
2004/0134347 A1 * 7/2004 Gobina B01D 63/065 95/45
2004/0211726 A1 * 10/2004 Baig B01D 53/22 210/640
2005/0229778 A1 * 10/2005 Backhaus B01D 53/22 95/45
2008/0163753 A1 * 7/2008 Bossard B01D 53/22 95/55
2010/0116129 A1 * 5/2010 Molaison B01D 53/229 96/5
2010/0205960 A1 * 8/2010 McBride F03G 6/074 60/595
2010/0210745 A1 * 8/2010 McDaniel C09D 7/48 521/55
2010/0269698 A1 * 10/2010 Yates B01D 71/64 96/13
2011/0005272 A1 * 1/2011 Wijmans B01D 53/225 62/617
2011/0195473 A1 * 8/2011 Wilhelm B01D 53/84 435/292.1
2011/0260112 A1 * 10/2011 Wijmans F23J 15/006 252/372
2012/0003722 A1 * 1/2012 Polak B01D 53/78 426/477
2012/0009109 A1 * 1/2012 Wright B01D 53/75 423/247
2012/0171053 A1 * 7/2012 Wang F04B 33/005 417/63
2013/0058853 A1 * 3/2013 Baker B01D 53/62 423/220
2013/0263734 A1 * 10/2013 Wynn B01D 71/32 95/54
2014/0286797 A1 * 9/2014 Tamm F01C 21/08 417/68
2014/0360365 A1 * 12/2014 Wynn B01D 53/22 95/45
2015/0292807 A1 * 10/2015 Romeo F28F 9/0131 165/104.21
2017/0021311 A1 * 1/2017 Berzinis B01D 67/00165
2017/0173520 A1 * 6/2017 Acharya F25J 3/061
2017/0271701 A1 * 9/2017 Berlowitz H01M 8/04805
2017/0320009 A1 * 11/2017 Hirata B01D 53/1443
2017/0341942 A1 * 11/2017 Harper, Jr. F01K 7/16
2018/0058008 A1 * 3/2018 Wright D21H 17/66
2018/0067091 A1 * 3/2018 Burkhalter G01N 33/0016
2019/0060835 A1 * 2/2019 Ding B01D 53/002
2019/0321787 A1 * 10/2019 Sivaniah B01D 71/0281
2020/0056578 A1 * 2/2020 Sheldon-Coulson ... B63B 1/048
2020/0061529 A1 * 2/2020 Zhu F25D 17/042
2020/0141410 A1 * 5/2020 Kawasaki F04C 23/001
2020/0318793 A1 * 10/2020 Kolodji F17C 9/02
2021/0016233 A1 * 1/2021 Noda B01D 65/003
2021/0060483 A1 * 3/2021 Lackner B01D 7/02
2021/0121826 A1 * 4/2021 Kolodji B01D 53/226
2022/0161197 A1 * 5/2022 Kolodji B01D 53/227
2025/0073632 A1 * 3/2025 Khalit B01D 53/229
- FOREIGN PATENT DOCUMENTS
- CN 109414653 A * 3/2019 B01D 65/003
CN 109475823 A * 3/2019 B01D 69/02
CN 110049808 A * 7/2019 B01D 69/04
CN 111939764 A * 11/2020 B01D 63/065
DE 102004049718 A1 * 4/2006 B01D 67/00041
DE 202019001414 U1 5/2019
GB 2457929 A 9/2009
WO WO-2010100432 A2 * 9/2010 B01D 71/0223
WO WO-2012153770 A1 * 11/2012 B01D 71/0281
WO WO-2012153809 A1 * 11/2012 B01D 63/065
WO WO-2017114522 A1 * 7/2017 B01D 69/10
WO WO-2018051053 A1 * 3/2018 B01D 69/08
WO WO-2019006438 A1 * 1/2019 B01D 69/14111
WO WO-2021065889 A1 * 4/2021 B01D 53/22
- OTHER PUBLICATIONS
- Shah "Construction, Working, Operation and Maintenance of Liquid Ring Vacuum Pumps" published Jan. 2017 accessed at <<https://practicalmaintenance.net/wp-content/uploads/Construction-Working-Operation-and-Maintenance-of-Liquid-Ring-Vacuum-Pumps.pdf>> (Year: 2017).*
- Sanz-Perez et al. "Direct Capture of CO₂ from Ambient Air" Chemical Reviews vol. 116/Issue 19 published Aug. 25, 2016 (Year: 2016).*
- Keith et al. "A Process for Capturing CO₂ from the Atmosphere" Joule vol. 2, Issue 8, Aug. 15, 2018, pp. 1573-1594 (Year: 2018).*

(56)

References Cited

OTHER PUBLICATIONS

Fujikawa et al. "Ultra-fast, Selective CO₂ Permeation by Free-standing Siloxane Nanomembranes" Chemistry Letters, vol. 48, Issue 11, Nov. 2019, pp. 1351-1354 (Year: 2019).*

Fujikawa et al. "A new strategy for membrane-based direct air capture" Polymer Journal vol. 53, pp. 111-119 (2021) (Year: 2021).*

Castro-Munoz et al. "A new relevant membrane application: CO₂ direct air capture (DAC)" Chemical Engineering Journal vol. 446, Part 2, Oct. 15, 2022, 137047 (Year: 2022).*

C. Maidana et al., Reduction of Fuel Consumption and Emissions of a Gas Turbine by Using of Oxygen-Enriched Combustion, 2nd Oxyfuel Combustion Conference.

B.A. Kimball et al. Effects of Increasing Atmospheric CO₂ on Vegetation printed in CO₂ and Biosphere by J. Rozema et al. at p. 65, Kluwer Academic Publishers, 1993.

T. Brinkman, Theoretical and Experimental Investigations of Flat Sheet Membrane Module Types for High Capacity Gas Separation Applications, Chemie Ingenieur Technik, vol. 85, Issue 8, pp. 1210-1220, May 17, 2013.

B. A. Kimball et al., Seventeen Years of Carbon Dioxide Enrichment of Sour Orange Trees: Final Results, Global Change Biology (2007) 13, 2171-2183.

T.C. Merkel et al., Power Plant Post-Combustion Carbon Dioxide Capture: An Opportunity for Membranes, Journal of Membrane Science 359 (2010) 126-139.

* cited by examiner

FIGURE 1

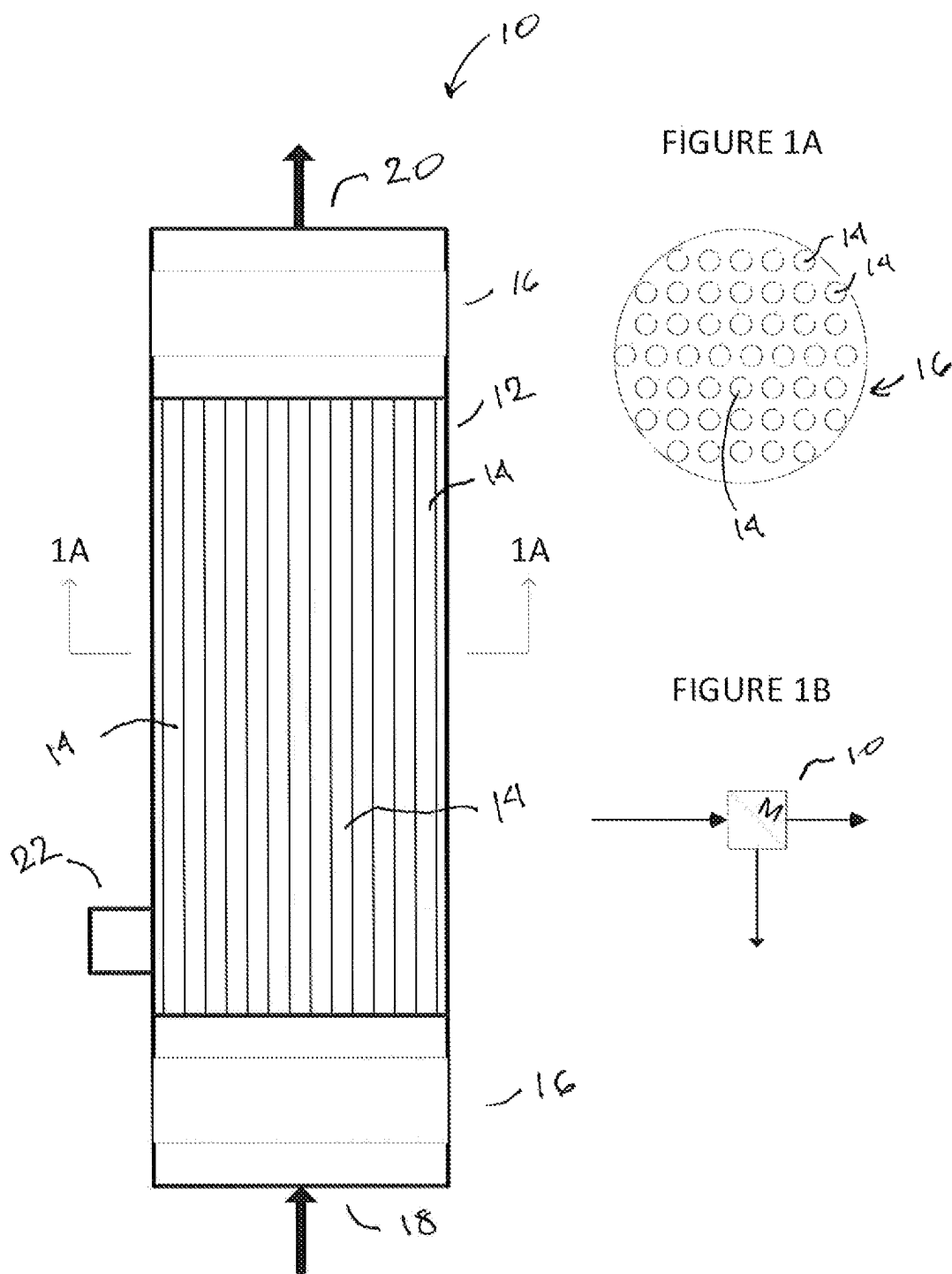


FIGURE 2

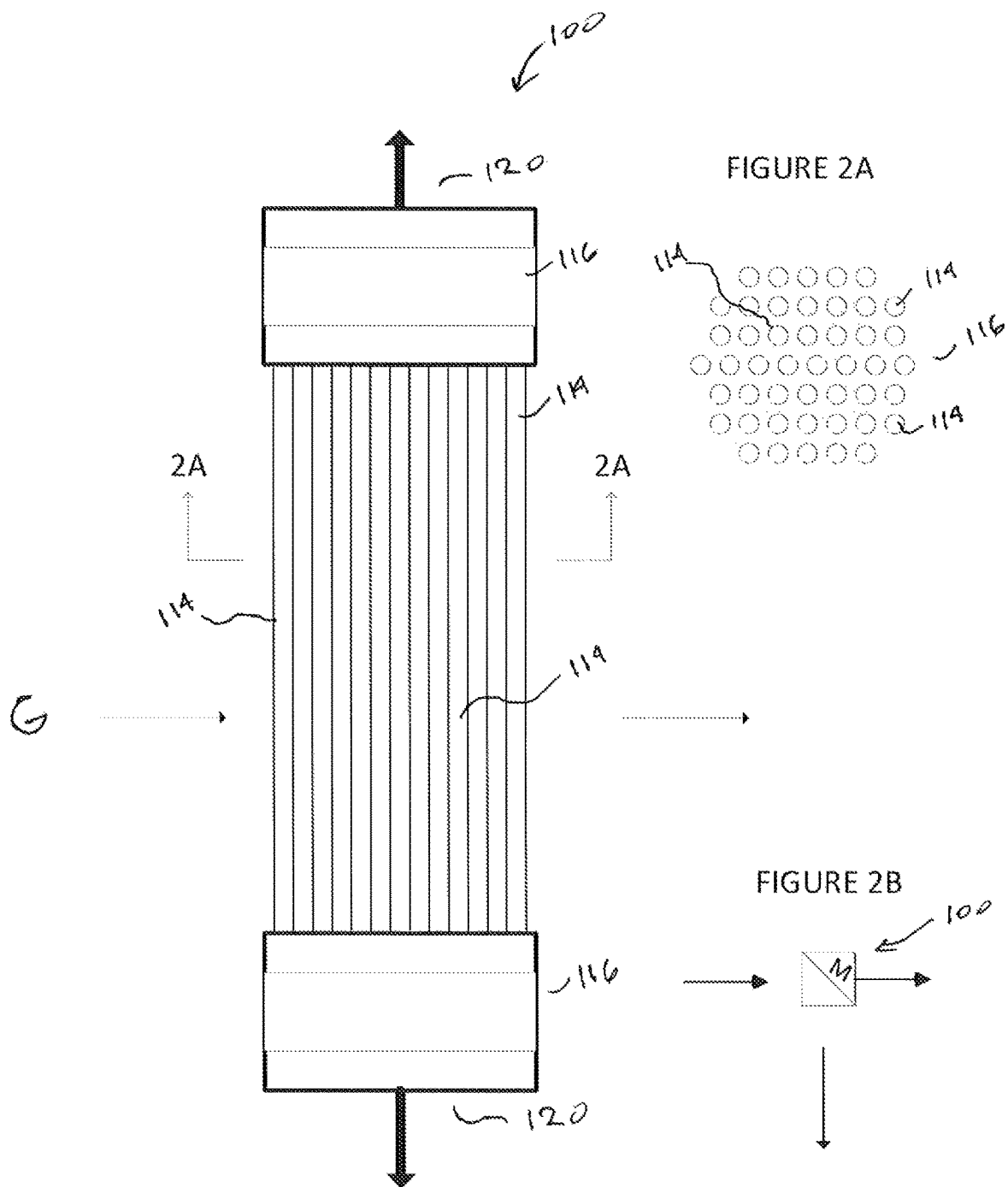


FIGURE 3

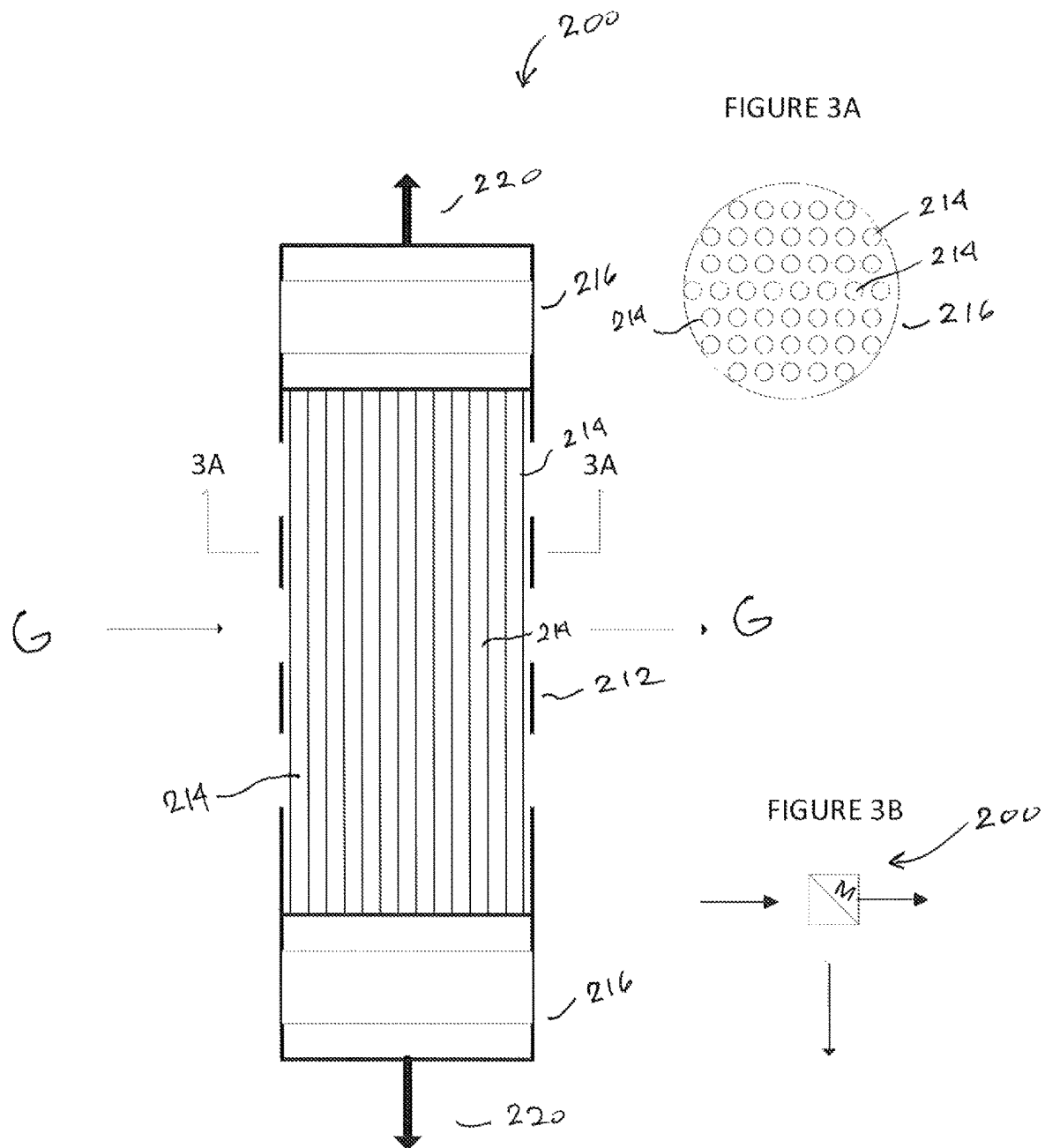


FIGURE 4

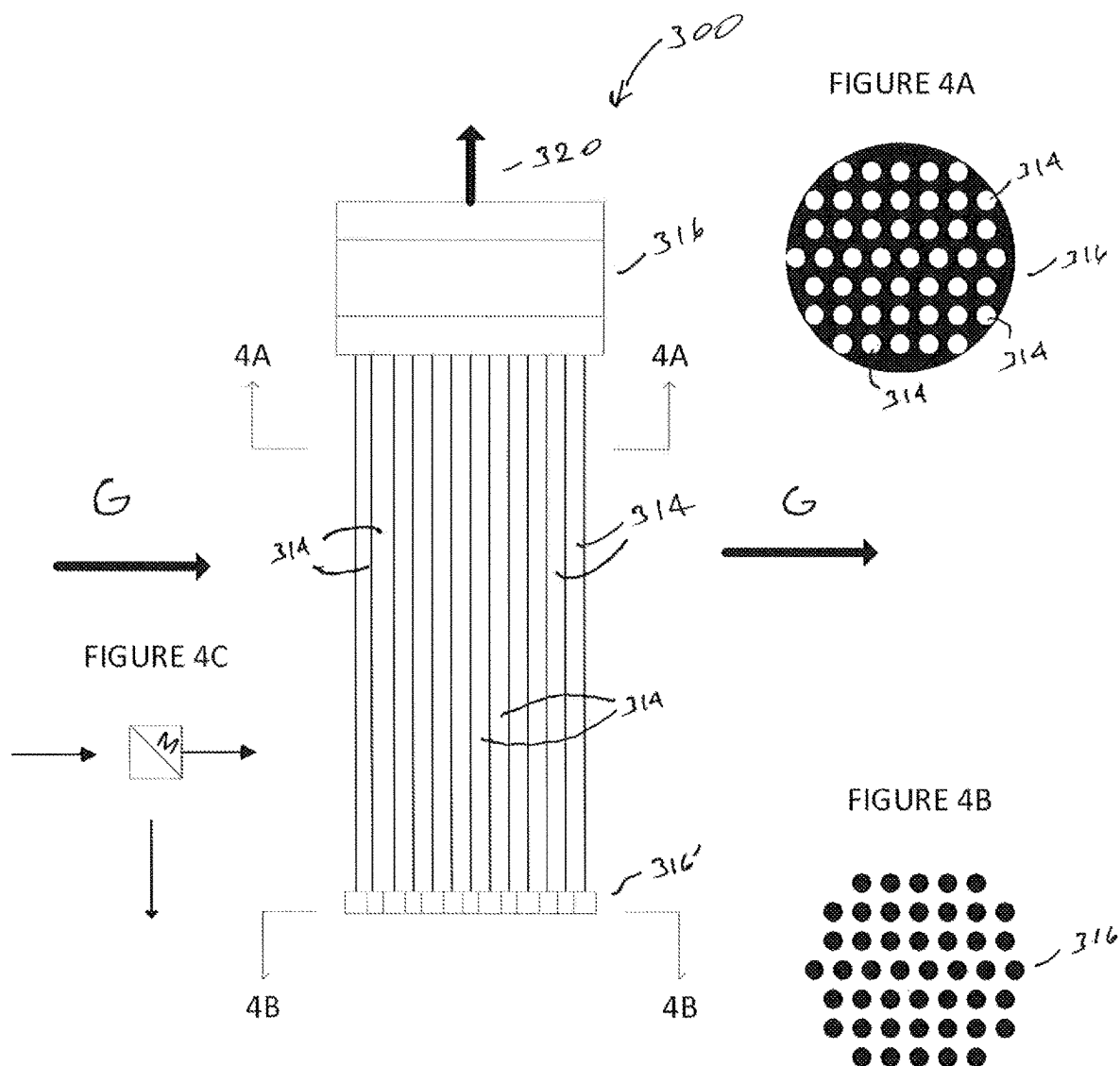


FIGURE 5

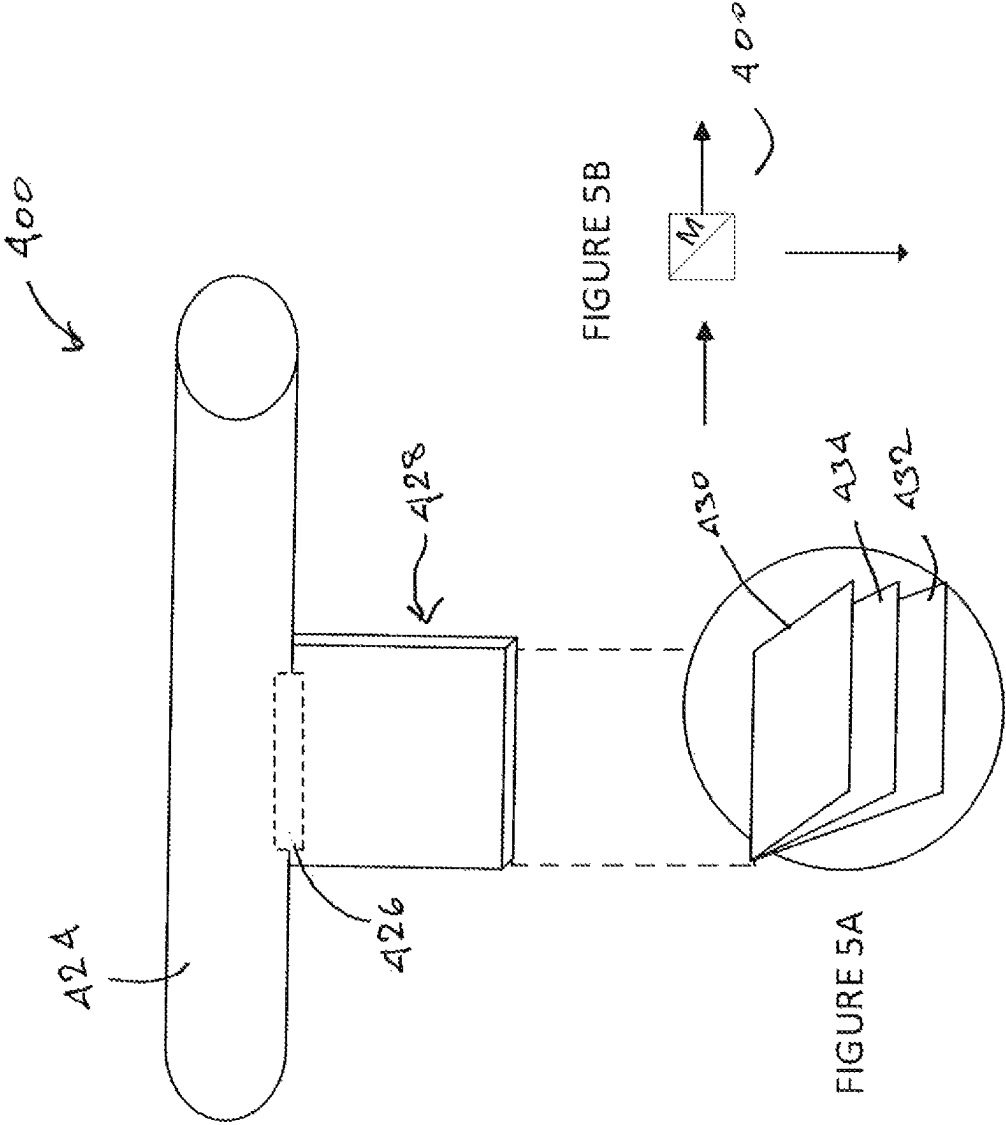


FIGURE 6

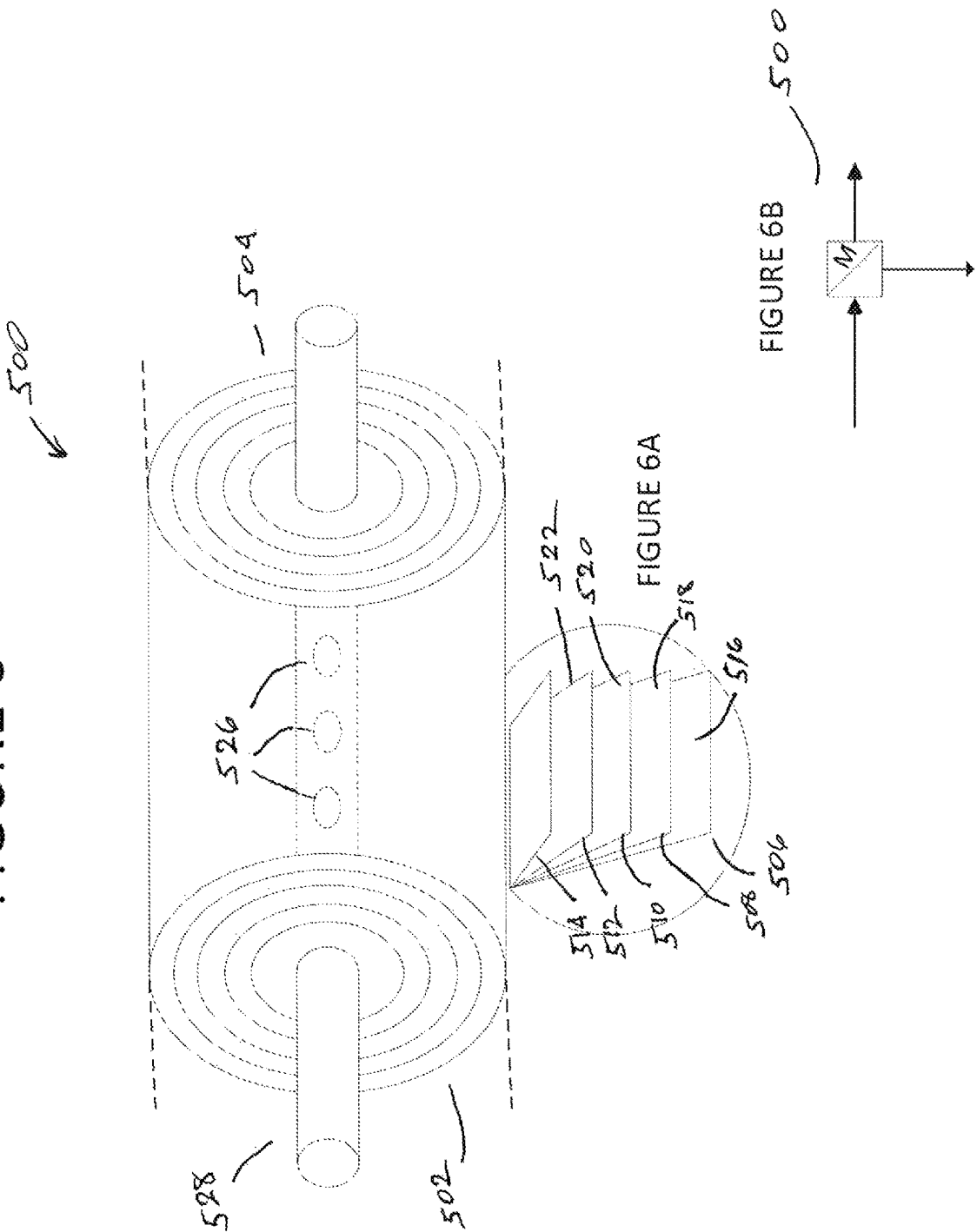


FIGURE 7

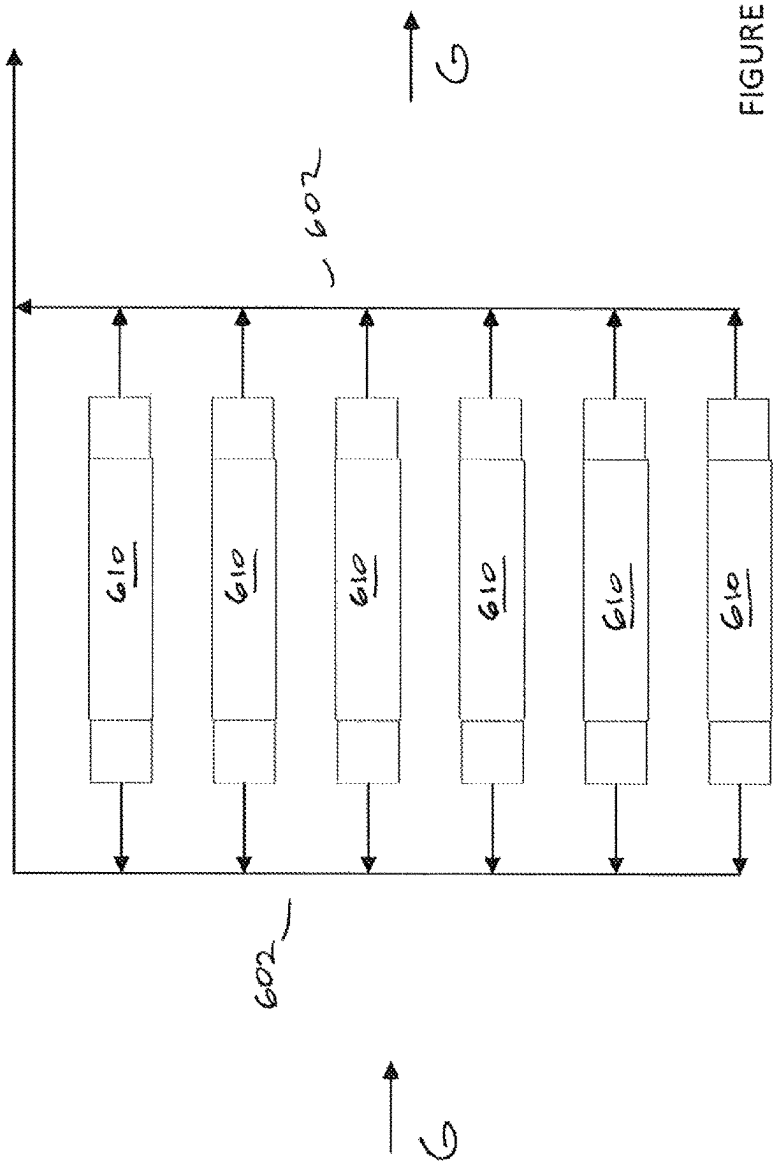


FIGURE 7A

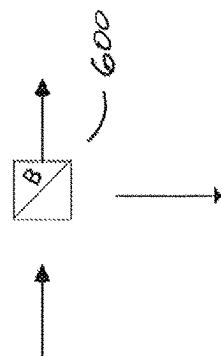


FIGURE 8

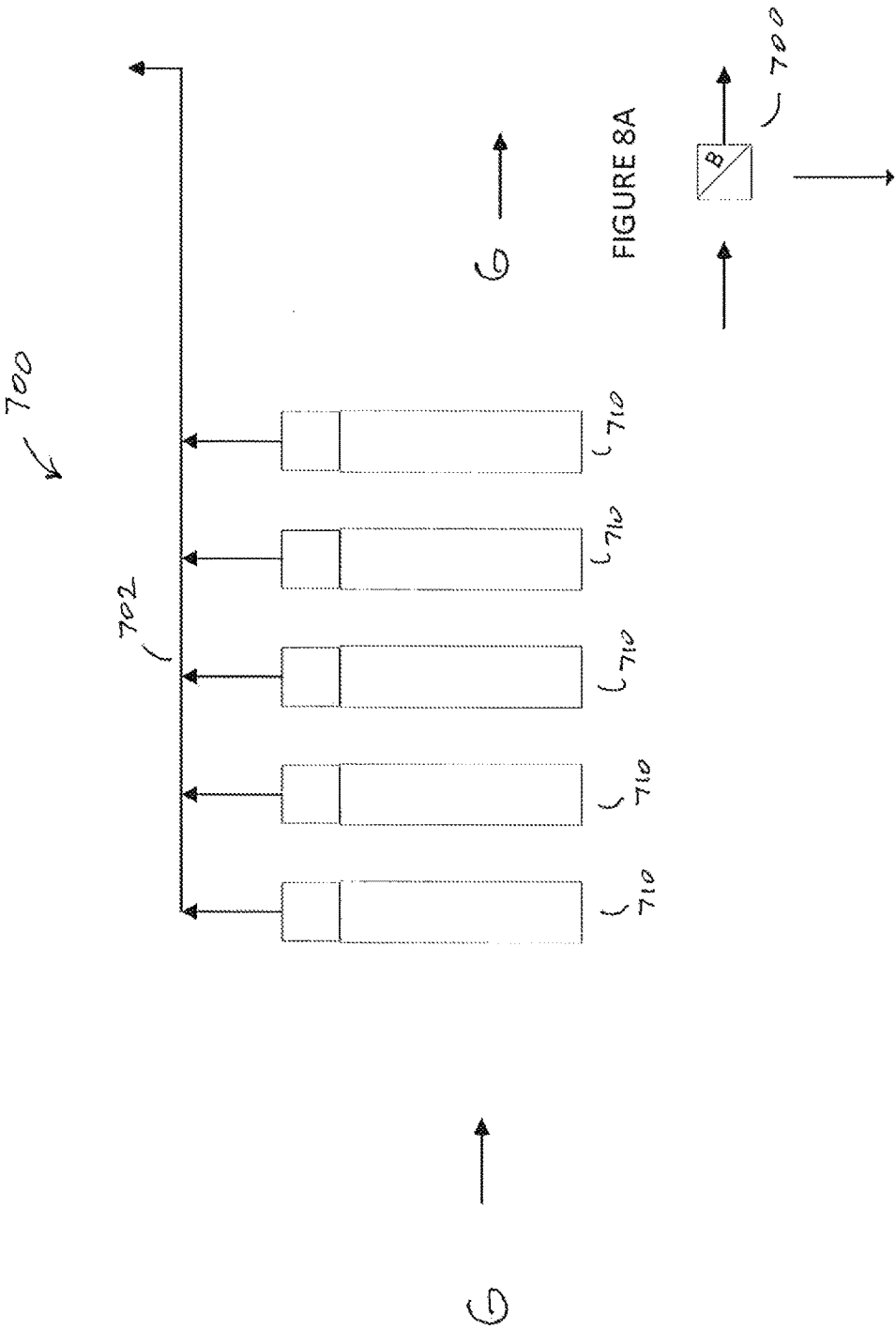


FIGURE 9

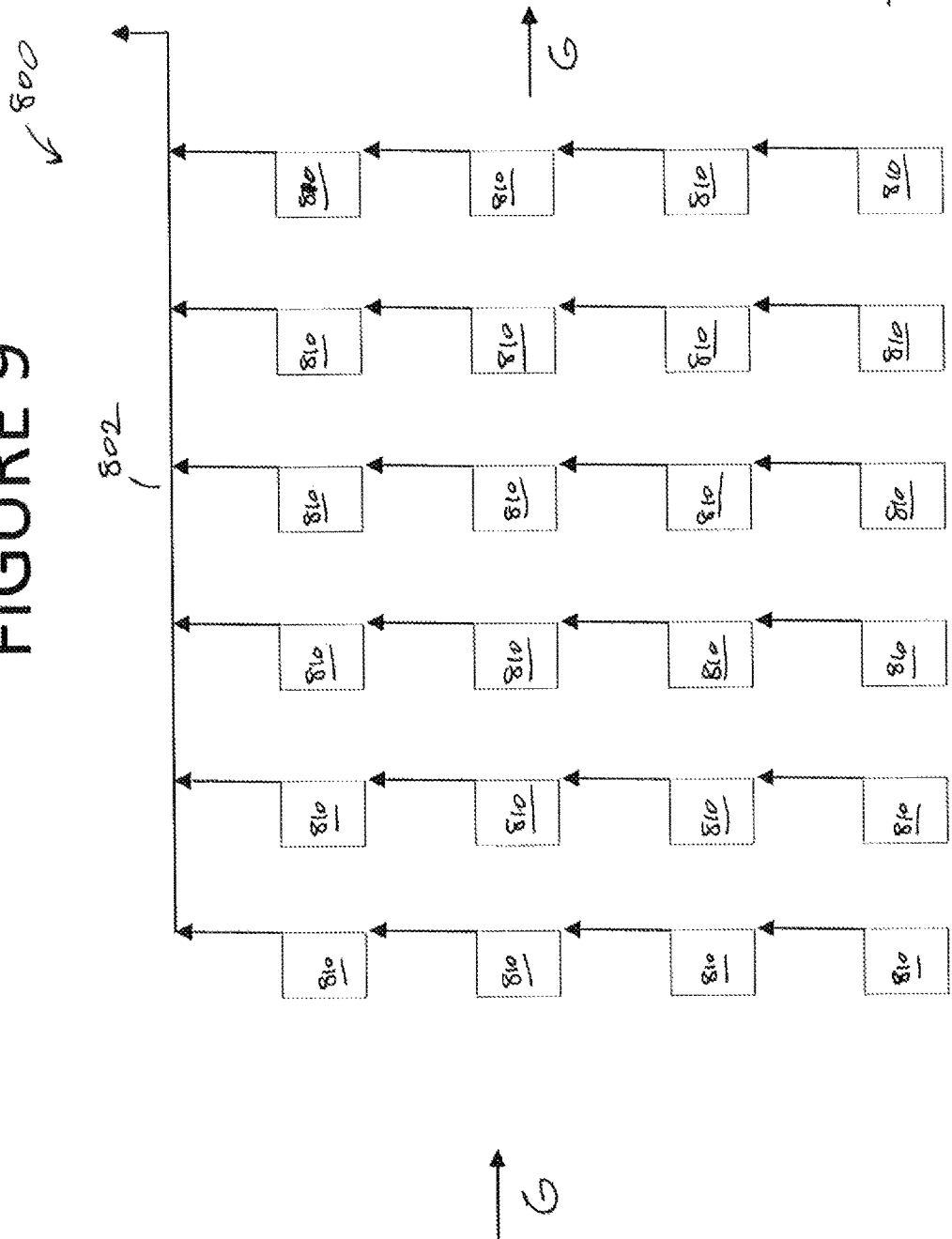


FIGURE 9A

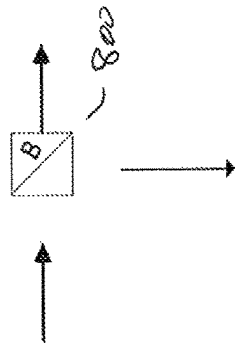


FIGURE 10

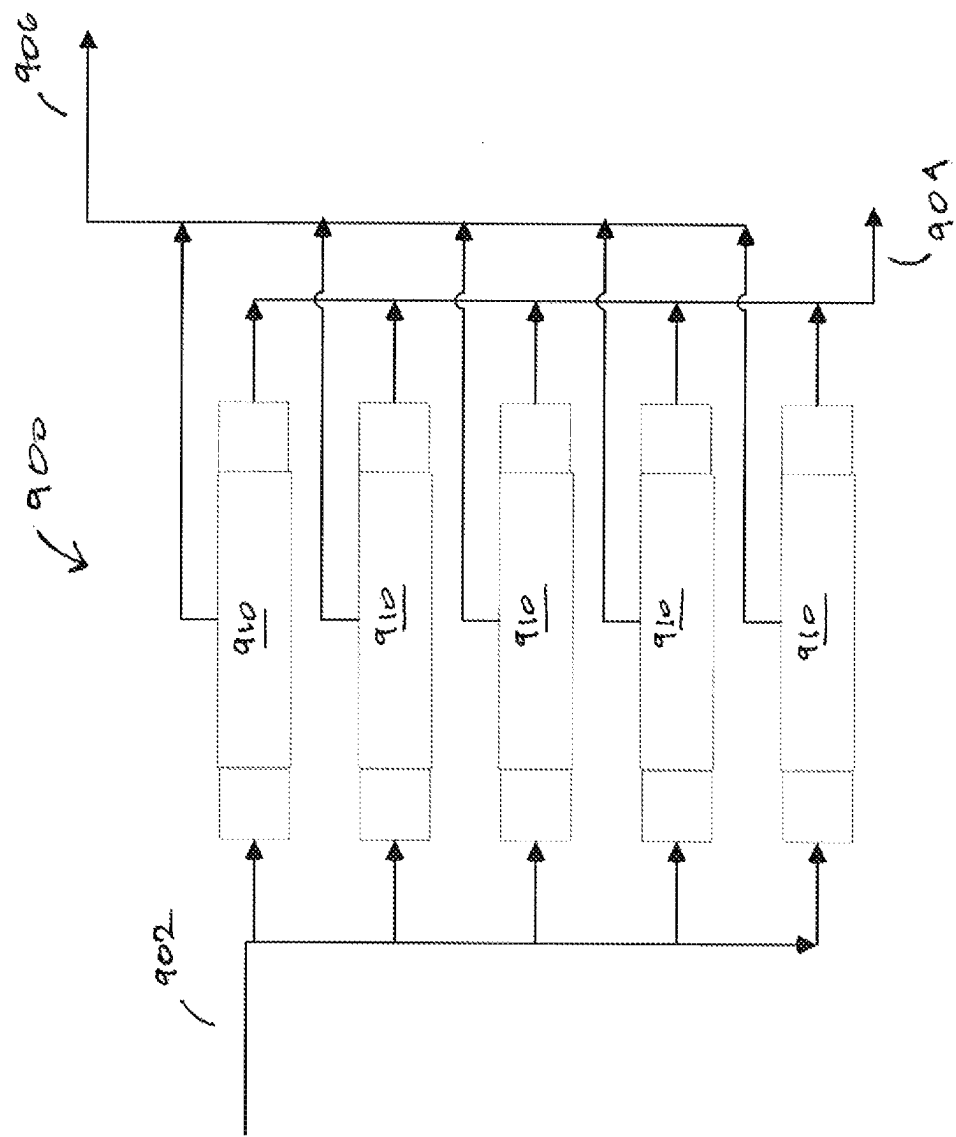


FIGURE 10A

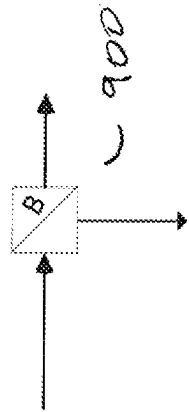


FIGURE 11

FIGURE 11A

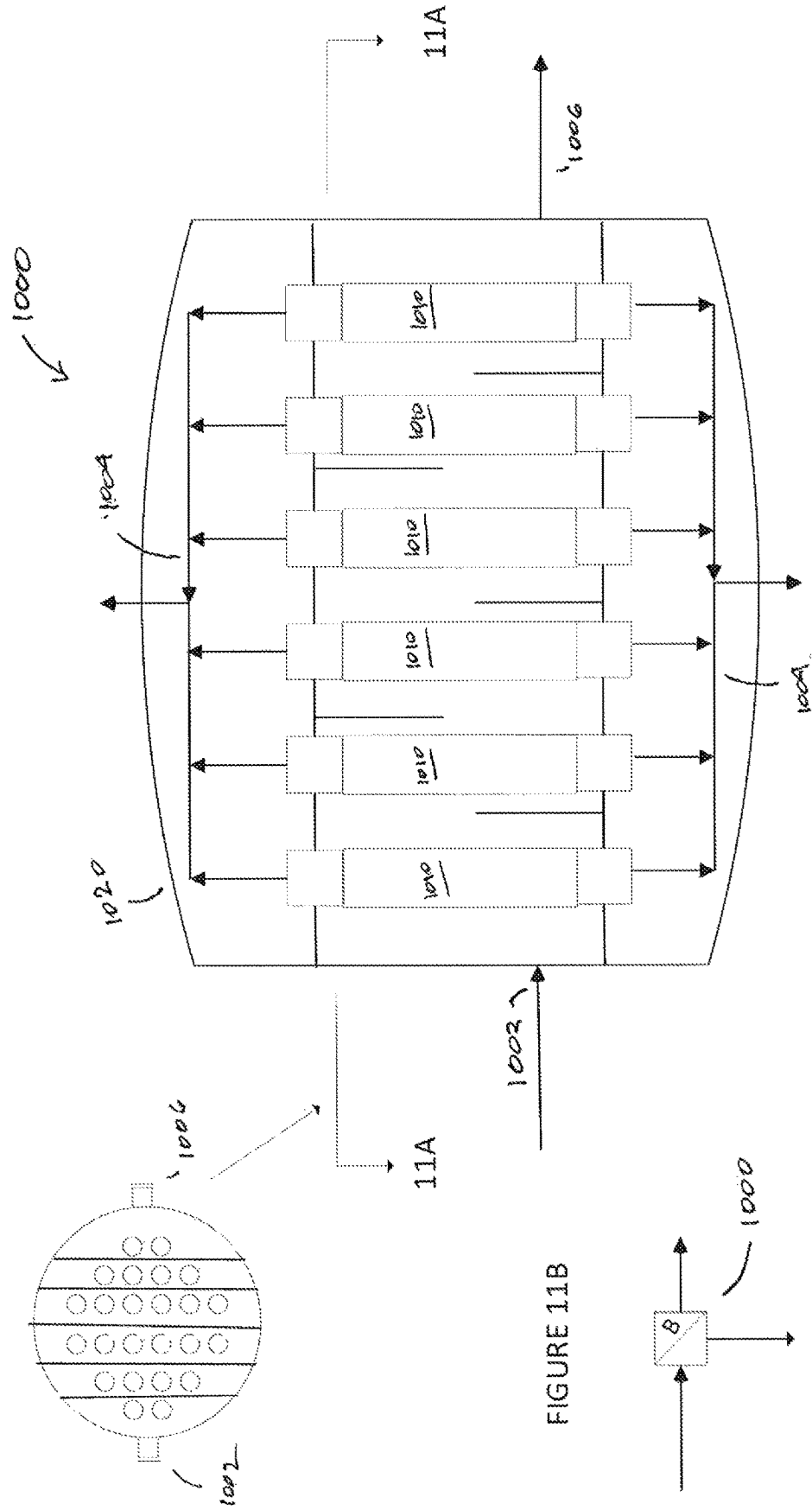
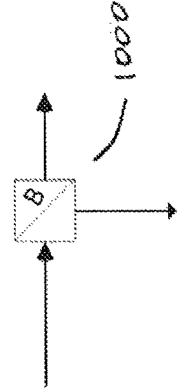
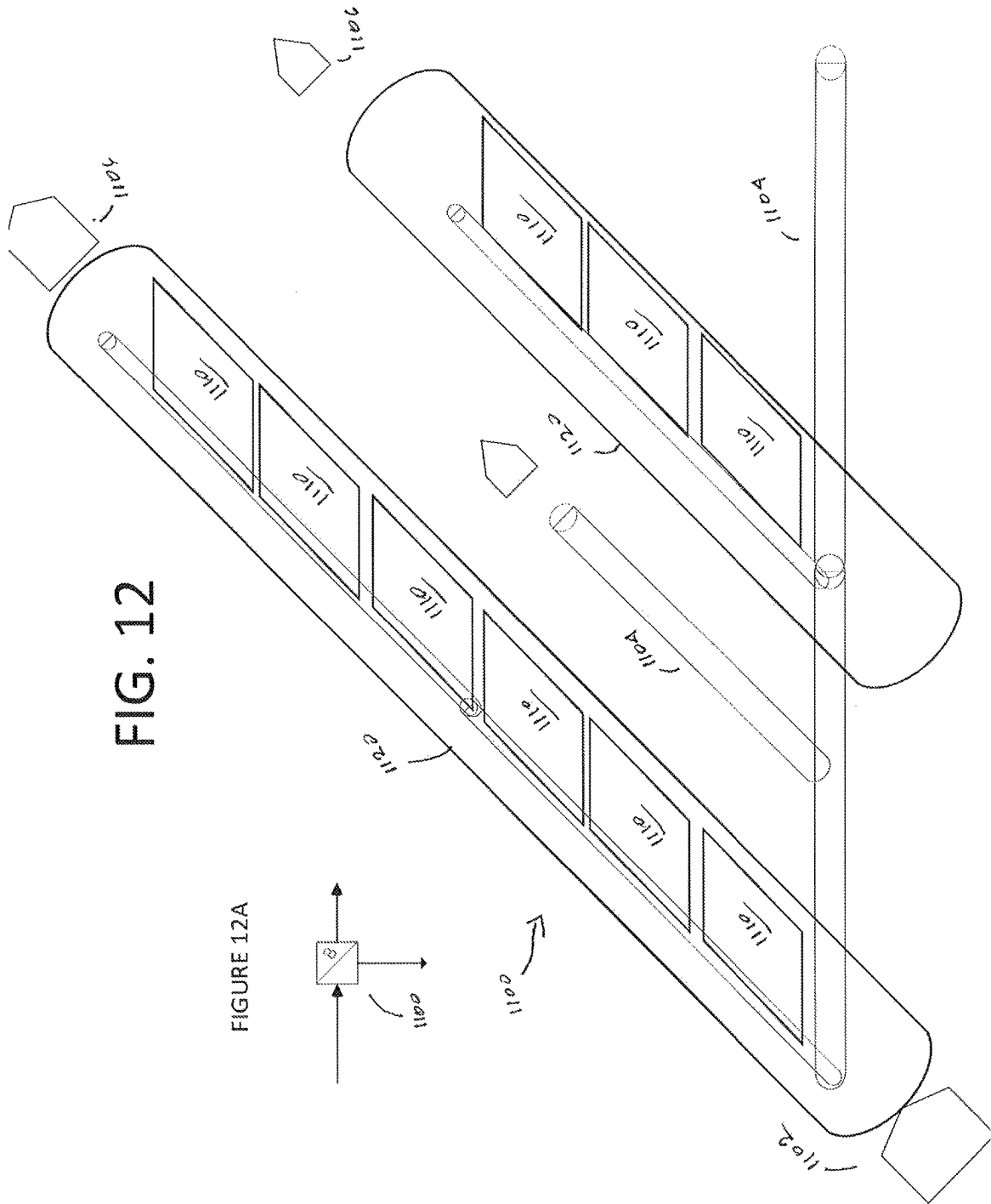


FIGURE 11B





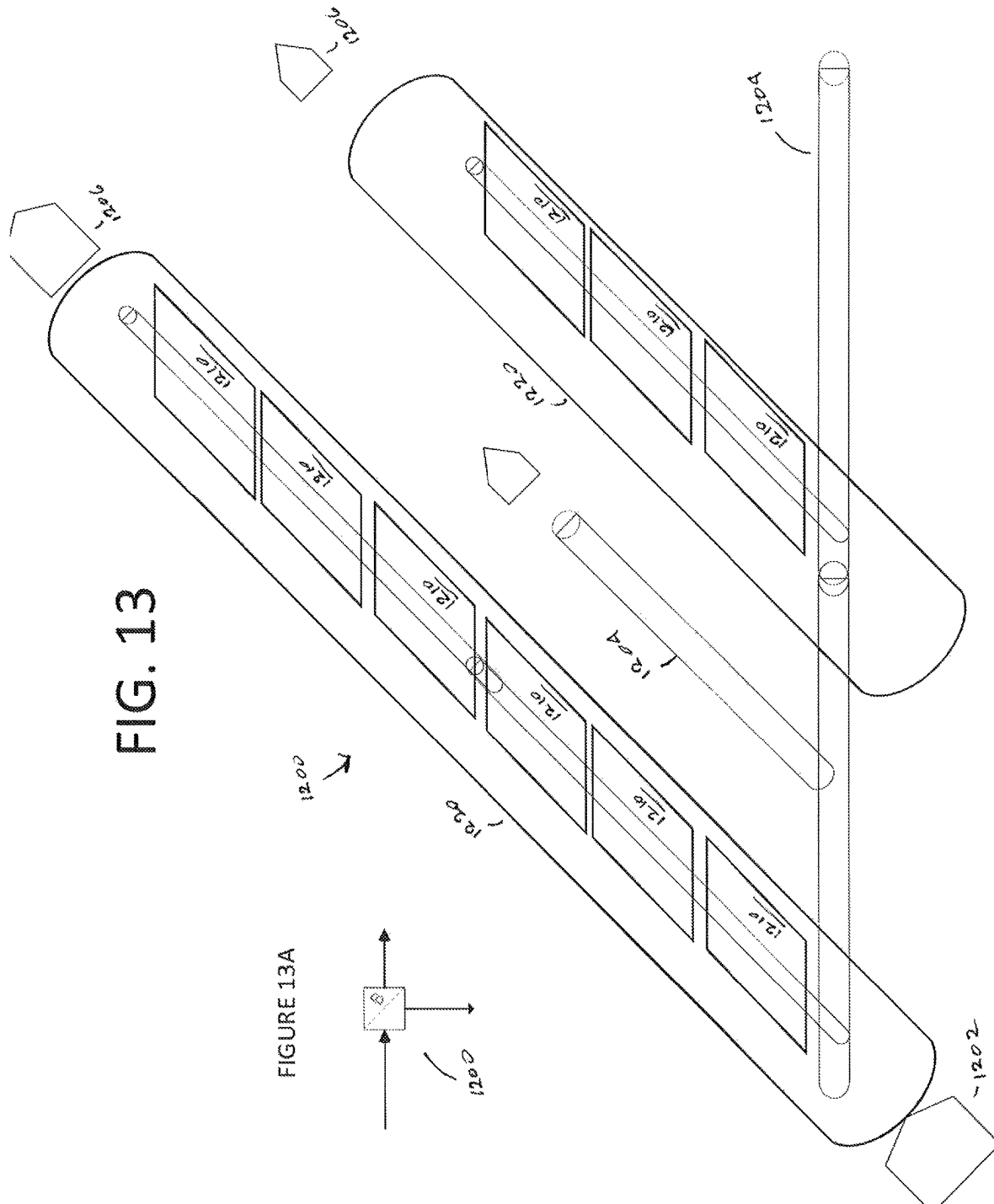


FIGURE 14

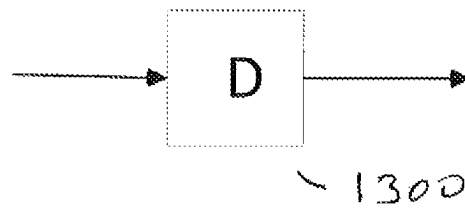


FIGURE 14A

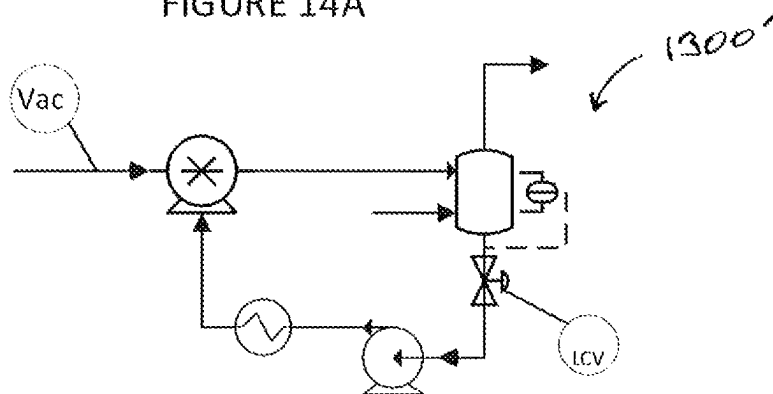


FIGURE 14B

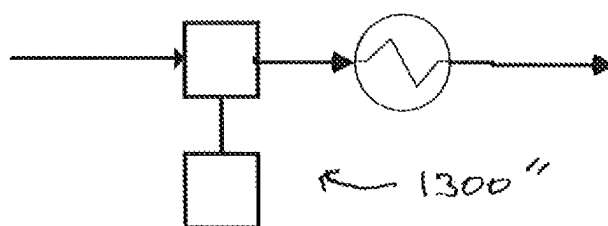


FIGURE 14C

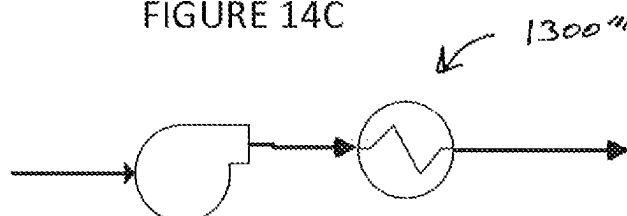


FIGURE 15

FIGURE 15A

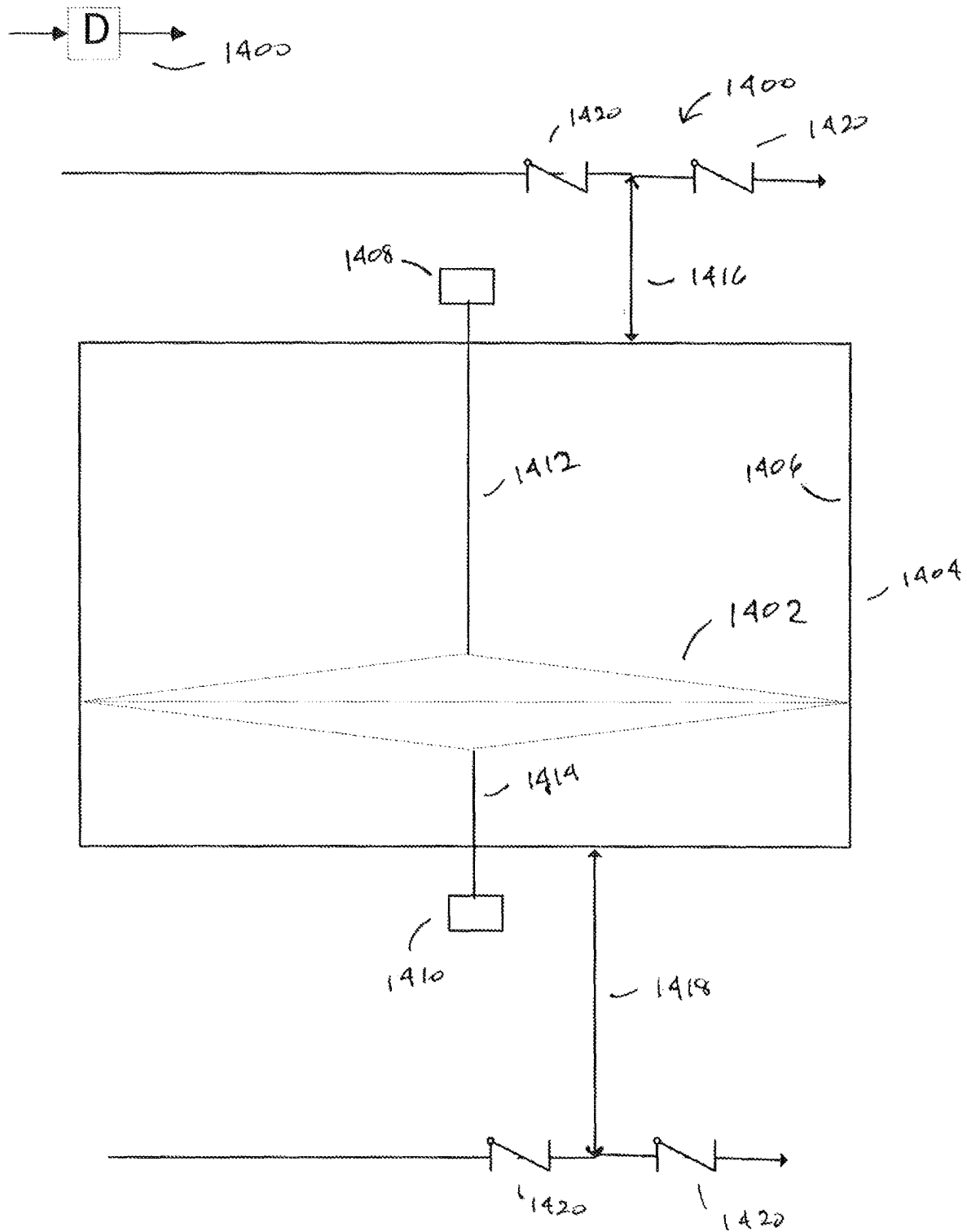


FIGURE 16

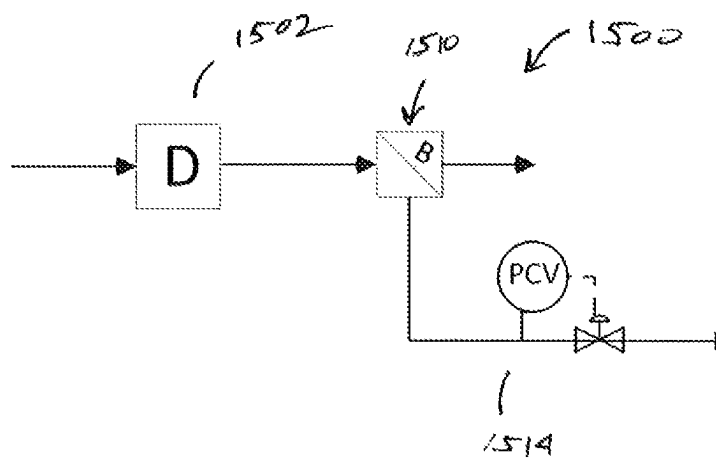


FIGURE 17

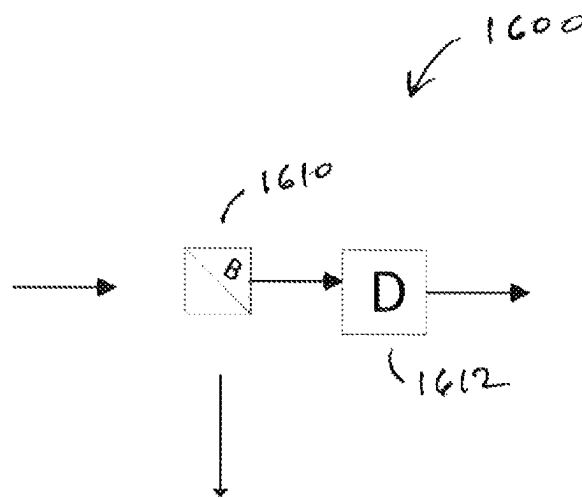


FIGURE 18

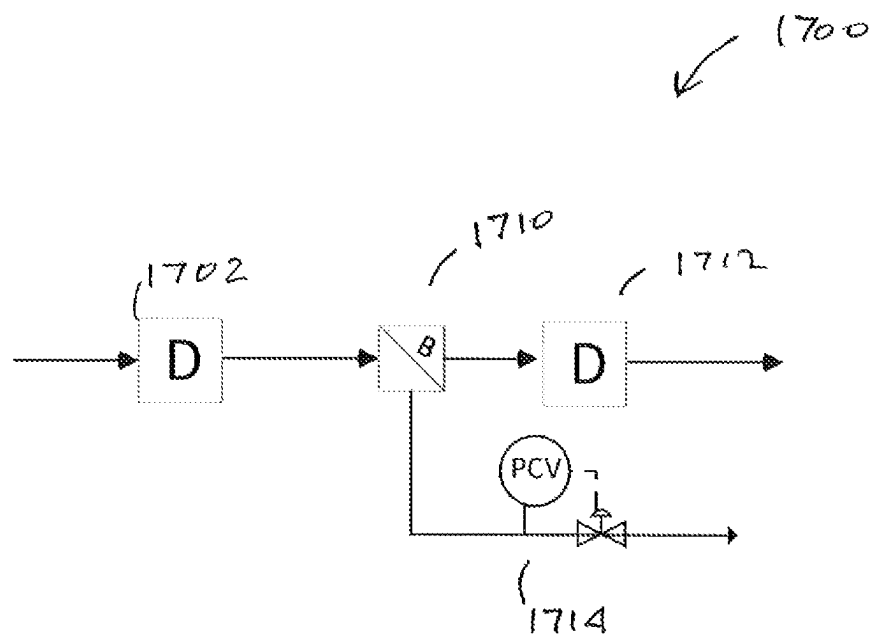


FIGURE 19

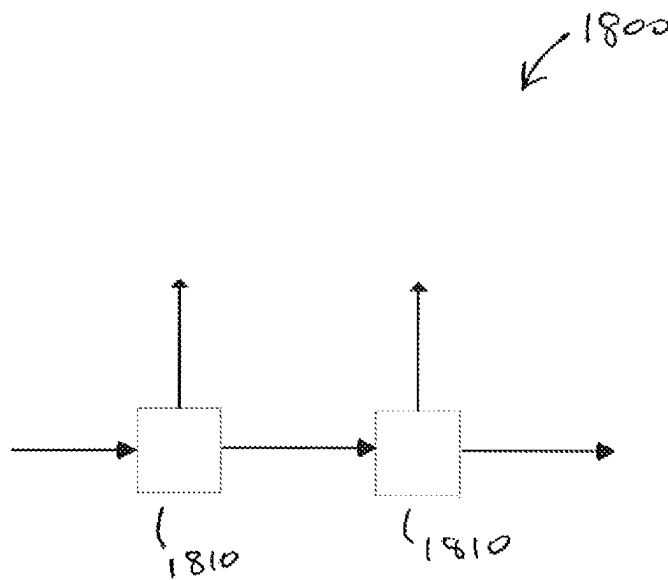


FIGURE 20

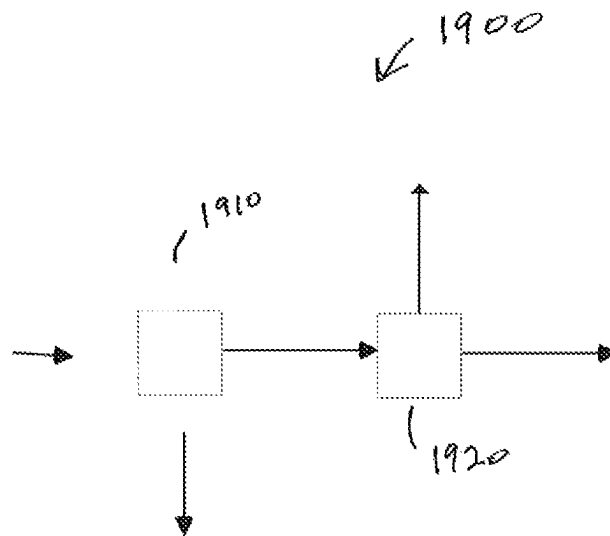


FIGURE 21

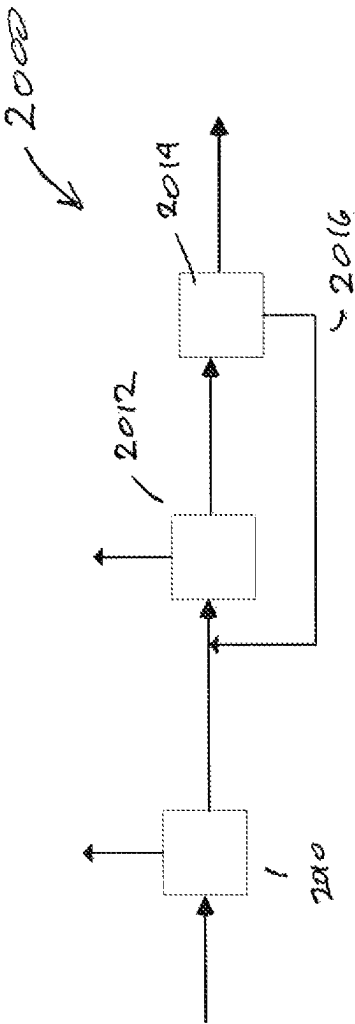


FIGURE 21A

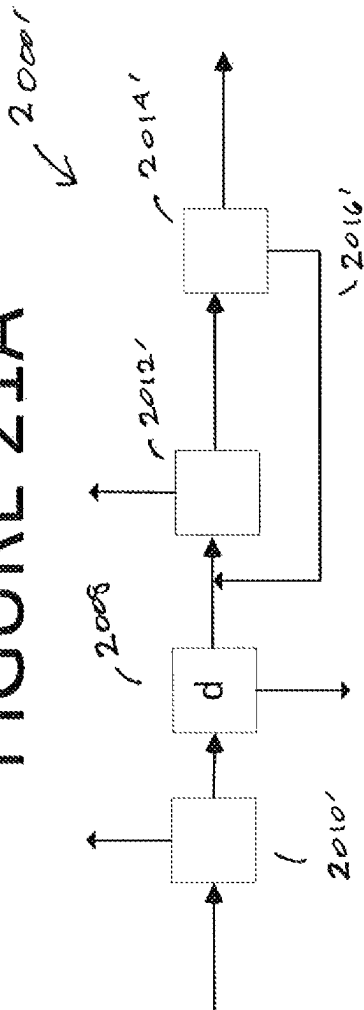


FIGURE 22

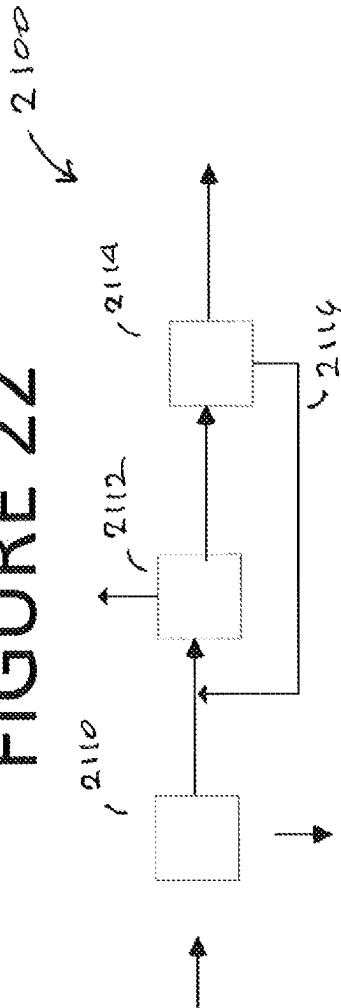


FIGURE 22A

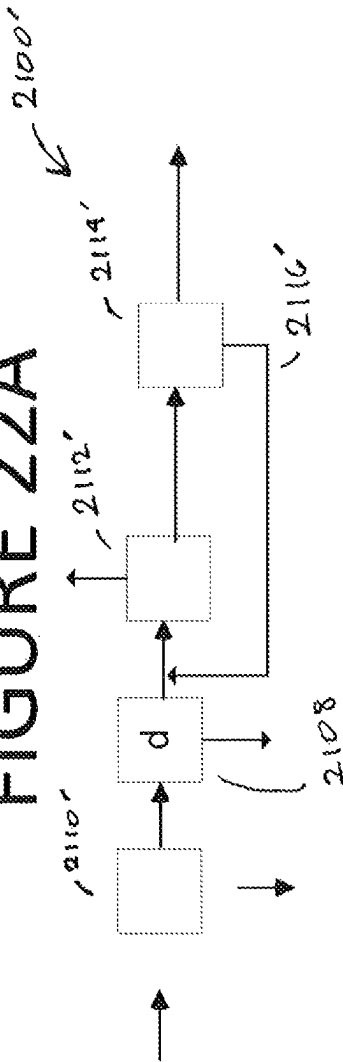


FIGURE 23

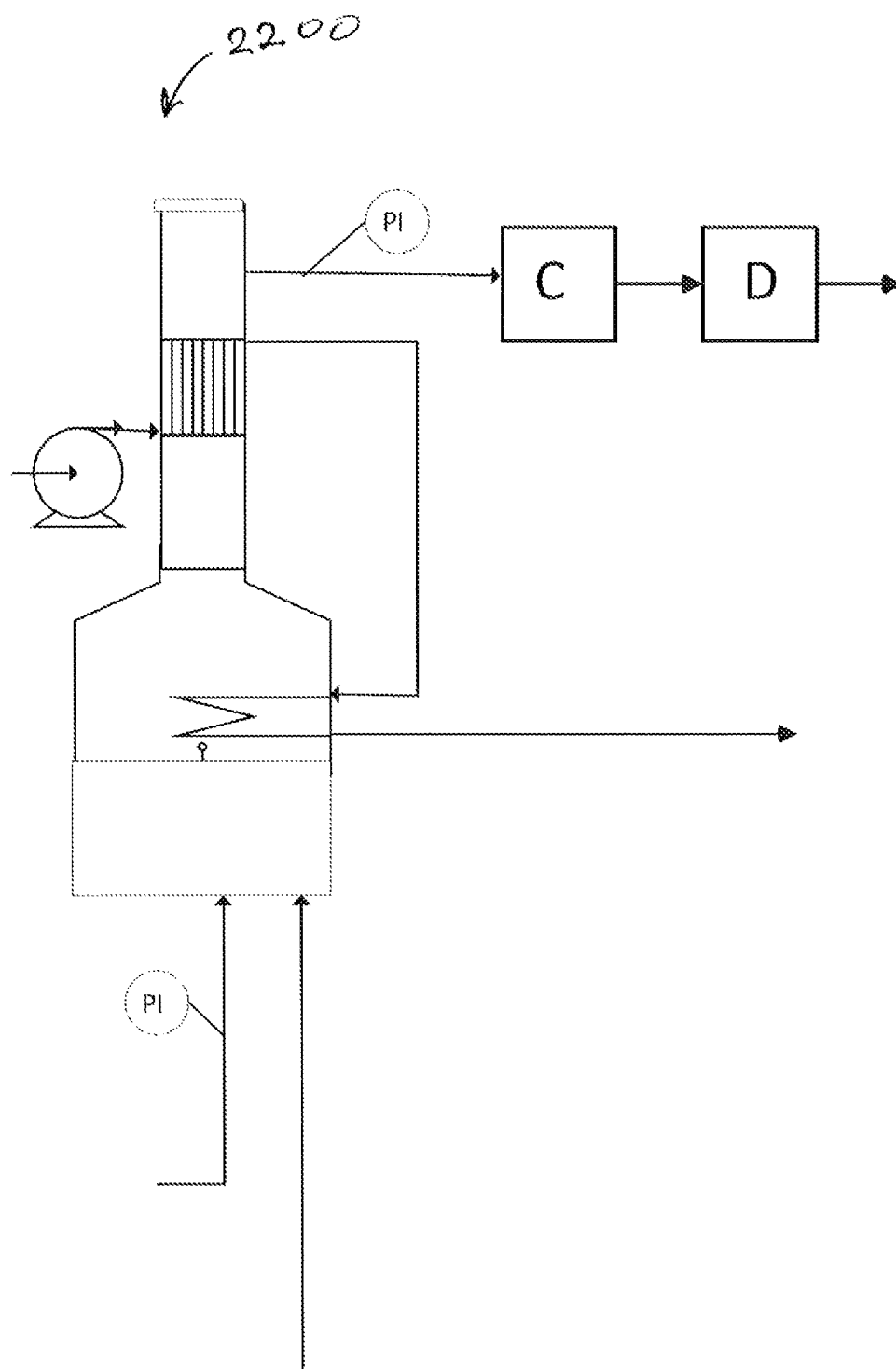


FIGURE 24

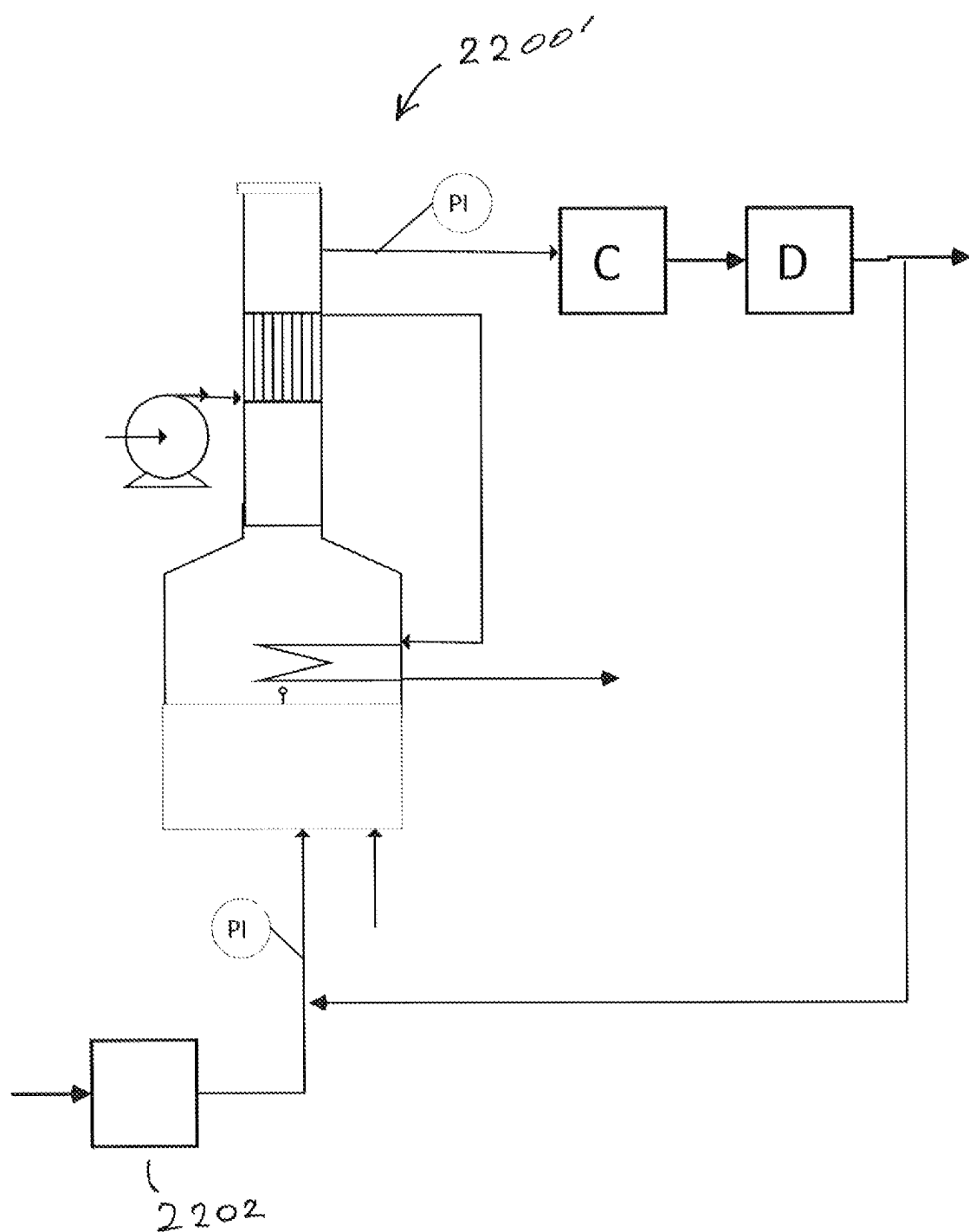


FIGURE 25

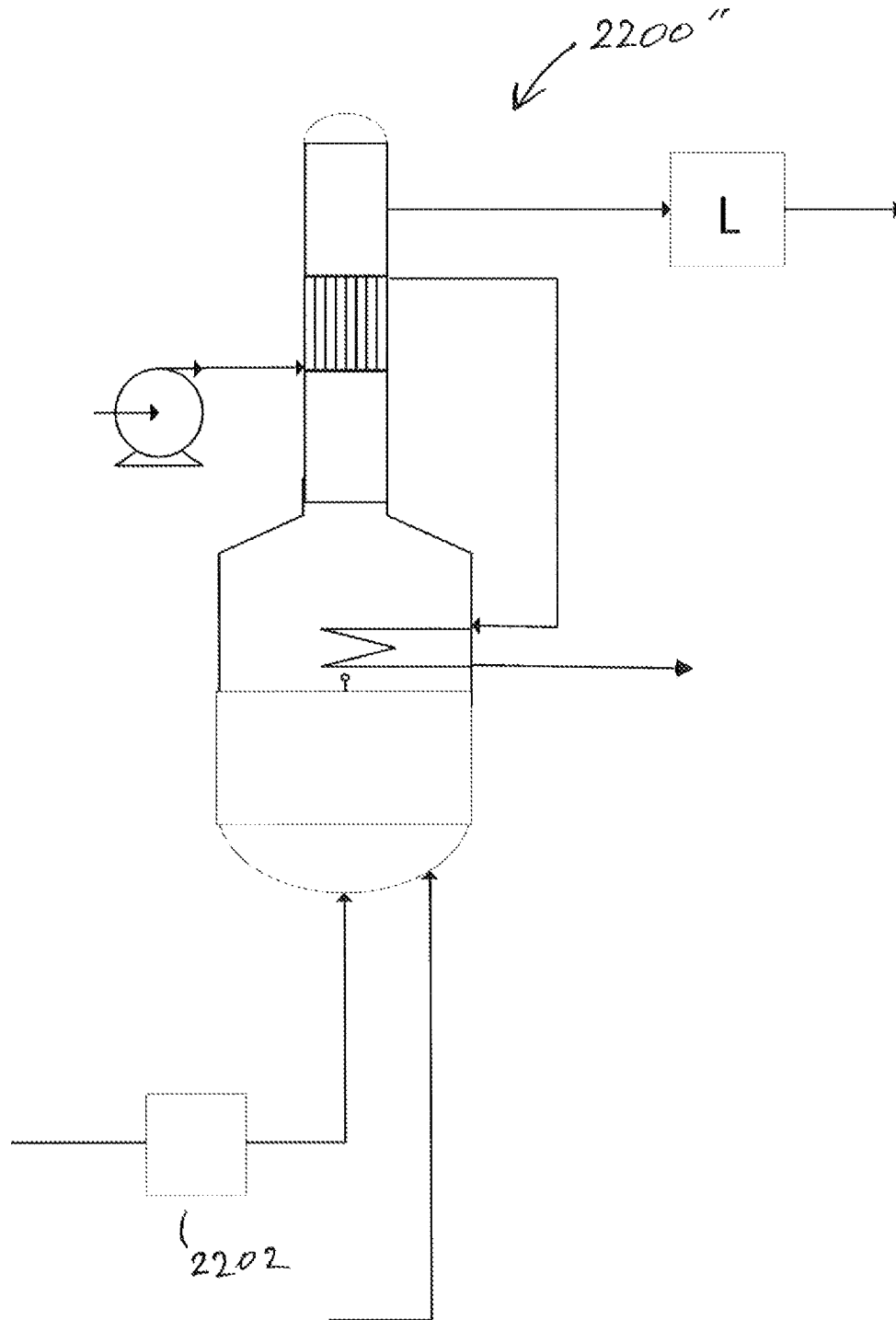


FIGURE 26

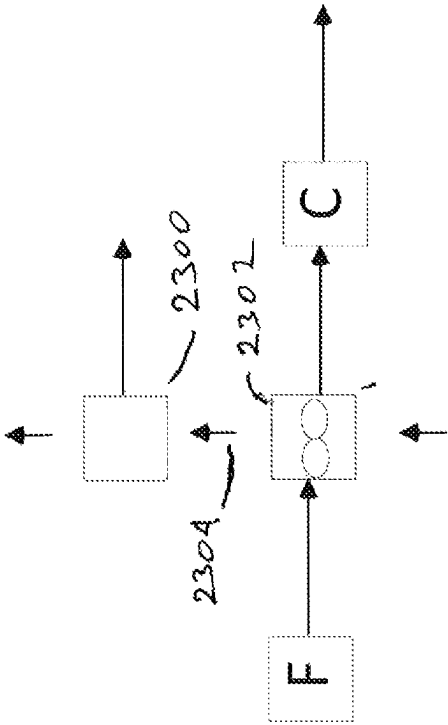
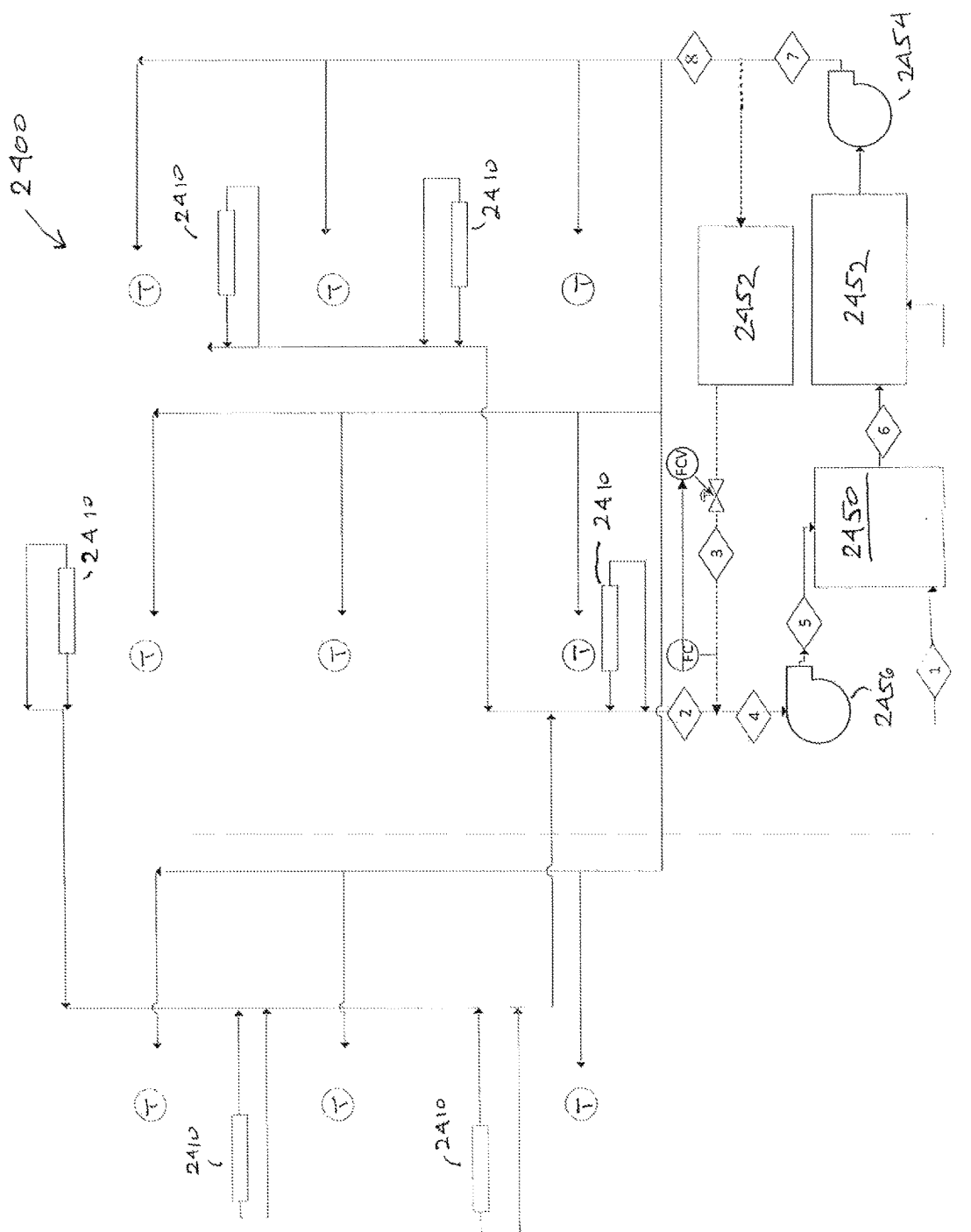


FIGURE 27



1

APPARATUS AND METHOD FOR OXYGEN AND CARBON DIOXIDE ENRICHMENT OF ATMOSPHERIC AIR

BACKGROUND OF THE INVENTION

This invention relates to enriching (increasing) the oxygen and carbon dioxide components into a permeate as generated from an atmospheric air stream as processed through a membrane configuration operating under an internally applied vacuum. Embodiments of the present invention may utilize what the inventor herein refers to as a “wig” configuration. This title refers to a membrane construction comprising a plurality of individual hollow fiber membrane elements which all pass a gas permeate into a collection member commonly, but not necessarily, at a common end of the membrane elements, which loosely approximates the configuration of individual strands of hair attached to a wig cap or caps.

It is known that carbon dioxide is a major contributor to global warming. Global warming is a result of increasing concentrations of greenhouse gases (“GHG”) in the atmosphere. Industrial facilities, power plants, and transportation are the primary greenhouse gas (CO₂) contributors accounting for over 80% of greenhouse gas production in the world. Carbon dioxide is the primary anthropogenic (i.e., man-made) GHG, accounting for a substantial portion of the human contribution to the greenhouse effect in recent (under 200) years.

A carbon dioxide enriched product produced by use of this membrane configuration may be forwarded to a sequestration facility to prevent release of the carbon dioxide into the atmosphere. Embodiments of this membrane configuration may be utilized to reduce the overall concentration of carbon dioxide in the atmosphere by direct removal of the CO₂ from the air, also known as Direct Air Capture. Embodiments of this membrane configuration may also be utilized to reduce CO₂ added to the atmosphere generated by energy consumed during a process, for example by reducing the consumption of non-renewable fuel utilized to power a process or fuel combusted within the process. The term “sequestration facility” is defined herein as anyone of a variety of mechanisms which sequester the carbon dioxide thereby preventing immediate release back into the atmosphere. The term may include systems which utilize bio-sequestration, such as orchards, crops, forests, and other photosynthetic organisms which either convert carbon dioxide utilizing photosynthesis or store the carbon dioxide in the organism. The sequestration facility may also include manufacturing processes which utilize or make a product with carbon dioxide, including production of dry ice utilized for preserving items requiring cold storage during transport such as various foods and medicines. The sequestration facility may also include a system which injects carbon dioxide into petroleum reservoirs for purposes of enhanced oil recovery such as miscible flooding.

A process of the presently disclosed invention utilizes membranes to provide an enriched oxygen stream—as opposed to the commonly used air feed stream—to a flue gas generator, or other devices which use air or oxygen in a reaction process to produce a product, (sometimes collectively referred to herein as “oxygen reaction devices”) to decrease the energy demand and/or increase the capacity of such oxygen reaction devices. The use of the enriched oxygen stream realized through the membrane configurations disclosed herein may thereby decrease non-renewable fuel (natural gas, gasoline, coal) consumption and thereby

2

reduce the production of green house (CO₂) gas emissions. As well, the CO₂ in the flue gas of an oxygen enriched flue gas generator is more highly concentrated, making the CO₂ more economically capturable.

For purposes of this disclosure, the term “flue gas generator” is defined as a stationary (non-mobile) or mobile device which normally emits elevated concentrations of carbon dioxide to atmosphere within an emitted gas stream. Examples of stationary flue gas generators are industrial steam generators, biogas/natural gas/coal fired power plants, ethanol plants, amine regenerators, cement manufacturing kilns, fermenters, water heaters and heater furnaces. Examples of mobile flue gas generators are automobiles, trains, and air planes with internal combustion or jet engines. Examples of other “oxygen reaction devices” include activated sludge reactors producing biogas, sulfur recovery units making sulfur from a refinery or gas plant acid gases, ethylene oxide production units, syngas plants, and apparatus utilized in pyrolysis processes and glass manufacturing.

In the case of stationary flue gas generators, the flue gas with highly enriched CO₂, can be captured and thus utilized for various commercial uses, which may include enhanced oil recovery operations, agricultural use, medical applications, and other known commercial applications.

There is an ongoing and critical need for additional mechanisms and methods for reducing consumption of non-renewable fuels and reducing energy’s contribution to atmospheric carbon dioxide, also known as energy carbon management.

SUMMARY OF THE INVENTION

Embodiments of the present invention exploit the unique property of membranes to economically achieve direct air capture and/or produce an enriched carbon dioxide stream from atmospheric air (i.e., having an approximate normal air dry composition of 20.9% Oxygen, 78.05% Nitrogen, and 0.04% or 400 ppm CO₂ by volume). Water composition in air varies more than other components and is significant depending on ambient temperature. Water vapor concentration in normal air can be as high as 4% at 120 F, and for example, at -40 F can be as low as 0.2%. Carbon dioxide, oxygen, and water vapor is separated from nitrogen in the air feed stream by the disclosed membrane configuration to produce a permeate or product stream comprising enriched (higher than normal air) concentration of carbon dioxide, oxygen and water, and a separate residue or biproduct stream with enriched nitrogen.

Processes utilizing the membrane configurations disclosed herein are distinguishable from other known processes which yield only highly purified (90%+) concentrations of carbon dioxide, nitrogen, and oxygen, such as cryogenic air separation units (ASUs) or Vacuum Pressure Swing Absorption (VPSA). ASU systems require significantly higher capital expense and significantly higher operating costs. Moreover, these systems may present significantly higher operational risks because of high operating pressures and/or sub-freezing operating temperatures. VPSA and conventional multiple stage prior art hollow fiber require higher feed and operating pressures. In comparison, embodiments of the present invention operate at low pressure and near ambient temperature. In the case of conventional membranes, the air is pressurized at conventionally 120 to 150 psig into the tube side channels, tube-sheets and through the internal bore of the hollow fiber tubes, and the

permeate passes through the pressurized tube inner wall to pass into the shell enclosed side encasing the bundle of membrane tubes.

In contrast, embodiments of the presently disclosed membrane units drive the feed not by pressurizing the much higher capacity feed stream, but by pulling a vacuum on the relatively smaller product permeate stream into the bore side of the tubes, a stream with $\frac{1}{3}$ to $\frac{1}{2}$ the total volume of the feed gas, thus requires $\frac{1}{3}$ to $\frac{1}{2}$ the energy required for conventional membrane. The performance of the membranes of the present invention is also approximately 30% higher than for conventional air separation membranes, because there is no pressure drop on the residue side, and the membranes of the present invention have air first contact with the hollow fiber tube on the exterior wall of the tube, which has inherently high area per tube than the conventional membrane's air first contact of the inner bore wall. Performance is further enhanced by the lack of any pressure drop on the residue side, and higher volume flow rates allowed on the "shell-less shell side." The commercial manufacturing cost of the membranes of the present invention may be significantly reduced, as embodiments of the membranes of the present invention can be produced with a single tube sheet instead of two tube-sheets and does not need a shell enclosure.

Embodiments of the present invention may further have a desiccant system on the 1st stage permeate, which potentially saves approximately 40% on the downstream stage energy in comparison to conventional membrane processes. It is noted that the materials and technology utilized in the field of membranes take advantage of an aspect not available to the cryogenic or specifically more competitive VPSA adsorption materials and technology. Specifically, a membrane can equally process CO₂ and oxygen in a vacuum as it can under pressure. Membranes perform based on Fick's law and the higher the partial pressure differential between the permeate and the feed, the primary process control parameter driving "flux" or a component's flowrate through the membrane to the permeate side of a specific material, the better the separation performance of the membrane. Thus, if the partial pressure drop is caused by a difference between two positive partial pressures or a negative or vacuum based partial pressure and positive partial pressure are equal, the performance of the membrane is the same, all else being equal. Not so for adsorbents. Adsorbent performance is based on the Langmuir isotherm where the fraction adsorbed varies linearly with partial pressure. Thus if the absolute partial pressure increases, then adsorption increases, and vice versa, thus this is why regeneration or desorption can occur in a vacuum.

Embodiments of the presently disclosed membrane units may be configured in with a primary (single stage) unit producing a mild or moderate increase (enrichment) in concentration of oxygen (up to 50%), water, and carbon dioxide (up to 1200 ppm) in a product stream which is achieved by utilizing the membrane unit to separate out nitrogen from normal ambient atmospheric air. When utilized for oxygen enrichment of the combustion air with a flue gas generator the resulting concentration of CO₂ emitted from the flue generator may be over 20%, and 33% when water is removed. The resulting permeate stream does not have to be highly purified in carbon dioxide or oxygen or water to attain significant benefits, although the resulting permeate may be further processed with embodiments of this invention to produce highly purified oxygen with a secondary and/or tertiary (2nd and/or 3rd stage) membrane or other form of enrichment, and highly purified CO₂ (up to

90% requires at least a third stage.) By capturing and removing water from the flue gas of a highly oxygen (up to 90%) enriched combustion oxygen fed stationary flue gas generator, a very highly purified (99%+- potable) water as removed from the CO₂ bearing flue gas of a flue gas generator with embodiments of the present invention can be achieved.

Embodiments of the presently disclosed membrane units may utilize membrane materials having properties similar to those of the cellulose acetate based sheet membrane units of the flat or spiral wound type such as used in the Separex™ membrane product as manufactured by Honeywell/UOP, or other polymeric based membrane materials such as used in "plate and frame" type Polaris™ membranes units as manufactured by MTR, Inc., or used in hollow fiber type membrane units such as Cynara™ membranes manufactured by Schlumberger, or PRISM™ membranes as manufactured by Air Products, or Nitrox™ membranes systems as manufactured by Generon. However, these known conventional membrane devices have significant supporting structure and require multiple blowers or compressors for operation of the systems as compared to the processes required for membranes having the wig configuration disclosed herein.

Membranes configured from the above listed membrane materials and products may be utilized to enrich the oxygen, water, and carbon dioxide concentrations of a gas stream processed through the membrane units. Carbon dioxide, water, and oxygen pass or permeate more rapidly through the membrane relative to nitrogen, thereby forming a permeate stream which is more concentrated or enriched in oxygen, water, and carbon dioxide than the "feed" stream. It is noted that the term "feed" is used somewhat loosely for purposes of this disclosure and does not refer to a stream delivered to the membrane via a compressor or blower and with an intake or similar structure. With embodiments of the presently disclosed wig membrane configuration, a "feed" side of the membrane unit is simply the air exposed exterior sides of a collection of membrane hollow fiber tubes, which are suspended on one or both ends by a tubesheet(s), where a gas (i.e., air) flows or blows against the exterior outside walls of the deployed tubes. The air can blow as wind naturally, or warm air under (150 F) can be force drafted, such as from the discharged air of an air-cooling unit, across the external wall of the membrane tubes. It may be noted that for this embodiment of the invention, providing a higher velocity air passing over the exposed hollow fiber tubes, and/or a higher temperature over the exposed hollow fiber tubes further improves the performance (energy savings and enrichment) of the wig membrane unit above the conventional prior art hollow fiber membrane units (CHFMU).

Other significant benefits of the "wig" membrane units over conventional membrane units, especially CHFMU, is the lower fabrication cost of the membranes having the wig configuration. As indicated above, these savings are due in part due to an embodiment of the primary wig membrane unit having only a single outlet tube sheet—as all CHFMU used for oxygen enrichment from air have two tube sheets, an inlet tube sheet and an outlet tubesheet. Further, all embodiments of the primary wig membrane unit have no shell unlike all CHFMU. Another benefit of the wig configuration over CHFMU is lower energy consumption due to lower pressure drop, higher performance (i.e., capable of producing higher concentrations of oxygen due to the lower pressure drop), and pliability of the membrane allowing better fit into secondary membrane structures as needed for other membrane configurations.

The permeate—nitrogen depleted air—is brought into the interior (bore) of each membrane tube by a vacuum applied to the open end or ends of each membrane tube at the outlet tubesheet(s). Gas components, predominantly nitrogen, which pass relatively slowly through the membrane in comparison to oxygen, carbon dioxide and water, remain mostly on the outside of the membrane tubes, and pass over the tubes remaining in the atmosphere. The permeate is collected through tubesheet(s) into a permeate conduit or channel, such as ducting, which collects the permeate from one or more of the wig membrane units and forwards the permeate as desired.

In one embodiment of the invention, a stationary flue gas generator may be disposed between a primary membrane unit and a sequestration facility as defined above. The oxygen reaction processes utilized in flue gas generators conventionally use atmospheric air that produce a wet (meaning concentration with water) flue gas that contains lower nitrogen concentrations (65 to 74%) and much higher carbon dioxide concentrations (5 to 11%) with respect to that found in wet atmospheric air (approximately 78% and 0.04%, respectively.) As indicated above, the flue gas produced by introducing the permeate stream generated from the disclosed membrane units in place of conventional atmospheric air, can have a lower yet (almost half) the concentration of nitrogen (down to 40%) and higher yet concentration (almost double) of over 20% carbon dioxide in the flue gas, thus a flue gas significantly more dilute in the component nitrogen and much more significantly higher in concentration of the component carbon dioxide than in atmospheric air or than in the flue gas exhaust from a conventional flue gas generator using atmospheric air for combustion. This carbon dioxide in the flue gas can be even more concentrated in CO₂ (up to 80%) when a secondary membrane unit is added, and the bulk component of water is removed (in a usable and pure form as a separate product) thus making the flue gas itself actually a highly concentrated CO₂ product that can be more economically transported, processed and capturable as may then be utilized in more of the types of sequestration facilities discussed above.

Further, these lower concentrations of nitrogen produced in the oxygen feed replacing combustion air to the flue gas generator contribute to decreasing the volume of gas processed through the flue gas generator, and thus allows for increased capacity and thermal efficiency (due to the thermal properties of CO₂ versus nitrogen) of the flue gas generator, providing fuel savings while lowering NO_x production and concentration in the flue gas emissions. Further, the higher firing temperature in the flue gas generator because of reduced nitrogen concentration, allows for low heat value fuels, such as renewable biogas, to be used without requiring supplemental feed of high heat value non-renewable fuels, such as natural gas. The higher firing temperature also produces a more valuable and recoverable waste heat, adding further to the thermal efficiency and fuel savings. In some embodiments of the invention the flue gas generator may be pressurized thereby eliminating the need for downstream cooling/pressurization of the flue gas prior to being processed for sequestration.

For higher than 90% concentration of oxygen, especially useful in other devices which use air or oxygen in a reaction process to produce a product other than flue gas generators, embodiments of the present invention may also comprise a secondary (or tertiary) enrichment system which utilizes the permeate from a primary or first stage membrane unit as a feed for secondary membrane units contained within enclosures such as conduit or piping or as feed for a cryogenic air

separation unit (ASU), or a vacuum pressure swing adsorption unit (VPSA), or a temperature swing absorption unit (TSA) or other forms of oxygen separation such as ion transport membranes (ITM). In the case of using 90% oxygen in a flue gas generator, the flue gas can have dry concentrations of CO₂ that exceeds 90%. Another benefit of using primary enrichment is the significant reduction in capital and operating cost of the secondary enrichment system.

A further benefit of another embodiment of the invention is the use of a recycle stream of cooled flue gas to the combustion zone (oxygen enriched feed location) to mitigate higher firing temperatures produced when oxygen enrichment to a flue gas generator is used, also known conventionally as oxy-combustion. This requires a larger vacuum device at the outlet tubesheet if only a primary wig membrane unit is used, or larger vacuum or blower device at the outlet of a secondary enrichment system when a secondary enrichment system is used. Secondary oxygen enrichment with recycle allows for even higher concentrations to be produced in the dried flue gas (over 90% CO₂.) Specifically, when high oxygen concentrations (higher than 35%) oxygen is processed conventionally in a flue gas generator, costly modifications to the furnace refractory and burner are conventionally required. With the disclosed embodiment of the recycle stream, plug and play is allowed with higher concentrations of oxygen enrichment. Plug and play is defined as no modifications being required of the existing burner or refractory of the flue gas generator, because the higher combustion temperature found in conventional oxygen enrichment combustion is mitigated or brought back to conventional air fired combustion temperatures with the cooled and recycled flue gas. Thus, the additional benefit of the recycle stream, that being plug and play, also provides significant savings of capital cost and schedule time due to simplicity of implementation of the embodiment of the invention. A unique vacuum system may be utilized for application of vacuum to the primary and secondary membrane units. The disclosed bellows system is relatively simple and requires low power input to generate the vacuum necessary to process a feed gas through the disclosed membrane units.

Methods of direct air capture of carbon dioxide utilizing membrane members under vacuum is also disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 depicts a prior art pressurized hollow fiber membrane unit with air “pressurized” into the feed tube sheet end of the membrane unit wherein the membrane tubes are fully enclosed (set) within a shell, with permeate flow to the shell nozzle of the membrane unit, for primary (first), secondary (second), or later (third, fourth, etc.) stage(s) bank(s) of an embodiment of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 1A is a sectional view along line 1A-1A of FIG. 1. FIG. 1B is a schematic depiction of a “pressurized” membrane unit including the membrane unit depicted in FIG. 1 which is utilized in other embodiments and figures of the present disclosure.

FIG. 2 depicts an embodiment of an ambient air/residue exposed or draft or pressurized hollow fiber membrane unit wherein there is no shell enclosure, having a “wig” configuration having permeate flowing to both hollow fiber membrane tube sheets of the hollow fiber wig draft membrane unit for primary (first) stage draft bank only, or any (primary,

7

secondary, etc.) stage pressurized bank embodiment of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 2A is a sectional view along line 2A-2A of FIG. 2.

FIG. 2B is a schematic depiction of a generalized embodiment of a draft membrane unit which includes the embodiment of the draft hollow fiber wig membrane unit depicted in FIG. 2.

FIG. 3 depicts an embodiment of a draft or pressurized hollow fiber wig membrane unit having a wig configuration having permeate flowing to both hollow fiber membrane tube sheets, wherein the membrane tubes are set within a perforated shell of the hollow fiber wig membrane unit for primary (first) stage draft bank only, and/or any (primary, secondary, etc.) stage pressurized bank embodiment of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 3A is a sectional view along line 3A-3A of FIG. 3.

FIG. 3B is a schematic depiction of a generalized embodiment of a draft membrane unit which includes the embodiment of the draft (only) hollow fiber wig membrane unit depicted in FIG. 3.

FIG. 4 depicts an embodiment of a draft (only) hollow fiber wig membrane unit wherein there is no shell enclosure having permeate flowing to a single tube sheet having a wig configuration having the tubes blocked on one end of the hollow fiber wig membrane unit for primary (first) stage draft bank only, and/or any (primary, secondary, etc.) stage pressurized bank embodiment of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 4A is a sectional view along line 4A-4A of FIG. 4.

FIG. 4B is a sectional view along line 4B-4B of FIG. 4.

FIG. 4C is a schematic depiction of a generalized embodiment of a draft membrane unit which includes the embodiment of the draft hollow fiber wig membrane unit depicted in FIG. 4.

FIG. 5 depicts an embodiment of a draft or pressurized sheet membrane unit having permeate flowing into slotted or perforated pipe from permeate channels of the sheet membrane unit for primary (first) stage draft bank only, and/or any (primary, secondary, etc.) stage pressurized bank which may be utilized in single or multistage pressurized bank(s) embodiment of a gas phase enrichment system of the present invention.

FIG. 5A is a schematic depiction of the individual membrane and spacer sheets of the sheet membrane unit of FIG. 5.

FIG. 5B is a schematic depiction of a generalized embodiment of a draft membrane unit which includes the embodiment of the draft (only) sheet membrane unit depicted in FIG. 5.

FIG. 6 depicts an embodiment of a pressurized spiral wound (sheet) membrane unit having permeate flowing into a central slotted or perforated pipe from permeate channels of the pressurized spiral wound (sheet) membrane unit for any (primary, secondary, etc.) stage pressurized bank which may be utilized in single or multistage pressurized bank(s) of an embodiment of a gas phase enrichment system of the present invention.

FIG. 6A schematically depicts the individual membrane and spacer sheets of the pressurized spiral wound (sheet) membrane unit of FIG. 6.

FIG. 6B is a schematic depiction of a generalized embodiment of a pressurized membrane unit which includes the embodiment of the pressurized spiral wound (sheet) membrane unit depicted in FIG. 6.

8

FIG. 7 depicts an embodiment of a draft membrane bank of draft (only) membrane units having the general configuration of the draft (only) membrane units depicted in FIGS. 2 and/or 3 herein for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 7A is a schematic depiction of a generalized embodiment of a draft (only) membrane bank including the embodiment of the draft membrane bank depicted in FIG. 7.

FIG. 8 depicts an embodiment of a draft membrane bank of draft (only) membrane units having the general configuration of the draft membrane units depicted in FIGS. 4 and/or 5 herein for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 8A is a schematic depiction of a generalized embodiment of a draft membrane bank including the embodiment of the draft membrane bank depicted in FIG. 8.

FIG. 9 depicts an embodiment of a draft membrane bank of draft (only) membrane units having the general configuration of the draft membrane units depicted in FIGS. 2 and/or 3 and/or 4, and/or 5 herein for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 9A is a schematic depiction of a generalized embodiment of a draft membrane bank including the embodiment of the draft membrane bank depicted in FIG. 9.

FIG. 10 depicts an embodiment of a pressurized membrane bank of membrane units utilized in any stage of a gas phase single or multistage bank(s) enrichment system, the pressurized membrane units including the embodiment of the pressurized membrane unit depicted in FIG. 1.

FIG. 10A is a schematic depiction of a generalized embodiment of a pressurized membrane bank including the embodiment of the pressurized membrane bank depicted in FIG. 10.

FIG. 11 depicts an embodiment of a pressurized membrane bank of membrane units utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system, the pressurized membrane units including the embodiments of pressurized membrane units (only) depicted in FIGS. 2 and 3.

FIG. 11A is a sectional view taken along line 11A-11A of FIG. 11.

FIG. 11B is a schematic depiction of a generalized embodiment of a pressurized membrane bank including the embodiment of the pressurized membrane bank depicted in FIG. 11.

FIG. 12 depicts an embodiment of a pressurized membrane bank of membrane units utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system, the pressurized membrane unit including the embodiment of pressurized membrane units (only) depicted in FIG. 5.

FIG. 12A is a schematic depiction of a generalized embodiment of a pressurized membrane bank including the embodiment of the pressurized membrane bank depicted in FIG. 12.

FIG. 13 depicts an embodiment of a pressurized membrane bank of pressurized membrane units utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system, the pressurized membrane unit including the embodiment of pressurized membrane units depicted in FIG. 6.

FIG. 14 schematically depicts a generalized pressure differential apparatus which may be utilized in embodiments of the disclosed system and process.

FIG. 14A depicts an embodiment a liquid ring vacuum pump system which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a vacuum.

FIG. 14B schematically depicts a reciprocating compressor which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a positive pressure.

FIG. 14C schematically depicts a centrifugal blower which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a positive pressure.

FIG. 15 depicts another embodiment of a pressure differential apparatus (bellows tank) which may be utilized in embodiments of the disclosed system and process.

FIG. 15A is a schematic depiction of a generalized pressure differential apparatus which includes the embodiment depicted bellows tank in FIG. 15.

FIG. 16 schematically depicts a pressurized primary (1st stage) membrane bank system which may utilize membrane banks as depicted in FIGS. 10 through 13, the system having a pressure differential apparatus upstream of the pressurized membrane bank, the pressurized membrane bank system also having a pressure control apparatus on the residue stream.

FIG. 17 schematically depicts a draft membrane bank system which may utilize membrane banks as depicted in FIGS. 7 through 9, the system having a pressure differential apparatus as depicted in FIGS. 14 through 15 downstream of the draft membrane bank.

FIG. 18 schematically depicts a membrane bank as depicted in FIGS. 10 through 13 having a pressure differential apparatus on both the upstream and downstream sides of the membrane bank, the membrane bank further comprising a pressure controlled residue stream.

FIG. 19 schematically depicts a two stages enrichment system with both stages having pressurized membrane banks as depicted in any of FIGS. 10 through 13 configured as pressurized membrane bank systems depicted in either FIG. 16 or 18.

FIG. 20 schematically depicts a two stages enrichment system with the first stage system configured as a draft membrane bank system as depicted in FIG. 17 and the second stage configured as a pressurized membrane bank system from in either FIG. 16 or 18.

FIG. 21 schematically depicts three stages of an enrichment system with the first two stages configured as in FIG. 19 with the third stage comprising a recycled residue stream to the intake of the second stage.

FIG. 21A schematically depicts the three stages of an enrichment system depicted in FIG. 21, but also comprising a dessicant or refrigeration apparatus between the first and second stage configured to provide water removal from the gas prior to entry into the second stage as well as provide a pressure driver for an optional outlet stream of permeate.

FIG. 22 schematically depicts three stages of an enrichment system with the first two stages configured as the system depicted in FIG. 20, with the third stage comprising a pressurized membrane bank system as depicted in FIG. 16 or 18 comprising a recycled residue stream to the intake of the second stage.

FIG. 22A schematically depicts the three stages of an enrichment system depicted in FIG. 22, but also comprising a dessicant or refrigeration gas drying apparatus between the first and second stage configured to provide water removal

from the gas prior to entry into the second stage as well as provide a pressure driver for an optional outlet stream of permeate.

FIG. 23 schematically depicts a flue gas generator with conventional combustion air feed and fuel gas, having a cooling apparatus and a gas driver apparatus on the flue gas.

FIG. 24 schematically depicts the flue gas generator of FIG. 23 to which any of the systems depicted in FIGS. 16 through 22 may be utilized to enrich the combustion air to the burner.

FIG. 25 schematically depicts a pressurized flue gas generator with recycled and cooled flue gas to flue gas feed to which any of the systems depicted in FIGS. 16 through 22 may be utilized to enrich the combustion air to the burner.

FIG. 26 schematically depicts a draft membrane bank disposed at an air cooler fan discharge for improving draft membrane unit performance, the draft membrane bank unit being any those as depicted in FIGS. 7 through 9.

FIG. 27 depicts a membrane system with a flue gas generator (mobile or stationary) which may be utilized in providing an enriched stream of carbon dioxide in an agricultural application.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Referring now to the Figures, FIGS. 1, 1A and 1B depict a prior art configuration of a hollow fiber membrane unit 10. Membrane unit 10 has a membrane housing 12 comprising a plurality of hollow fiber membrane tubes 14, where the wall of each of the hollow fiber membrane tubes is a selective barrier through which certain components readily pass through and other components do not. The membrane unit 10 has tube sheets 16 at each of the ends of the membrane unit, which bind the outer walls of the hollow fiber tubes to each other and support the tube bundle within the membrane housing 12. An inlet 18 is at one end of the membrane unit 14 and an outlet 20 is at the other end.

Gas having an initial composition comprising both fast gas components and slow gas components enters the membrane unit 10 through inlet 18, with the fast gas components permeating the selective barrier of the tube walls more readily than the slow gas components. A residue gas exits the membrane unit 14 through outlet 20 and a permeate stream exists the membrane unit through permeate nozzle 22. The residue gas has, on a per volume basis, a reduced concentration of the faster gas components and an enriched concentration of the slower gas components. Likewise, the permeate stream has, on a per volume basis, a reduced concentration of the slower gas components and an increased concentration of fast gas components. This configuration of a hollow fiber membrane unit 10 receives the gas through the inlet 18 under pressure and membrane housing (or shell) 12 is necessary to contain the pressurized gas and to support the membrane tubes 14. It is to be appreciated that housing 12 is relatively heavy and it adds to the weight and expense of the membrane unit 10.

FIGS. 2, 2A and 2B depict a membrane unit 100 of the present invention having a "wig" configuration which may be utilized in an open air (i.e., "draft") application. As discussed above, "wig" configuration refers to a construction comprising a plurality of individual hollow fiber membrane elements 114 which all pass a gas permeate into a collection member commonly, but not necessarily, at a common end of the membrane elements. Membrane unit 100 has the same hollow fiber membrane tubes 114, such that the fast gas components passing more readily through

11

the selective barrier of the walls of tubes **114** than the slow gas components. In contrast to the prior art membrane unit **10**, membrane unit **100** has no housing **12** and does not have a discrete inlet comparable to that of inlet **18** of the prior art membrane unit **10**. Instead, the exteriors of tubes **114** are exposed to gas **G** of an ambient environment. In one of the embodiments of the present invention fast gas components preferentially flow through the selective barrier of each membrane tube **114**, with permeate gas flowing out through permeate outlets **120**. Gas components making up a “residue” stream simply comprise those components which do not pass through the walls of the membrane tubes **114** flowing past the membrane unit **100**. Membrane unit **100** comprises tubesheets **116**, which will be substantially lighter than tube sheets **16** of the prior art membrane unit **10** thereby saving on weight and expense.

Gas **G** may comprise ambient air having a concentration of oxygen, nitrogen, carbon dioxide and water vapor. For the selective barrier of the hollow fiber membrane elements of the present invention, oxygen, carbon dioxide and water vapor are considered to be “fast gas” components and nitrogen is a “slow gas” component. Thus, in one embodiment of the invention, a membrane unit **100** disposed in an environment of ambient air will produce a permeate having an enriched concentration of oxygen, carbon dioxide and water vapor where the permeate will also have a depleted concentration of nitrogen.

FIGS. **3**, **3A**, **3B** depict a membrane unit **200** of the present invention depicts an embodiment of a draft or pressurized hollow fiber wig membrane unit having a wig configuration having permeate flowing to both hollow fiber membrane tube sheets **216**. Similar to membrane unit **100**, membrane unit **200** comprises a plurality of hollow fiber membrane tubes **214** with each tube having a selective barrier wall which, in some embodiments of the invention, passes fast gas components to the interior of each tube more readily than slow gas components. The resulting permeate having a higher concentration of fast gas components than the ambient gas **G** flows to the outlets **220** adjacent tube sheets **216**. However, in contrast to the embodiments of the membrane unit depicted in FIGS. **2** and **2A**, membrane unit **200** is set within a perforated shell **212**, thereby providing additional support and containment for the hollow fiber membrane tubes **214**.

FIGS. **4**, **4A** and **4B** depict an embodiment of a draft (only) hollow fiber wig membrane unit **300** having no shell or enclosure and having permeate flowing to a single tube sheet **316**. In this embodiment of the membrane unit **300**, hollow fiber tubes **314** have one end of each of the hollow fiber tubes **314** blocked with plug sheet **316'** which collectively blocks all of the tubes or each tube may be individually plugged or capped. Similar to membrane units **100** and **200**, membrane unit **300** comprises a plurality of hollow fiber membrane tubes **314** with each tube having a selective barrier wall which, in some embodiments of the invention, passes fast gas components to the interior of each tube more readily than slow gas components. The resulting permeate has a higher concentration of fast gas components than the ambient gas **G** flows to the outlet **320** adjacent the tube sheet **316**.

FIGS. **5**, **5A** and **5B** depict an embodiment of a draft or pressurized sheet membrane unit **400** having permeate flowing into slotted or perforated pipe from permeate channels of the sheet membrane unit for primary (first) stage draft bank only, and/or any (primary, secondary, etc.) stage pressurized bank which may be utilized in single or multistage pressurized bank(s) embodiment of a gas phase enrichment system

12

of the present invention. Membrane unit **400** has a slotted collection pipe **424** having a permeate collection pipe slot **426**. A sheet membrane element **428** may have a top membrane sheet **430** and a bottom membrane sheet **432** glued only on three sides to a ribbed sheet **434**, where a top permeate channel is defined between the top membrane sheet **430** and the ribbed sheet **434** and a bottom permeate channel is defined between the bottom membrane sheet **432** and the ribbed sheet **434**. The fourth side of sheet membrane element is not glued comprising open ends of top and bottom membrane elements which extend over the permeate collection pipe slot **426**.

FIGS. **6**, **6A** and **6B** depict an embodiment of a pressurized spiral wound (sheet) membrane unit **500**. In this embodiment of the membrane unit **50** feed enters into the front face **502** of each unit and the residue stream leaves the rear face **504** of each unit. Spiral wound membrane unit **500** is fabricated from alternating sheets of membrane sheets, each comprising a selective barrier, and spacer sheets. FIG. **6A** shows an expanded detail of an unwound membrane unit, where the spiral membrane unit has the following elements: (1) a bottom feed/residue spacer **506**; (2) a bottom membrane sheet **508**; (3) a permeate spacer **510**; (4) a top membrane sheet **512**; (5) a top feed/residue spacer **514**; (6) a bottom feed/residue channel **516**; (7) a bottom feed permeate channel **518**; (8) a top permeate channel **520**; and (9) a top feed/residue channel **522**. The membrane sheet layers **508**, **512** are glued to the feed/residue spacers **506**, **514** at the front edges only and glued to the permeate spacer **510** at the front and the side edges. The open ends of permeate channels **518**, **520** are attached over perforations **526** in a permeate collection pipe **528**. The top feed/residue spacer **514** is longitudinally ribbed on the bottom of the spacer and the bottom feed/residue spacer **506** is longitudinally ribbed on the top of the spacer. Permeate spacer **510** is laterally ribbed on the top and bottom of the spacer.

Gas flows in a spiral pattern through the spiral wound membrane unit **500** with the permeate received by permeate collection pipe **528**. The ends of permeate collection pipe **528** may be threaded so that the spiral wound membrane units **500** may be attached in end-to-end configuration for collection of the permeate. An assembly of multiple spiral wound membrane units **500** may be connected to a permeate collection header.

FIGS. **7**, **7A** depict an embodiment of a draft membrane bank **600** of draft (only) membrane units **610** having the general configuration of the membrane units **100**, **200** described above and depicted in FIGS. **2** and/or **3** or the like. Draft membrane bank **600** is utilized as a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention. The exteriors of the banked membrane units **610** are exposed to gas **G** of an ambient environment. Fast gas components preferentially flow through the selective barrier of each membrane unit with permeate gas flowing out and collected through permeate headers **602** and directed to a permeate processing facility, which may include a second stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility.

FIGS. **8**, **8A** depict an embodiment of a draft membrane bank **700** of draft (only) membrane units **710**, which may include membrane units **300**, **400** described above and depicted in FIGS. **4** and/or **5** or the like. Draft membrane bank **700** is utilized for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention. The exteriors of the banked membrane units **710** are exposed to gas **G** of an ambient

13

environment. Fast gas components preferentially flow through the selective barrier of each membrane unit **710** with permeate gas flowing out and collected through permeate header **702** and directed to a permeate processing facility, which may include a second stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility.

FIGS. **9**, **9A** depict an embodiment of a draft membrane bank **800** of draft (only) membrane units **810**, which may include membrane units **100**, **200**, **300**, **400** described above and depicted in FIGS. **2** and/or **3** and/or **4**, and/or **5** or the like. Draft membrane bank **800** is utilized for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention. The exteriors of the banked membrane units **810** are exposed to gas **G** of an ambient environment. Fast gas components preferentially flow through the selective barrier of each membrane unit **810** with permeate gas flowing out and collected through permeate header **802** and directed to a permeate processing facility, which may include a second stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility.

FIGS. **10**, **10A** depict an embodiment of a pressurized membrane bank **900** of pressurized membrane units **910** utilized in any stage of a gas phase single or multistage bank(s) enrichment system. The pressurized membrane units **910** may include embodiments of the pressurized membrane unit **10** depicted in FIG. **1**. Pressurized bank **900** receives a stream of gas through inlet header **902** and may discharge the resulting permeate gas through permeate outlet header **904** and may discharge residual gas through residual outlet header **906**. Permeate outlet header **904** may direct the permeate to a permeate processing facility, which may include a further stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility. Residual outlet header **906** may appropriately discharge or recycle the residual gas stream.

FIGS. **11**, **11A**, **11B** depicts an embodiment of a pressurized membrane bank **1000** of membrane units **1010**. Membrane units **1010** utilized in pressurized membrane bank **1000** may include embodiments of the membrane units **100**, **200** described above and depicted in FIGS. **2** and **3**. Pressurized membrane bank receives a stream of gas through inlet **1002** and may discharge the resulting permeate gas through permeate outlet headers **1004** and may discharge residual gas through outlet **1006**. Permeate outlet headers **1004** may direct the permeate to a permeate processing facility, which may include a further stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility. Outlet **1006** may appropriately discharge or recycle the residual gas stream. Membrane units **1010** are contained within a shell **1020**. Pressurized membrane bank **1000** may be utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system.

FIGS. **12**, **12A** depict an embodiment of a pressurized membrane bank **1100** of membrane units **1110**. Membrane units **1110** utilized in pressurized membrane bank **1100** may include embodiments of the membrane units **400** described above and depicted in FIG. **5**. Pressurized membrane bank **1100** receives a stream of gas through inlet **1102** and may discharge the resulting permeate gas through permeate outlet headers **1104** and may discharge residual gas through residual outlets **1106**. Permeate outlet headers **1104** may direct the permeate to a permeate processing facility, which may include a further stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility. Residual outlets **1106** may appropriately discharge or

14

recycle the residual gas stream. Membrane units **1110** are contained within a shell **1120** which may include low pressure ducting. Pressurized membrane bank **1100** may be utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system.

FIGS. **13**, **13A** depict an embodiment of a pressurized membrane bank **1200** of membrane units **1210**. Membrane units **1210** utilized in pressurized membrane bank **1200** may include embodiments of the membrane units **500** described above and depicted in FIG. **6**. Pressurized membrane bank **1200** receives a stream of gas through inlet **1202** and may discharge the resulting permeate gas through permeate outlet headers **1204** and may discharge residual gas through residual outlets **1206**. Permeate outlet headers **1204** may direct the permeate to a permeate processing facility, which may include a further stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility. Residual outlets **1206** may appropriately discharge or recycle the residual gas stream. Membrane units **1210** are contained within a shell **1220** which may include low pressure ducting. Pressurized membrane bank **1200** may be utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system.

FIG. **14** schematically depicts a generalized pressure differential apparatus **1300**, which may be utilized in embodiments of the disclosed system and process to provide pressure or vacuum to the selective barriers of the various disclosed membrane units discussed above. FIG. **14A** schematically depicts a pressure differential apparatus **1300'** comprising a liquid ring vacuum pump system which is one embodiment of differential pressure apparatus which may be utilized, comprising a liquid ring vacuum pump system. FIG. **14B** schematically depicts a pressure differential apparatus **1300''** comprising a reciprocating compressor system which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a positive pressure. FIG. **14C** schematically depicts a pressure differential apparatus **1300'** comprising a centrifugal blower system which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a positive pressure.

Another embodiment of a pressure differential apparatus is depicted in FIGS. **15**, **15A**. This embodiment of pressure differential apparatus comprises a bellows tank **1400**. Bellows tank **1400** may have a double-acting piston **1402** set within a large cylinder **1404**. Piston **1402** may have graphite rings and/or the cylinder walls **1406** may comprise graphite. Actuation devices **1408**, **1410** respectively utilize connectors **1412**, **1414** to actuate piston **1402** in either direction within the cylinder **1404**. It is to be appreciated that large cylinder **1404** need not be a pressure vessel and that actuation devices **1408**, **1410** may be small winches driven by small motors and connectors **1412**, **1414** may be light rods or small diameter cables. Double-acting piston **1402** may be diamond-shaped to provide additional structural integrity under vacuum conditions. Bellows tank **1400** applies vacuum to a connected membrane unit on each upstroke, relative to the position of intake/discharge lines **1416**, **1418** which are connected to the membrane units, with an upstroke causing permeate to be pulled into cylinder **1404** through the intake/discharge line receiving vacuum on the upstroke. On each downstroke permeate is pushed out of the cylinder **1404** through intake/discharge lines **1416**, **1418**, with the flow direction controlled by the action of check valves **1420**.

FIG. **16** schematically depicts a pressurized primary (1st stage) membrane bank system **1500** comprising a pressur-

15

ized membrane bank **1510**. The pressurized membrane bank **1510** may comprise embodiments of pressurized membrane banks **900**, **1000**, **1100**, **1200** described above and depicted in FIGS. **10** through **13**. Membrane bank system **1500** has a pressure differential apparatus **1502** upstream of the pressurized membrane bank, where the pressure differential apparatus may comprise the various embodiments depicted in FIG. **14** (including **14A**, **14B** and **14C**) and the bellows tank **1400** depicted in FIG. **15**. The pressurized membrane bank **1500** may also have a pressure control apparatus **1514** on the residue stream.

FIG. **17** schematically depicts a draft membrane bank **1600** system comprising a membrane bank **1610**. Membrane bank **1610** may comprise membrane banks **600**, **700**, and **800** described above and depicted in FIGS. **7** through **9**. Membrane bank system **1600** has a pressure differential apparatus **1612** downstream of the pressurized membrane bank **1610**, where the pressure differential apparatus may comprise the various embodiments depicted in FIG. **14** (including **14A**, **14B** and **14C**) and the bellows tank **1400** depicted in FIG. **15**.

FIG. **18** schematically depicts a pressurized primary (1st stage) membrane bank system **1700** comprising a pressurized membrane bank **1710**. The pressurized membrane bank **1710** may comprise embodiments of pressurized membrane banks **900**, **1000**, **1100**, **1200** described above and depicted in FIGS. **10** through **13**. Membrane bank system **1700** has a pressure differential apparatus **1702** upstream of the pressurized membrane bank, where the pressure differential apparatus may comprise the various embodiments depicted in FIG. **14** (including **14A**, **14B** and **14C**) and the bellows tank **1400** depicted in FIG. **15**. Membrane bank system **1700** also has a pressure differential apparatus **1712** downstream of the pressurized membrane bank **1710**, where the pressure differential apparatus may again comprise the various embodiments depicted in FIG. **14** (including **14A**, **14B** and **14C**) and the bellows tank **1400** depicted in FIG. **15**. The pressurized membrane bank **1700** may also have a pressure control apparatus **1714** on the residue stream.

FIG. **19** schematically depicts a two stages enrichment system **1800** with both stages having pressurized membrane banks **1810**. Membrane banks **1810** may comprises membrane banks **900**, **1000**, **1100**, **1200** described above and as depicted in any of FIGS. **10** through **13** and configured as pressurized membrane bank systems **1500**, **1700** as described above and depicted in either FIG. **16** or **18**.

FIG. **20** schematically depicts a two stages enrichment system **1900** with a first stage system **1910** which may be configured utilizing draft membrane system **1600** as described above and depicted in FIG. **17**. Second stage **1920** may be configured as a pressurized membrane bank system utilizing pressurized bank systems **1500**, **1700** as as described above and depicted in FIG. **16** or **18**.

FIG. **21** schematically depicts a three stage of an enrichment system **2000** comprising a first stage **2010**, a second stage **2012** and a third stage **2014**. First stage first **2010** and the second stage **2012** may utilize a two-stage enrichment system utilizing the configuration of two stage system **1800** described above and as depicted in FIG. **19**. Third stage **2014** comprises a conduit **2016** which provides a recycled residue stream to the intake of the second stage **2012**.

FIG. **21A** schematically depicts a three stage of an enrichment system **2000'** comprising a first stage **2010'**, a second stage **2012'** and a third stage **2014'**. First stage first **2010'** and the second stage **2012'** may utilize a two-stage enrichment system utilizing the configuration of two stage system **1800** described above and as depicted in FIG. **19**. Third stage

16

2014' comprises a conduit **2016'** which provides a recycled residue stream to the intake of the second stage **2012'**. However enrichment system **2000'** further comprises a desiccant or refrigeration apparatus **2008** between the first stage **2010'** and the second stage **2012'** configured to provide water removal from the gas prior to entry into the second stage as well as provide an optional outlet stream of water.

FIG. **22** schematically depicts a three stage enrichment system **2100** comprising a first stage **2110**, a second stage **2112** and a third stage **2114**. First stage first **2110** and second stage **2112** may a two-stage enrichment system utilizing the configuration of two stage system **1900** described above and as depicted in FIG. **20**. Third stage **2114** comprises a conduit **2116** which provides a recycled residue stream to the intake of the second stage **2112**.

FIG. **22A** schematically depicts a three stage of an enrichment system **2100'** comprising a first stage **2110'**, a second stage **2112'** and a third stage **2114'**. First stage first **2110'** and the second stage **2112'** may utilize a two-stage enrichment system utilizing the configuration of two stage system **1900** described above and as depicted in FIG. **20**. Third stage **2114'** comprises a conduit **2116'** which provides a recycled residue stream to the intake of the second stage **2112'**. However enrichment system **2100'** further comprises a desiccant or refrigeration apparatus **2108** between the first stage **2110'** and the second stage **2112'** configured to provide water removal from the gas prior to entry into the second stage as well as provide an optional outlet stream of water.

FIG. **23** schematically depicts a flue gas generator **2200** with conventional combustion air feed and fuel gas, having a cooling apparatus C and a gas driver apparatus D on the flue gas. FIG. **24** schematically depicts a flue gas generator **2200'** similar to that depicted in FIG. **23** but further comprising a combustion air enrichment apparatus **2202**. Air enrichment apparatus may include in of the systems **1500**, **1600**, **1700**, **1800**, **1900**, **2000** and **2100** described above and as depicted in FIGS. **16** through **22** to enrich the combustion air to the burner. FIG. **25** schematically depicts a pressurized flue gas generator **2200"** having a liquid water removal apparatus L on the flue gas discharge and a combustion air enrichment apparatus **2202** with recycled and cooled flue gas to flue gas feed. Air enrichment apparatus may include in of the systems **1500**, **1600**, **1700**, **1800**, **1900**, **2000** and **2100** described above and as depicted in FIGS. **16** through **22** to enrich the combustion air to the burner.

FIG. **26** schematically depicts a flue gas generator F having flue gas discharged to an air cooler fan **2302** and processed through cooling apparatus C. A draft membrane bank **2300** is disposed at the air cooler fan discharge **2304** for improving draft membrane unit performance, where the draft membrane banks may comprise draft membrane banks **600**, **700** and **800** as described above and depicted in FIGS. **7** through **9**.

FIG. **27** depicts an enrichment system **2400** deployed within an orchard comprising trees T. It is to be appreciated that a tree orchard may be utilized as a sequestering facility which utilizes photosynthetic organisms (trees) to sequester carbon dioxide. Enrichment system **2400** may comprise a plurality of membrane units **2410** as disclosed herein. Membrane units **2410** may capture and enrich carbon dioxide in the vicinity of the trees T. Membrane units **2410** may also be disposed around the perimeter of the orchard to capture "fugitive" carbon dioxide which has not been utilized in photosynthesis. Moreover, for orchards utilizing carbon dioxide emitting mechanisms, such as flue gas generators, for support purposes, the enrichment system may be utilized to both make those flue gas generators more fuel efficient by

17

increasing oxygen concentration in the intake air and to also capture carbon dioxide in the exhaust and enrich and cool it for application to the orchard. Thus, enrichment system **2400** may further comprise a stationary or mobile flue gas generator **2450**. Flue gas generator **2450** may have an economizer (not shown). Membrane units **2410** may also be utilized to provide oxygen enriched air to the intake of the flue gas generator **2450**. Flue gas generator **2450** may provide a flue gas having elevated level of carbon dioxide which may be enriched with membrane units **24** an enriched stream of carbon dioxide in an agricultural application. Flue gas generator **2450** may send hot gas to one or more cooling devices **2452** which may comprise a dry ice containment or a quench column device. Discharge from cooling devices **2452** will have an enriched carbon dioxide concentration which may be pressurized by a blower **2454** for further distribution for either distribution to trees **T** or to provide additional cooling for the air intake of the flue gas generator **2450**. A vacuum pump **2456** may be utilized to provide vacuum to the various membrane units **2410**.

18

As indicated, FIG. **27** depicts the following flow streams for five different cases

- 1—fuel gas to the flue gas generator
- 2—enriched O₂/CO₂ from the membrane permeate header to vacuum pump **2456**.
- 3.—dried CO₂ recirculated for cooling.
- 4.—intake at vacuum pump **2456**.
- 5.—vacuum pump discharge for cooling into the flue gas generator economizer.
- 6.—hot exhaust from the flue gas generator **2450**.
- 7.—cooled gas discharge from blower **2454**.
- 8.—intake to second cooling device **2454**.
- 9.—enriched CO₂ stream for orchard distribution.

The tables presented below provide examples of the heat and material balances which may be realized utilizing a system as shown in FIG. **27** for five different scenarios utilizing the presently disclosed Membrane Air Enrichment (“MAE”) process in a ten tree orchard utilized as a sequestration facility.

TABLE 1

for Case 1: Simplified Heat and Material Balance for MAE Process								
Air Feed Case (20.8% O ₂)								
BASIS: 50 Tons CO ₂ /Y for 10 almond trees, Quench Makes 35 Tons Water/Y								
Process Parameters/Stream Names	Stream Numbers							
	1	2	3	4	5	6	7	8
	Fuel****	Air	Dry Recirc	Vac Suct	Vac Disch	Flue Gas	Cool FG	Crop Carbon
Absolute Pressure, psia	25	14.7	N/A	N/A	N/A	14.7	15	15
Temperature F. **	Ambient	Ambient				350	90	90
Gas Standard Volumetric Rate, SCFM	6.32	60.70				67.02	55.83	55.83
Total Molar Flow Rate- LbMole/Hr)	1	9.602				10.602	8.831288	8.831287082
Mole Balance, lb mols/hr								
Methane (CH ₄ — LbMole/Hr)	1	0				0	0	0
Oxygen (O ₂ — LbMole/Hr)	0	2				0	0	0
Nitrogen (N ₂ — LbMole/Hr)	0	7.4				7.4	7.4	7.4
Water (H ₂ O— LbMole/Hr)	0	0.196				2.196	0.41957	0.4195703
Carbon Dioxide (CO ₂ — LbMole/Hr)	0	0.006				1.006	1.006	1.006
Mole Percent								
Methane (CH ₄ — Mole Percent)	100.0	0.0				0.0	0.0	0.0
Oxygen (O ₂ — Mole Percent)	0.0	20.8				0.0	0.0	0.0
Nitrogen (N ₂ — Mole Percent)	0.0	77.1				69.8	83.8	83.8
Water (H ₂ O— Mole Percent)	0.0	2.0				20.7	4.8	4.8
Carbon Dioxide (CO ₂ — Mole Percent)	0.0	0.0625				9.5	11.4	11.4
Total	100.0	100.0				100.0	100.0	100.0
Mass Balance, Tons/yr								
Methane (CH ₄ — Tons/yr)	17.5	0.0				0.0	0.0	0.0
Oxygen (O ₂ — Tons/yr)	0.0	70.1				0.0	0.0	0.0
Nitrogen (N ₂ — Tons/yr)	0.0	226.9				226.9	226.9	226.9
Water (H ₂ O— Tons/yr)	0.0	3.9				43.3	8.3	8.3
Carbon Dioxide (CO ₂ —Tons/yr)	0.0	0.3				48.5	48.5	48.5
Total, Tons/yr	17.5	301.1				318.6	283.6	283.6

for Case 2 Simplified Heat and Material Balance for MAE Process
33% O2 Enrich Feed Case
BASIS: 50 Tons CO₂/Y for 10 almond trees, Quench Makes 35 Tons Water/Y
Gross 30% Increase in Duty of Steam/Power Generation- Net 20% Increase with vacuum pump deduct

TABLE 3

Heat and Material Balances for New MAE Process: BASIS 50 Tons/Year CO₂ for 10 almond trees Using Quench
40% Increase in Duty of Existing Steam/Power Generation Device

[illegible]

TABLE 3-continued

for Case 3 Heat and Material Balances for New MAE Process: BASIS 50 Tons/Year CO2 for 10 almond trees Using Quench 40% Increase in Duty of Existing Steam/Power Generation Device								
Process Parameters/Stream Names	Stream Numbers							
	1 Fuel****	2 Comb O2	3 Dry Recirc	4 Vac Suct	5 Vac Disch	6 Flue Gas	7 Cool FG	8 Crop Carbon
Mass Balance, Tons/yr ***								
Methane (CH4— Tons/yr)	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen (O2— Tons/yr)	0.0	70.1	0.0	70.1	70.1	0.0	0.0	0.0
Nitrogen (N2— Tons/yr)	0.0	61.3	30.7	92.0	92.0	92.0	92.0	61.3
Water (H2O— Tons/yr)	0.0	1.6	0.0	1.6	1.6	41.0	0.0	0.0
Carbon Dioxide (CO2—Tons/yr)	0.0	0.1	25.4	25.5	25.5	73.7	76.1	50.7
Total, Tons/yr	17.5	133.1	56.0	189.2	189.2	206.7	168.1	112.1

TABLE 4

for Case 4								
Heat and Material Balances for New MAE	Basis 50 T 50% O2		/Year Enrich	CO2 Without		Recirc		
60% Increase in Duty of New Steam/Power Generation								
	Stream Numbers							
Process Parameters/Stream Names	1 Fuel****	2 Comb O2	3 Dry Recirc	4 Vac Suct	5 Vac Disch	6 Flue Gas	7 Cool FG	8 Crop Carbon
Absolute Pressure, psia	25	3.8			16		16	15
Temperature F. **	Ambient	Ambient		Ambient	200		170	60
Gas Standard Volumetric Rate, SCFM	6.32	25.81			25.81	32.13	19.30	19.30
Total Molar Flow Rate- LbMole/Hr)	1	4.083			4.083	5.083	3.053	3.053
Mole Balance, lb mols/hr								
Methane (CH4— LbMole/Hr)	1	0	0	0	0	0	0	0
Oxygen (O2— LbMole/Hr)	0	2	0	2	2	0	0	0
Nitrogen (N2— LbMole/Hr)	0	2	0	2	2	2	2	2
Water (H2O— LbMole/Hr)	0	0.08	0	0.08	0.08	2.08	0	0
Carbon Dioxide (CO2— LbMole/Hr)	0	0.003	0	0.003	0.003	1.003	1.053	1.053
Mole Percent								
Methane (CH4— Mole Fraction)	100.0	0.0	0	0.0	0.0	0.0	0.0	0.0
Oxygen (O2— Mole Fraction)	0.0	49.0	0	49.0	49.0	0.0	0.0	0.0
Nitrogen (N2— Mole Fraction)	0.0	49.0	0	49.0	49.0	39.3	65.5	65.5
Water (H2O— Mole Fraction)	0.0	2.0	0	2.0	2.0	40.9	0.0	0.0
Carbon Dioxide (CO2— Mole Fraction)	0.0	0.07	0	0.1	0.1	19.7	34.5	34.5
Total	100.0	100.0	0	100.0	100.0	100.0	100.0	100.0
Mass Balance, Tons/yr ***								
Methane (CH4— Tons/yr)	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen (O2— Tons/yr)	0.0	70.1	0.0	70.1	70.1	0.0	0.0	0.0
Nitrogen (N2— Tons/yr)	0.0	61.3	0.0	61.3	61.3	61.3	61.3	61.3
Water (H2O— Tons/yr)	0.0	1.6	0.0	1.6	1.6	41.0	0.0	0.0
Carbon Dioxide (CO2—Tons/yr)	0.0	0.1	0.0	0.1	0.1	48.3	50.7	50.7
Total, Tons/yr	17.5	133.1	0.0	133.1	133.1	150.6	112.1	112.1

TABLE 5

for Case 5								
Heat and Material Balances for New MAE Process: BASIS 80 Tons/Year CO ₂ for 10 almond trees Using 9.6 Tons/Yr Dry Ice Standard Air to Bio Gas Supplemented with Natural Gas								
Process Parameters/Stream Names	Stream Numbers							
	1	2	3	4	5A	6	7	8
	Fuel	Comb O ₂	Dry Recirc	Vac Suct	Air	Flue Gas	Cool FG	Crop Carbon
Absolute Pressure, psia	25	3.8	3.8	3.8	14.7	15	16	15
Temperature F. **	Ambient	Ambient	50	Ambient	Ambient	350	170	60
Gas Standard Volumetric Rate, SCFM	9.17	0.00	0.00	0.00	60.69	69.85	57.24	57.24
Total Molar Flow Rate- LbMole/Hr)	1.45	0	0	0	9.6	11.05	9.054	9.054
Mole Balance, lb mols/hr								
Methane (CH ₄ — LbMole/Hr)	1	0	0	0	0	0	0	0
Oxygen (O ₂ — LbMole/Hr)	0	0	0	0	2	0	0	0
Nitrogen (N ₂ — LbMole/Hr)	0	0	0	0	7.4	7.4	7.4	7.4
Water (H ₂ O— LbMole/Hr)	0	0	0	0	0.196	2.196	0	0
Carbon Dioxide(CO ₂ — LbMole/Hr)	0.45	0	0	0	0.004	1.454	1.654	1.654
Mole Percent								
Methane (CH ₄ — Mole Fraction)	69.0	0.0	0	0.0	0.0	0.0	0.0	0.0
Oxygen (O ₂ — Mole Fraction)	0.0	0.0	0	0.0	20.8	0.0	0.0	0.0
Nitrogen (N ₂ — Mole Fraction)	0.0	0.0	0	0.0	77.1	67.0	81.7	81.7
Water (H ₂ O— Mole Fraction)	0.0	0.0	0	0.0	2.0	19.9	0.0	0.0
Carbon Dioxide (CO ₂ — Mole Fraction)	31.0	0.00	0	0.0	0.0	13.2	18.3	18.3
Total	100.0	0.0	0.0	0.0	100.0	100.0	100.0	100.0
Mass Balance, Tons/yr ***								
Methane (CH ₄ — Tons/yr)	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen (O ₂ — Tons/yr)	0.0	0.0	0.0	0.0	70.1	0.0	0.0	0.0
Nitrogen (N ₂ — Tons/yr)	0.0	0.0	0.0	0.0	226.9	226.9	226.9	226.9
Water (H ₂ O— Tons/yr)	0.0	0.0	0.0	0.0	3.9	43.3	0.0	0.0
Carbon Dioxide (CO ₂ —Tons/yr)	21.7	0.0	0.0	0.0	0.2	70.1	79.7	79.7
Total, Tons/yr	39.2	0.0	0.0	0.0	301.0	340.2	306.6	306.6

While the above is a description of various embodiments of the present invention, further modifications may be employed without departing from the spirit and scope of the present invention. Thus the scope of the invention should not be limited according to these factors, but according to the claims of the forthcoming non-provisional patent application.

What is claimed is:

1. An apparatus for direct air capture of gas components from an ambient environment at atmospheric pressure, wherein the ambient environment comprises a first concentration of fast gas components and a first concentration of slow gas components, the apparatus comprising:

a shell-less membrane unit comprising a selective barrier and a permeate channel wherein the selective barrier is exposed to the first concentration of fast gas components at atmospheric pressure and the selective barrier is exposed to the first concentration of slow gas components at atmospheric pressure, wherein a portion of fast gas components and a portion of slow gas components flow through the selective barrier surface to the permeate channel as a result of a pressure differential across the selective barrier;

a pressure differential device which applies the pressure differential across the selective barrier of the shell-less membrane unit, the pressure differential device selected from the group consisting of a liquid ring vacuum system, a reciprocating compressor system, a centrifugal blower system, and a bellows tank;

a conduit connecting the permeate channel to a permeate processing facility, wherein as the pressure differential is applied across the barrier of the shell-less membrane unit, a first permeate stream forms in the permeate channel, wherein the first permeate stream comprises a second concentration of fast gas components and a second concentration of slow gas components, wherein the second concentration of fast gas components is greater than the first concentration of fast gas components and the second concentration of slow gas components is less than the first concentration of slow gas components; and

wherein at least a portion of the first permeate stream is delivered through the conduit to the permeate processing facility.

2. The apparatus of claim 1 comprising a plurality of shell-less membrane units configured into a membrane bank.

3. The apparatus of claim 1 wherein the pressure differential applied to the shell-less-membrane unit comprises a vacuum produced with the pressure differential device disposed between the shell-less membrane unit and the permeate processing facility.

4. The apparatus of claim 1 wherein the permeate processing facility comprises a second stage apparatus which processes the at least a portion of the first permeate stream into a second permeate stream having a third concentration of fast gas components and a third concentration of slow gas components, wherein the third concentration of fast gas components is greater than the second concentration of fast

25

gas components and the third concentration of slow gas components is less than the second concentration of slow gas components, and at least a portion of the second permeate stream is delivered to a second permeate processing facility.

5. The apparatus of claim 4 wherein the second stage apparatus comprises a plurality of shell-less membrane units configured into a membrane bank, wherein the membrane bank has been disposed within a shell connected to the conduit, the shell comprising a second conduit for delivery of the at least a portion of the second permeate stream to the second permeate processing facility.

6. The apparatus of claim 4 further comprising a gas drying device which receives the at least a portion of the first permeate stream prior to entry into the second stage apparatus wherein the gas drying device is selected from the group consisting of a dessicant apparatus and a refrigeration apparatus.

7. The apparatus of claim 1 wherein the permeate processing facility comprises a flue gas generator.

8. The apparatus of claim 7 wherein at least a portion of a flue gas produced by the flue gas generator is recycled through a conduit to a gas intake of the flue gas generator.

9. The apparatus of claim 1 wherein the permeate processing facility comprises a sequestration facility.

10. The apparatus of claim 9 wherein the sequestration facility comprises a plurality of photosynthetic organisms.

11. An apparatus for direct air capture of components of ambient air at atmospheric pressure, where the ambient air comprises a first concentration of oxygen, a first concentration of nitrogen, and a first concentration of carbon dioxide:

a hollow fiber membrane unit comprising a first selective barrier surface directly exposed to the ambient air at atmospheric pressure, the hollow fiber membrane unit further comprising a first permeate channel configured to receive a flow of oxygen, nitrogen and carbon dioxide from the selective barrier surface;

a vacuum applying apparatus which applies a vacuum to the hollow fiber membrane unit wherein the vacuum applying apparatus is selected from the group consisting of a vacuum pump, a liquid ring vacuum pump system and a bellows system;

a conduit connecting the permeate channel to a permeate processing facility;

wherein, as the vacuum is applied to the hollow fiber membrane unit, a permeate forms in the permeate channel, wherein the permeate comprises a second concentration of oxygen, a second concentration of nitrogen and a second concentration of carbon dioxide; wherein the second concentration of oxygen is greater than the first concentration of oxygen, the second concentration of carbon dioxide is greater than the first concentration of carbon dioxide, and the second concentration of nitrogen is less than the first concentration of nitrogen; and

wherein at least a portion of the permeate is delivered through the conduit to the permeate processing facility.

12. The apparatus of claim 11 wherein the hollow fiber membrane unit is not contained within an outer shell.

13. The apparatus of claim 11 wherein a plurality of the hollow fiber membrane units are configured into a membrane bank.

26

14. The apparatus of claim 13 wherein the membrane bank is disposed within a shell.

15. An apparatus for direct air capture of gas components from an ambient environment at atmospheric pressure, wherein the ambient environment comprises a first concentration of fast gas components at atmospheric pressure and a first concentration of slow gas components at atmospheric pressure, the apparatus comprising:

a spiral wound sheet membrane unit comprising a selective barrier exposed to the first concentration of fast gas components at atmospheric pressure and the selective barrier is exposed to the first concentration of slow gas components at atmospheric pressure, and a permeate channel configured to receive a flow of fast gas components and slow gas components through the selective barrier;

a conduit connecting the permeate channel to a permeate processing facility;

a pressure differential device which applies a pressure differential across the selective barrier, the pressure differential device located within a portion of the conduit connecting the permeate channel to the permeate processing facility, the pressure differential device selected from the group consisting of a liquid ring vacuum system, a reciprocating compressor system, a centrifugal blower system and a bellows tank;

wherein as the pressure differential is applied across the selective barrier, a permeate forms in the permeate channel, wherein the permeate comprises a second concentration of fast gas components and a second concentration of slow gas components,

wherein the second concentration of fast gas components is greater than the first concentration of fast gas components and the second concentration of slow gas components is less than the first concentration of slow gas components; and

wherein at least a portion of the permeate is delivered through the conduit to the permeate processing facility.

16. The apparatus of claim 15 wherein the spiral wound sheet membrane unit is not contained within an outer shell.

17. The apparatus of claim 15 wherein comprising a plurality of spiral wound membrane units configured into a membrane bank.

18. The apparatus of claim 15 wherein the permeate processing facility comprises a second stage apparatus which processes the at least a portion of the first permeate stream into a second permeate stream having a third concentration of fast gas components and a third concentration of slow gas components, wherein the third concentration of fast gas components is greater than the second concentration of fast gas components and the third concentration of slow gas components is less than the second concentration of slow gas components, and at least a portion of the second permeate stream is delivered to a second permeate processing facility.

19. The apparatus of claim 18 wherein the second stage apparatus comprises a plurality of shell-less spiral wound sheet membrane units configured into a membrane bank, wherein the membrane bank has been disposed within a shell connected to the conduit, the shell comprising a second conduit for delivery of at least a portion of the second permeate stream to a second permeate processing facility.

* * * * *



Title: Direct Air Capture (DAC) Redefined- The Power of Breath

Author: Brian Kolodji • Owner- Kolodji Corporation/Black sWan, LLC- Energy Carbon Mngmt/IP Holding

Author Biography: Kolodji targets Million-Ton-per-Year (MMT/Y) Carbon Dioxide (CO₂) DAC by 2027, with 8-DAC patents allowed since 2021 and 3-DAC pilot facilities in Kern County, CA. Kolodji's gas-processing experience includes design/operations for high-risk Special Nuclear (weapons-grade) Materials (SNM) and live chemical (nerve/mustard) agent munitions facilities for USDOD/DOE; methyl isocyanate (post-Bhopal) and acrolein plant operations; and in 2010, the same year as BP/Macondo/Deepwater-Horizon, successfully commissioned onboard during float out and post mooring 100,000BPD/100MMSCFD O&G Production with MM+T/Y CO₂ Separation/Purification for 10,000+psig deep-water EOR injection from an FPSO offshore Brazil for Petrobras. Kolodji played management roles with petrochemical manufactures Union Carbide, Huntsman, and Baker; with O&G producers MODEC and Chevron; and engineering firms UOP, Parsons, and Worley (as Chief Process Engineer) serving Exxon, Shell, and BP. Kolodji holds a BSc in chemical engineering from the University of Southern California (USC), is a registered chemical engineer in TX/CA, authored the first USPSM legislation, lectured on Chemical Plant Risk Analysis at USC, published on HAZOPs for then fledgling Process Safety Progress, served as state Office of Emergency Services, city, and industrial Hazmat Emergency Response firefighter/trainer for real time toxics release preparedness, and was the only Carbider presenting at the 2004 (20-year anniversary) Bhopal Conference in India. Email: bkolodji@sbcglobal.net; website: K-O2.com

Deck: Kolodji, holder of 7 DAC patents and owner of three DAC pilot plants, brings attention to the urgent quintessential challenge of rapidly advancing DAC, arguably the only technology capable of achieving carbon neutrality. No better example of the challenge is with the very definition of DAC still being in flux and becoming grossly more complicated. This is epitomized by USDOE's new definition advanced as of January 2025 compared to the last USDOE pass in August 2024, making for even less agreement between other leading major organizations (IPCC, IAE, and CARB) and does a disservice in making a gauntlet for DAC innovation. In many of the major organization's definition there is a distinct and undue bias towards absorbent-based DAC with Storage (aDACs). DAC innovation and advancement is better encouraged with a broader simpler definition of DAC. This is demonstrated with a discussion on permanence as related to enhanced nature-based DAC (eDAC) and DAC with uses (DACU) such as with membrane-based DAC (mDAC) for production of low carbon sustainable renewable fuels.

Manuscript:

CARBON CYCLE MISMANAGED

In the beginning⁽¹⁾ the carbon cycle⁽²⁾ created kept atmospheric carbon dioxide (CO₂) levels in check with reversible biological/ geological chemical reactions, such as the one shown below:

Fauna Mammal/Respiration Products

Flora Biomass/Bio-Sequestration Products



From left to right, fauna (mammal) respiration products of breath, CO₂ and water (H₂O), react with energy from sunlight through flora (living plant) photosynthesis to evolve oxygen (O₂) to the atmosphere and produce carbohydrates (C₆H₁₂O₆ or biomass), building blocks of a plant and a form of bio-sequestration through natural direct air capture (nDAC). This cycle reverses (right to left) with metabolized carbohydrates (plant matter eaten and stored in a mammalian body) that react with inhaled O₂ in air to be respired with reaction products of CO₂ and H₂O in exhaled breath. The natural carbon

...Peace be with you...



cycle was “permanently” maintained with ambient CO₂ under 300 ppm, as evidenced with almost 1,000,000 years of ice core data⁽³⁾ (see Figure 1, below.) As can also be seen, this robust carbon cycle was disrupted in the industrial age with accelerating global rise in CO₂ emission rates, unabated at 40 billion tons or gigatons/year (GT/Y) in 2024⁽⁴⁾, that is still accelerating year after year at 3 ppm/year/year⁽³⁾ or 0.7 GT CO₂ equivalent/Y/Y⁽⁴⁾, because of a similar reaction to metabolism shown below:

Reactants

Products

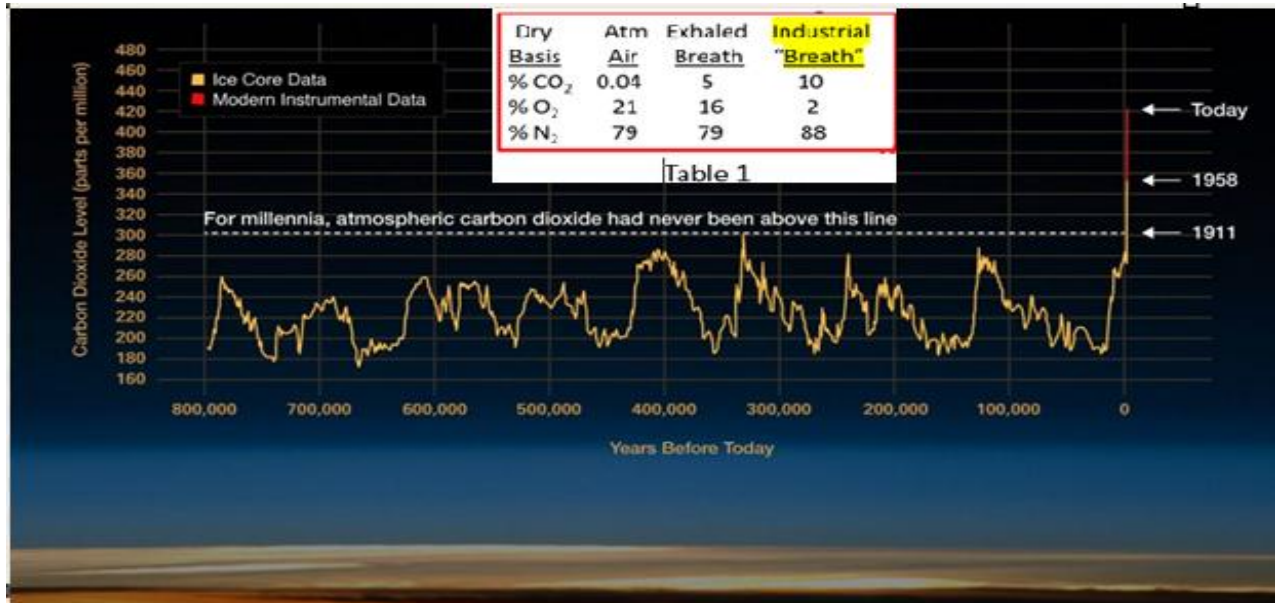
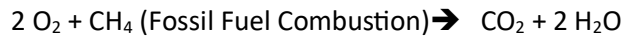


Figure 1- Atmospheric Carbon Dioxide Level in parts per million over the last 800,000 years.

Industrial emission or “industrial breath”, with the same components as that of biological breath (see dry composition in Table 1 inset on Figure 1, above), is more heavily laden with CO₂. As a result, the CO₂ concentration in the miles of upper atmosphere surrounding the globe continues an unprecedented rapid exponential rise, relative to the prehistoric time scale in Figure 1 above, leaping in less than 100 years from 300 parts per million (ppm) to over 400 ppm CO₂ today, fueled by this culprit “industrial breath” and aided by accomplices of rapid deforestation and urbanization. This rise is also the predominant cause of climate change which unabated leads to a high confidence of negative global consequences per the Intergovernmental Panel on Climate Change (IPCC)⁽⁴⁾, thus the intense interest to rapidly advance the leading and maybe only solution capable of abating this seemingly inexorable rise, Direct Air carbon dioxide Capture (DAC).

The International Energy Agency (IEA)⁽⁵⁾, United States Department of Energy (USDOE)⁽⁶⁾, and the State of California, as led by the California Air Resources Board (CARB)⁽⁷⁾ are in rare agreement regarding DAC in that it is not possible to abate this rise, that is achieve “Net Zero” or “Carbon Neutrality”, without DAC. There is also agreement regarding the maturity level of DAC. IEA states “Future capture cost estimates for DAC are wide-ranging and uncertain, reflecting the early stage of technology development.”⁽⁵⁾ USDOE states “The field of Direct Air Capture is at a relatively early developmental stage...result(ing) in uncertainties surrounding its ultimate scale, definition, and market landscape.”⁽⁶⁾ And CARB states “DAC...is under development today.”⁽⁷⁾

...Peace be with you...



Multi GT/Y DAC scale is needed to accomplish global carbon neutrality goals by 2050^(4,5,6,7). This goal appears bleak for DAC with still rapidly emerging and evolving DAC technologies not reported as successfully deployed at any significant scale, with gross capacity of around 20,000 tons or 0.00002 GT/Y reported^(4,5,6,7) to date. Not helping is the amount of contrast existing between USDOE's very specific and IEA's very broad definition. Not surprisingly, there is even more daylight between IEA versus CARB's definition. These distinctions may be a disservice to the development of such a nascent technology as DAC, through premature elimination of effective, deployable, scalable, permanent, profitable, and sustainable DAC innovation or prejudiced acceptance of DAC boondoggles that don't work.

DAC ILL-DEFINED

IEA has by far the simplest DAC definition of "removing CO₂ directly from air"⁽⁵⁾. This broad definition is the most inclusive to innovation so as to speed discovery, deployment, and scalability, and not cause the elimination of a "silver bullet" technology due to arbitrary or prejudicial whims. USDOE's DAC definition as of August 2024 was "a technology that directly separates planet-warming CO₂ from the atmosphere for permanent, safe geologic storage or the manufacture of clean, low-carbon fuels and chemicals"⁽⁸⁾ USDOE's much more complex definition as of January 2025 is "a technology that regenerates a capture medium in a closed loop and/or uses a mechanical air contactor to chemically or physically separate carbon dioxide directly from the outdoor or indoor ambient atmosphere without reliance on above-average carbon dioxide concentrations caused by nearby point sources of emissions."⁽⁶⁾ CARB likewise has a complex DAC definition with a variety of caveats, restrictions, and exclusions. CARB specifically restricts DAC to technologies "not designed to be attached to a specific source or smokestack."⁽⁷⁾ Unlike IEA for DAC, CARB specifically excludes any use of "biological sequestration or nature-based processes"⁽⁹⁾...typically accomplished through Natural and Working Lands (NWL) management and conservation practices that enhance the storage of carbon or reduce CO₂ emissions with nature-based approaches."⁽⁷⁾ This is a contradiction to California's emphasized "climate smart" goal of finding nature-based solutions.^(10,11) CARB is further prescriptive of DAC by relegation to a form of "Mechanical Carbon Dioxide Removal (CDR)... where CO₂ is removed directly from the atmosphere using mechanical and/or chemical processes⁽⁷⁾ ... that capture and concentrate ambient CO₂"⁽⁷⁾. Thus, as even USDOE doesn't do, classifying DAC only as a CDR per CARB's definition, CARB inextricably ties DAC to storage, making DAC equivalent to DAC and Storage (DACS), with the further restriction of only one form of sequestration or storage choice, that being geologic sequestration⁽⁷⁾. With this, CARB in fact specifically excludes any potential for DAC with use of CO₂ (DACU). USDOE and CARB have moved closer to each other on what the yet to be developed DAC can't be, making a tortuous gauntlet for DAC fruition efforts.

Absorption based DAC (aDAC) such as solid absorbent DAC (sDAC) and liquid absorbent DAC (lDAC) are the most highly adopted form of DAC drawing on decades of proven commercial industrial scale gas processing for CO₂ removal. With air having a CO₂ concentration magnitudes lower than industrial gases, combined with the necessity for storage of CO₂, this aDAC has become a very high capital and energy intensive challenge (\$1000+/ton) almost impossible to overcome. Nevertheless aDAC is being built today at an unprecedentedly rapid scaleup with potential of up to 1 million tons/year in 2026^(12,13). The dilemma in development is the skipping of technology readiness levels that prejudice discovery of major show-stoppers before big bucks are spent producing more CO₂ than removed while one goes broke. A most recent disclosure⁽¹⁴⁾ is telling in that the very concept of aDAC has a fatal self-defeating flaw and simply will not work because the performance of the absorbent in the aDAC facility drops dramatically as the feed concentration of the air surrounding the facility drops. Most frightening is if it did work, it does not remove CO₂ from the miles of upper atmosphere, but immediately strips the

...Peace be with you...



CO₂ only from the small sliver (100 feet) of biosphere above the earth required for life, starving plant life of the CO₂ required to sustain agricultural with the very real possibility of creating severe food security issues, see Figure 2⁽¹⁵⁾ below. Questions continue to arise as to the viability of the aDAC concept being able to work at large scale carbon removal and do no harm^(12,14). The world's largest sDAC facility built to-date at just 4000 T/Y, costing over \$1000/ton (over \$1 Billion, or \$trillions at the GT/Y scale), has recently been shuttered⁽¹³⁾ with very little fanfare.

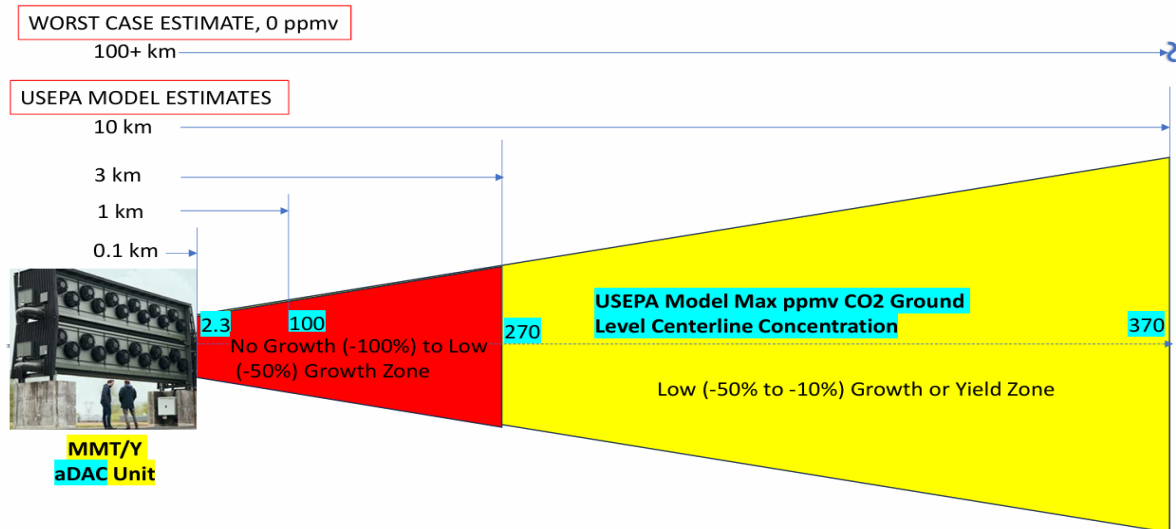
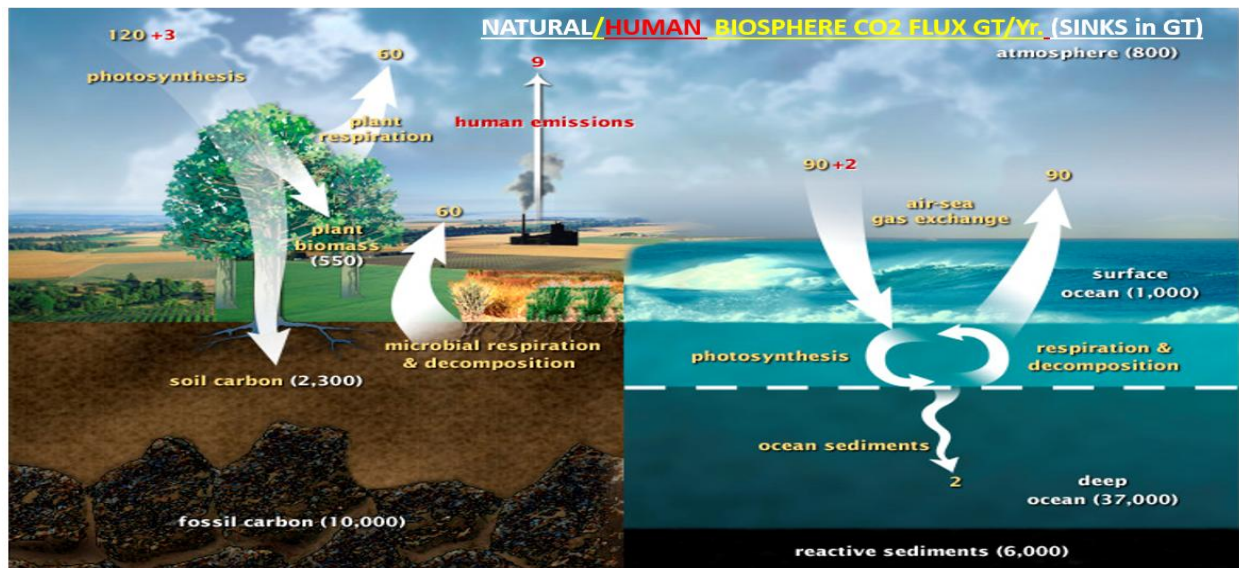


Figure 2- USEPA Model Results Showing MMT/Y aDAC Impact at 5mph wind and worst case at 0 mph.

CARBON MANAGEMENT/ DAC DEFINITION CORRECTED

Figure 1 attests to outstanding permanence for natural storage of CO₂ with a time-scale in the 100s of thousands of years. In Figure 3, the record of large magnitudes of nature's CO₂ storage scale in the air at 800 GT and in biomass at 550 GT held over the time-scale shown in Figure 1 also attest the ability of the storage to remain permanent. This extent of permanence far exceeds the permanence limits estimated by IPCC⁽⁴⁾ of 1000 GT for 10,000 years by geologic storage. Figure 3⁽²⁾ also shows how potent and rapid the buildup of nature-based DAC (nDAC) is. Photosynthesis (with plant respiration deducted) is credited with nature's only method for net removal of CO₂ from the atmosphere, and accounts for a whopping 60 GT/Y of flux or removal of CO₂ globally from ambient air, dwarfing all other efforts at DAC by man to-date. It is remarkable that CO₂ as a minority component in air with just 400 ppm is proven as the workhorse that produces the majority of a plant's biomass.



(Diagram adapted from U.S. DOE, [Biological and Environmental Research Information System](#), 12/2008)

Figure 3- Natural Global Carbon Cycle Sinks and Fluxes at normal 400 ppm CO₂

Enhancing natural photosynthesis to effect higher levels of DAC (eDAC) has the potential for climate impacting scale of atmospheric CO₂ reductions. A general form of eDAC is crop carbon dioxide enrichment, the practice of increasing the CO₂ levels in a plant's biosphere from 400 ppmv to between 600 and 1200 ppmv to effect increased growth rates, biomass production, and water utilization efficiency, as practiced for almost a century in greenhouses^(16,17). Presented in Figure 4⁽¹⁸⁾ and Figure 5^(19,20) below are published results in Open Top Chambers (OTC) showing between 100% to 200% increases in crop yields and water utilization efficiency of cotton and citrus, respectively, "with complete lack of change to elemental composition."⁽¹⁹⁾ Another form of eDAC is Free Air Carbon Dioxide Enrichment (FACE)⁽²¹⁾ which is crop carbon dioxide enrichment without enclosures, with the same results expected, as studied for over 50 years by USDOE and USDA. "What was learned from these experiments? If there is a single scientific conclusion from the many years of investigation and more than \$100 million invested, it might simply be that most of the C₃ plants and terrestrial ecosystems studied do respond positively to increased concentrations of atmospheric CO₂. This response is due to the primary effects of CO₂ on photosynthesis and stomatal aperture..."⁽²¹⁾ Over 95% of all flora are C₃ Plants, including most crops.

FACE goes counter to many elements and rules defining DAC(S). FACE can use emissions from a stack say of a power plant or other flue gas generator (post-combustion) to supply large quantities of conditioned CO₂ from flue gas to orchards, as "industrial breath" to increase biomass production. Prior to FACE, the concentrated CO₂ in flue gas never reached the orchard. With elevated high temperature buoyant discharge at high velocity, the highly concentrated CO₂ in flue gas at the release point was shot miles into the upper atmosphere and only trickled back down to the biosphere at grade after being diluted by the magnitude greater volume of upper atmosphere (see Figure 6⁽²²⁾ below). FACE feeds a conditioned higher than ambient CO₂ concentration stream into an orchard for proven increased agricultural production. FACE enhances photosynthesis and involves bio-sequestration, and is thus not a chemical or mechanical process. FACE does not capture CO₂ from air as CO₂, nor does FACE concentrate CO₂, thus geologic storage for this form of DAC is not in play. Instead, FACE uses the increased CO₂ concentration in the biosphere to directly produce more biomass in the form of carbohydrates, as has been done since "In the beginning..." The only rule FACE does not break in DAC definitions is that it

...Peace be with you...



“removes CO₂ directly from air”. In the search for the answer for a profitable, deployable, effective, scalable, permanent form of DAC, the failure to discover eDAC or FACE has been suffering from a terminal case of “not seeing the forest for the trees.” FACE is highly scalable and deployable because of profit (\$10/Ton), plug and play with existing facilities (power plants/farms) ⁽²²⁾ and nature’s effectiveness.

The enhanced nature-based DAC (eDAC) technology like FACE makes plants into little green CO₂ absorbing machines. The capture rate is estimated at 10 T/Y/Acre of crop ⁽¹⁵⁾. CARB’s 2030 DAC capture goal of 7 MMT (on page 96, Table 2-3 of the Scoping Plan for Achieving Carbon Neutrality ⁽⁷⁾) could be exceeded with just a fraction of the acreage of a single crop, that being almonds ⁽¹⁵⁾ and make a profit with increased crop yield doing so. FACE can potentially capture between 30 and 120 GT/Y of additional CO₂, while drawing down the CO₂ in the upper atmosphere by growing more biomass (see Figure 7, below.) FACE is scalable and deployable at Million Ton/Year DAC scales ⁽¹⁵⁾. As biomass production continues above that needed, the biomass is culled as a low carbon renewable and sustainable fuel and becomes a fossil-based fuel replacement with lower life-cycle emissions. “The traditional biofuel production reaction is:

Biomass + O₂ >>>> Gasification/Fischer-Tropsch >>> Hydrocarbon fuels + CO₂

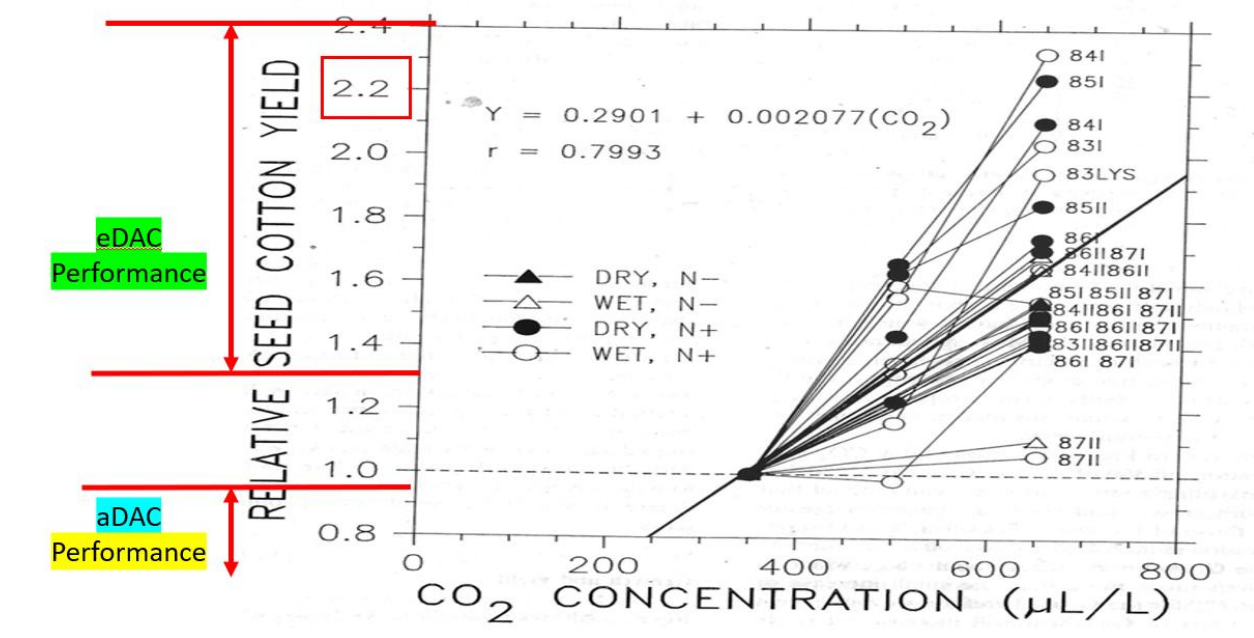


Figure 4⁽¹⁸⁾

Cotton Carbon Yield increase up to 50% at 500 PPM, up to 100% (Doubles) at Enrichment to 650 ppm



Global Change Biology (2007) 13, 2171–2183, doi: 10.1111/j.1365-2486.2007.01430.x

USDA STUDY!

Seventeen years of carbon dioxide enrichment of sour orange trees: final results

BRUCE A. KIMBALL*, SHERWOOD B. IDSO†, STEPHANIE JOHNSON* and MATTHIAS C. RILLIG‡§

A
Form of
eDAC

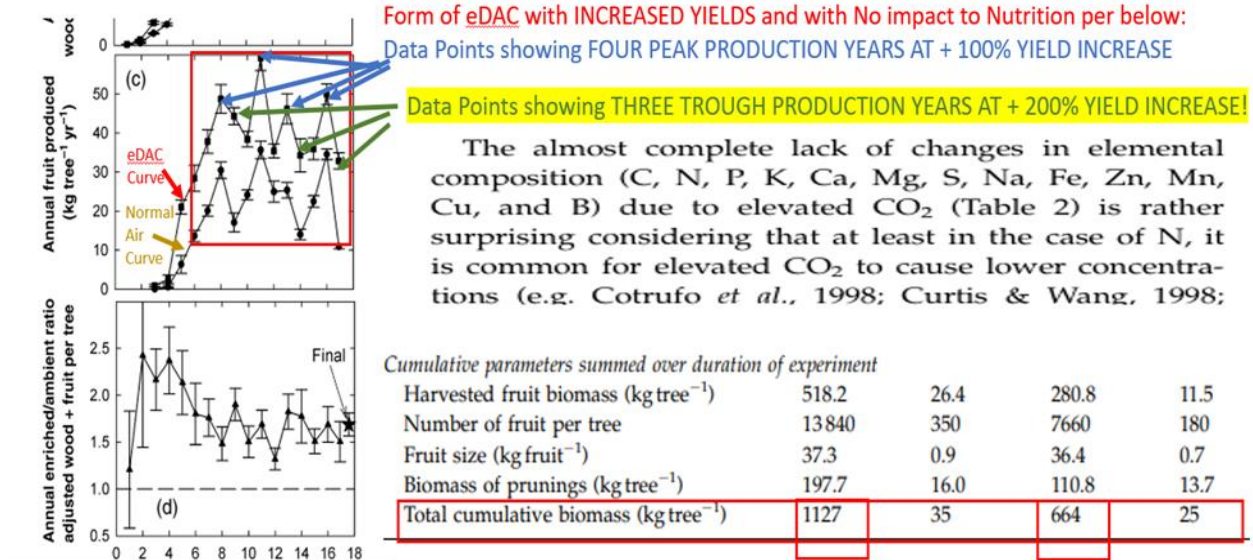


Figure 5⁽¹⁹⁾

Citrus Yield/Flux Increases 100 to 200% (Doubles and Triples) at Enrichment to 550 ppm

In traditional biofuel production, the cost of biofuels is driven by the cost of biomass.^{”(24)} FACE’s increase in biomass production makes producing sustainable renewable carbon negative fuels more economic. If the cost of oxygen production can be brought down, biofuels production becomes even more economic.

Introducing membrane based Direct Air Capture (mDAC), a technology capable of the co-capture for both oxygen and CO₂ from air. Like aDAC, mDAC is based upon leading commercial industrially proven air separation technology. mDAC is also effective when applied pre-combustion to a power plant⁽²²⁾ (see Figure 8) as a replacement to the combustion air source allowing significant reduction of fuel consumption through oxy-combustion per USDOE⁽²⁵⁾, (see Figure 9.)⁽²²⁾

Both eDAC and mDAC make a case for Direct Air Capture with Use (DACU). Per IEA, DACU demonstrates permanence and “can still deliver clear climate benefits, particularly when the application is scalable, uses low-carbon energy and displaces a product with higher life cycle emissions. In the decarbonisation path towards net zero emissions, atmospheric CO₂ will eventually need to displace the use of fossil-based carbon. While CO₂ use can deliver climate benefits under the circumstances mentioned above, it is a complement rather than an alternative to CO₂ storage, which is expected to be deployed at a much larger scale in order to reach international climate goals.”⁽⁵⁾

The goal is to further the target to net zero or carbon neutrality (Figure 10), as can only be evidenced by the halt to acceleration and the halt to the rise of CO₂ concentration in the atmosphere,

...Peace be with you...



let alone lowering of CO₂ concentration (carbon management). This can only be achieved by supplanting high carbon unsustainable non-renewable fossil fuels with low carbon sustainable renewable biofuel production as shown in the complete Black Swan Cycle (see Figure 11.)



Free Air Carbon dioxide Enrichment

FACE

FLUE GAS RELEASE POINT

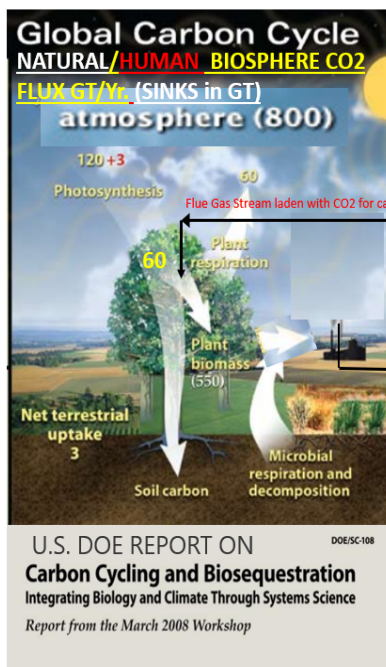
Before FACE

With FACE

- | | | |
|------------------------|--------------|---------------------|
| 1.Release Elevation: | 100 + Ft | < 10 Ft (grow zone) |
| 2.Release Temp: | Hot (320F) | Cold (80F) |
| 3.Water Content | High | Very Low |
| 4.Density/Congestion: | Low | High |
| 5.Velocity/ Direction: | High/Upwards | Low/Downwards |

Cool, Denser than Air, Slumping Enriched Gas Lingers In Orchard

Figure 6⁽²²⁾



NOW...

... and with Global Carbon Neutrality Targets for 2035!!!

17 MILE TROPO/STRATOSPHERE ATMOSPHERIC SINK

Before FACE

With FACE

- | | | |
|-------------------------------------|---------|------------------------|
| 1. Atmospheric CO ₂ Sink | 800 GT | Target: 650 GT (-19%) |
| 2. Avg Atmos CO ₂ Conc. | 400+PPM | Target: 350 PPM (-12%) |

FLOOD Global Boundary (100') Layer Growing Zone

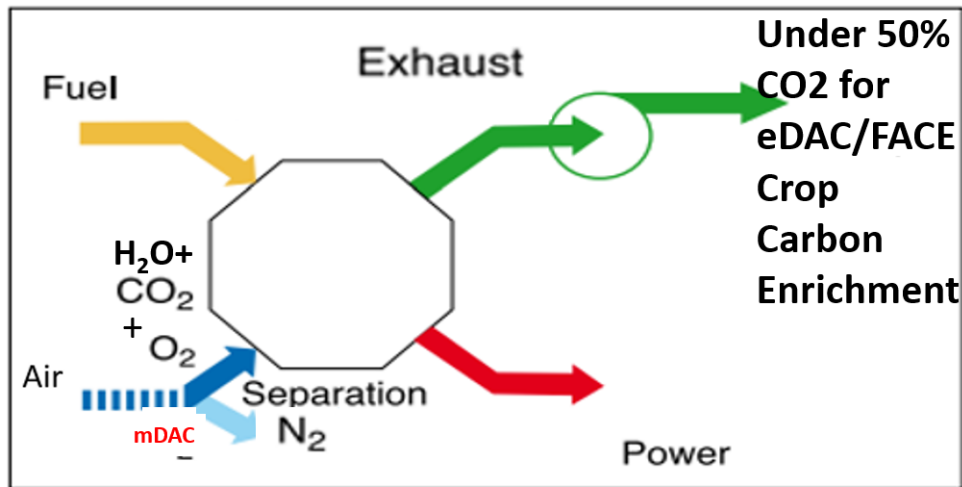
- | | | |
|---------------------------------------|------------|---------------------|
| 3. Carbon Inventory/ Flux | 0.150 GT/Y | +60 GT/Y Available |
| 4. CO ₂ Concentration, PPM | 400 | Target: 800 (+100%) |
| 5. Plant Biomass CO ₂ Sink | 550 GT | 700 GT (+19%) |
| 6. Atm to Plant Flux, GT/Y | 60 | 90 |
| 7. Biomass Fuel to Power | 0.001 GT/Y | 30 GT/Y |

PRODUCED
POTABLE
WATER

Figure 7⁽²²⁾- With FACE as eDAC, carbon neutrality by 2035 can be achieved.

...Peace be with you...

BLACK · SWAN mDAC/ eDAC



SAVES CAPITAL/FUEL with CO-CAPTURE
MEMBRANE DIRECT AIR CAPTURE (mDAC) of CO2 WITH O2

Figure 8⁽²²⁾

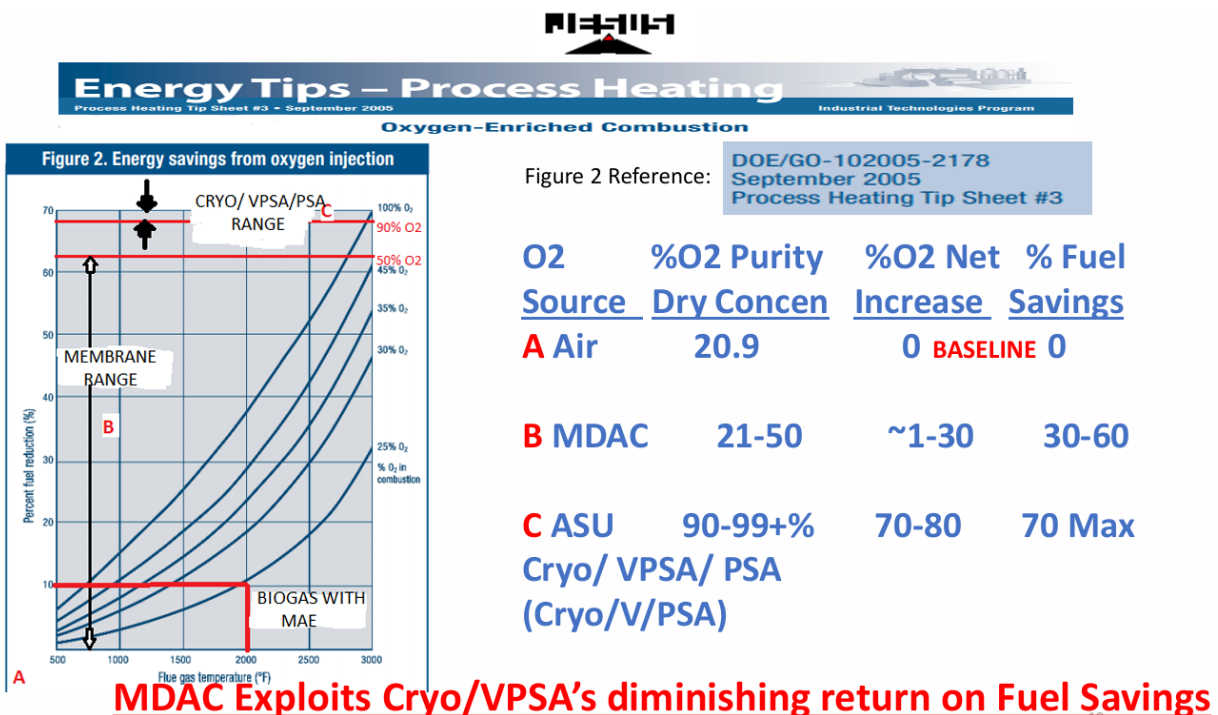


Figure 9⁽²²⁾



"Keeling-Kimball-Kolodji" Curve
can only be achieved with **eDAC** that...

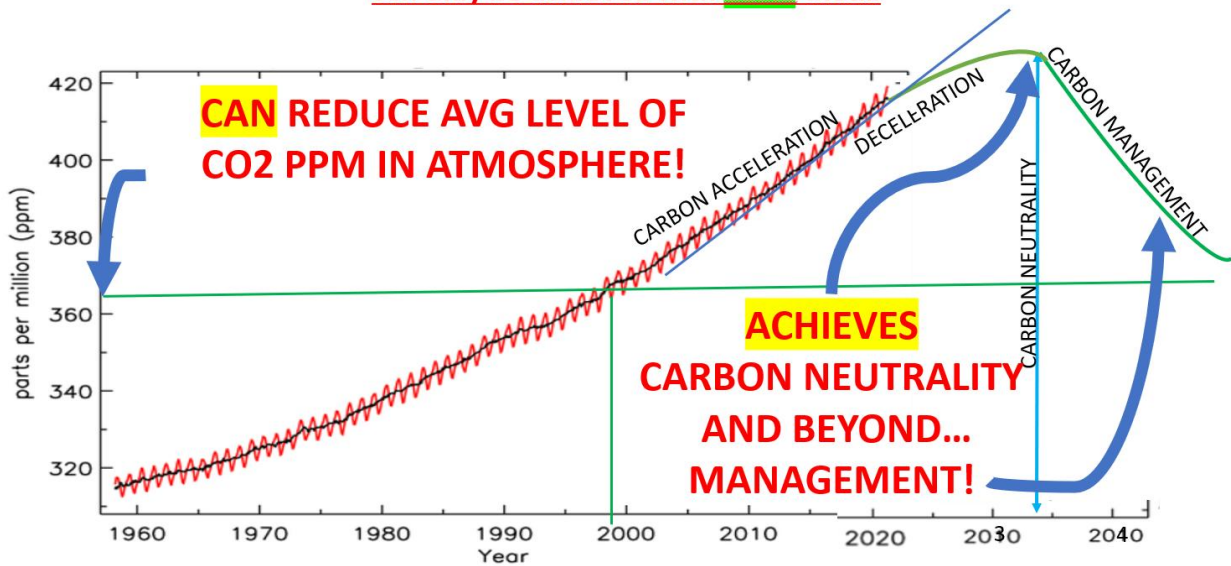


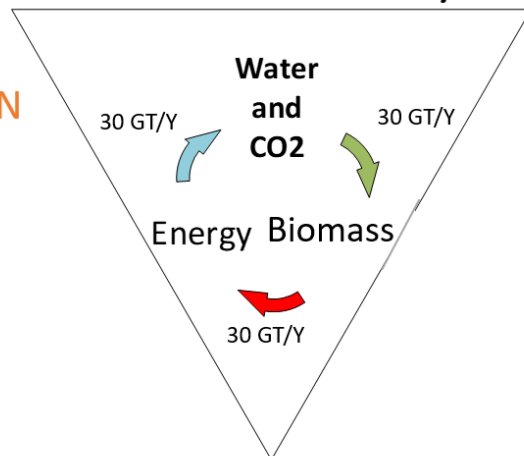
Figure 10⁽²²⁾ - Modified Keeling Curve to show process to Carbon Management



BLACK · SWAN Cycle

mDAC/
OXY-COMBUSTION

eDAC/ FACE



BIOMASS/ BIOFUEL

CARBON MANAGEMENT HARNESSSED with "POWER OF BREATH"

Figure 11⁽²²⁾

REFERENCES AND LINKS

...Peace be with you...

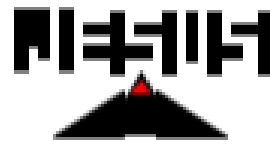


- (1) Genesis 1-2
- (2) [Carbon Cycling and Biosequestration | Genomic Science Program \(energy.gov\)](#)
- (3) [Evidence - NASA Science](#); [The Keeling Curve](#) UC Davis, Scripps Institute of Oceanography, and NASA related links with ICE Core Data and Keeling Curve Data.
- (4) [IPCC AR6 SYR FullVolume.pdf](#) (6a) page 45, Figure c; (6b); See note on bottom of page 86 and 2nd to last sentence in column 1 on page 86
- (5) [Direct Air Capture: A key technology for net zero \(iea.blob.core.windows.net\)](#); (7a) page 9, 2nd paragraph, last sentence; (7b) page 34, bottom paragraph; (7c) Table on page 19 and page 45, 1st paragraph, last sentence; (7d) pages 3,6,8 and 13.
- (6) [Direct Air Capture Definition and Company Analysis Report.pdf](#); by Faber, G., USDOE Office of Fossil Energy and Carbon Management, January 2025
- (7) [2022 Scoping Plan Update \(ca.gov\)](#) for Achieving Carbon Neutrality; (6a) page 92, bottom paragraph; (6b) page 84, bottom paragraph; (6c) page 96, Table 2.3; (6d) Figure 2-2 on page 84 and page 92; (6e) page 85, 1st paragraph; (6f) page 85, paragraph 1, last sentence; (6g) page 93, 2nd paragraph; (6h) page 217, Figure 4-10.
- (8) Go to USDOE link: [Direct Air Capture Factsheet August 2024.pdf](#)
- (9) [GFO-24-303 Questions and Answers ada.docx](#) see Q16 and A16 on pages 4 and 5.
- (10) [Expanding Nature-Based Solutions \(ca.gov\)](#)
- (11) [Executive Order N-82-20](#)
- (12) [World's Largest Carbon Capture Plant Being Built in Texas - Newsweek](#)
- (13) [Swiss CO₂ removal firm Climeworks to downsize - SWI swissinfo.ch](#)
- (14) [How Do Variations in Ambient Carbon Dioxide Concentration Affect Direct Air Capture Performance?](#)
- (15) [\(64a\) Enhanced Nature Based Direct Air Capture \(eDAC\) Scaled to 1MM Ton/ Year By 2026. | AIChE](#)
- (16) CO₂ Enrichment of Greenhouse Crops; by Enoch, H. Z. and Kimball, B. A.; 1985.
- (17) Controlled Environment Agriculture: A Global Review of Greenhouse Food Production; Dalrymple, D. G.; 1973
- (18) *Effects of increasing atmospheric CO₂ on the growth, water relations, and physiology of plants grown under optimal and limiting levels of water and nitrogen, Response of Vegetation to Carbon Dioxide*; Kimball, B.A., J.R. Mauney, D.H. Akey, D.L. Hendrix, S.G. Allen, S.B. Idso, J.W. Radin, and E.A. Lakatos. 1987. No. 049., U.S. Dept. of Energy, Carbon Dioxide Res. Div. and USDA, ARS, Wash. DC.
- (19) Kimball, B.A., Idso, S.B., Johnson, S.M., Rillig, M.C. 2007. Seventeen Years of CO₂ Enrichment of Sour Orange Trees: Final Results. Global Change Biology 13: 2171-2183: Link: [Publication : USDA ARS](#)
- (20) [The effect of long-term atmospheric CO₂ enrichment on the intrinsic water-use efficiency of sour orange trees - PubMed](#) Chemosphere, 2003 Jan;50(2):217-22 by [S W Leavitt¹](#), [S B Idso](#), [B A Kimball](#), [J M Burns](#), [A Sinha](#), [L Stott](#)
- (21) [facereport2020.pdf](#)
- (22) [Utilizing Direct Air Capture for Reduced Power Plant Fuel Consumption and Lower Cost Agriculture Production/ Bio-Sequestration; 2022 AIChE Annual Meeting](#) <Proceedings link to 2022 AIChE Annual Meeting presentation by Kolodji, et al, by Kolodji, B.; Kimball, B. A.; Marsh, B.; Straub, M; 2022 AIChE National Meeting Proceedings (Phoenix, AZ). Paper_647759.pdf, paper No. 649f
- (23) [USDA/NASS 2024 State Agriculture Overview for California](#)

...Peace be with you...



- (24) What is the Future of Liquid Hydrocarbon and Feedstocks; by Forsburg, C. and Dale, B.; Chemical Engineering Progress; April 2025
- (25) [oxygen enriched combustion process htgts3 \(1\).pdf](#) ;"USDOE Process Heating Energy Tip Sheet #3, Oxygen Enriched Combustion; DOE/GO-102005-2178, September 2005.



Black Swan, LLC

“-then the Lord God formed the man out of the dust of the ground and blew into his nostrils the breath of life, and the man became a living being.” **Genesis 2:7**

Enhanced Nature-Based Direct Air Capture (**eDAC**)

Scaled to 1 million Tons/Year of CO₂ by 2027

Making Food by Using Free Air Carbon dioxide Enrichment (FACE)

as opposed to absorbent-based DAC (**aDAC**) with potential for Negative Impact to Food Security

presented at

American Institute of Chemical Engineers

April 9th, 2025

by

Brian Kolodji, PE, President and Owner

bkolodji@sbcglobal.net, cell: (713) 907-8742

Kolodji Corp / Black Swan, LLC

ENERGY CARBON MANAGEMENT/ INTELLECTUAL PROPERTY HOLDING COMPANY

Broken Natural CO₂ Cycle- Repaired with enriched Direct Air Capture (eDAC)

Over 95% of plant growth is dependent upon carbon supplied at 400ppm CO₂
 $6\text{CO}_2 + 6\text{H}_2\text{O} + \text{sunlight} \gg 6\text{O}_2 + \text{C}_6\text{H}_{12}\text{O}_6$: photosynthesis

Natural Cycle is broken and overwhelmed by industrial respiration

$6\text{O}_2 + \text{C}_6\text{H}_{12}\text{O}_6$ (carbohydrate) $\gg 6\text{CO}_2 + 6\text{H}_2\text{O}$: natural respiration

$(3X/2+1)\text{O}_2 + \text{C}_x\text{H}_{x+2}$ (fossil fuel) $\gg X\text{CO}_2 + (X+2)/2 \text{H}_2\text{O}$: industrial “respiration”

Where: $X= 6000$

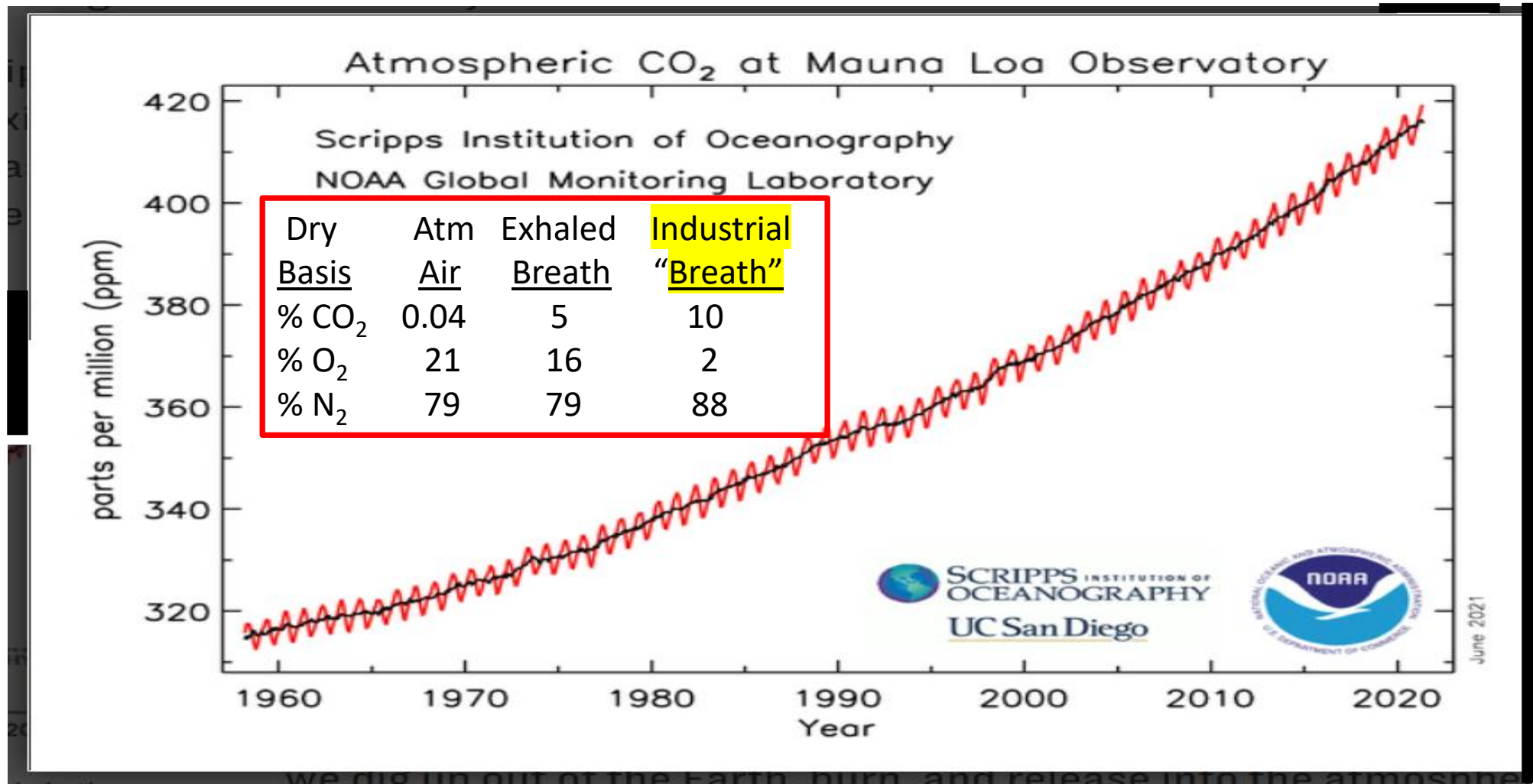
Double down on photosynthesis- to match overactive respiration

Spiking crop biosphere with CO₂ between 600 to 1000 PPM

Biomass/ agricultural production increased 40% to 200%

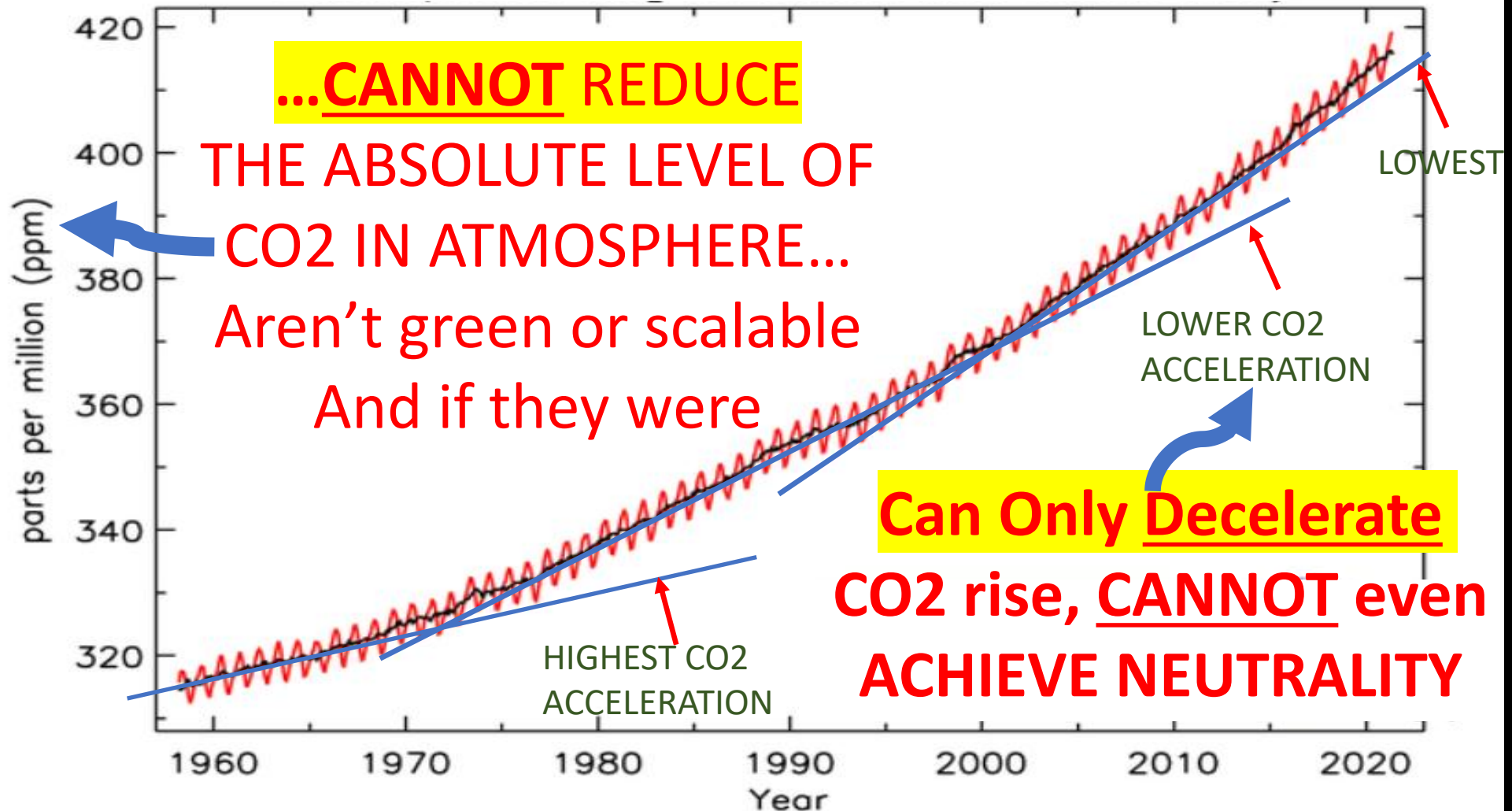
eDAC- Low Cap/Energy/Resource Intensive Direct Air Capture

“Keeling Curve” Started in 1959



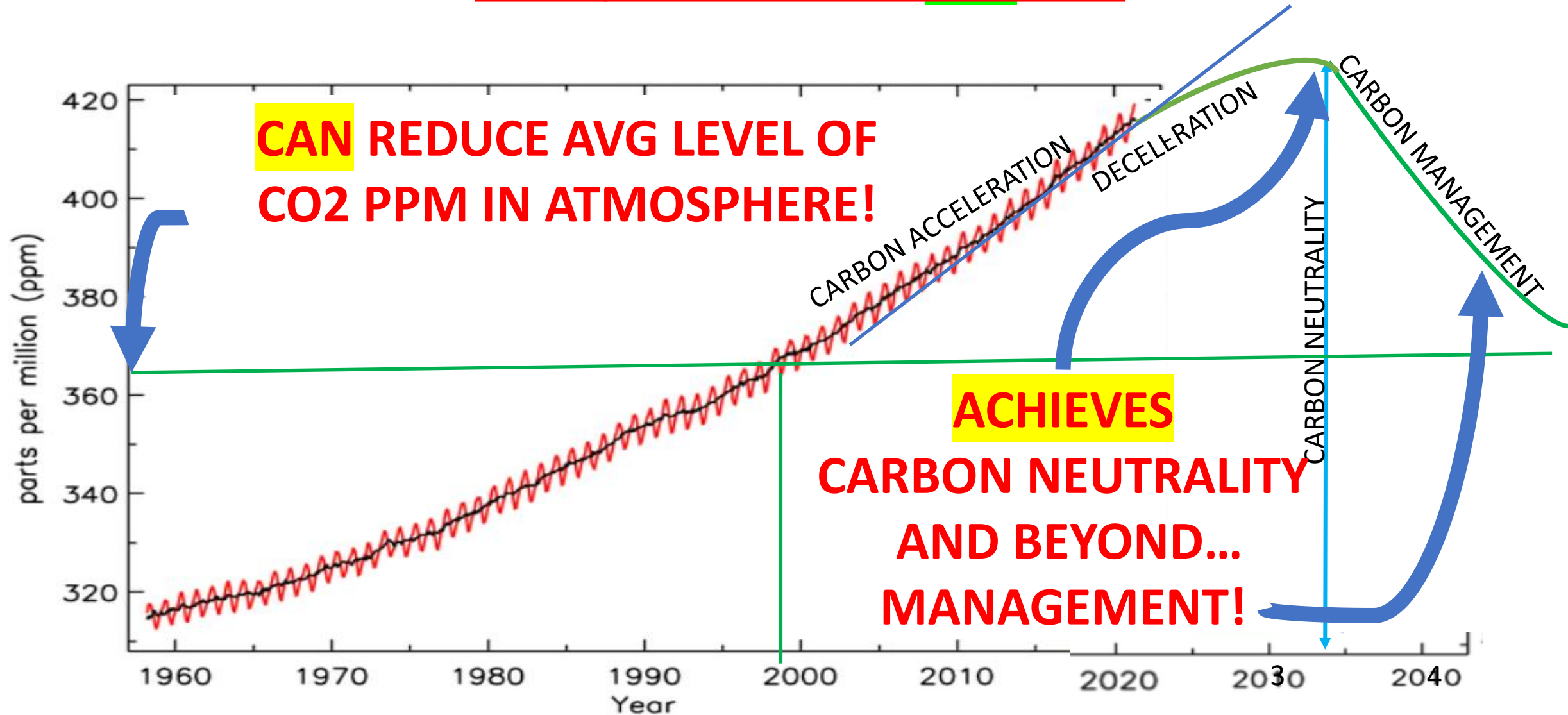
Cause? Energy Carbon Mis-management

CURRENT CONVENTIONAL DIRECT absorbent-based AIR CAPTURE (aDAC) TECHNOLOGY





“Keeling-Kimball-Kolodji” Curve
can only be achieved with **eDAC** that...





2022 Scoping Plan for Achieving Carbon Neutrality

Refer to pages 92 and 96 (Table 2.3)

Reference Link: [2022 Scoping Plan Update \(ca.gov\)](https://www2.arb.ca.gov/sites/default/files/2023-04/2022-sp.pdf)

<https://www2.arb.ca.gov/sites/default/files/2023-04/2022-sp.pdf>

“Preliminary estimates indicate that, globally, capacity from already announced projects will range from ... about 2,000 metric tons per year (MTCO₂/y) to 1 MMT CO₂/y from DACs by 2027 which indicates that California’s 2030 target is an ambitious, but achievable, goal” (as identified by Governor Newsom and the Legislature- see Pages 95-97 and Table 2-3 below.)

STATEMENT AND TARGETS FROM CARB 2022 SCOPING PLAN FOR CARBON NEUTRALITY:

“To achieve carbon neutrality, mechanical CDR will therefore need to be deployed... Direct air capture (DAC) is one available option that is under development today and could be widely deployed.”

	2030 (MMTCO ₂ e)	2045 (MMTCO ₂ e)
GHG Emissions	233	72
AB 32 GHG Inventory Sector Emissions	226	65
Net NWL GHG Emissions Across All Landscapes (annual average from 2025–2045)	7	7
Carbon Capture and Sequestration (CCS): Avoided GHG Emissions from Industry and Electric Sectors	(13)	(25)
Carbon Dioxide Removal (CDR) including natural and working lands carbon sequestration, ¹⁶⁵ Direct Air Capture, and Bioenergy with CCS (BECCS).	(7)	(75)
Net Emissions (GHG Emissions + CDR)	226	(3)

SEE TABLE LISTING DAC FACILITIES FROM PAGE 19 OF REFERENCE IN NEXT SLIDE



Direct Air Capture

A key technology for net zero

2022



International
Energy Agency

Reference Link: [Direct Air Capture: A key technology for net zero \(iea.blob.core.windows.net\)](https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf)

https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf

TWO KNOWN LEADING DAC TECH TYPES:

#2 Greenhouse Crop CO₂ Enrichment (eDAC)
Commercialized for 60 years in greenhouses>>>

DAC plants in operation worldwide

Company	Country	Sector	CO ₂ storage or use	Start-up year	CO ₂ capture capacity (tCO ₂ /year)
Global Thermostat	United States	R&D	Not known	2010	500
Global Thermostat	United States	R&D	Not known	2013	1 000
Climeworks	Germany	Customer R&D	Use	2015	1
Carbon Engineering	Canada	Power-to-X	Use	2015	Up to 365
Climeworks	Switzerland	Power-to-X	Use	2016	50
Climeworks	Switzerland	Greenhouse fertilisation	Use	2017	900
Climeworks	Iceland	CO ₂ removal	Storage	2017	50
Climeworks	Switzerland	Beverage carbonation	Use	2018	600
Climeworks	Switzerland	Power-to-X	Use	2018	3
Climeworks	Italy	Power-to-X	Use	2018	150
Climeworks	Germany	Power-to-X	Use	2019	3
Climeworks	Netherlands	Power-to-X	Use	2019	3
Climeworks	Germany	Power-to-X	Use	2019	3
Climeworks	Germany	Power-to-X	Use	2019	50
Climeworks	Germany	Power-to-X	Use	2020	50
Climeworks	Germany	Power-to-X	Use	2020	3
Climeworks	Germany	Power-to-X	Use	2020	3
Climeworks	Iceland	CO ₂ removal	Storage	2021	4 000

#1 Solid Absorbent (aDAC) eg. Climeworks' ORCA>>>


[About CRC](#)
[Our Business](#)
[ESG](#)
[Carbon TerraVault](#)
[Investor Relations](#)
[News](#)
[Interest Owners](#)
[Careers](#)


Carbon Dioxide Management Agreements (CDMAs)¹, submitting new permits to the EPA and attracting new greenfield project capital to California,” said Francisco Leon, CRC’s President and Chief Executive Officer. “The most recent release of California’s first draft Class VI permits for the 26R reservoir and the Department of Energy (DOE) development grant awarded to the California Direct Air Capture (DAC) Hub reflects our continued commitment to carbon management solutions for hard-to-abate industries and decarbonization technologies in the Golden State. Finally, the recently announced agreement to combine with Aera Energy will enhance our carbon management business, providing greater scale with which to accelerate CRC’s efforts to decarbonize California.”

2023 Highlights

Solid Absorbent (aDAC)

MORE FAST TRACK DEVELOPMENT (rapid scale-up and skipping smaller pilots) HEADLINES

- The Environmental Protection Agency (EPA) released California’s first draft Class VI well permits for underground CO₂ injection at the 26R storage vault, located at the proposed Clean Energy Park at Elk Hills Field in Kern County
- California DAC Hub, led by CTV’s subsidiary CTV Direct, LLC, was selected to receive approximately \$12 million in DOE funding for a regional initiative focused on the development of California’s first full-scale DAC plus storage (DAC+S) network
- Submitted 51 million metric tons (MMT) of Class VI permits to EPA for CTV IV and CTV V storage reservoirs in Northern California. In total, CTV has submitted permits for 191 MMT of CO₂ storage with an estimated injection rate of 5.3 MMT per year
- Announced CTV’s first capture-to-storage project at CRC’s Elk Hills cryogenic gas plant, located in Kern County. This project is expected to sequester 100 thousand metric tons per year (KMTPA) of CO₂ in the 26R reservoir by year-end 2025
- Signed 760 KMTPA of storage-only CDMAs¹ with several greenfield project developers. helping to decarbonize California’s energy value chain
- CTV’s total CO₂ injection rate capacity under CDMAs¹ or agreements is 1.1 million metric tons per year (MMTPA)

Solid Absorbent (aDAC)

FAST TRACK DEVELOPMENT HEADLINES (skipping pilots)

Newsweek

Better Planet

Texas

Climate Change

Greenhouse Gas Emissions

Carbon Dioxide

CO2

World's Largest Carbon Capture Plant Being Built in Texas

Published Oct 31, 2024 at 3:45 PM EDT

Updated Nov 01, 2024 at 10:53 AM EDT

A facility under construction in West Texas aims to be the world's largest direct air carbon capture plant, though experts remain divided on the technology's viability and environmental impact.

Houston-based Occidental Petroleum (Oxy) is spearheading the STRATOS project, a \$1 billion venture designed to remove 500,000 metric tons of carbon dioxide from the atmosphere annually once commercially operational in mid-2025.

<https://www.newsweek.com/worlds-largest-carbon-capture-plant-being-built-texas-1978220>

EXPERTS REMAIN DIVIDED ON ABSORBENT DAC (aDAC) TECHNOLOGY'S VIABILITY...

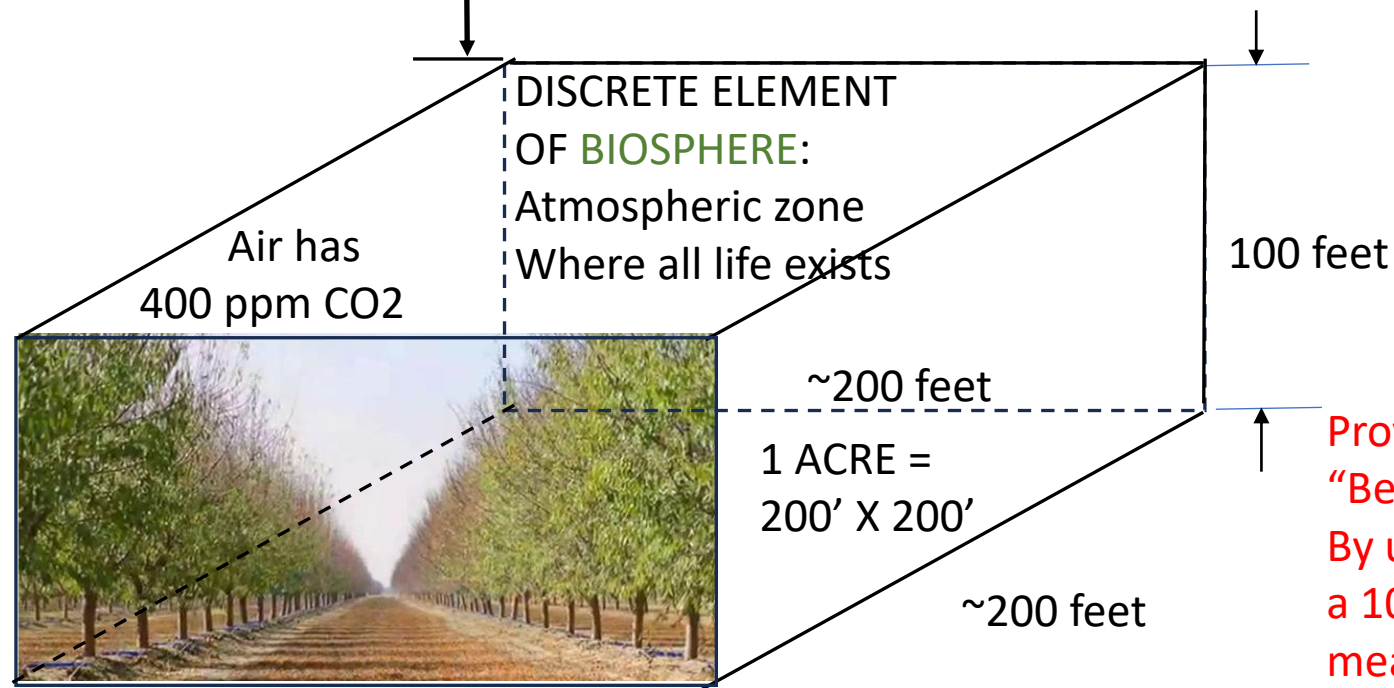
- COST: \$1Billion / 0.5 Million Tons/Year = \$2000/Ton of CO2 Captured
- To Achieve Neutrality: Remove 5 Billion Tons/Year of CO2 at \$2000/Ton = Budget Busting \$10 Trillion

AND WORST CASE ENVIRONMENTAL IMPACT...

- RISK: Absorbent based DAC (aDAC) is banking on the trickle down of CO2 from the miles (62) of upper atmosphere to prevent Excessive Depletion of CO2 in the tiny sliver (100 feet) of biosphere from Impacting Food Security. Plants cannot grow without CO2 in the biosphere. This facility will be taking CO2 from near grade atmosphere.
- CO2 in absorbent DAC (aDAC) is removed at near grade level, within the biosphere of fauna and flora where all life thrives:
0.5 Million Tons CO2 at near grade / 0.1 Tons/A-100' = Equivalent to 5 million acres of Biosphere depletion/Year

62 miles = 300,000 feet
of **Upper Atmosphere**
where no life exists

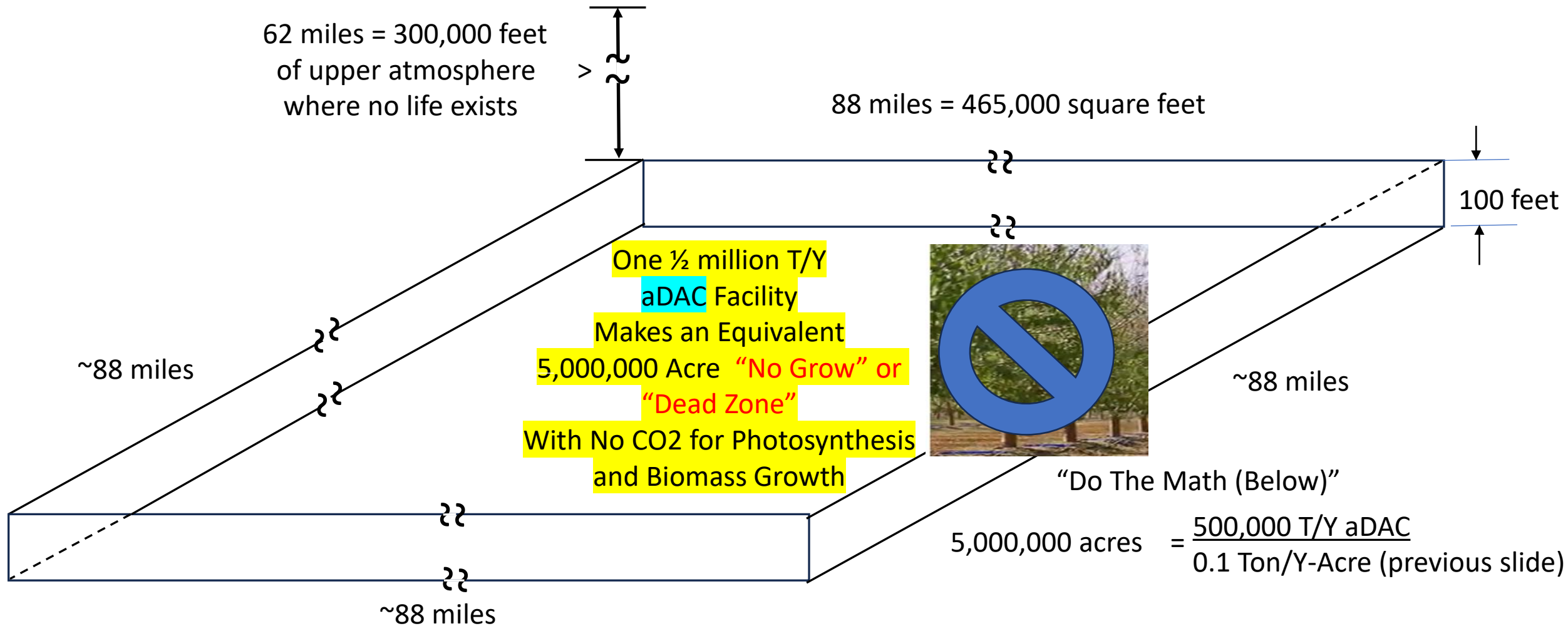
**Calculated and Depicted Below: ONLY 200
pounds of CO2 in an acre X 100 feet of Air!!!**



Prove this with the
“Bedroom Dry Ice Challenge”
By using 1 ounce of Dry Ice in
a 10’X10’X10’ room, and
measure with a CO2 monitor
to get 800 ppm in the room.

- Baseline: Ambient Mass of CO2 in a discrete volume of biosphere 100 Feet High X Acre with 400 ppm:
- $$1 \text{ Acre} \times \frac{43,560 \text{ Sq. Ft}}{\text{ACRE}} \times 100 \text{ Ft High Air} \times \frac{400 \text{ PPMV CO}_2}{1,000,000 \text{ Parts Air}} \times \frac{0.114 \text{ Lbs CO}_2}{\text{Cubic Ft CO}_2} = \frac{200 \text{ Lbs CO}_2}{\text{Acre} \times 100 \text{ Ft Volume of Air (Biosphere)}} = 0.1 \text{ Ton CO}_2/\text{A}-100'$$

WORST CASE ABSORBENT DAC (aDAC) TECHNOLOGY'S IMPACT...



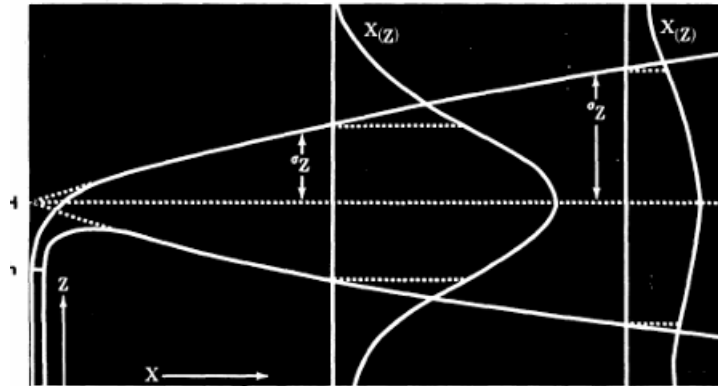
10 Million Tons/Yr of aDAC (1/7 of CARB 2050 Goal of 70 Million Tons of CO₂)

Is Equivalent to Depleting a 100-foot high layer of biosphere for California's Entire ~100 Million Acre Land Mass

Kern County, California's largest ag producing county has 80 Million Tons/Year DAC planned before 2035

ABSORBENT DAC (aDAC) TECHNOLOGY'S NEGATIVE IMPACT on AGRICULTURE
...per Decades Accepted USEPA Methods

**WORKBOOK
OF
ATMOSPHERIC DISPERSION
ESTIMATES**



U.S. ENVIRONMENTAL PROTECTION AGENCY

1973

ABSORBENT DAC (aDAC) TECHNOLOGY'S IMPACT

Calculation for Concentration of Depleted CO₂ Near Ground Level Concentration Miles Downwind of a Million Ton/Year aDAC Facility

$$\chi(x, 0, 0; 0) = \frac{Q}{\pi \sigma_y \sigma_z u}$$

SIGMA Y SIGMA Z from curves that follow:

Ground Level Continuous Concentration (χ) Directly Down Wind at Distance x from the Source

χ (g m^{-3}) or, for radioactivity (curies m^{-3})

Q (g sec^{-1}) or (curies sec^{-1}) Uniform Emission Rate

u (m sec^{-1}) Mean Wind Speed

$\sigma_y, \sigma_z, H, x, y,$ and z (m) Stack and Plume Height (H and z) and y are zero

SIGMA Y, SIGMA Z – Gaussian Distribution of Standard Deviation Plume Concentrations in the Horizontal and Vertical Planes

USEPA DATA TABLE USED TO ACCOMMODATE WIND AND CLIMATE
used in SIGMA Y and SIGMA Z Curves that follow:

KEY TO STABILITY CATEGORIES

Surface Wind Speed (at 10 m), m sec ⁻¹	Day			Night	
	Incoming Solar Radiation			Thinly Overcast or	≅3/8
	Strong	Moderate	Slight	≧4/8 Low Cloud	Cloud
< 2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

The neutral class, D, should be assumed for overcast conditions during day or night.

Curve for SIGMA Y Values

SIGMA Y Values at
"D" Stability for
MM Ton/Y aDAC

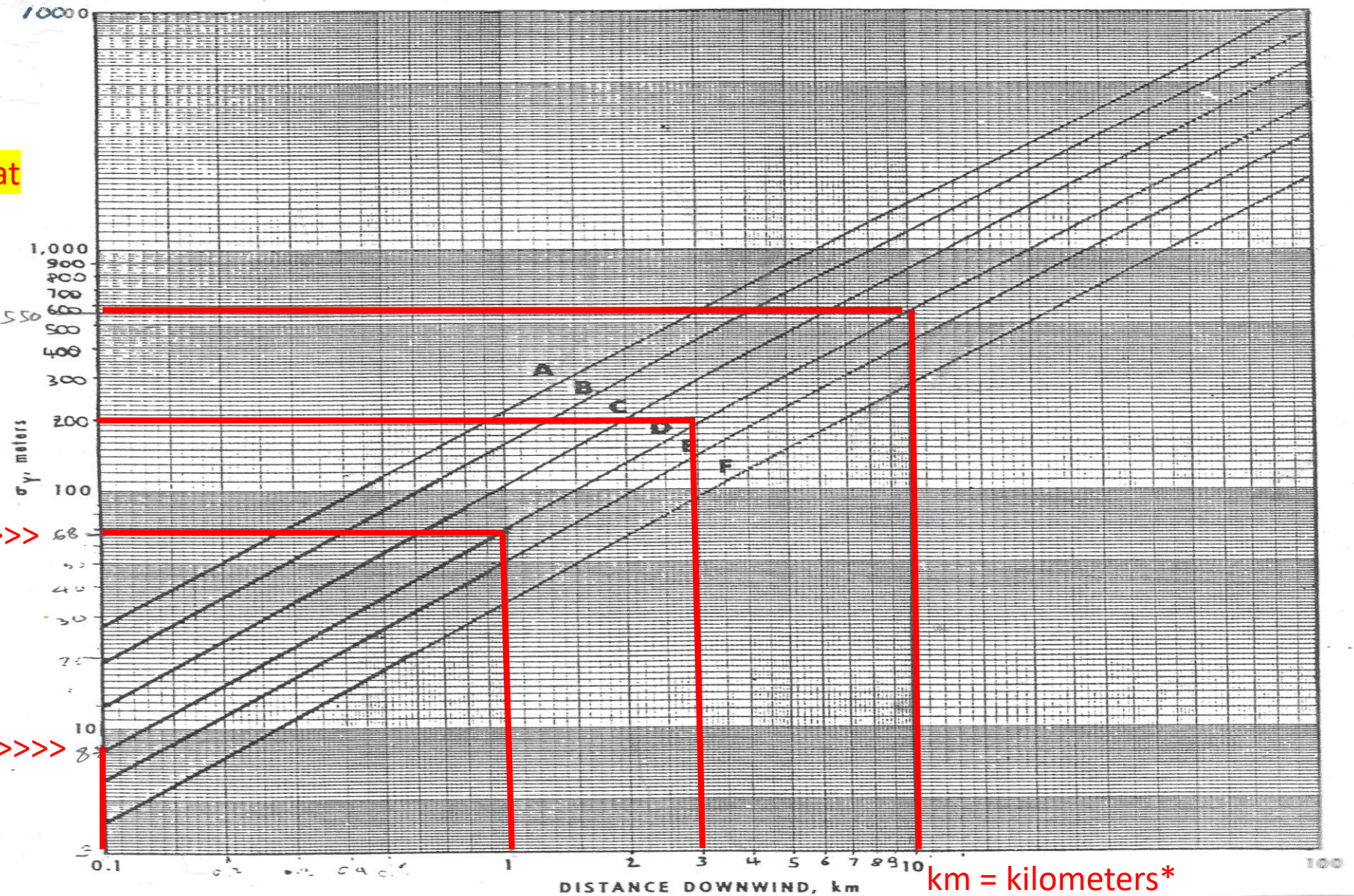
550m @ 10 km*

>

200m @ 3 km >

70m @ 1 km >>>>>>

8m @ 0.1 km >>>>>>



Curve for SIGMA Z Values

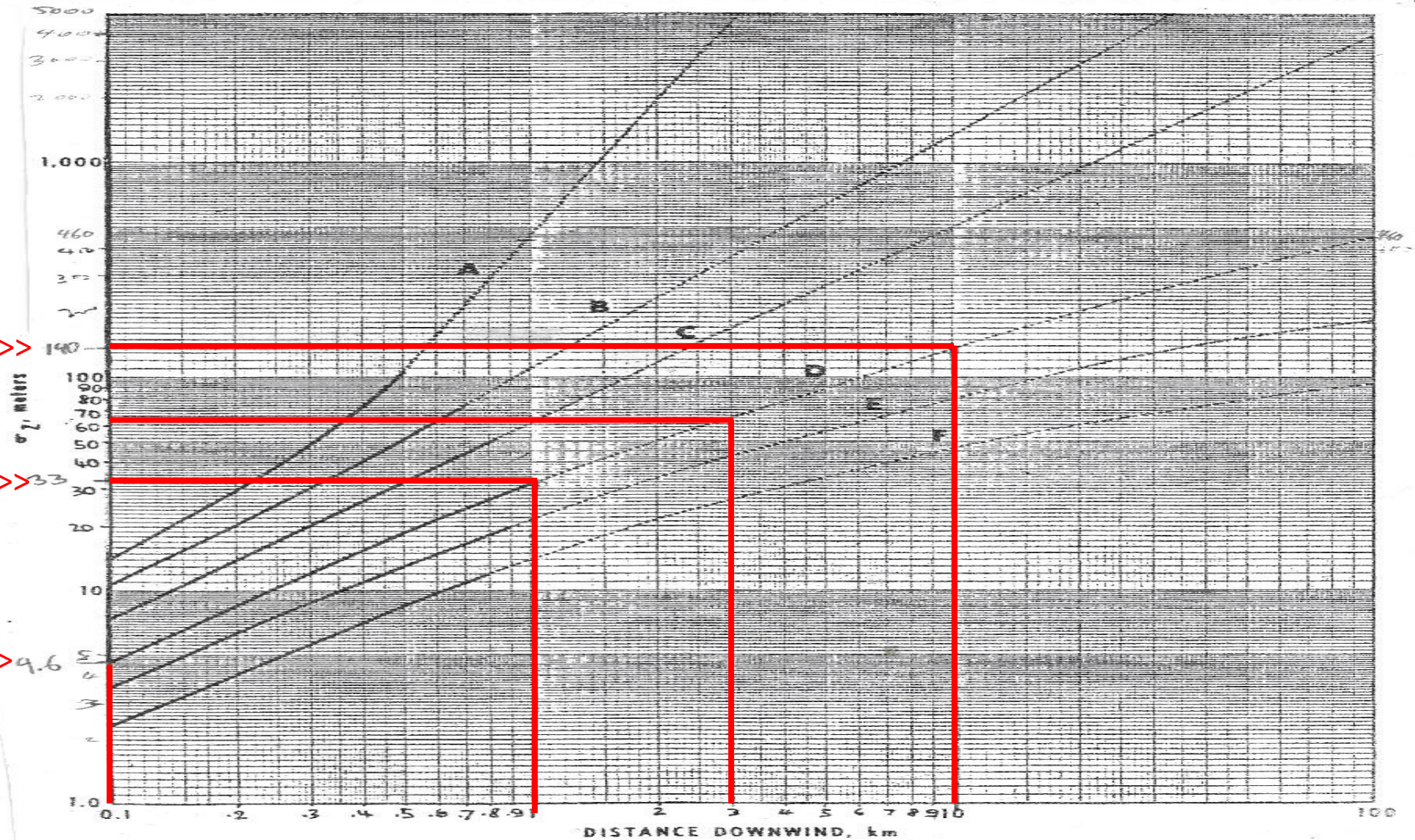
SIGMA Z Values at
"D" Stability for
MM Ton/Y aDAC

140m @ 10 km >>>>>>>

64m @ 3 km >>>>>>>

32m @ 1 km >>>>>>>>

4.6m @ 0.1 km >>>>>>>



Calculation for Ground Concentration ($x_{(0.1\text{km},0,0,0)}$ in g/m^3)
as Mass of Depleted Air, as g released
into Volume of Normal Air, as m^3

with "D" Stability and 2 m/s Wind at $x=0.1$ km Downstream of 1MMT/Y aDAC

$$x(x,0,0;0) = \frac{Q}{\pi \sigma_y \sigma_z U}$$

Q, Depleted Air Emission Rate (g/s) = CO₂ Removed (g/s) / Mass Fraction Concentration of CO₂ in Normal Air

CO₂ Removed from Normal Air (g/s) = (1MM T/Y) X (1MM grams/T) X (1 year/31,536,000 seconds) = 28,827 g/s

Conc conversion in Normal Air = (200 lbs of CO₂ / 4365000 cubic feet air) X (1000 g / 2.2 lbs) X (1 cubic foot / 0.028317 cubic meter) = 0.736 g CO₂ / m³ normal air (g/m³)

Using results from above and the R Constant 8.206×10^{-5} the Q, Depleted Air Emission Rate (g/s) is calculated below:

Q, Depleted Air Rate from aDAC (g/s) = 28,827 g/s CO₂ X (29 g/gmol Air) / 0.736 g/m³ / 8.206×10^{-5} / 298.15 K = 4.8×10^7 g/s

$x_{(0.1\text{km},0,0,0)} = 4.8 \times 10^7 \text{ g/s} / (\pi \times 8 \times 4.5 \times 2 \text{ m/s}) = 212,207 \text{ g Depleted Air / m}^3 \text{ Air (g/m}^3\text{) at 0.1 km from MMT/Y aDAC}$

Convert concentration Depleted Air in Normal Air ($x_{(0.1\text{km},0,0,0)}$ in g/m^3) to ppmv CO2 in Atmosphere with "D" Stability & 2 m/s Wind

Depleted CO2 Concentration at $x = 0.1$ km Downstream of 1MMT/Y aDAC

For x at 0.1 km, the R Constant of 10.73 calculates a conversion factor to ppmv Depleted Air in Normal atmospheric air:

$$(1 \text{ lb}/29 \text{ lbmol}) \times (2.2 \text{ lb}/1000 \text{ g}) \times (10.73/14.7 \text{ psia}) \times (520 \text{ R} \times 0.028317 \text{ m}^3/\text{ft}^3 \times 10^6) = 815.4 \text{ ppmv}/(\text{g}/\text{m}^3)$$

$$815.4 \text{ ppmv}/(\text{g}/\text{m}^3) \times (212,207 \text{ g}/\text{m}^3) = 173 \times 10^6 \text{ ppmv of Depleted Air in Air at } x \text{ from aDAC}$$

Calculating the concentration ppmv of CO2 in Atm at x , the following equation is derived:

$$\text{ppmv of CO2 in Atm at } x = \text{ppmv of CO2 in Depleted Air at } x + \text{ppmv of CO2 in Normal Atmosphere at } x:$$

Since ppmv of CO2 in Depleted Air at $x = \text{zero or } 0 \text{ ppmv}$, thus

$$\text{ppmv of CO2 in Atm at } 0.1\text{km} = (400 \text{ parts CO2 in Normal} / (173 \times 10^6 \text{ parts Depleted Air} + 1 \times 10^6 \text{ Parts Normal Air})) \times 10^6$$

2.3 ppmv CO2 in "D" Stability atmosphere at 0.1 km downwind from 1MMT/Y aDAC unit

x or Depleted Air in Normal Air, ppmv and CO2 in atmosphere, ppmv
at 0.1, 1, 3, and 10 km Downstream of 1MMT/Y aDAC

$$x_{(0.1\text{km},0,0,0)} = (4.8 \times 10^7 \text{ g/s} / (\pi \times 8 \times 4.5 \times 2 \text{ m/s})) \times 815.4 = 173 \times 10^6 \text{ ppmv Depleted/Normal Air at 0.1 km from MMT/Y aDAC}$$
$$2.3 \text{ ppmv CO2 at 0.1km} = (400 \text{ parts in Normal} / (173 \times 10^6 \text{ parts Depleted Air} + 1 \times 10^6 \text{ Parts Normal Air})) \times 10^6$$

$$x_{(1.0\text{km},0,0,0)} = (4.8 \times 10^7 \text{ g/s} / (\pi \times 70 \times 32 \times 2 \text{ m/s})) \times 815.4 = 2.8 \times 10^6 \text{ ppmv Depleted/Normal Air at 0.1 km from aDAC}$$
$$100 \text{ ppmv CO2 at 1km} = (400 \text{ parts in Normal} / (2.8 \times 10^6 \text{ parts Depleted Air} + 1 \times 10^6 \text{ Parts Normal Air})) \times 10^6$$

$$x_{(3\text{km},0,0,0)} = (4.8 \times 10^7 \text{ g/s} / (\pi \times 200 \times 64 \times 2 \text{ m/s})) \times 815.4 = 0.49 \times 10^6 \text{ ppmv Depleted/Normal Air at 0.1 km from aDAC}$$
$$270 \text{ ppmv CO2 at 3km} = (400 \text{ parts in Normal} / (0.49 \times 10^6 \text{ parts Depleted Air} + 1 \times 10^6 \text{ Parts Normal Air})) \times 10^6$$

$$x_{(10\text{km},0,0,0)} = (4.8 \times 10^7 \text{ g/s} / (\pi \times 550 \times 140 \times 2 \text{ m/s})) \times 815.4 = 0.085 \times 10^6 \text{ ppmv Depleted/Normal Air at 0.1 km from aDAC}$$
$$370 \text{ ppmv CO2 at 10km} = (400 \text{ parts in Normal} / (0.085 \times 10^6 \text{ parts Depleted Air} + 1 \times 10^6 \text{ Parts Normal Air})) \times 10^6$$

Distances from MMT/Y aDAC

WORST CASE ESTIMATE, 0 ppmv

100+ km

USEPA MODEL ESTIMATES

10 km

3 km

1 km

0.1 km



MMT/Y
aDAC Unit

2.3

100

270

USEPA Model Max ppmv CO2 Ground
Level Centerline Concentration

370

No Growth (-100%) to Low
(-50%) Growth Zone

Low (-50% to -10%) Growth or Yield Zone

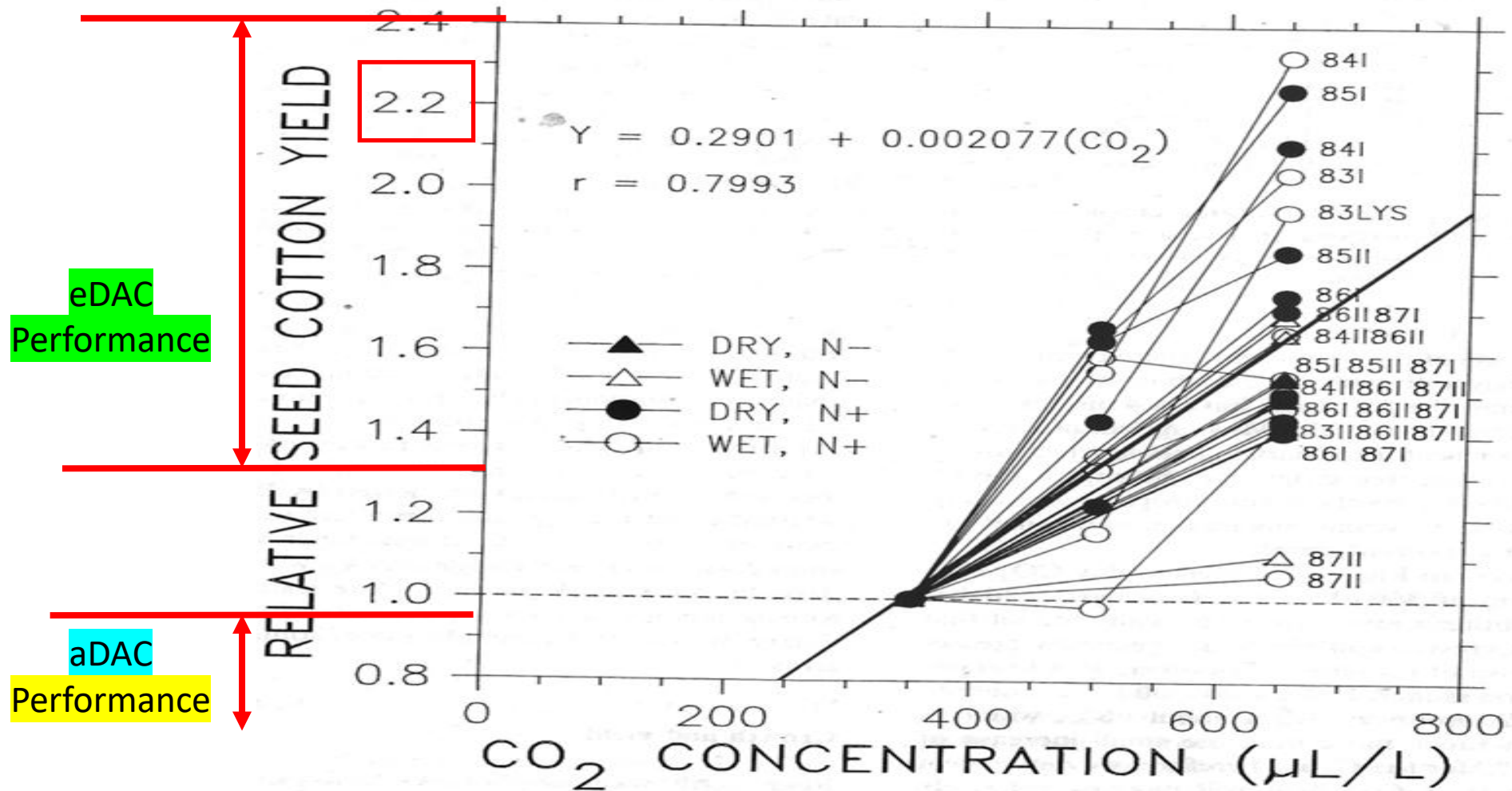


Fig. 2. Seed cotton yield (lint and seed) relative to the yield obtained from ambient CO₂ control chambers versus CO₂ concentration for 5 years' worth of experiments with open-top chambers at Phoenix, AZ. The labels on the right identify the year and replicate of the particular data points. From Kimball *et al.* (1987).

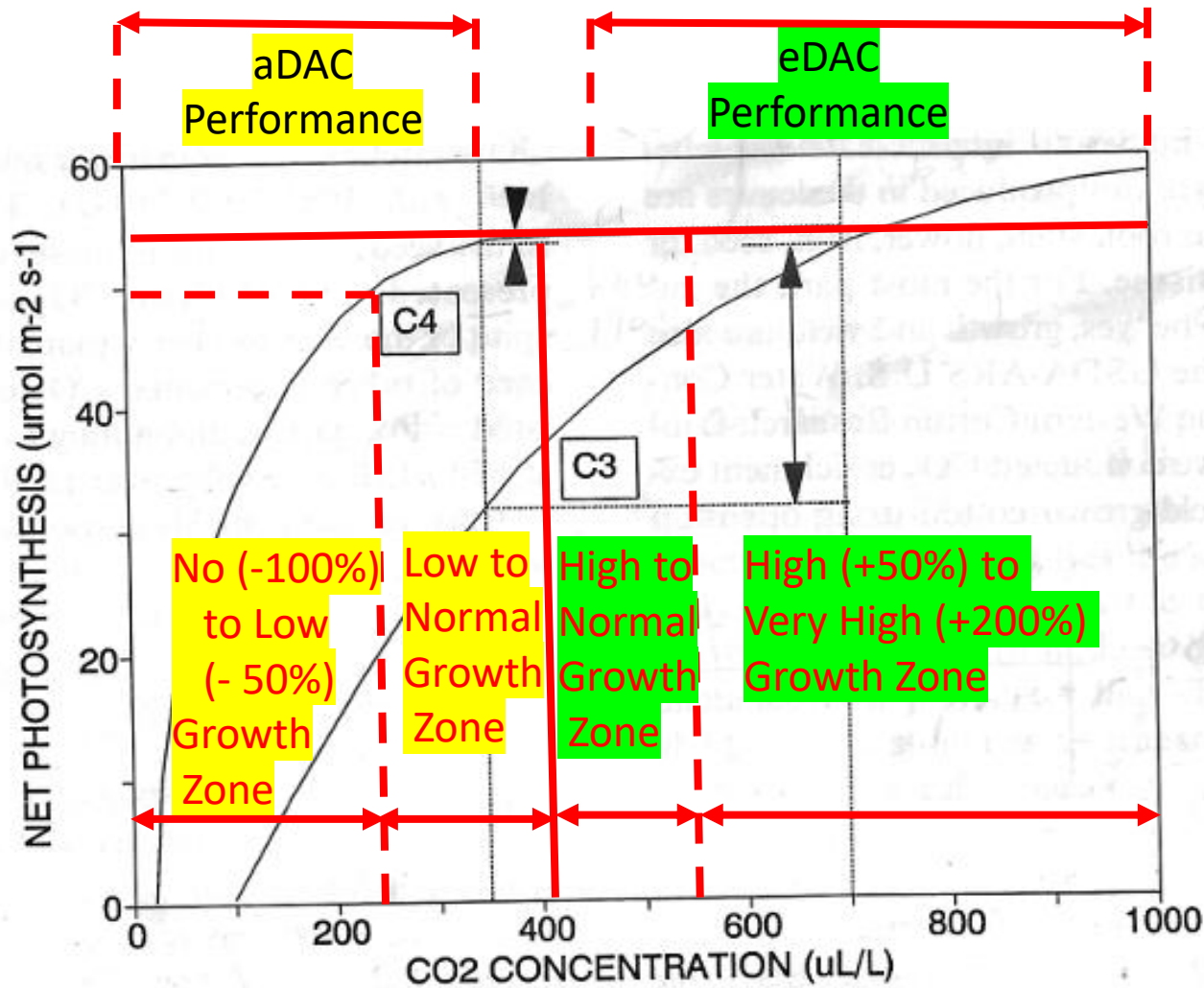
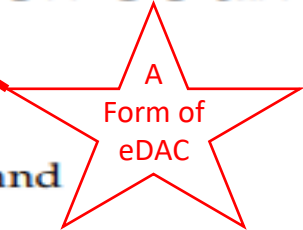


Fig. 1. Net photosynthesis of typical C₃ and C₄ plants versus CO₂ concentration, adapted from Taiz and Zeiger (1991). The vertical dotted lines at 350 and 700 $\mu\text{L/L}$ indicate the present-day CO₂ concentration and the doubled concentration projected to occur sometime near the end of the next century (Houghton *et al* 1990). The double arrows indicate the amounts of increase in photosynthesis due to the CO₂ doubling.

USDA STUDY!

Seventeen years of carbon dioxide enrichment of sour orange trees: final results

BRUCE A. KIMBALL*, SHERWOOD B. IDSO†, STEPHANIE JOHNSON* and MATTHIAS C. RILLIG‡§



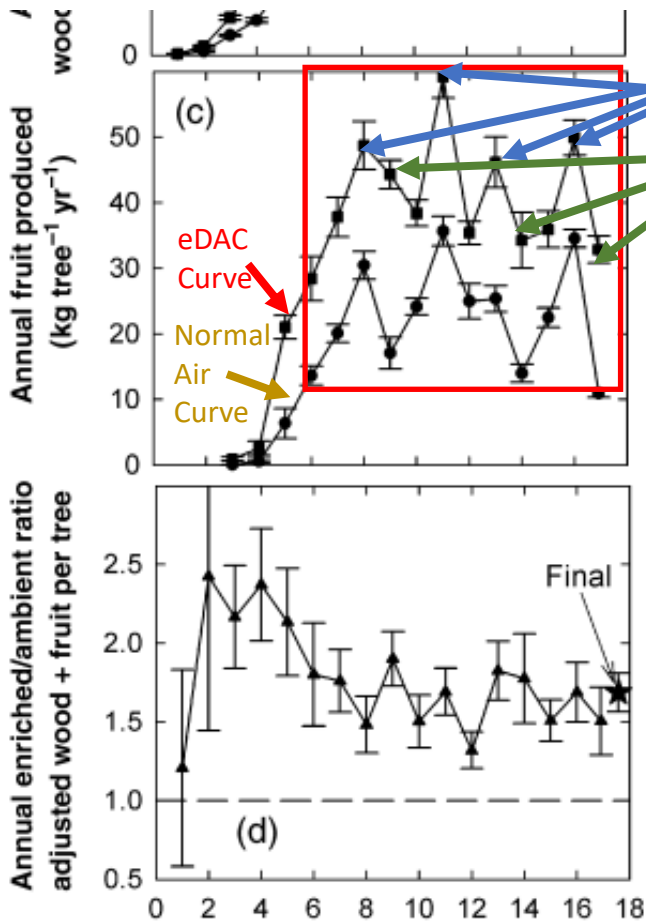
Form of eDAC with INCREASED YIELDS and with No impact to Nutrition per below:
Data Points showing FOUR PEAK PRODUCTION YEARS AT + 100% YIELD INCREASE

Data Points showing THREE TROUGH PRODUCTION YEARS AT + 200% YIELD INCREASE!

The almost complete lack of changes in elemental composition (C, N, P, K, Ca, Mg, S, Na, Fe, Zn, Mn, Cu, and B) due to elevated CO₂ (Table 2) is rather surprising considering that at least in the case of N, it is common for elevated CO₂ to cause lower concentrations (e.g. Cotrufo *et al.*, 1998; Curtis & Wang, 1998;

Cumulative parameters summed over duration of experiment

Harvested fruit biomass (kg tree ⁻¹)	518.2	26.4	280.8	11.5
Number of fruit per tree	13 840	350	7660	180
Fruit size (kg fruit ⁻¹)	37.3	0.9	36.4	0.7
Biomass of prunings (kg tree ⁻¹)	197.7	16.0	110.8	13.7
Total cumulative biomass (kg tree ⁻¹)	1127	35	664	25



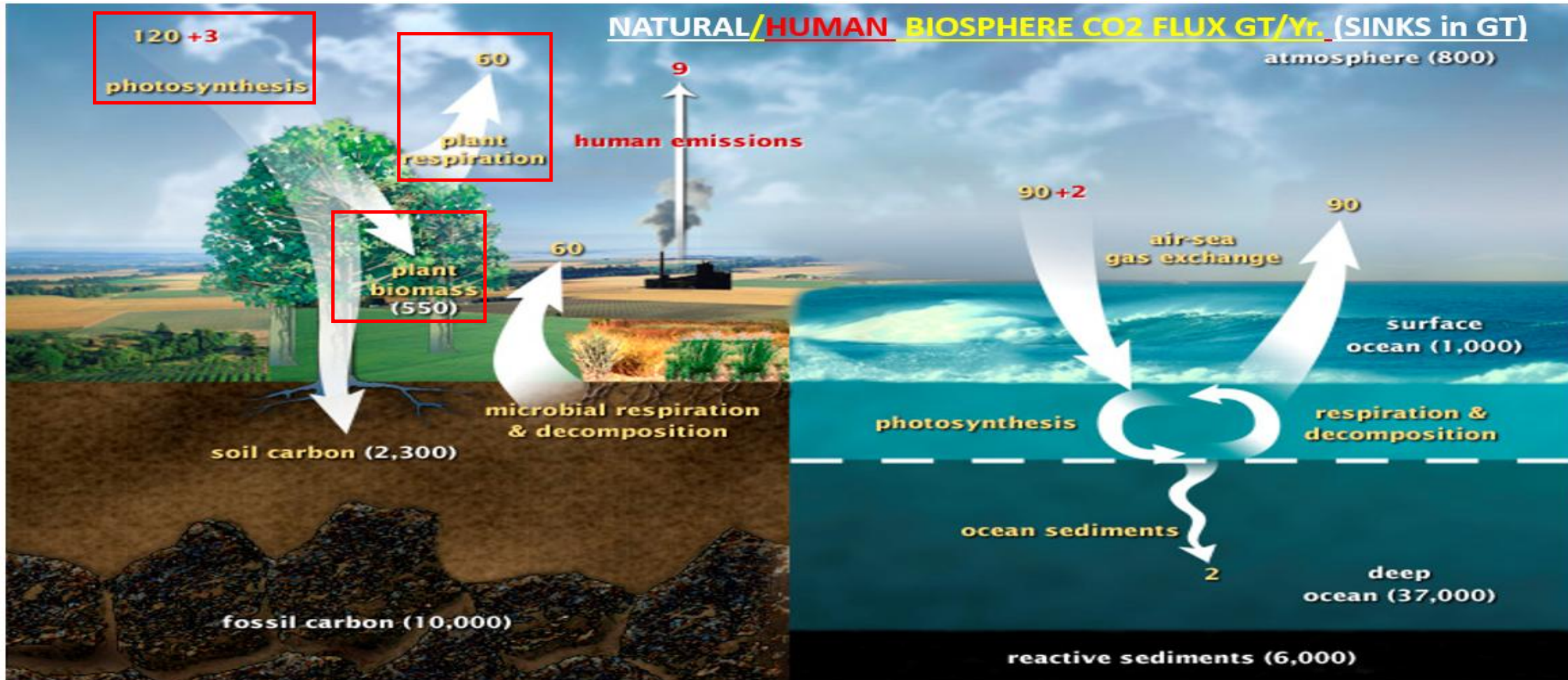


eDAC- Enhanced Nature Based Direct Air Capture, Use, and Bio-Sequestration

	Basis:	Tons/Year Captured				
	100	Trees/acre				
	Total Cumulative Biomass (kg/Tree)					
	Summed over duration of experiment (10 Producing Years)					
	Enriched	Ambient	Net	Kg/Tree/Year	kg/acre/yr	
Total Biomass Increase/Tree	1127	- 664	= 463	46.3	4630	
	MINUS					
	or about		est			
	5 MT/Year/acre		10 MT/Year/acre			
CO2 ENRICHMENT LEVEL	at 550 ppm		at 1000ppm			

- The Difference between aDAC and eDAC?
- Enhanced Nature Based DAC (eDAC) is banking on building an “Infrastructure of CO2 Absorbing Machines” in the form of nature based Biomass Generating Plants converting and drawing down the CO2 concentration levels from the miles of upper atmosphere by supplementing CO2 in the tiny sliver (100 feet) of biosphere and improving Food Security by increasing yields.

Nature Based Direct Air Capture (nDAC)



(Diagram adapted from U.S. DOE, [Biological and Environmental Research Information System](#). 12/2008)

120 GT/Y Photosynthesis Flux – 60 GT/Y Plant Respiration Flux = 60 GT/Y Global Plant Biomass Sink (Biosequestration) Increase
 Enhanced nature-based DAC (eDAC), can increase bio-sequestration potentially 50% or to 90 GT/Y

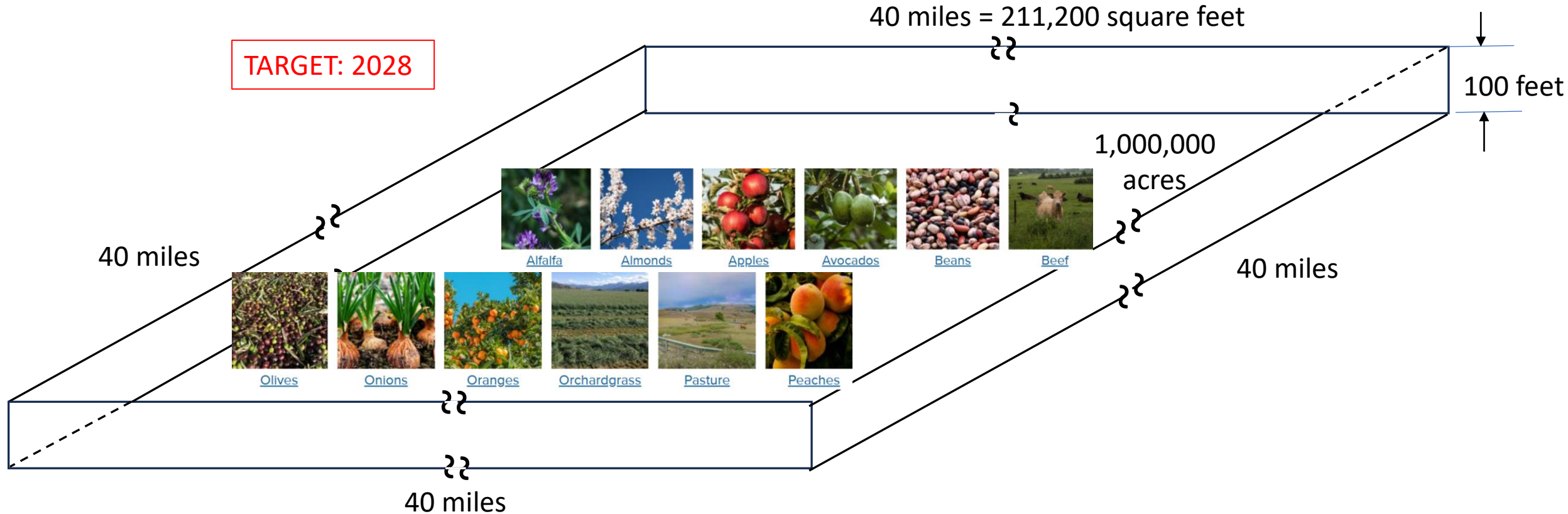
<https://ess.science.energy.gov/wp-content/uploads/2020/12/facereport2020.pdf>



Quote from “Lessons and Legacy of US DOE’s CO₂ Research Program of FACE, a Form of eDAC” stated on page 99:

“What was learned from these experiments? If there is a single scientific conclusion from the many years (40-YEARS see below) of investigation and more than \$100 million invested, it might simply be that most of the C₃ plants and terrestrial ecosystems studied do respond positively to increased concentration of atmospheric CO₂.”

5 to 10 Million Tons/Yr of capture potential with 1,000,000 acres of eDAC (up to 1/6 of CARB 2050 Goal)
Is Equivalent to Doubling the CO2 in a 100-foot high layer of biosphere
for 1/2 of California's Almond and Pistachio Crop
Potentially adding \$3 Billion to California's \$25 Billion Farm Operations Economy (over 10% increase)



REFERENCE:

https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=CALIFORNIA

SAMPLE COSTS TO ESTABLISH AN ORCHARD AND PRODUCE
ALMONDS



SAN JOAQUIN VALLEY SOUTH

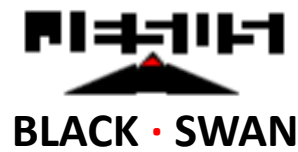
DOUBLE LINE DRIP IRRIGATION - 2016

Mohammad Yaghmour
David R. Haviland
Elizabeth J. Fichtner
Blake L. Sanden
Mario Viveros
Daniel A. Sumner

UC Cooperative Extension Area Orchard Systems Advisor, Kern County
UC Cooperative Extension Farm Advisor, Kern County
UC Cooperative Extension Farm Advisor, Tulare County
UC Cooperative Extension Farm Advisor, Kern County
UC Cooperative Extension Farm Advisor Emeritus, Kern County
Director, UC Agricultural Issues Center

2016 EXPECTED INCREASED RETURN ABOVE COST Per UC Davis for eDAC

Net Return per Acre above Total Costs for Almond							
PRICE (\$/lb.)	YIELD (lb./acre)						
Almonds	2,000	2,300	2,600	3,000	3,300	3,600	3,900
1.00	<u>-4,185</u>	<u>-3,902</u>	<u>-3,619</u>	<u>-3,241</u>	<u>-2,957</u>	<u>-2,674</u>	<u>-2,391</u>
1.50	<u>-3,185</u>	<u>-2,752</u>	<u>-2,319</u>	<u>-1,741</u>	<u>-1,307</u>	<u>-874</u>	<u>-441</u>
2.00	<u>-2,185</u>	<u>-1,602</u>	<u>-1,019</u>	<u>-241</u>	343	926	1,509
2.50	<u>-1,185</u>	<u>-452</u>	281	1,259	1,993	2,726	3,459
3.00	<u>-185</u>	698	1,581	2,759	3,643	4,526	5,409
3.50	815	1,848	2,881	4,259	5,293	6,326	7,359
4.00	1,815	2,998	4,181	5,759	6,943	8,126	9,309



eDAC

2016 EXPECTED INCREASED RETURN ABOVE COST Per UC Davis

CITRUS CROP CARBON ENRICHMENT

BASIS: MIN + 60% YIELD

<u>Dollars/Carton</u>	<u>%</u>	<u>\$/100 ACRES/Y</u>
18.80	888%	\$362,000
19.80	436%	\$400,000
20.80	304%	\$422,000

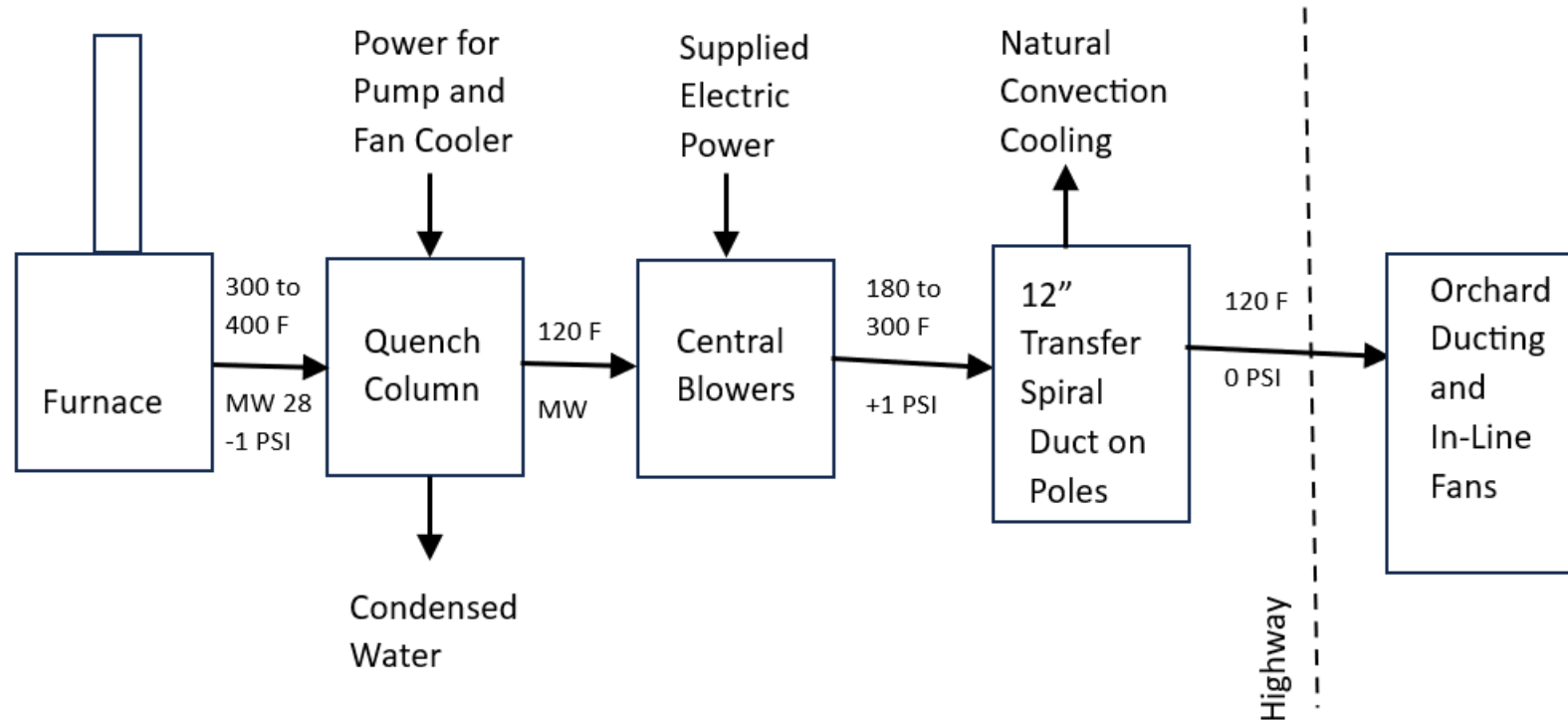
ALMOND CROP CARBON ENRICHMENT

BASIS: MIN + 50% YIELD

<u>Dollars/lb</u>	<u>%</u>	<u>\$/100 ACRES/Y</u>
3.00	318%	\$335,300
3.50	200%	\$445,300
4.00	145%	\$510,300

**With eDAC...enough capacity to capture global industrial carbon...AND ... with a profit ... that benefits food security
... not like aDAC...a societal budget busting cost... and food security threat...**

CONVENTIONAL DESIGN BLOCK FLOW DIAGRAM FOR eDAC





eDAC

Schedule to Scale/ Cost of Implementation

PHASE 1: Complete 2024- circa 500 tons/year to 10 trees

1 or 2 Legs of flex ducting at 20" with distributed fans, quench column in orchard.

Cost: under \$1 Million.

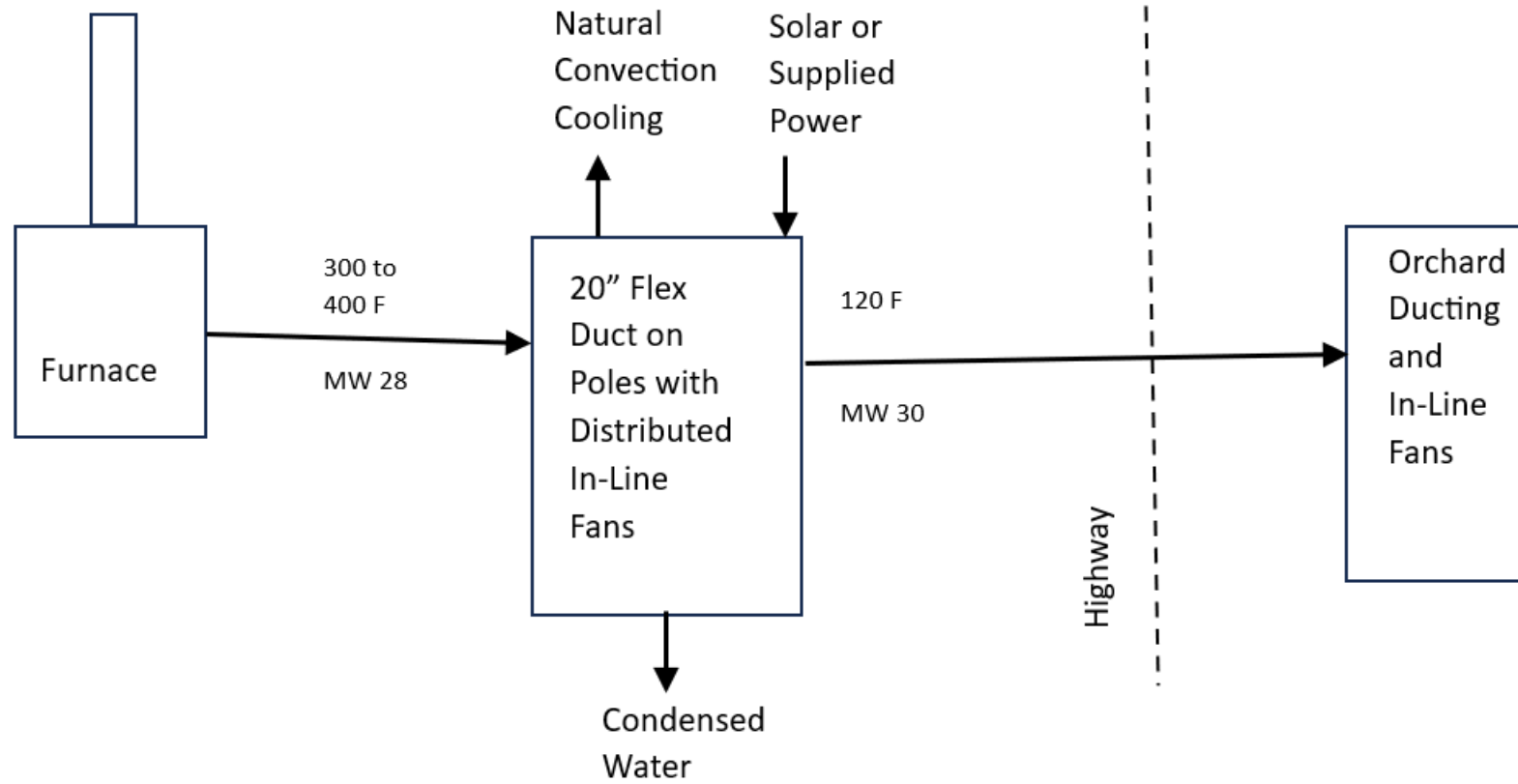


“Does a lion roar in the forest when it has no prey?” Amos 3:4



Black Swan, LLC

LOW-COST DESIGN- Low Op Cost/ Low Energy/ Med Cap Cost



eDAC Block Flow Diagram



Black Swan, LLC

500 HP Natural Gas Fired Engine for an Irrigation Well Pump

eDAC SCALE: 2000 tons/year CO₂





eDAC

Pathway and
Temperature
of CO₂ Bearing
Flue Gas

- 3-400 F
- 200 F
- 60-80 F





CO2 Distribution Ducting Delivers CO2 for Dispersal of CO2 into Almond Tree Canopy



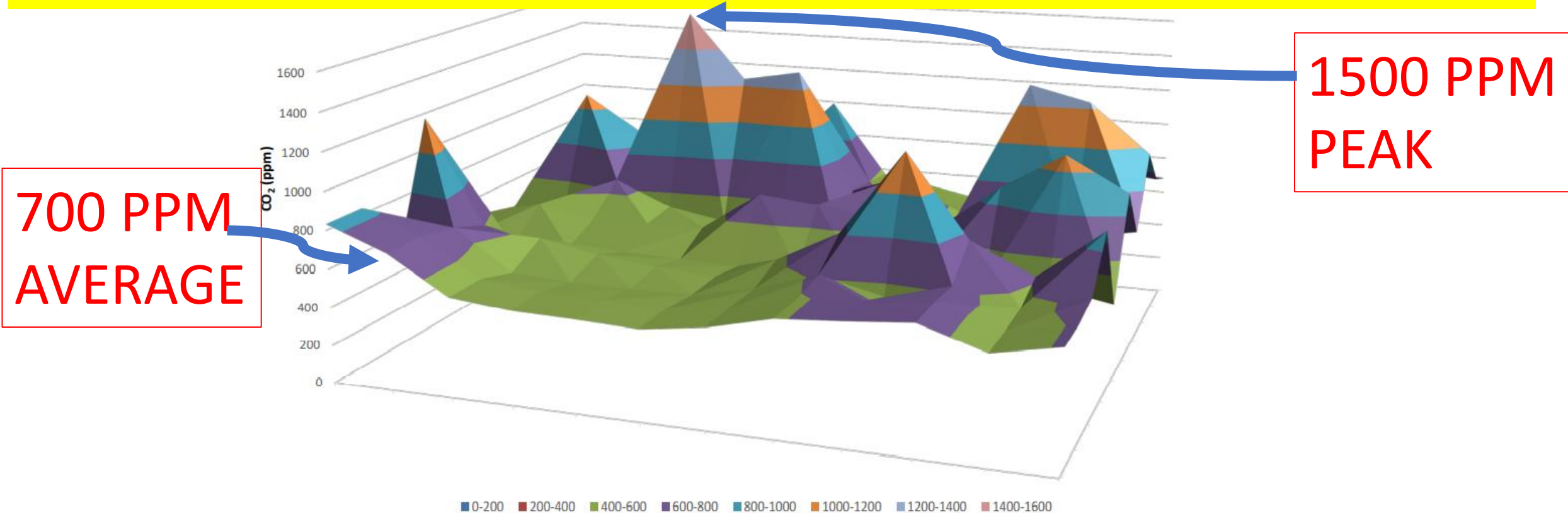
CO2 Monitors Located in Almond Tree Canopy



BLACK • SWAN

eDAC Results

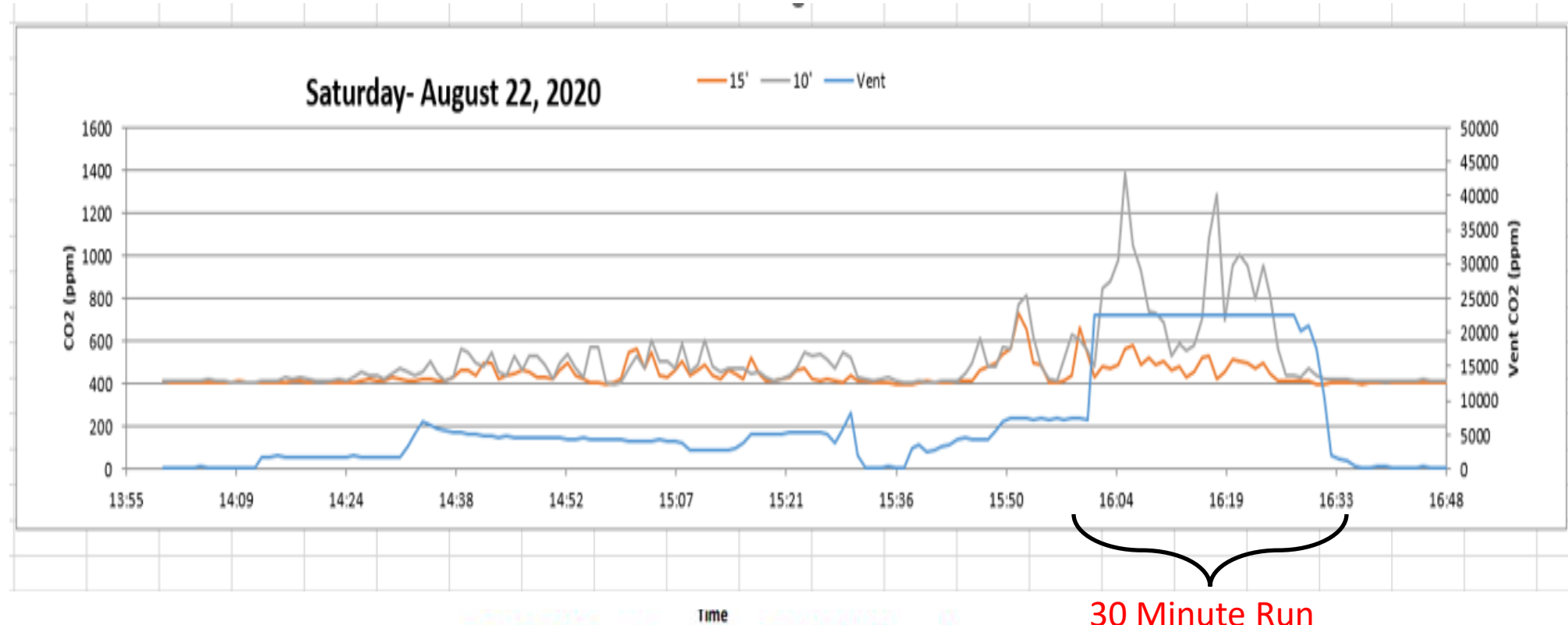
TWO TREE ENRICHED CO₂ 3-D CONCENTRATION PROFILE BELOW 10 FEET PEAKS





BLACK · SWAN

“KITTY HAWK MOMENT”



eDAC Results

30 Minute Run
1000 ppm avg at 10'
550 ppm avg at 15'



Schedule to Scale/ Cost of Implementation

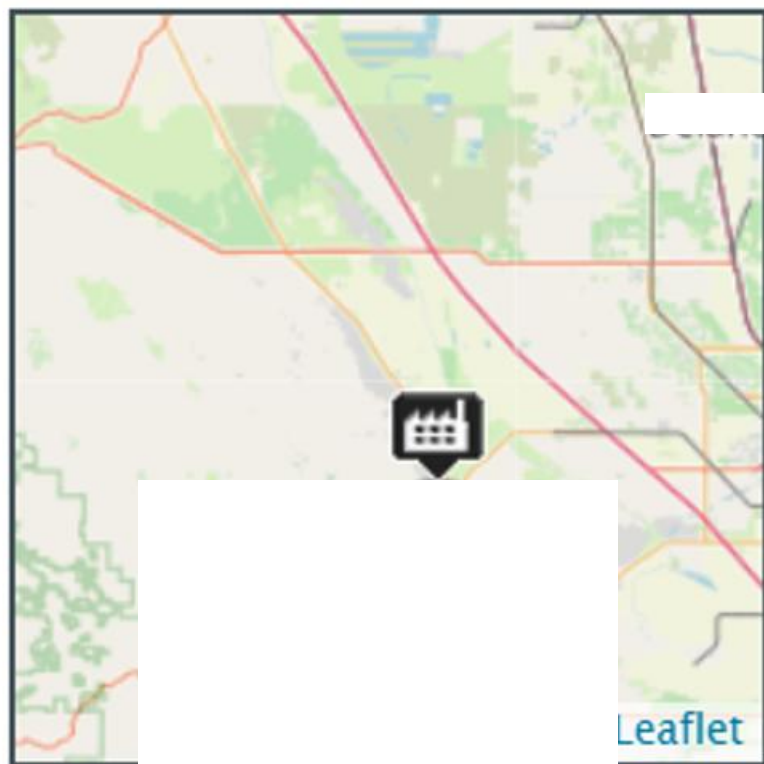
PHASE 3: 100,000 to 200,000 Tons/Year Sequestration Target 10,000 to 40,000 acres: Complete 2026

Costs Scaled off of above.

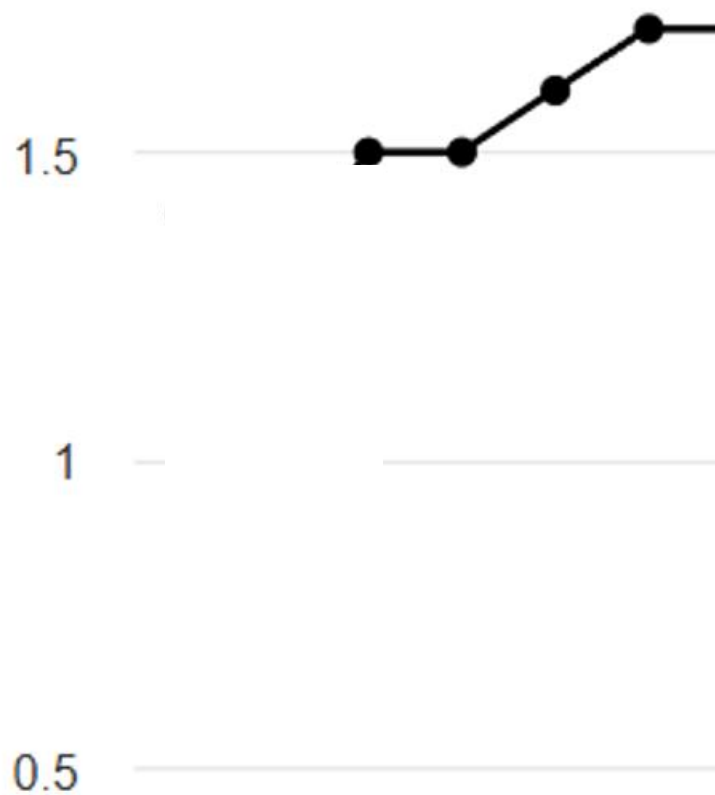


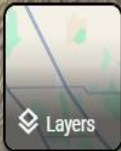
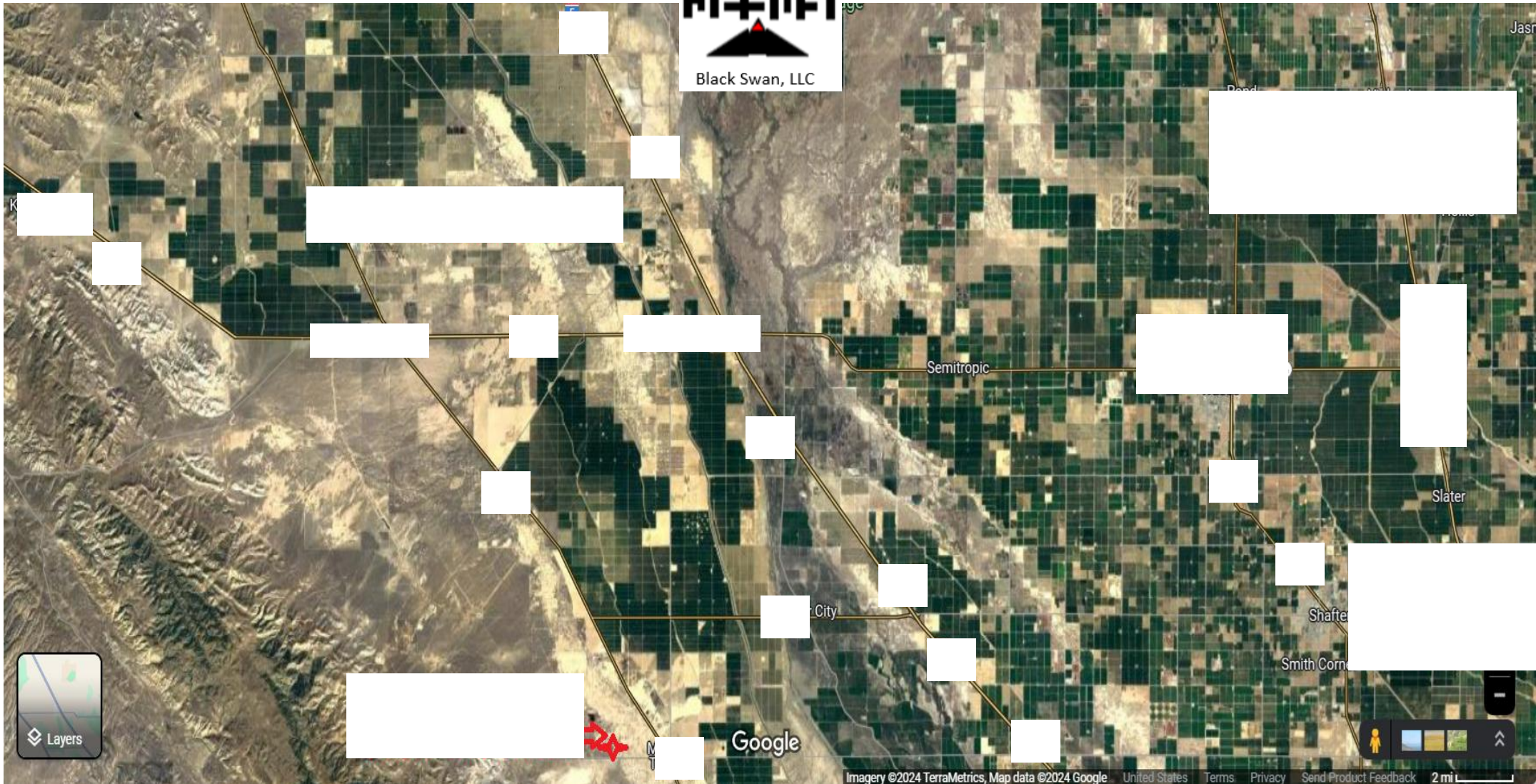
Black Swan, LLC

2



Million Metric Tons CO₂e

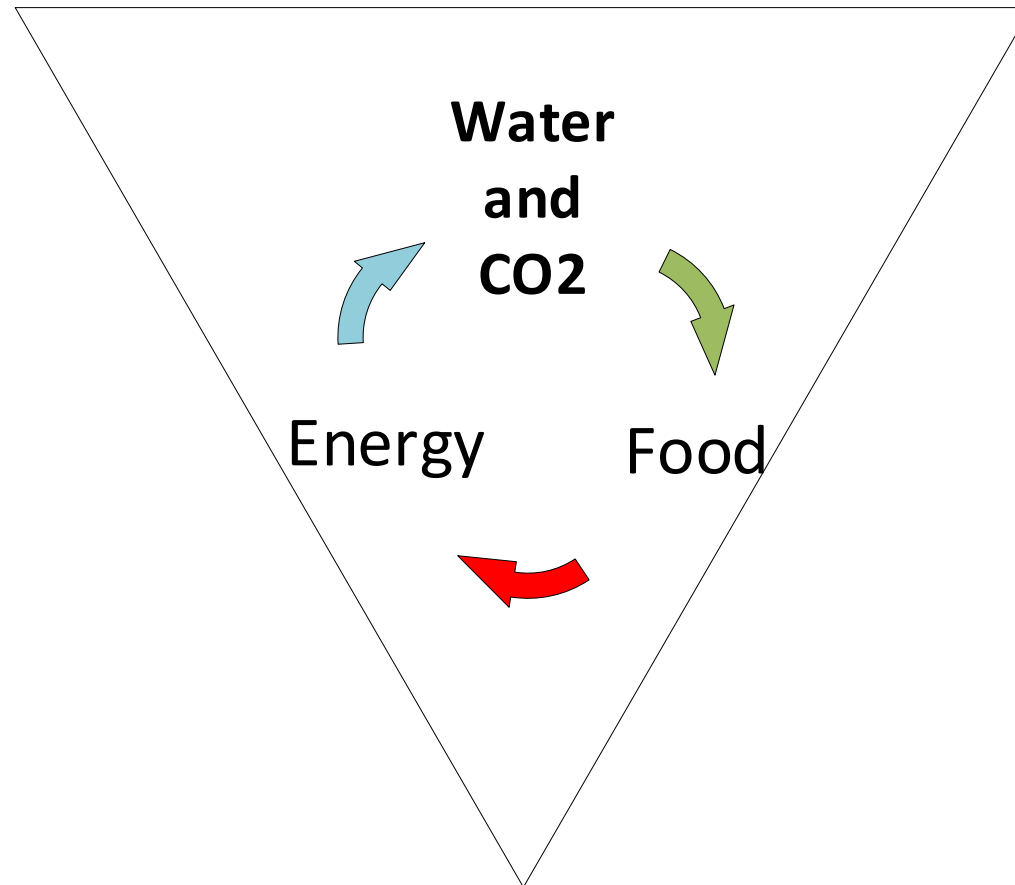


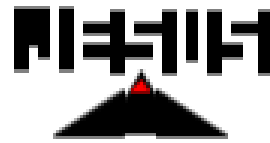


SUMMARY OF ROUGH ORDER OF MAGNITUDE COST ANALYSIS:

		<u>IN&OUT-OF-ORCHARD OPTION CAP COSTS</u>		<u>IN-ORCHARD (\$2000/ACRE)</u>		INCREASED
	TONS/YEAR <u>CAPTURED</u>	DISTRIBUTED OPTION <u>CAP COST</u>	<u>OPER HP</u>	ACRES <u>APPLIED</u>	TOTAL <u>CAP COST</u>	20Y RETURN <u>+50% YIELD</u>
CAP COST/TON/20 YEAR LIFE		\$52				
EARLY CASE	2,000	\$2.1MM	58HP	200	\$0.4MM	\$12MM
MID CASE	20,000	\$21MM	580HP	2000	\$4MM	\$120MM
MAX CASE	140,000	\$145MM	4,000HP	14,000	\$28MM	\$840MM

Black Swan Cycle





Black Swan, LLC

11/13/2024

Jesus said to them, again,

“Peace be with you. As the Father has sent Me, so I send you.”

And when He had said this,

He breathed on them and said to them,

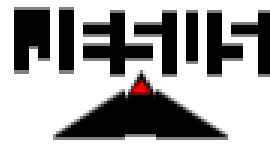
“Receive the Holy Spirit.”

THANK YOU FOR YOUR TIME & PATIENCE!!!!

Brian Kolodji, PE, President and Owner

Kolodji Corp and Black Swan, LLC

bkolodji@sbcglobal.net, cell: (713) 907-8742



Black Swan, LLC

“-then the Lord God formed the man out of the dust of the ground and blew into his nostrils the breath of life, and the man became a living being.” **Genesis 2:7**

Enhanced Nature-Based Direct Air Capture (eDAC)

Scaled to 1 million Tons/Year of CO₂ by 2027

Making Food by Using Free Air Carbon dioxide Enrichment (FACE)

as opposed to absorbent-based DAC (aDAC) with potential for Negative Impact to Food Security

presented at

American Institute of Chemical Engineers

April 9th, 2025

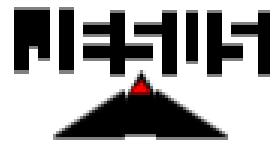
by

Brian Kolodji, PE, President and Owner

bkolodji@sbcglobal.net, cell: (713) 907-8742

Kolodji Corp / Black Swan, LLC

ENERGY CARBON MANAGEMENT/ INTELLECTUAL PROPERTY HOLDING COMPANY



Black Swan, LLC

“-then the Lord God formed the man out of the dust of the ground and blew into his nostrils the breath of life, and the man became a living being.” **Genesis 2:7**

POWER PLANT MDAC AND FGXB REDUCES FUEL CONSUMPTION AND BIOSEQUESTERS

American Institute of Chemical Engineers 2022 National Meeting

Brian Kolodji, PE, President and Owner

Kolodji Corp and Black Swan, LLC

bkolodji@sbcglobal.net, cell: (713) 907-8742

ENERGY CARBON MANAGEMENT

Dr. Bruce Kimball, Retired USDA (Green Leaf Group);

Dr. Brian Marsh, County Director Advisor University of California Cooperative Extension- Kern County

Paramjit Dosanjh, Manager/Owner Dosanjh Brothers Orchards

Dr. Amit Gunasakara, Formerly with California Department of Agriculture, Chief Scientist

Manual Aguayo, Kolodji Corporation, Supervisor Operations

Dr. Marc Straub, Vice President, Formerly with Generon

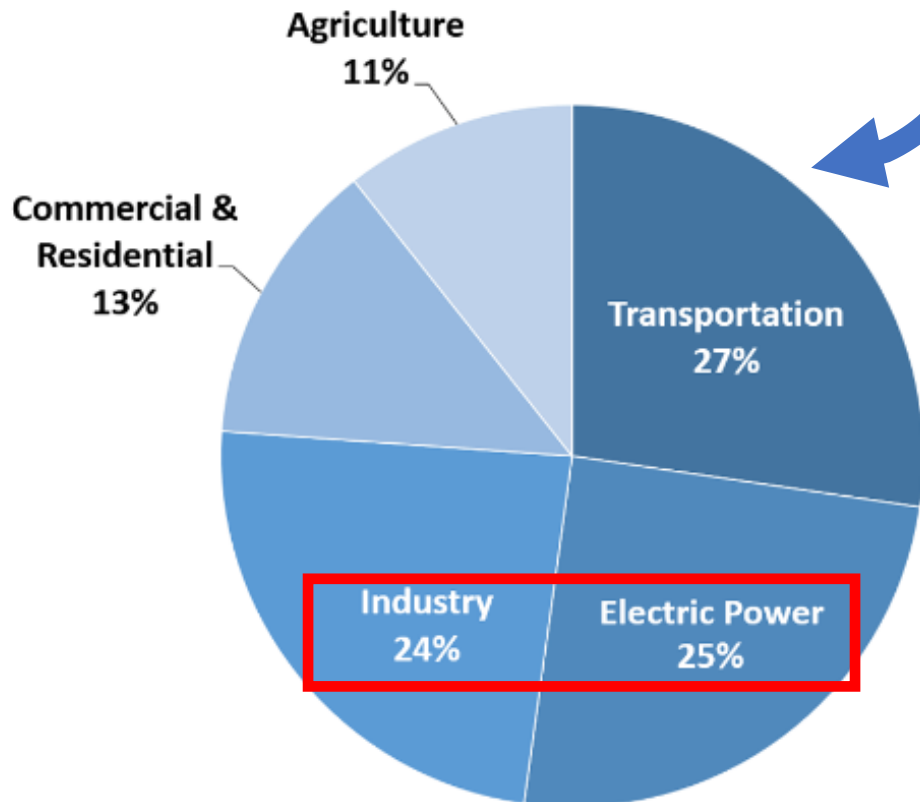
11/14/2022



2020 REFERENCE



Total U.S. Greenhouse Gas Emissions
by Economic Sector in 2020

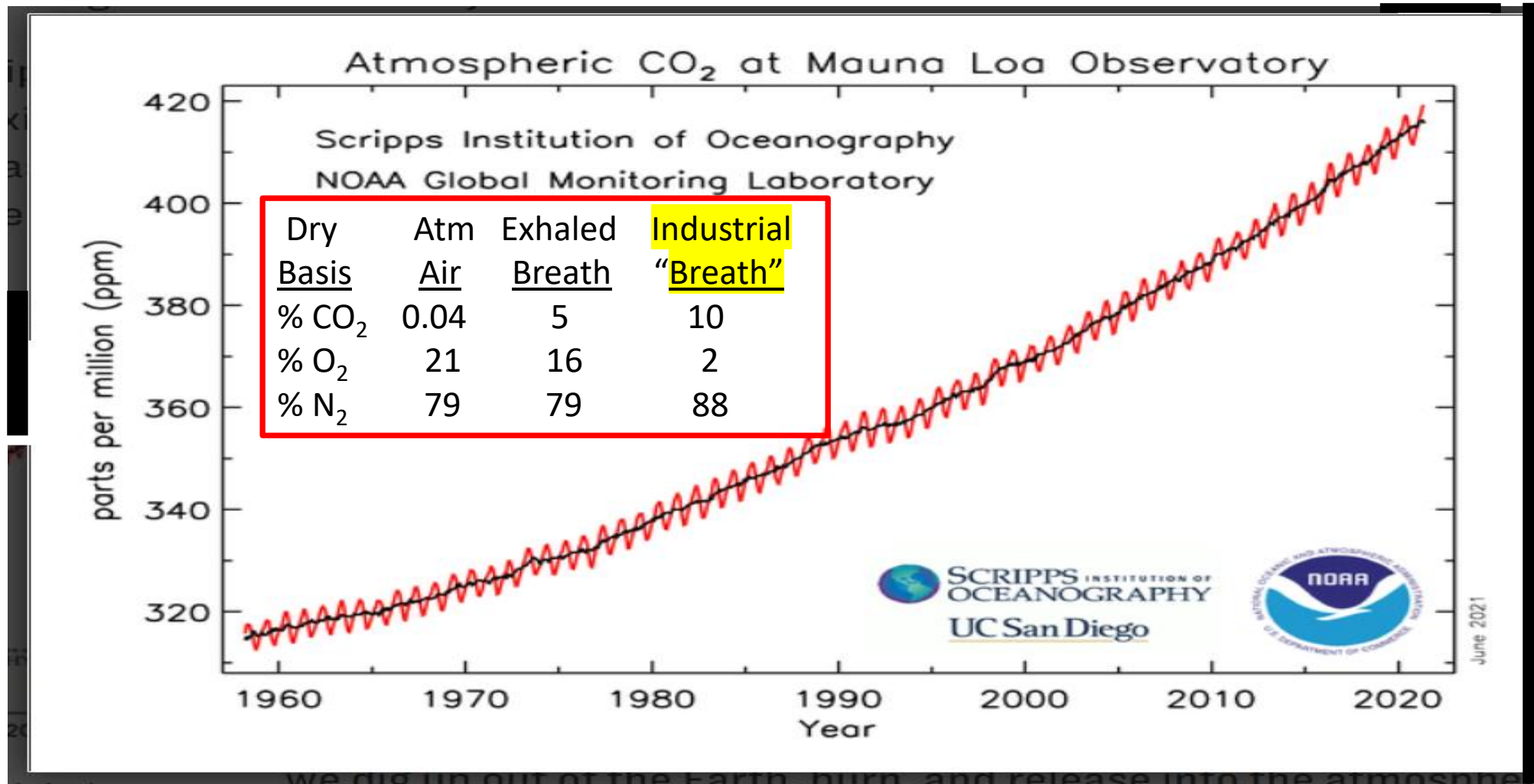


BLACK · SWAN FXGB & MDAC:

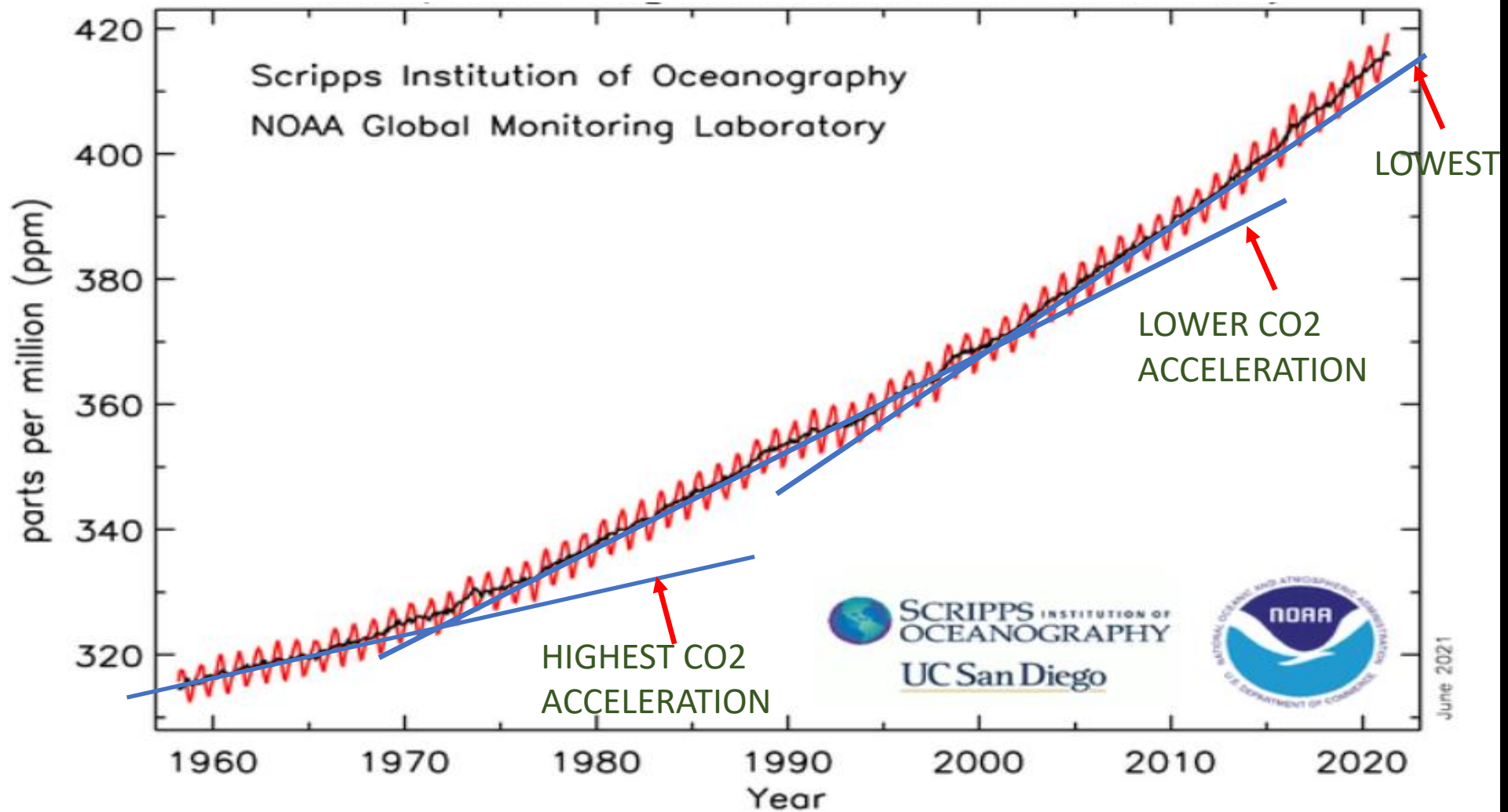
1. Remove All five (5) GT/Y CO₂ produced from All US Sectors
2. Remove another 5 GT/Y from air
3. Achieve Carbon Neutrality and beyond...Carbon Management...

Energy Carbon Management!!!

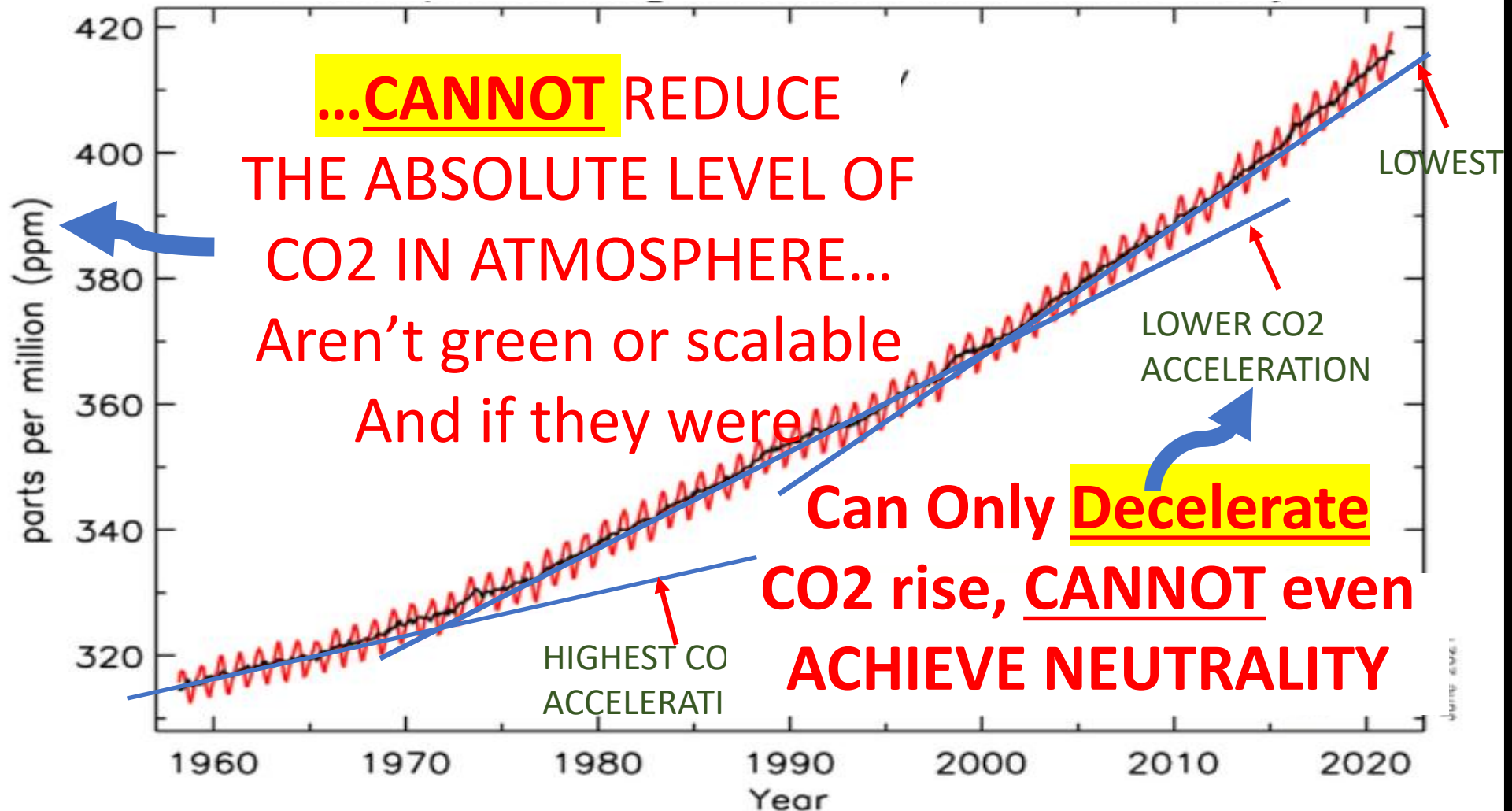
“Keeling” Curve



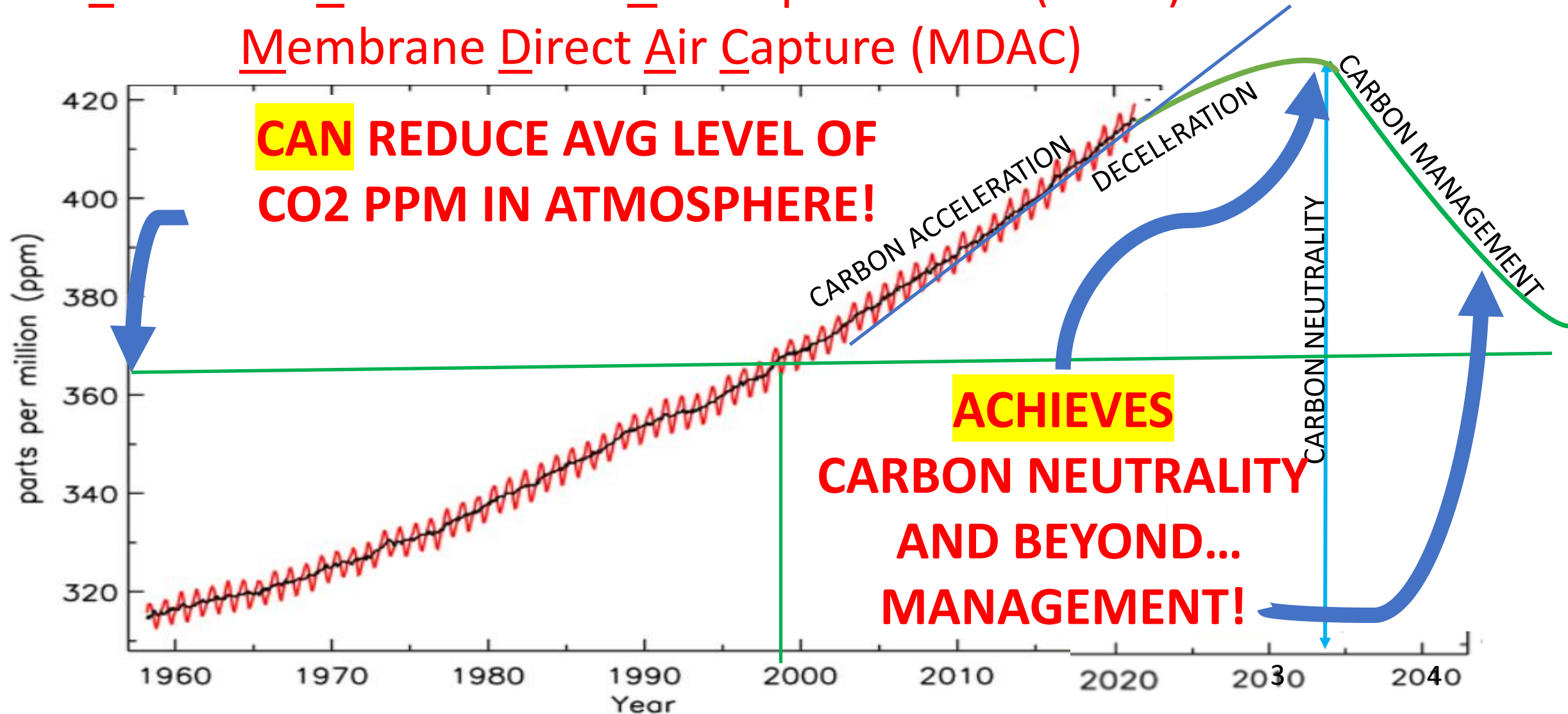
Cause? Energy Carbon Mis-management



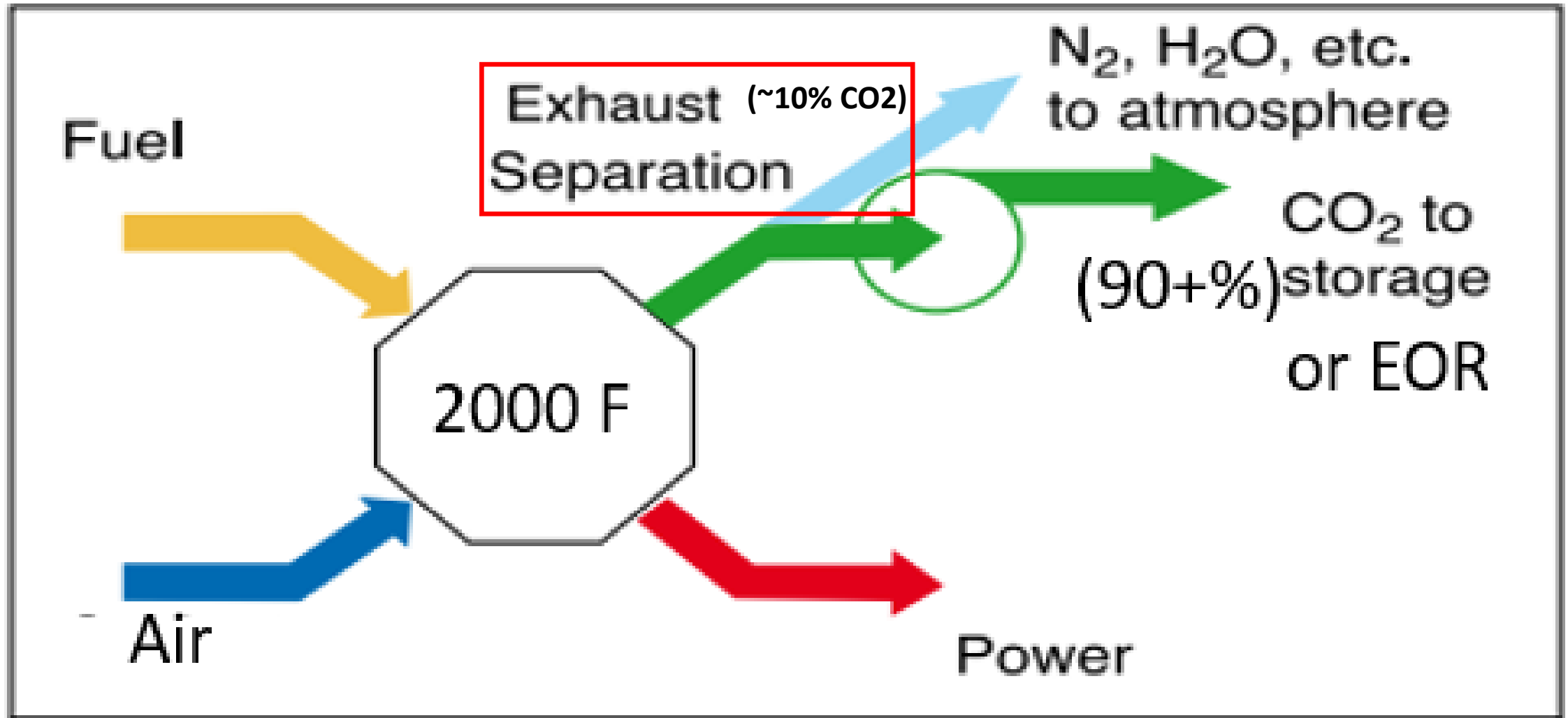
CURRENT CONVENTIONAL CO2 CAPTURE TECHNOLOGY



Flue Gas eXtraction and Bio-sequestration (FGXB) & Membrane Direct Air Capture (MDAC)



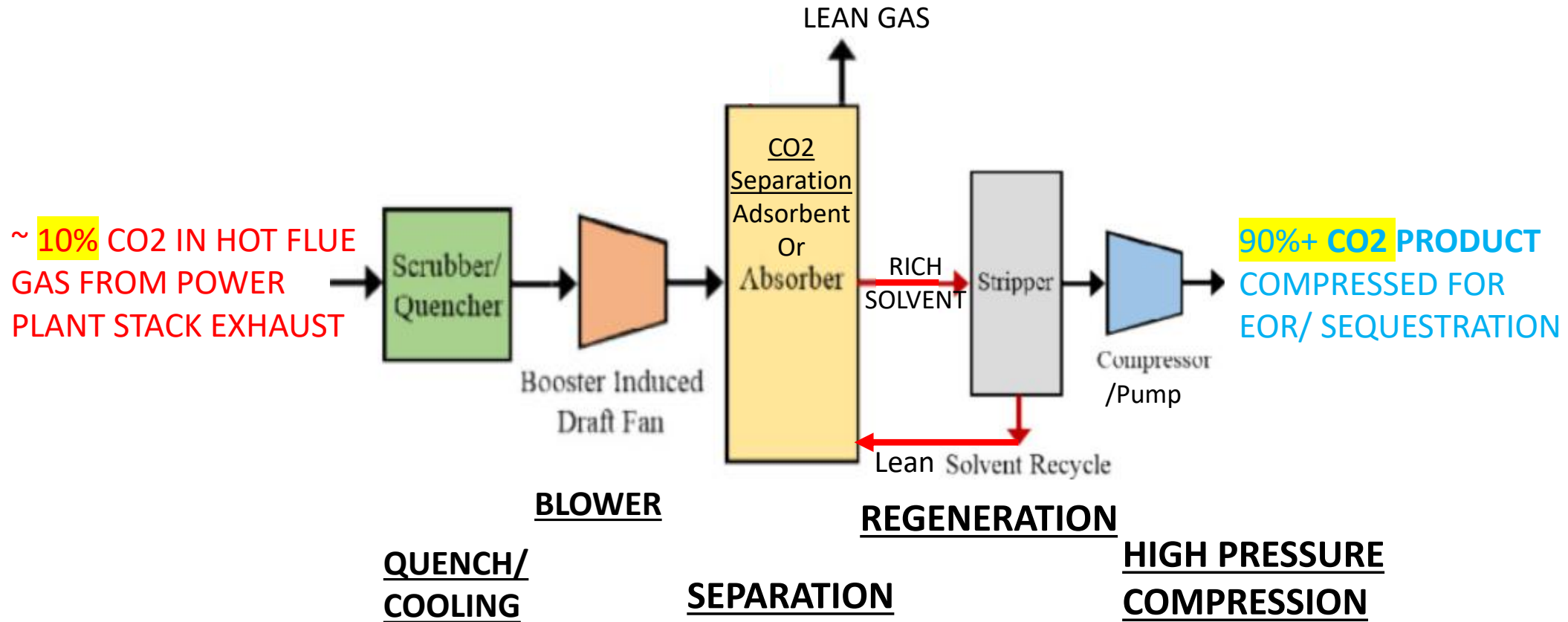
CONVENTIONAL POST-COMBUSTION CO₂ CAPTURE



Separates CO₂ from Exhaust Stream

CONVENTIONAL POST-COMBUSTION CO2 CAPTURE UNIT

KEY COMPONENTS, SEQUENCE, STREAMS



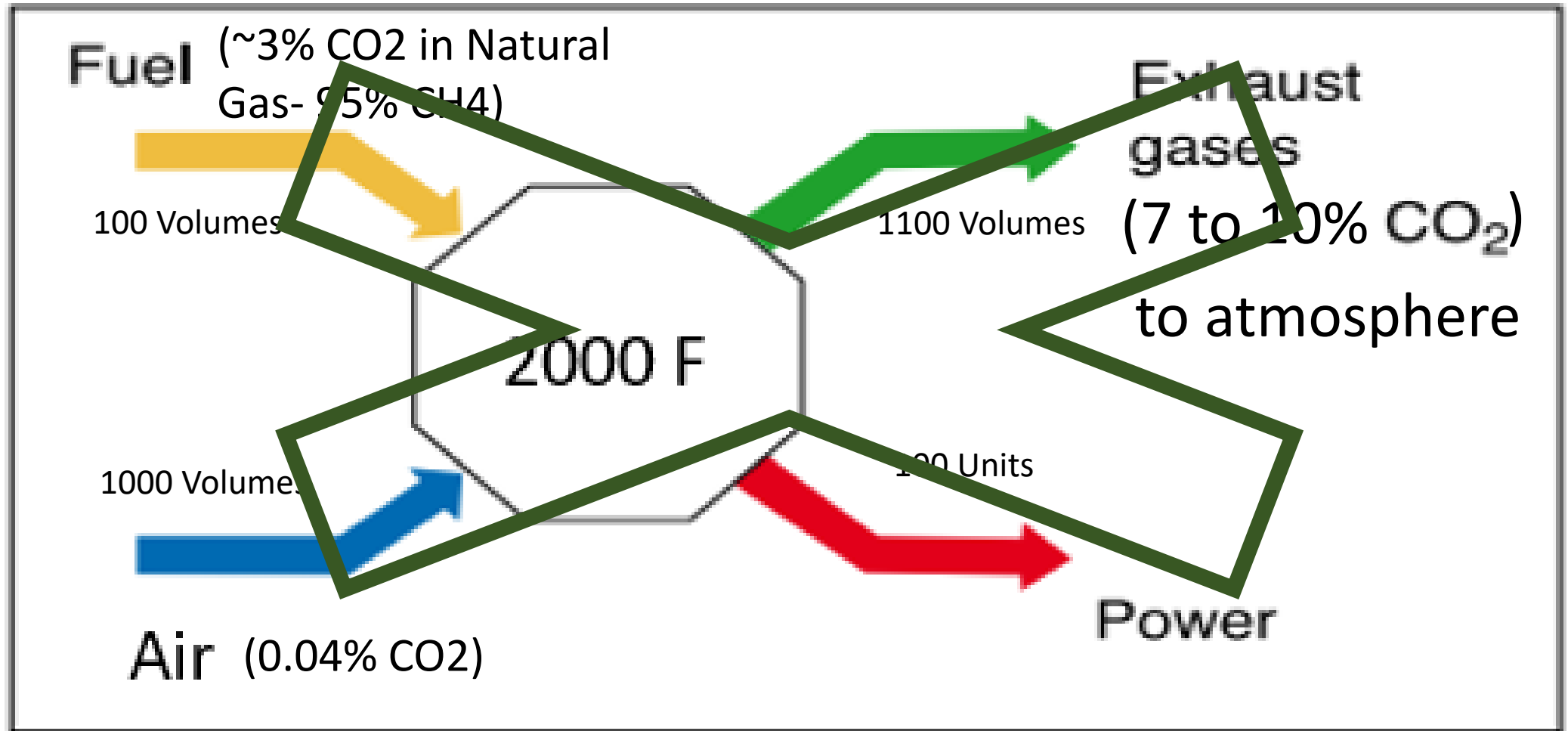
HIGH CAPITAL/ ENERGY/ RESOURCE CONSUMPTION COMPONENTS

PETRA NOVA- CONVENTIONAL POST-COMBUSTION CAPTURE



- LARGEST: 1.6 Million Ton/Year (MMT/Y)
- 99% CO₂ Product from 10% in Fluegas
 - for Enhanced Oil Recovery (EOR)
 - (Carbon Positive, Not Green)
 - Makes more carbon than removed!
- Not Economic at \$1B (\$600+/Ton)
- Cost: \$4 Trillion for US 6GT/Y Removal

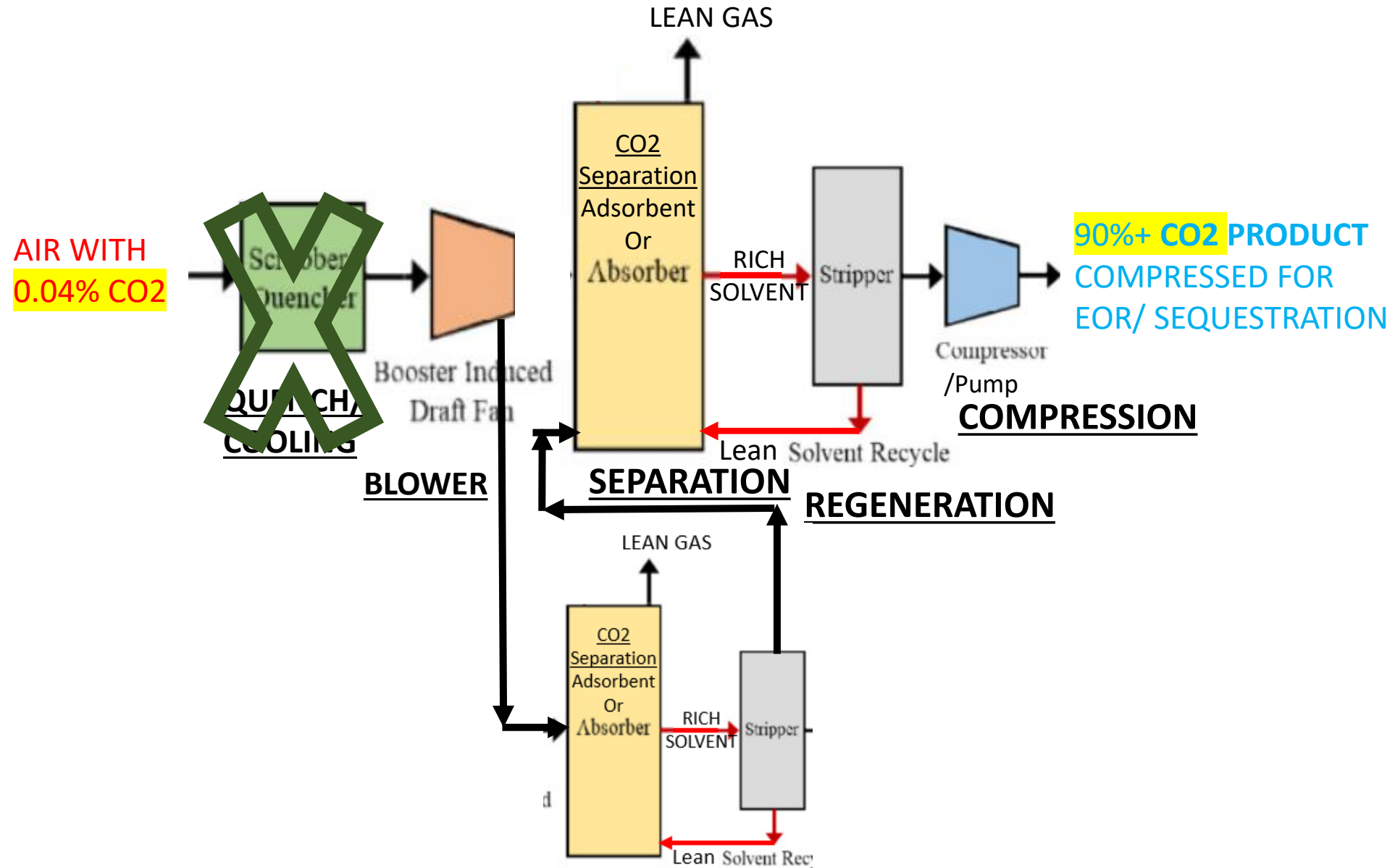
CONVENTIONAL DIRECT AIR CAPTURE (DAC)



NOT RELIANT UPON POWER GENERATION

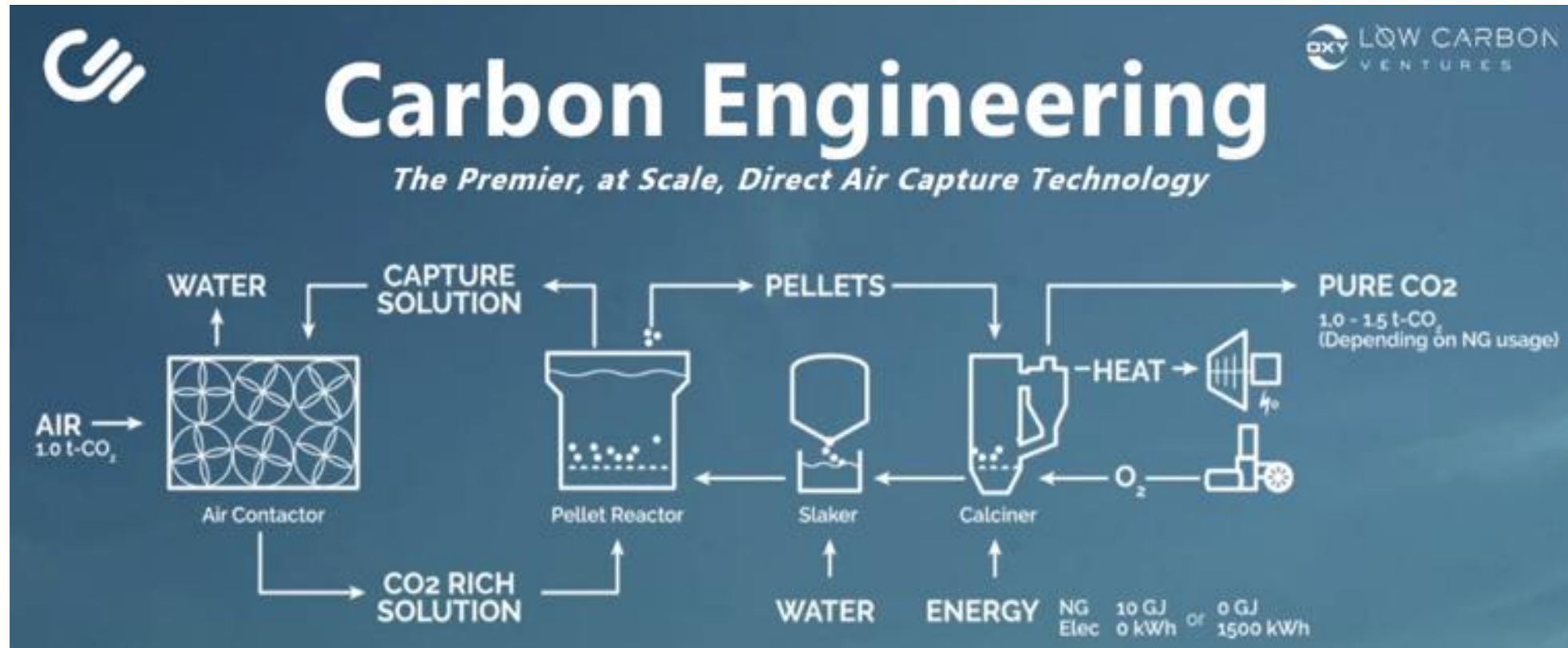
CONVENTIONAL DAC or Direct Air Capture Unit

KEY COMPONENTS, SEQUENCE, STREAMS- Same but double the number as Post-Comb



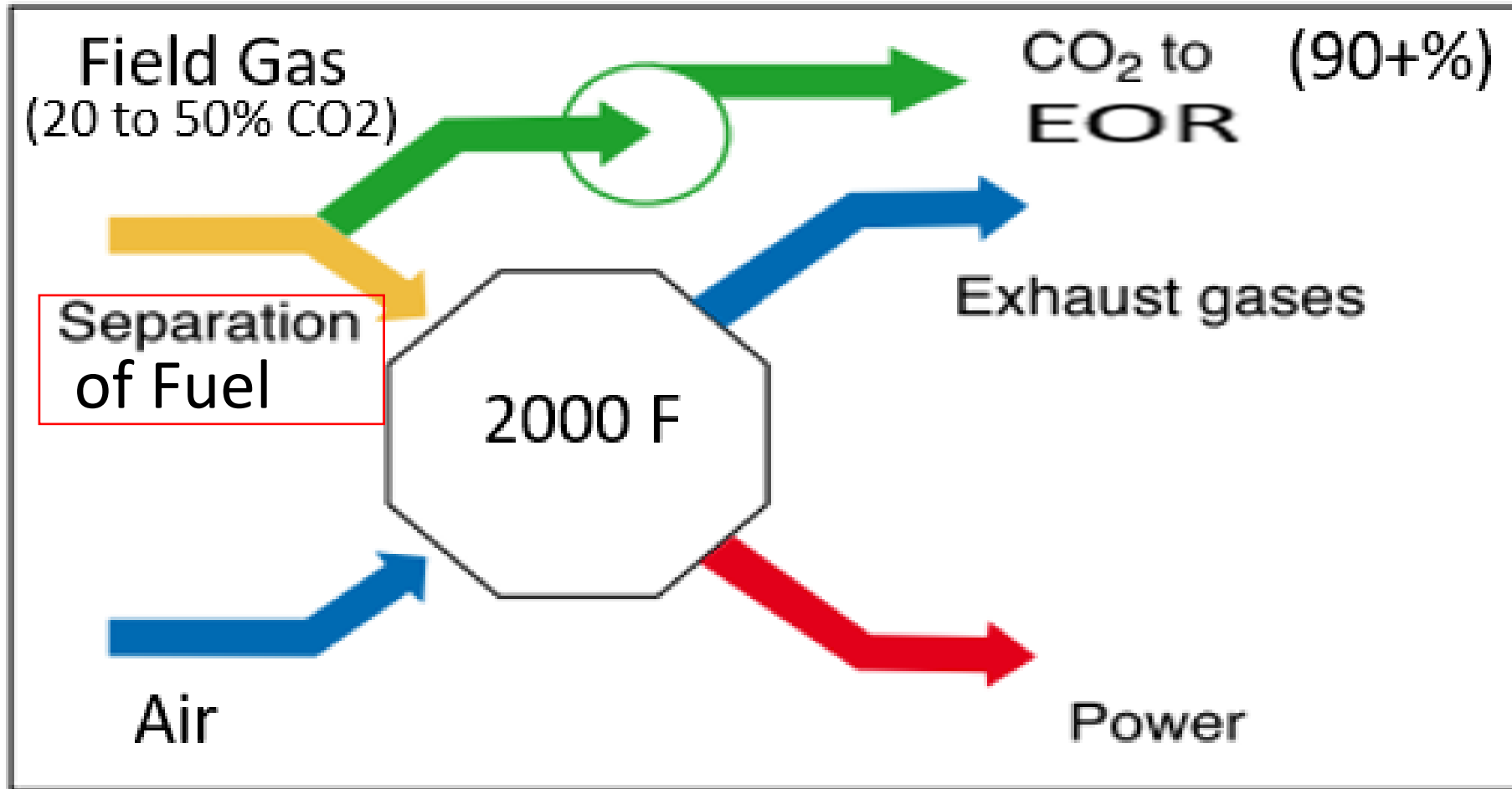
CONVENTIONAL DIRECT AIR CAPTURE (DAC)/ EOR

OXY LOW CLIMATE VENTURES/ CARBON ENGINEERING
\$1000+/Ton, Looks expensive/complicated? It is!



Highest Driving Force Required- Dual sep/regen cycles & EOR

CONVENTIONAL PRE-COMBUSTION CO₂ CAPTURE

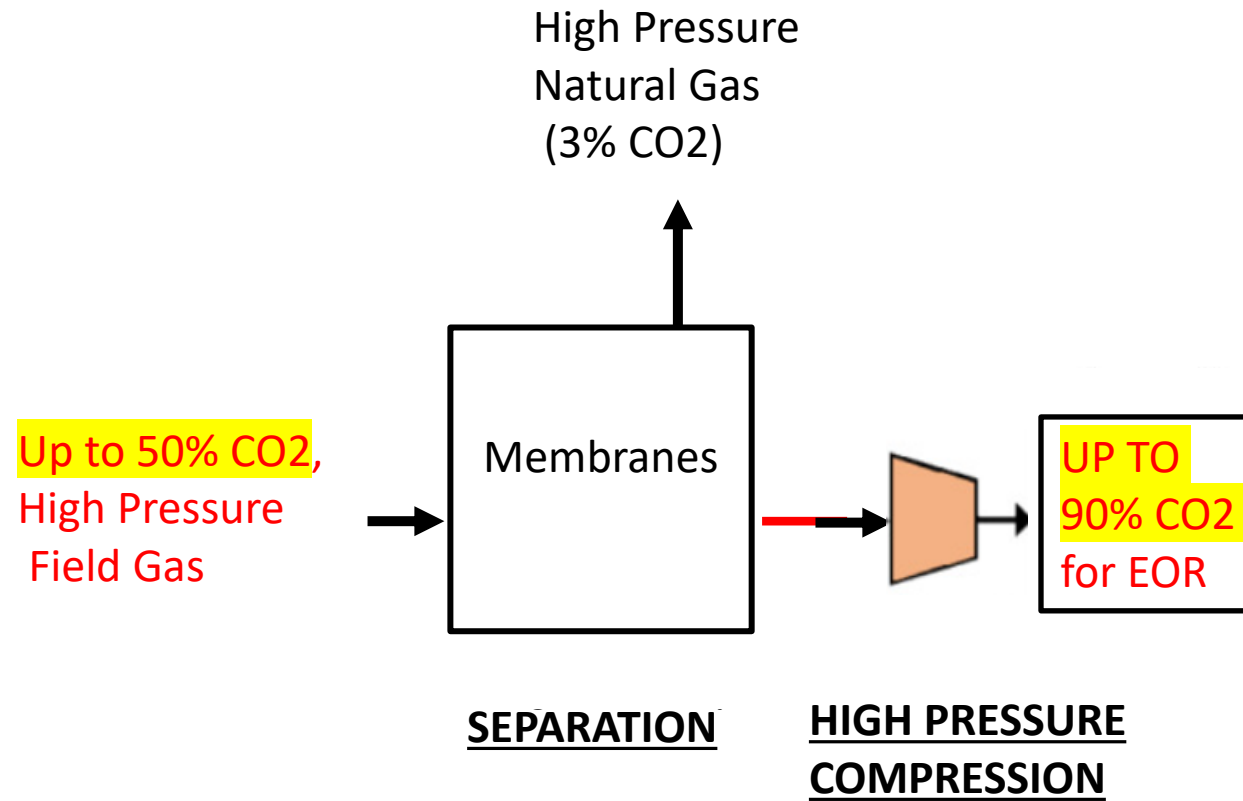


Separates CO₂ from Fuel Stream



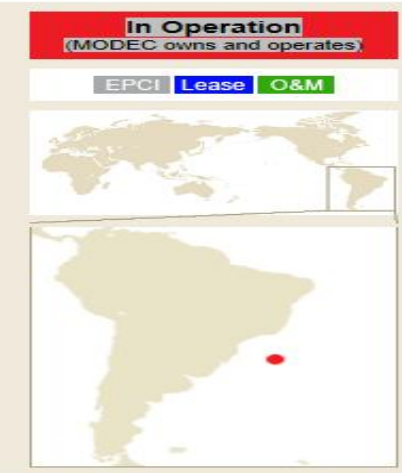
BLACK · SWAN

CONVENTIONAL PRE-COMBUSTION CAPTURE



PRE-COMBUSTION Carbon Capture/ EOR with Membranes

FPSO Cidade de Angra dos Reis MV22



3.2 Million Tons CO₂/ Year **LARGEST EVER** Captured

The FPSO Cidade de Angra dos Reis MV22 is moored in 2,149m of water in the Lula (formerly Tupi) field, Santos Basin.

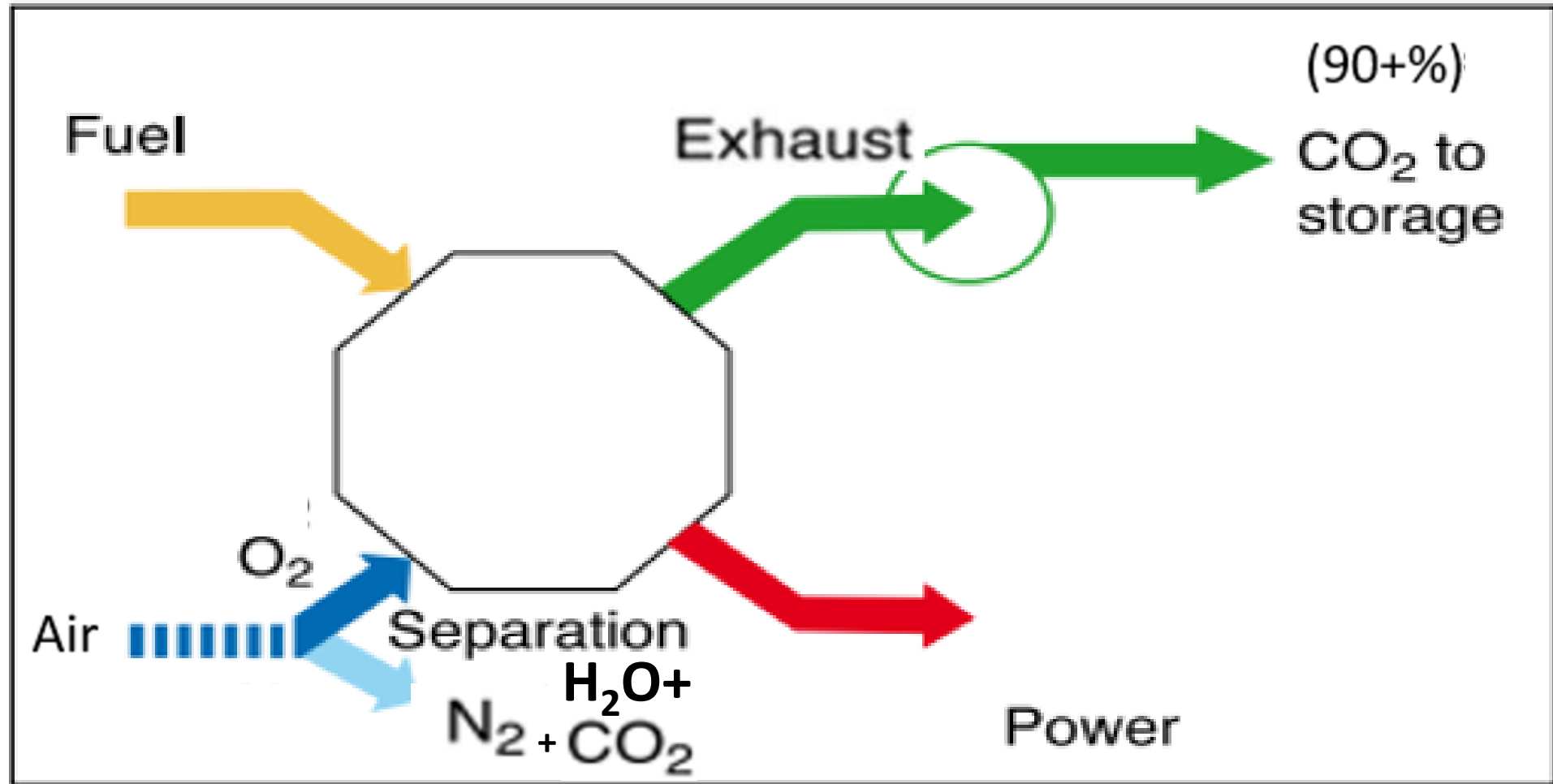
MODEC converted the VLCC "M/V Sunrise IV" into the FPSO. The FPSO is capable of processing up to 100,000 barrels of oil per day and 5 million m³ of gas. The facility is designed for H₂S and CO₂ removal and is capable of reinjecting CO₂ downhole at 550 bar in addition to exporting sales gas to shore. The FPSO will initially gather production from five subsea wells and has the ability to accommodate four additional production wells in the future.

The contract is for a 15 year lease with 5 one-year options. The FPSO is designed to remain on the field for up to 20 years.

Unit Name : FPSO Cidade de Angra dos Reis MV22			
Field Location	: Lula (formerly Tupi) Field	Storage Capacity	: 1,600,000 bbls
Country	: Brazil	Oil Production	: 100,000 bopd
Water Depth	: 2,149 m	Gas Production	: 150 mmscfd
Mooring Type	: SOFEC Spread Mooring	Water Injection	: 100,000 bwpd
		New/Conv	: Conversion
Client : Petróleo Brasileiro S.A. (Petrobras)			

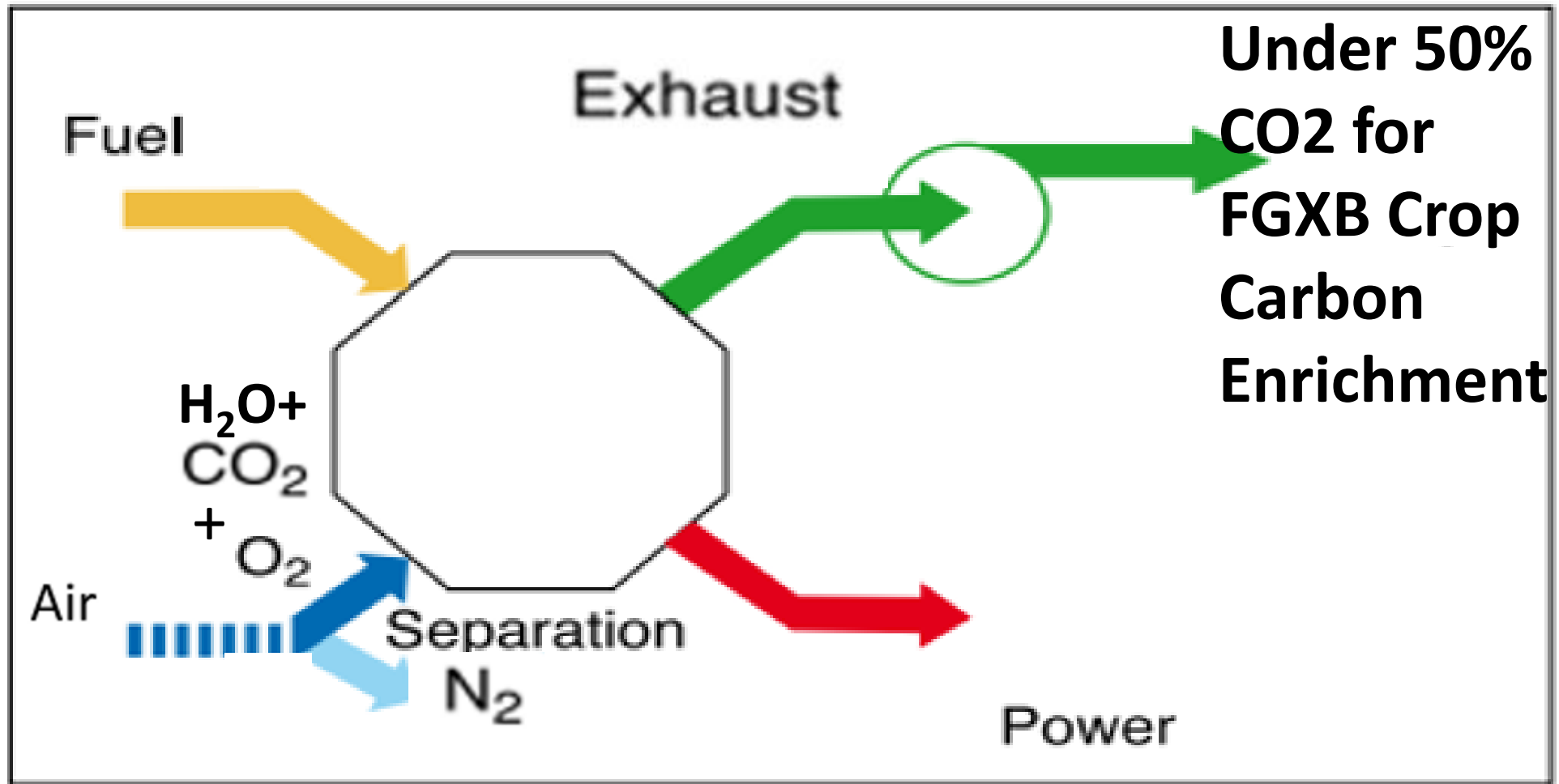
CO₂ for EOR Produces 100,000 BOPD & 150MMSCFD Oil and Gas

SEPARATING NITROGEN FROM AIR TO CONCENTRATE CO₂ IN EXHAUST



CONVENTIONAL OXY-FUEL COMBUSTION

BLACK · SWAN MDAC/ FGXB



**SAVES CAPITAL/TAKES ADVANTAGE OF DIMINISHING RETURNS ON
FUEL SAVINGS AND DIRECT AIR CAPTURES CO₂ WITH O₂**



Energy Tips – Process Heating

Process Heating Tip Sheet #3 • September 2005

Industrial Technologies Program

Oxygen-Enriched Combustion

Figure 2. Energy savings from oxygen injection

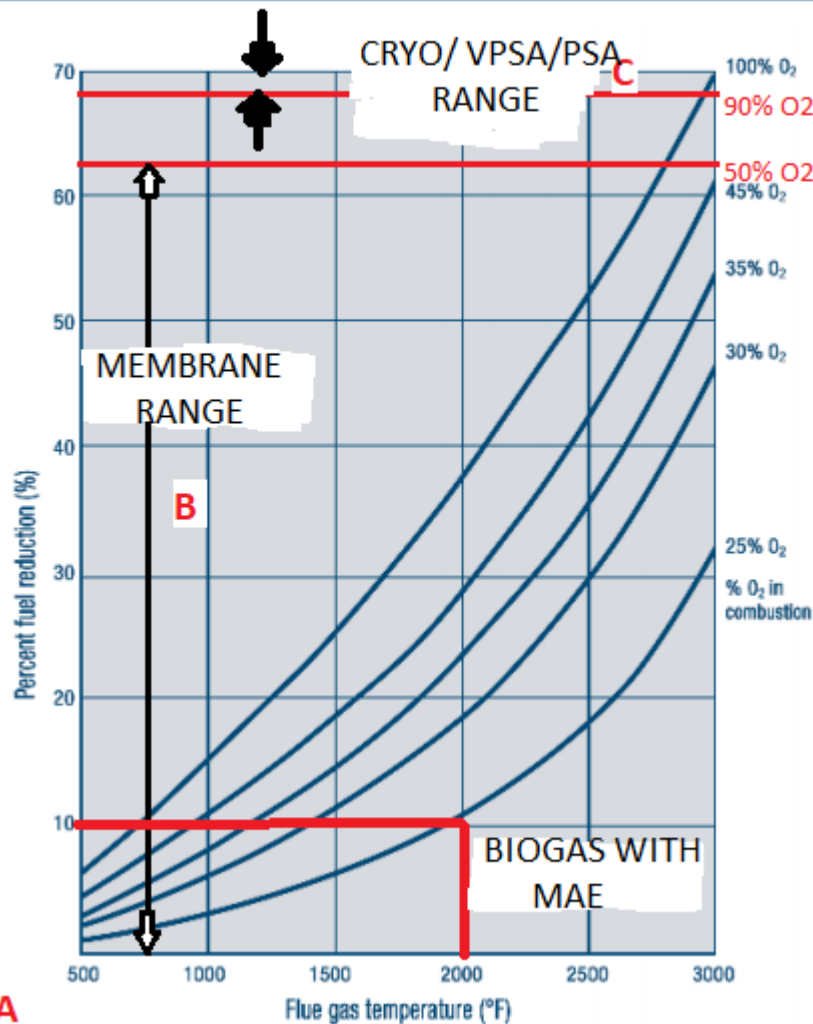


Figure 2 Reference:

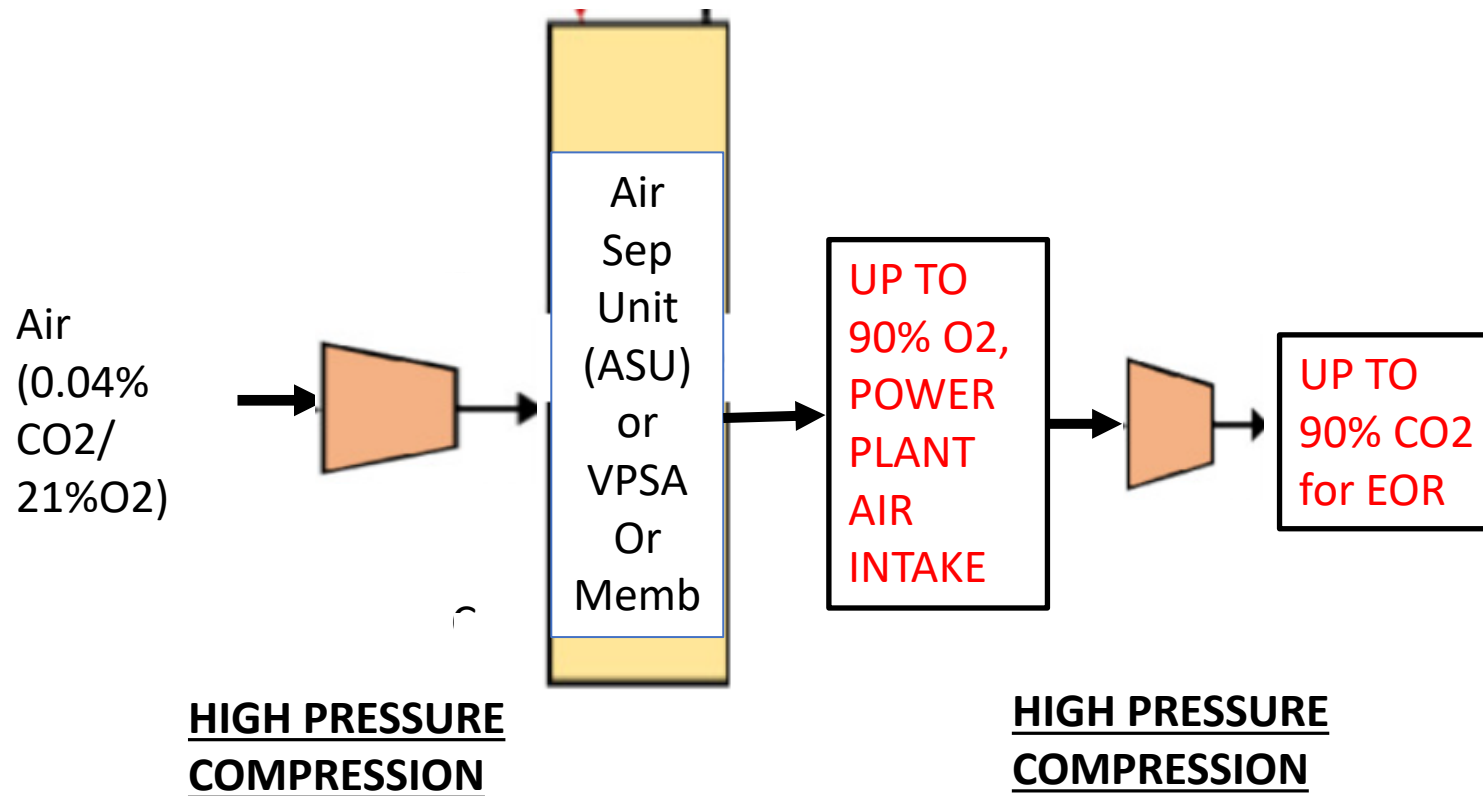
DOE/GO-102005-2178
September 2005
Process Heating Tip Sheet #3

<u>O2 Source</u>	<u>%O2 Purity Dry Concen</u>	<u>%O2 Net Increase</u>	<u>% Fuel Savings</u>
A Air	20.9	0 BASELINE	0
B MDAC	21-50	~1-30	30-60
C ASU Cryo/ VPSA/ PSA (Cryo/V/PSA)	90-99+%	70-80	70 Max



BLACK · SWAN

CONVENTIONAL OXY-COMBUSTION

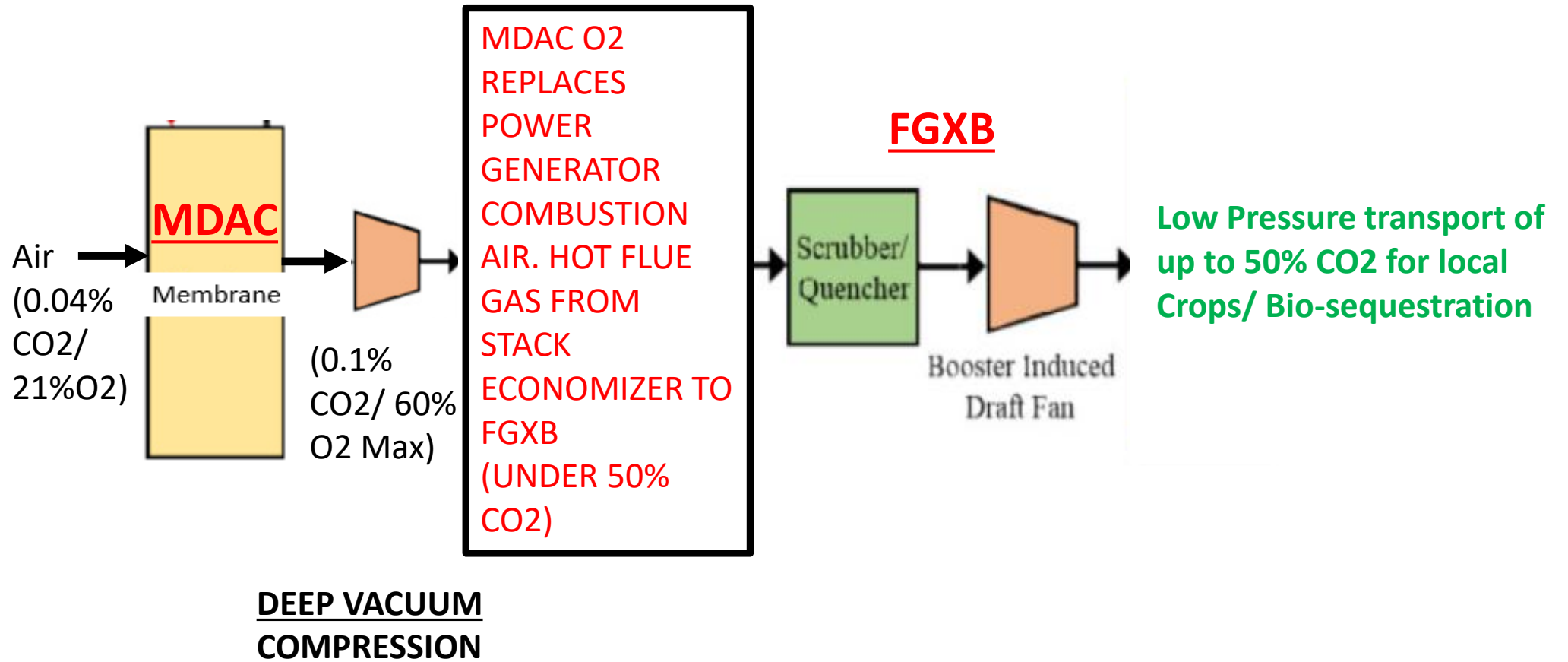




BLACK · SWAN

MDAC/FGXB

PRE/POST/ DAC/ OXY-COMBUSTION CO₂ CAPTURE





Only “Green” Capture : **BLACK · SWAN** **MDAC/FGXB** Advantage Summary

“Cherry picks” from the best, decades proven **SCALABLE** technologies

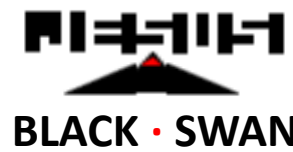
- Both are Direct Air Capture (DAC), Pre- and Post-Combustion
- Both based on large scale commercial practice for over 50 years
- Bio-sequestration (per USDA/USDOE/UCBerkeley) to 30 GT/Y Capture

Least capital/energy/resource intensive, hence **only** “green” tech

- No regeneration, high pressure compression/ high temperatures
- Min 30% less power plant fuel consumption/ No recycle for cooling

Least investment/ profitable (**2 y ROI**)/ sustainable renewable energy

- “Plug and play”-No furnace/pipe material mods- simplifies install
- 1/5 cost for conventional oxy-combustion/ a tenth of conv. DAC
- Fuel, water savings, more agriculture/biomass (renewable fuel)



Free Air Carbon dioxide Enrichment **FACE**

FLUE GAS RELEASE POINT

Before FACE

With FACE

1.Release Elevation:	100 + Ft	< 10 Ft (grow zone)
2.Release Temp:	Hot (320F)	Cold (80F)
3.Water Content	High	Very Low
4.Density/Congestion:	Low	High
5.Velocity/ Direction:	High/Upwards	Low/Downwards

Cool, Denser than Air, Slumping Enriched Gas Lingers In Orchard

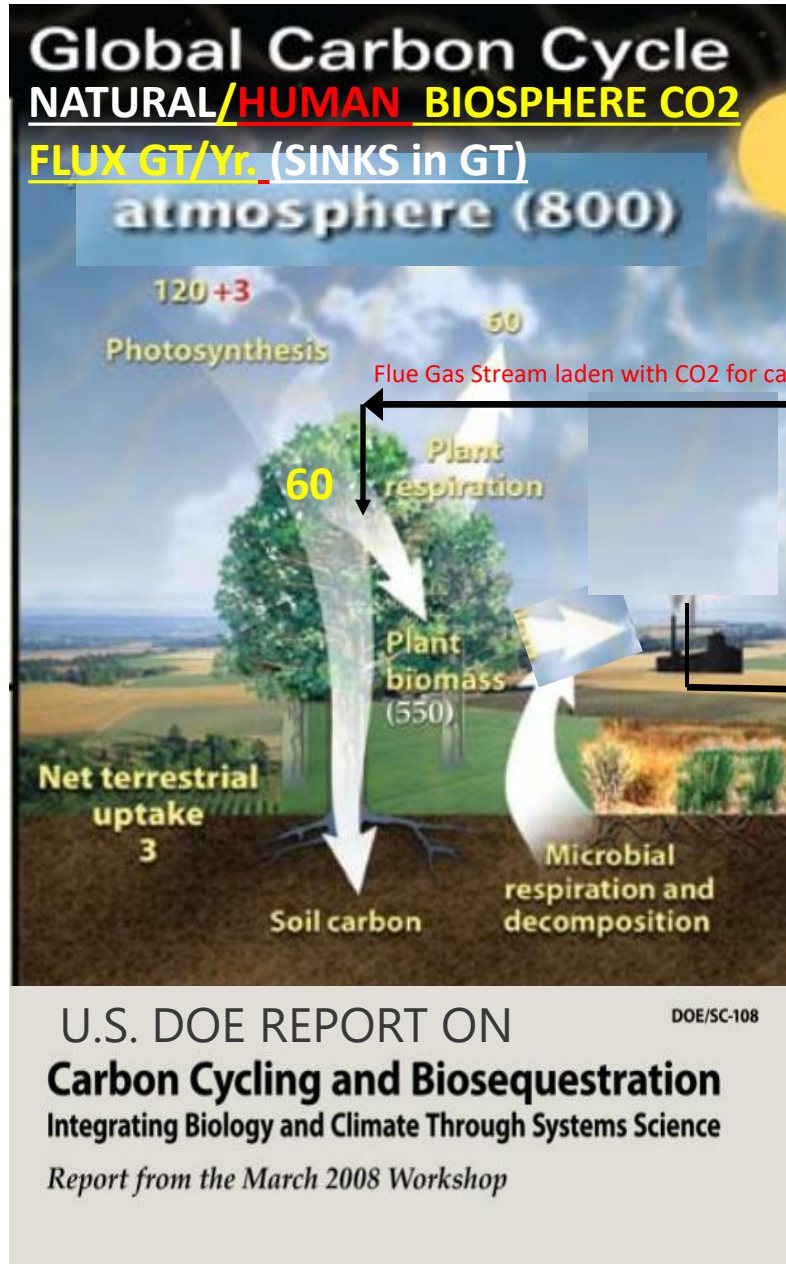


BLACK · SWAN

NOW...

... and with Global Carbon Neutrality Targets for 2035!!!

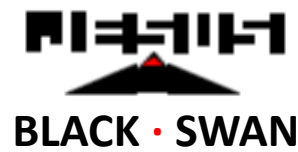
17 MILE TROPO/STRATOSPHERE ATMOSPHERIC SINK



	Before FACE	With FACE
1. Atmospheric CO2 Sink	800 GT	Target: 650 GT (-19%)
2. Avg Atmos CO2 Conc.	400+PPM	Target: 350 PPM (-12%)

FLOOD Global Boundary (100') Layer Growing Zone

3. Carbon Inventory/ Flux	0.150 GT/Y	+60 GT/Y Available
4. CO2 Concentration, PPM	400	Target: 800 (+100%)
5. Plant Biomass CO2 Sink	550 GT	700 GT (+19%)
6. Atm to Plant Flux, GT/Y	60	90
7. Biomass Fuel to Power	0.001 GT/Y	30 GT/Y



MORE RECENT GROUND BREAKING RESEARCH!

2020 BERKELEY NATURAL CYCLE/ BIOSEQUESTRATION STUDY

- GLOBAL CO2 CONCENTRATIONS...GREW...17% HIGHER FROM 360 PPM TO 420 PPM...
- 12% HIGHER PHOTOSYNTHESIS...FROM 1982 TO 2020...AN ALMOST 40 YEAR PERIOD...
- **14 GIGATONS/YR** OF ADDITIONAL CARBON (WAS) REMOVED BY PLANTS (BIOSEQUETERED)...
- ...EQUIVALENT OF THE CARBON EMITTED WORLDWIDE FROM BURNING FOSSIL FUELS IN 2020

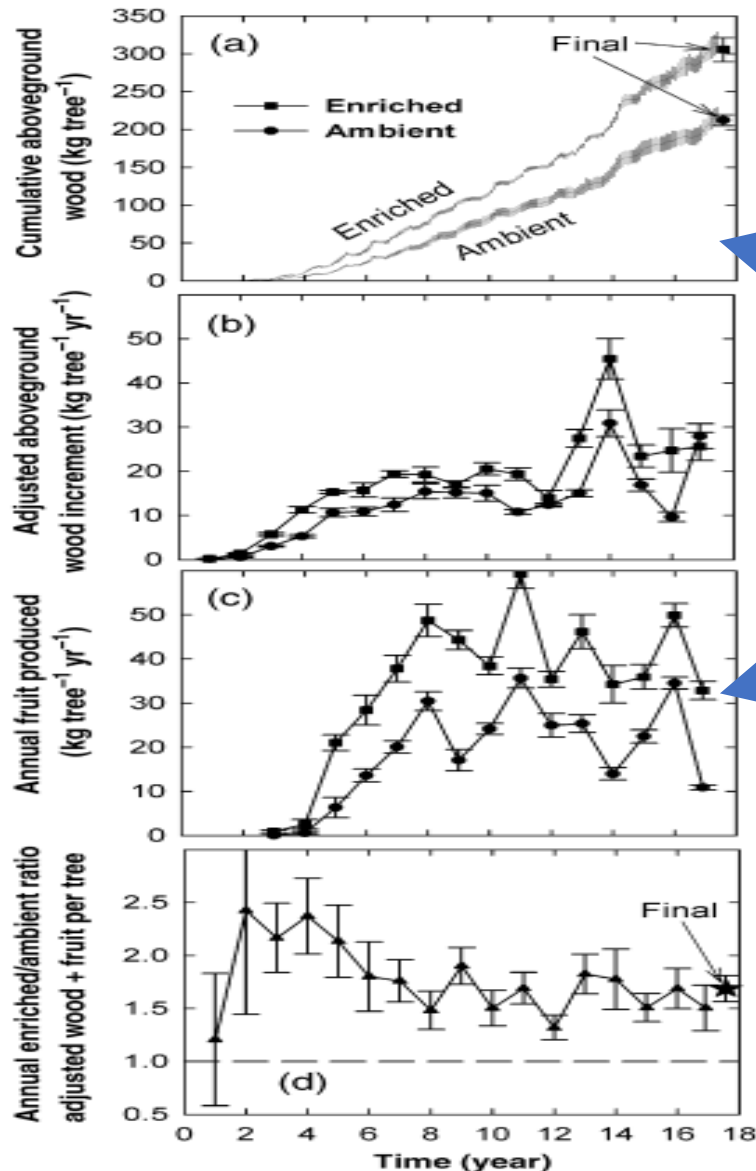
2020 BERKELEY STUDY by KEENAN ET AL WAS PUBLISHED IN NATURE...

17-YEAR CO₂ ENRICHMENT OF ORANGE TREES

B. A. KIMBALL *et al.*

MOST DRAMATIC EVIDENCE!

USDA/USDOE PUBLISHED 2007 STUDY



CIRCA 650 PPM in Open Top Chamber Crop Carbon Enrichment

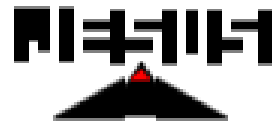
- CAPTURE: AVG 50.5% INCREASE IN BIOMASS
 - MOST BIOMASS INCREASE IN FRUIT YIELD
 - 10 MT/Y/A more than unenriched mature trees

• AVG +70% YIELD (including 4 non-producing years)

- FOUR PEAK YEARS AT +100% YIELD (6,7,11,13)
- THREE TROUGH YEARS AT +200% YIELD (9,14,17)

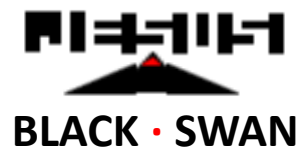
• WATER UTILIZATION EFFICIENCY (WUE) INCREASED 70%

Up to Double the Fruit with 10% Less Water!



Dozen other Crop Studies on Benefits of Crop Carbon Enrichment
60 Years of Data where Biosphere is Raised from 300 to 650 ppm CO₂
of +80 to 200% for Corn, Soybeans, Cotton, and Sweet Potatoes Yields
with Boost of Agricultural Yield and Water Use Efficiency With
USDOE/BNL Free Air Carbon Dioxide Enrichment (FACE) Technology

- 1967: Ford & Thorne (Corn +70% yield)*
- 1983: Rogers (Corn and Soybean Water Use Efficiency +100%)*
- 1984: Havelka (Wheat +35% yield)*
- 1985: Acock & Allen (Soybean +40% biomass)*
- 1985: Bhattacharya et al (Sweet Potatoes +83% yield)*
- 1986: Cure & Acock (Cotton +200% yield)*
- 1987/1989: Kimball et al (Cotton +100% yield)*
- 1993: Kimball et al (Rice/Soybeans)*
- 1994-7: Bindi et al: Grapes (+50 to 70% yield)
- 2002: Leavitt, Kimball, et al 70% Water Utilization Efficiency Increase for Citrus
- 2007: Kimball et al: Citrus (up to +70% yield, +55% WUE- using OTC, see previous slide)



FGXB

MIN EXPECTED INCREASED RETURN ABOVE COST Per UC Davis

CITRUS CROP CARBON ENRICHMENT

BASIS: MIN + 60% YIELD

<u>Dollars/Carton</u>	<u>%</u>	<u>\$/100 ACRES</u>
18.80	888%	\$362,000
19.80	436%	\$400,000
20.80	304%	\$422,000

ALMOND CROP CARBON ENRICHMENT

BASIS: MIN + 50% YIELD

<u>Dollars/lb</u>	<u>%</u>	<u>\$/100 ACRES</u>
3.00	318%	\$335,300
3.50	200%	\$445,300
4.00	145%	\$510,300



BLACK · SWAN

POTENTIAL Immediate BENEFITS of FGXB FACE Implementation

100% GREEN Capture With Just CA ALMOND ACREAGE (1.6MM):

16 Million Tons/ Year CO2

This is Over 5% of California's 300 MM T/Y CO2 Emissions

POTENTIAL ADDITION TO CALIFORNIA GDP:

\$4.5+ BILLION/YR PROFIT (NOT COST!!)

BONUS: MINIMUM 10% LESS WATER USAGE

IN CALIFORNIA'S HIGHEST WATER USER (Agriculture!)

WITH CO2 SUPPLIED BY INDUSTRIALLY SOURCED FLUE GAS



BLACK • SWAN

KOLODJI CORPORATION- DOSANJH ALMOND ORCHARD CARBON ENRICHMENT PILOT FGXB

QUENCH COLUMN MADE WITH DUCTING AND SPRAYERS

Reduce gas temperature



UC
CE

University of California

Agriculture and Natural Resources | Cooperative Extension



BLACK • SWAN

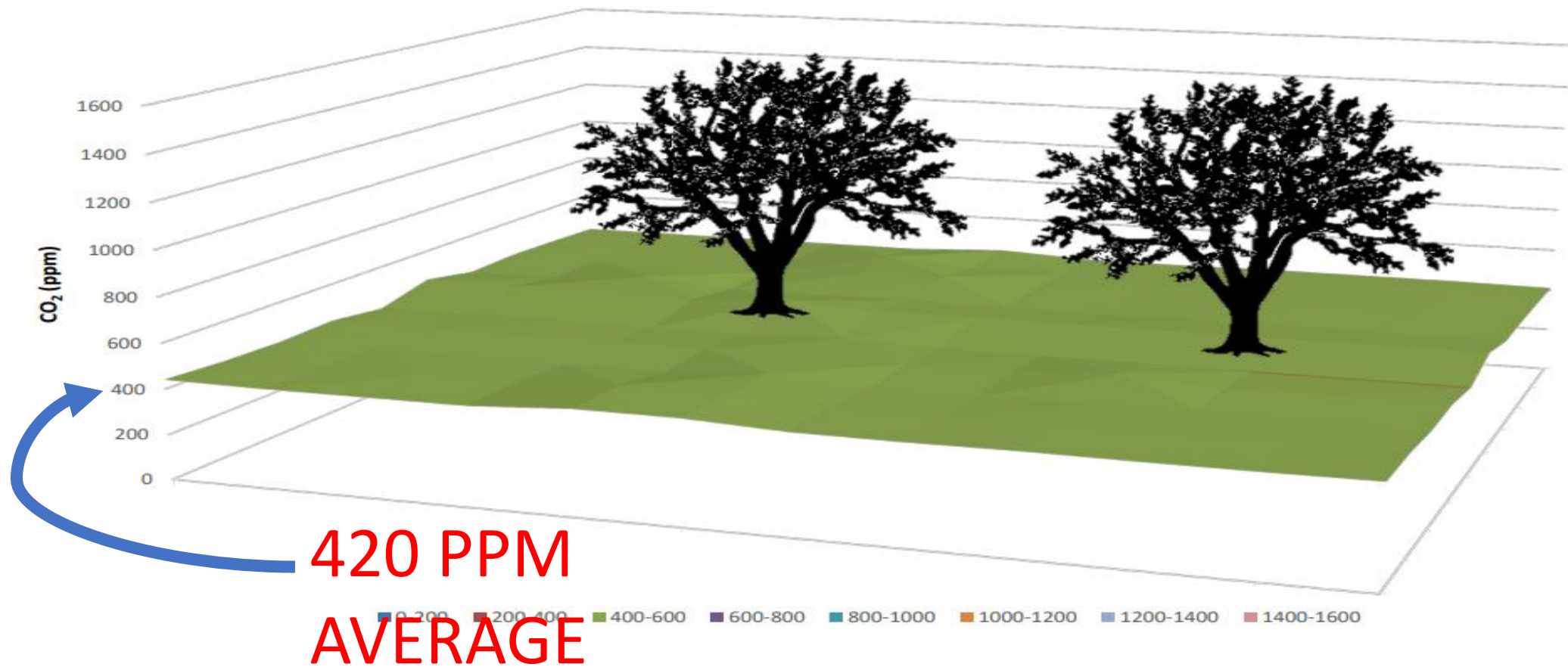
KOLODJI CORPORATION- DOSANJH ALMOND ORCHARD CARBON ENRICHMENT PILOT FGXB
CARBON DIOXIDE INSTRUMENTATION AND DISTRIBUTION DUCTING



600+PPM Sustained for Multiple Hours!

BASE LINE AMBIENT CO₂ (3-CONCENTRATION AT GRADE)

Ambient day time CO₂ concentration. Tree images display the location of trees in relation to 3D CO₂ data for the following images of CO₂ concentration over time during enrichment.

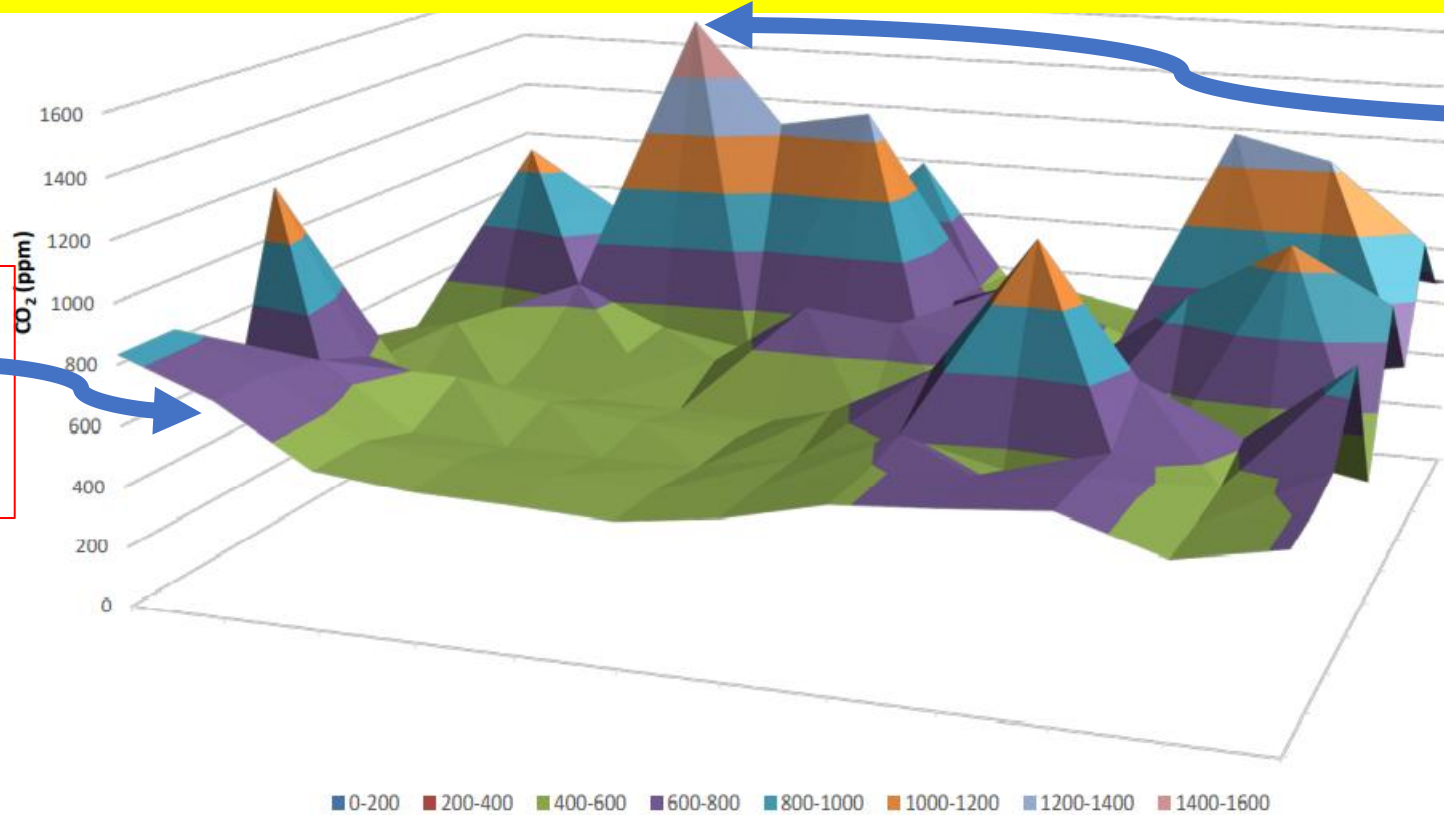




BLACK • SWAN
FGXB

TWO TREE ENRICHED CO₂ 3-D CONCENTRATION PROFILE BELOW 10 FEET PEAKS

700 PPM
AVERAGE

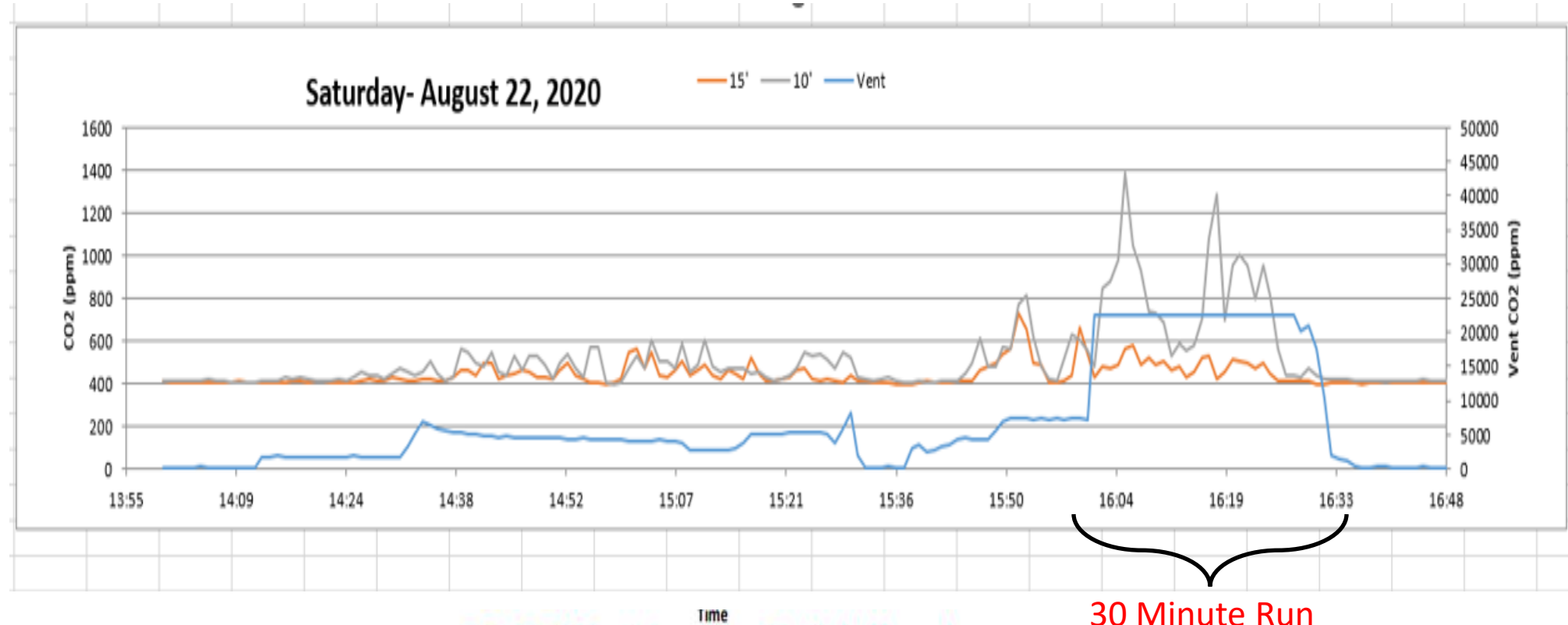


1500 PPM
PEAK



BLACK · SWAN

“KITTY HAWK MOMENT”



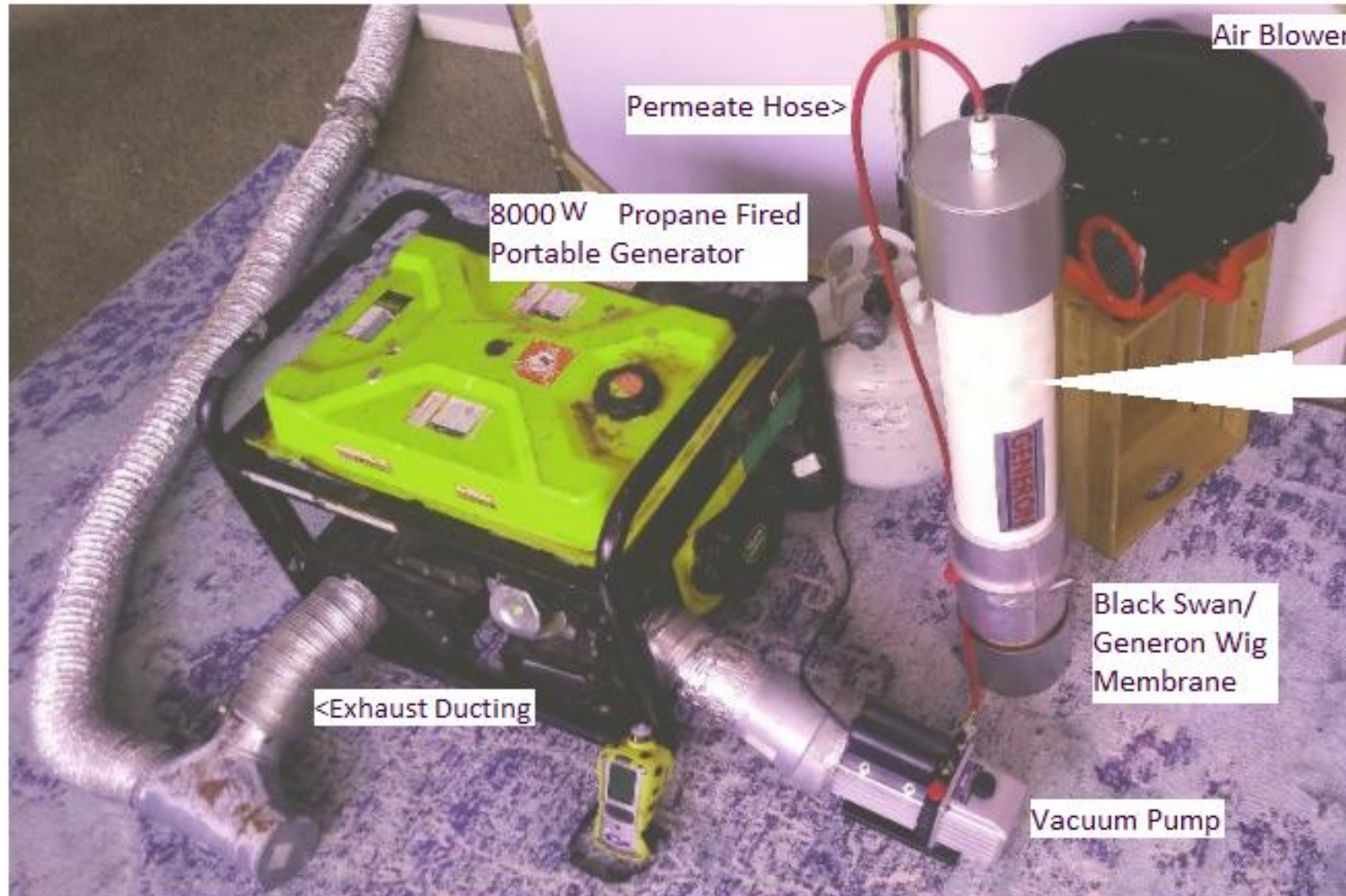
30 Minute Run
1000 ppm avg at 10'
550 ppm avg at 15'



BLACK · SWAN

100 Ton/Year CO₂, 12HP, 8 KW

Bench Scale M/DAC OxyComb Wig™ Membrane



DETAIL OF AIR INLET PORTS

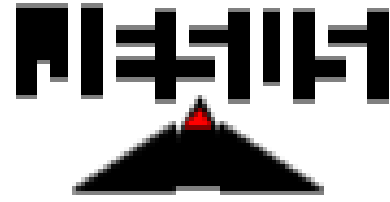




...ELEGANT...NATURAL...GRACEFUL...

OBVIOUS ONLY IN HINDSIGHT

COUNTER-INTUITIVE



BLACK · SWAN

THE ONLY “GREEN” ECONOMIC CAPTURE TECHNOLOGY
QUICKLY SCALABLE TO 50 GT/YEAR

- Achieve Carbon Neutrality in CA by 2025!
- Achieve US Carbon Deceleration at -0.04 GT/Yr^2 by 2030!
- Achieve Carbon Neutrality around the World by 2035.

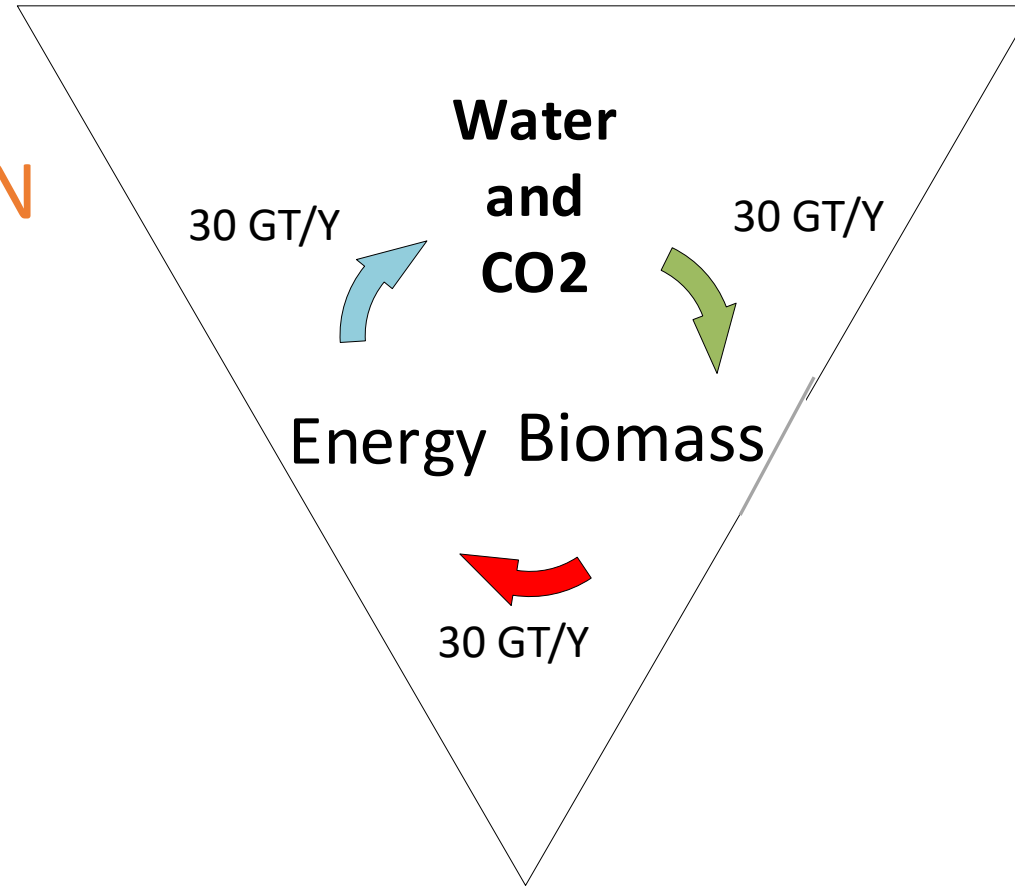
Carbon Management that Profitably makes Fuel, Water, and Sugar with...!



BLACK • SWAN Cycle

mDAC/
OXY-COMBUSTION

eDAC/ FACE



BIOMASS/ BIOFUEL

CARBON MANAGEMENT HARNESSSED with “POWER OF BREATH”



Black Swan, LLC

11/14/2022

Jesus said to them, again,

“Peace be with you. As the Father has sent Me, so I send you.”

And when He had said this,

He breathed on them and said to them,

“Receive the Holy Spirit.”

THANK YOU FOR YOUR TIME & PATIENCE!!!!

Brian Kolodji, PE, President and Owner

Kolodji Corp and Black Swan, LLC

bkolodji@Csbcbglobal.net, ell: (713) 907-8742